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Achieving sustainable cultivation of oil palm

Volume 2: Diseases, pests, quality and sustainability

Edited by Professor Alain Rival
Center for International Cooperation in Agricultural Research for Development (CIRAD), France

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Volume 2: Diseases, pests, quality and sustainability

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Introduction

Oil palm is widely cultivated in tropical countries for use in food and feed, personal care products and other applications such as biodiesel. Cultivation faces a range of challenges, such as its environmental impact (deforestation and biodiversity loss), threats from pests and diseases, and the need to better support smallholders. There is thus an urgent need to make oil palm cultivation more efficient as well as environmentally and socially sustainable.

These challenges are addressed in the two volumes of *Achieving sustainable cultivation of oil palm*:

- Volume 1: Introduction, breeding and cultivation techniques
- Volume 2: Diseases, pests, quality and sustainability

Volume 1 covers breeding and cultivation techniques, while Volume 2 (this volume) reviews advances in understanding and managing fungal and other diseases affecting oil palm as well as insect pests. It includes integrated management tools in pest and disease control and the generation of disease-resistant oil palm varieties. It also discusses the latest research on palm oil and human health, addressing debates about the nutritional value and health effects of palm oil. The key issues of sustainability and conservation are also examined. Chapters cover the monitoring of the environmental impacts of oil palm cultivation, including life cycle analysis, sustainability certification, conservation, waste management and recycling. Finally, the volume looks at how best to support smallholders in attaining sustainable oil palm production in practice.

Part 1 Diseases and pests

The first part of the volume reviews the latest research in understanding and managing fungal and other diseases affecting oil palm, such as basal stem rot (BSR), vascular wilt and bud rot, as well as insect pests.

Chapter 1 focuses on fungal disease affecting oil palm. The chapter concentrates on one agent of basal stem rot, *Ganoderma boninense*, but it also addresses *Fusarium* wilt and bud rot disease. It examines the symptoms and sources of *Ganoderma* disease and infection, the latest research on resistant materials, including laccase gene discoveries, and techniques for developing resistance against BSR in plant material. It also reviews future trends in research in this field.

Chapter 2 then looks at the exotic and emerging diseases affecting oil palm production, especially in West Africa, Southeast Asia, and South and Central America. It describes these key diseases, including basal stem rot, dry basal rot disease (*Thielaviopsis paradoxa*), bud rot disease (*Phytophthora palmivora*) and vascular wilt disease (*Fusarium oxysporum* f.sp. *elaeidis*). It also discusses phytoplasma diseases in South and Central America, such as lethal wilt disease (LWD) and leaf stripe disease (LSD). In the case of each disease, the chapter outlines its biology, symptoms and effects on yield, as well as its epidemiology. The chapter also highlights the methods that are currently being applied to control them.

In Chapter 3 attention turns to the insect pests affecting oil palms. Monocultures such as oil palm are known to face stronger parasitic pressure. *Coleoptera* and *Lepidoptera* are the main insect pests affecting the oil palm on all continents where it is cultivated. This chapter offers an overview of the major types of oil palm pests (23 species), which have been specifically selected to illustrate the relationships found between the oil palm and the most damaging groups of herbivorous arthropods. It concentrates on the major oil palm insect pests found in oil palm plantations in Latin America, West Africa, Southeast Asia and the Pacific, and assesses future research trends in the study of oil palm pests.

Continuing on the theme of pests in oil palm, Chapter 4 examines Integrated Pest Management (IPM) protocols which are central to sustainable palm oil production. This chapter explores the rapid expansion of oil palm and its impact on the environment, the range of pest species found in plantations, and the impact of replanting on pest numbers. The chapter introduces the concept and history of IPM in oil palm as well as the diverse range of approaches which form IPM strategies, including plant breeding, targeted chemical applications, management to reduce pest numbers and transmission, and management to increase the numbers of natural enemies and pathogens of pests. The chapter concludes by considering how approaches that are focused towards more diverse oil palm landscapes and more diverse pest control species assemblages can increase the effectiveness of IPM.

Chapter 5 continues to examine integrated management techniques but returns to the subject of diseases in oil palm. It considers the integrated management of bud rot disease and *Phytophthora palmivora* in oil palm. This chapter provides a general overview of the history of research on oil palm bud rot disease, which is believed to constitute the most important limiting factor for palm oil production in Central and South America. It presents the different approaches adopted in identifying the causative agent of the disease and its management. The chapter describes recent research work undertaken by the Colombian Oil Palm Research Centre (Cenipalma) which is aimed at providing evidence that *Phytophthora palmivora* can be considered as the causative agent of bud rot, as well as suggesting strategies for controlling its spread throughout oil palm stands. Such a historical overview is necessary in order to understand the importance of the disease, and to show how knowledge regarding its biological determinants is required for developing a successful integrated pest management programme. This will be a prerequisite go any further development of sustainable palm oil production in Central and Latin America.

In the last chapter in Part 1, attention turns to disease-resistance in oil palm varieties. Chapter 6 describes advances in the breeding of disease-resistant varieties, presenting the key issues associated with oil palm disease-resistance, including the usefulness and sustainability of resistance, simple modelling of disease development and the agricultural practices and screening required to enable it. The chapter focuses on the achievement of improving genetic resistance to three major diseases of oil palm: *Fusarium* wilt, *Ganoderma* basal/upper stem rot, and bud rot. The chapter ends by looking ahead to potential future developments in the field of oil palm disease-resistance.

Part 2 Nutritional and sensory quality

There is a great deal of confusion regarding the nutritional value and health effects of palm oil. The second part of this volume therefore focuses on the health and nutritional impacts of oil palm.

Chapter 7 looks at bioactive compounds in oil palm. There is growing evidence for the protective effect of plant bioactives against diseases, and this has led to interest from the functional food and nutraceutical industries for the development of bioactive-enriched food and supplements. The oil palm fruit is a source of both lipid and water-soluble bioactives. This chapter begins by considering lipid-soluble bioactives and their potential health benefits. It then considers water-soluble bioactives which have only recently received attention. These include phenolic compounds and shikimic acid, which show potential health benefits against a whole spectrum of diseases, including cardiovascular disease, cancer and diabetes. These water-soluble compounds enter the aqueous stream (vegetation liquor) and are usually discarded as palm oil mill effluent. The valorisation of palm oil milling waste for the production of functional food and nutraceuticals offers an opportunity for increased productivity and sustainability of the oil palm industry. The chapter ends with a look at future trends and developments.

Continuing the theme of the previous chapter, Chapter 8 reviews the effects of palm oil consumption on human health, including its effects on cardiovascular risk markers such as fasting lipids and lipoproteins and post-prandial plasma lipids and lipoproteins. The evidence for a connection between cardiovascular problems and the consumption of saturated fatty acids more generally is also considered. While palm oil is often criticised for its supposed effects on human health, due to its high saturated fatty acid content, it is this high saturated fatty acid content (50%) which makes it a solid oil, and therefore a good technological alternative to partially hydrogenated trans fatty acids. Palm oil has therefore enabled a reduction in the intake of trans fatty acids. This chapter argues that there is a place for palm oil in a healthy, balanced diet.

Part 2 closes with a specific case study. Chapter 9 investigates the nutritional value of red palm oil. It looks at the controversy and conflicting views that still persist on whether or not palm oil is atherogenic. The primary focus of this chapter is on the nutritional value of crude (red) palm oil, specifically as a source of vitamin A. The chapter includes a detailed case study on the use of red palm oil in Burkino Faso, specifically the effects on the vitamin A status of women and children. It also looks at the use of red palm oil in food biofortification as well as its effects on women's income and empowerment. It also looks ahead to future trends for research in this area.

Part 3 Sustainability and supporting smallholders

The third part of this volume looks at the environmental impacts of and sustainability of palm oil cultivation, and how best to support smallholders in oil palm production. Chapters 10 and 11 begin by looking at the life cycle assessment (LCA) of palm oil. LCA is a tool for evaluating the environmental impact of a product or process throughout its entire life cycle.

Chapter 10 looks at the methods and applications of LCA of palm oil. Oil palm impacts on the environment both during cultivation and as a result of land use change for new plantations. It is therefore crucial to have adapted models and tools that allow the best oil palm cultivation practices to be identified in order to reduce the environmental impacts of cultivation. Chapter 10 describes the principles and methodology of LCA of oil palm products. It reviews the results from published LCA and greenhouse gas (GHG) assessments on palm oil products, including the environmental impact of oil-based bioenergy and of oil palm fruits and palm oil. Finally, it discusses the information yielded by existing studies on the environmental impacts of palm oil and outlines the remaining challenges regarding LCA development and applications for palm oil products.

Chapter 11 discusses the practical application of LCA, taking Malaysia as an example. The chapter charts the environmental performance of the production of crude palm oil (CPO) and suggests measures to mitigate its environmental impact. Case studies examine the environmental impact of different scenarios, including land use change from logged-over forest to oil palm production, and assesses the impact of biogas emissions from palm oil mills. The chapter argues that biogas capture facilities and methane avoidance are positive steps towards mitigating the environmental impact of the oil palm industry. It closes with a look at future trends.

Chapter 12 moves on to discuss approaches to modelling the environmental impacts of oil palm agriculture. The cultivation of crops affects the environment via flows of energy and materials. Impacts are felt in the atmosphere, hydrosphere, surrounding terrestrial ecosystems and the field itself. Models are useful tools for improving our understanding of the processes and predicting how they might be affected by changes in management. Current models range from simple indicators of risk or impact, based on empirical relationships, to dynamic process-based models. Increasingly complex and comprehensive models with greater spatial and temporal resolution and extent are being developed, mostly by coupling diverse sub-models. This chapter reviews the range of models developed for oil palm systems, and discusses how other existing models might be adapted for oil palm.

Building on the previous chapters, Chapter 13 discusses sustainability certification in oil palm cultivation. In recent years, transnational private regulations, aimed at implementing sustainable development principles, have emerged across several commodity sectors. To address the growing environmental and social concerns raised by oil palm expansion, the sector has adopted voluntary sustainability standards led by industry and civil society, as well as national standards and regulations implemented by the main producing countries. This chapter presents these sustainability initiatives as well as addressing some of their important limitations, due to the increasing complexity of the regulatory framework, the market segmentation associated with a growing demand for non-certified palm oil from emerging countries, and the unresolved issues of smallholders' inclusion in certification. The chapter suggests a way forward for sustainability certification, which includes strengthening global cooperation and including smallholders in the process, and looks ahead to future research in this area.

Chapter 14 looks at the issue of balancing oil palm cultivation with forest and biodiversity conservation. With the formation of the Roundtable for Sustainable Palm Oil, environmentalists and consumers anticipated a decrease in the indiscriminate destruction of tropical rainforests. Ten years later, thousands of hectares of tropical rainforests continue to be cleared for oil palm plantations in the tropical world and endangered species are being lost in the process. This chapter, based on six years of collaboration between Copenhagen Zoo and United Plantations Bhd in Central Kalimantan, Malaysia, describes how measuring, monitoring and managing the environmental impact of plantation operations are key components in sustainable palm oil production. The chapter examines the impacts of oil palm cultivation on biodiversity. The chapter recommends that dedicated companies develop environmental divisions at estate level in order to ensure that biodiversity concerns are integrated into standard operational procedures.

In Chapter 15 the discussion turns to waste management and recycling in oil palm cultivation. In a typical palm plantation, almost 70% of the fresh fruit bunches are turned into wastes in the form of empty fruit bunches, fibres and shells, as well as liquid effluent. Until recently, most of the wastes from palm oil mills were either burnt in the open or thrown away in waste ponds or open areas. This has contributed enormously to global climate change by emitting carbon dioxide and methane. This chapter reviews the technological advancements which now make it possible to convert palm oil waste products into useful energy or to recycle them into value-added products to generate additional profits for the industry.

In the remaining chapters of Part 3, smallholder producers become the focus. Chapter 16 begins this section by defining and categorising smallholders in oil palm cultivation. This chapter provides insights on oil palm smallholders in the Riau Province of Sumatra, Indonesia. The chapter characterises smallholders' production structures in terms of human, social and physical assets. The chapter looks ahead towards forming a typology of independent smallholders and ends with an examination of future trends in this area.

This section then moves on to looking at ways to improve cultivation practices. Chapter 17 looks at ways of closing yield gaps for small- and medium-scale oil palm producers. The proportion of small- and medium-scale growers in the Colombian oil palm sector has increased in recent years, both in terms of the land area planted and the number of growers. However, a yield gap has been found between producers, based on their size, with large-scale producers attaining average yields of 6.6 ton FFB per hectare per year, which is higher than those obtained by small- and medium-scale producers. One reason that could explain this yield gap is the failure to adopt technologies which could improve yields. This chapter makes use of a detailed case study of the strategies that were implemented by Cenipalma in Colombia to narrow the yield gap between large and small oil palm producers. These strategies included the use of organic matter on palm stands to improve soil conservation and nutrition, improved irrigation, developing institutional arrangements and adopting a technology transfer strategy. The chapter proposes future lines of research on further improving the efficiency of oil palm production at both large and small scales.

In the final chapter of Part 3, Chapter 18, the focus returns to artisanal mills and the local production of palm oil by smallholders, this time in Africa. In Africa, there are two oil palm supply chains. The first goes from industrial plantations and surrounding smallholdings to a formal market of commercial oils complying to international quality standards, while the second goes from smallholdings and 'wild groves' to an informal market of artisanal red palm oil. It is the second of these that is discussed in this chapter. The chapter reviews the emergence of artisanal extraction of red palm oil in Africa, considers who is involved in this supply chain and why, and discusses the major operations and equipment involved in artisanal processing, from harvesting, storage, threshing and steam sterilising to crushing, mixing, oil extraction, clarification and oil drying. It then reviews the composition and quality of artisanal palm oil and its various uses (in human health and for human consumption at home and in the food industry). Finally, it considers the sustainable development issues associated with artisanal red palm oil production.

Dedication

The two volumes of *Achieving sustainable cultivation of oil palm* are dedicated to the memory of our very esteemed colleague Hubert de Franqueville. Hubert was a renowned and brilliant scientist with an elegant and precise mind who was highly appreciated by the whole palm community. I would have loved sharing the editing of these two volumes with Hubert. We all miss his sharp understanding and exquisite humor.

Alain Rival
Editor

Part 1

Diseases and pests

Chapter 1

Fungal diseases affecting oil palm

Tan Joon Sheong, Lee Yang Ping and Sharifah Shahrul Rabiah Syed Alwee, FELDA Global Ventures Research and Development, Malaysia; Létizia Camus-Kulandaivelu, Maxime Mercière, Alba Zaremski and Frédéric Breton, CIRAD, France; and Christophe Klopp, INRA, France

1 Introduction

Oil palm has proved to be the most efficient and productive oil crop, giving far higher yields when compared to soybean, rapeseed and sunflower. As of October 2014, the production of palm oil was reported at 53.67 million tonnes, compared to soybean at 41.66 million tonnes, rapeseed at 24.48 million tonnes and sunflower at 14.8 million tonnes (www.oilpalmresearch.org). Based on the statistics obtained from the Malaysian Palm Oil Board in 2015, Malaysia's export of palm oil reached 17.31 million tonnes. The majority of Malaysian palm oil was exported to India (3.25 million tonnes), China (2.84 million tonnes) and the Netherlands (1.60 million tonnes). However, oil palm is also prone to attack by a number of fungal diseases such as basal stem rot (BSR), *Fusarium* wilt (vascular wilt) and bud rot disease. To date, only partial resistance materials have been identified for the BSR, and we will be providing more insights into the BSR that is causing a major problem on plantations particularly in Malaysia and Indonesia. Meanwhile, resistant planting materials were found for the latter two fungal diseases.

In Southeast Asia, one of the most devastating diseases at the moment is BSR. The disease was first described in 1915 in the Republic of Congo, West Africa (Wakefield, 1920). Thompson (1931) detected the disease infecting palms aged over 25 years in

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Figure 1 The presence of *G. boninense* mature fruiting body (basidiomata) found on an oil palm tree showing basal stem rot disease.

Malaysia on old palms due for replanting. BSR disease, which is caused by the fungal species *Ganoderma boninense* (Fig. 1), is the most serious disease affecting the oil palm in Malaysia and Indonesia (Ariffin et al., 1989; Rao, 1990). The disease progresses slowly and eventually causes the death of infected palms. The disease can infect all stages of the oil palm, and palms infected at the early stage of their life cycle usually show no symptoms until after they are more than 12 years old (Lubis, 1992).

2 BSR caused by *Ganoderma boninense*

Ganodermataceae are cosmopolitan basidiomycetes which cause white rot of hardwoods such as oak, maple, maple, sycamore and ash by decomposing lignin, cellulose and related polysaccharides (Hepting, 1971; Blanchette, 1984; Adaskaveg and Ogawa, 1990; Adaskaveg et al., 1991, 1993). *G. boninense* Pat. is known to be the causal agent of BSR in oil palm (Ho and Nawawi, 1985; Abadi, 1987; Khairuddin, 1993; Utomo, 1997; Soepena et al., 2000).

Figure 2 Plantation with severe BSR disease with vacant planting spots in the field.

Soepena et al. (2000) reported that in the second and third cycles of replanting oil palms in the same place, the symptoms can appear as early as one to two years after planting. A more acute *G. boninense* problem is likely to surface over the next few years as the fungus increases its geographical range and virulence (Murphy, 2007). Singh (1991) conducted a study aimed at quantifying yield losses based on fresh fruit bunch (FFB) production and concluded that FFB production was adversely affected by the incidence of the disease. Losses due to BSR are not only through the direct reduction in oil palm numbers in stands, but also through a decrease in fruit bunch number and weight from diseased standing palms (Fig. 2), as well as from those with sub-clinical infections (Turner, 1981). The disease can result in the death of more than 80% of the plants by the time that they are halfway through their normal economic life and losses, reaching 30% have quite frequently occurred (Turner, 1981).

2.1 Symptoms of *Ganoderma* disease

In young palms, the external symptoms of BSR normally include a one-sided yellowing, or mottling of the lower fronds, followed by necrosis (Singh, 1991a). Ariffin et al. (2000) reported that in cases of infection, the newly unfolded leaves were shorter than normal, chlorotic, and the tips may be necrotic. As the disease progresses, palms may take on an overall pale appearance, with retarded growth and spear leaves remaining unopened.

Similar symptoms are observed in mature palms, with multiple unopened spear leaves and an overall pale leaf canopy. Often, when foliar symptoms are observed, it is found that at least one-half of the basal stem tissue has already been killed by the fungus. Infected young oil palms normally die at 6–24 months after the first appearance of symptoms, although mature palms can take 36 months to die.

2.2 Possible sources of *Ganoderma* infection

There have been numerous theories on the possible source of *Ganoderma* infection in oil palm. Oil palm stands were found to exhibit BSR symptoms at 10–14 years after planting following the conversion of rubber plantations (Flood et al., 2000). Meanwhile, a more widely accepted hypothesis proposes that *Ganoderma* attacks the root system from second and subsequent replanting cycles of oil palm. Through a series of controlled *Ganoderma* nursery trials, Rees et al. (2007, 2009b) clearly indicated that controlled root infection leads to typical symptoms. Rees et al. (2007) showed that root infection in the field originates from multiple, natural infections of different roots in a single palm. This finding, which is consistent with results from Flood et al. (2005), indicated that infection of the seedlings resulted from nearby colonized oil palms, with those seedlings nearer to the colonized trunks becoming diseased more quickly than others.

More recent findings showed that basidiospores were involved in the development of both manifestations (upper and basal) of stem rot (Rees et al., 2012). Authors reported that basidiospores were produced in prolific numbers throughout the sampling period, with a maximum release intensity during the evening, earlier than the midnight maximum release reported by Ho and Nawawi (1986). This suggested a constant potential for inoculum to colonize wounds and palm debris throughout the plantation (Rees et al., 2012; Cooper et al., 2011). The idea that spores from fruiting bodies (basidiomata) were identified is not new, as Lim and Fong (2005) and Utomo et al. (2005) had hypothesized the most likely sources of inocula for further infection via root contact.

2.3 Studies of BSR caused by *Ganoderma* sp. in oil palm

BSR was found to be a significant constraint for the oil palm plantation industry (Miller et al., 1999). In the subsequent year, Flood et al. (2000) stated that BSR has been a serious disease of oil palm for over 80 years, with severe economic loss in both Malaysia and North Sumatra (Indonesia). Bridge and Utomo (2005) suggested that *Ganoderma* infections occur over a period of several years, which is much longer than the timescales for other severe fungal plant pathogens (e.g. *Fusarium oxysporum*).

Ariffin et al. (2000) described how basidiomata develop at either the stem base, leaf base, or infected root, with the location providing a guide to the diseased area inside the palm. Abdullah's (2000) study on *Ganoderma* in coconut hypothesized a spread from independent secondary inocula, and their work did not support root-to-root spread and/or airborne spore spread. In contrast, a review by Paterson (2007) suggested that roots were thought to be the mode of spread. This idea, that infection results from contact between healthy roots and diseased tissue remaining in the soil, appears to be widely accepted. Interestingly, Bridge et al. (2004) mentioned that almost all isolates of *G. boninense* differed from one another. Therefore, the author emphasized the importance of basidiospores, and argued that ignoring this route of infection and the generation of new pathogen variation would be a mistake.

2.4 Effects of BSR on Malaysia's oil palm plantations

Due to the scarcity of available arable land in Malaysia, and the implementation of new land regulations on land use change, the expansion of oil palm plantations is now very limited. Plantation companies have to deal with this limitation by embarking on intensive replanting activities, including planting land that is heavily infected with BSR. Based on the

G. census conducted in Malaysia by Idris et al. (2011), 632 out of 1061 plantations (~60%) have recorded BSR incidence.

It was estimated by the Federal Land Development Authority (FELDA) that 200 million Malaysian Ringgit (US$45 million) had been lost due to the impact of BSR in the first generation of oil palm planting in Malaysia (Sirrul et al., 2016). Astonishingly in the same report, *Ganoderma* infection was found to be on the rise, as 264 plantations (61%) were found to be infected with BSR disease in 2015. Through this census, where all the FELDA's plantation schemes participated, BSR was observed in plantations two years after replanting had been completed.

A field study was conducted by Sirrul et al. (2016) in order to compare the levels of *Ganoderma* incidence between sanitation-windrowing palm debris (*standard practice*), under-planting practices (Fig. 3), and sanitation, against non-sanitation areas. Through these observations, it was found that plots practising under-planting showed a very high incidence of *Ganoderma*, which was to be 110% higher than plots cultivated under standard practice. The results, after eight years of the re-planting programme in the non-sanitation area, recorded *Ganoderma* incidence at about 4.47–4.66%. In comparison, no *Ganoderma* incidence was observed in areas where proper sanitation processes has been practised. Therefore, under-planting is not recommended where oil palm replanting programme takes place, although this method is commonly practised by the non-participating FELDA settlers. The sanitation practice is currently being enforced in all plantations where BSR is recorded.

Figure 3 Scenario where under-planting is adopted in replanting areas, where old palms are not removed to allow proper field sanitation to take place. New planting materials were planted close to the dead palms which will eventually be culled by trunk injection (chemical). Image courtesy of Sirrul Asrar Husain Fatimi (FGV R&D Sdn Bhd).

2.5 SSR genotyping of *G. boninense* strains (Southeast Asia and Africa)

G. boninense, a soil-borne basidiomycete, is the main causative agent of one of the more devastating oil palm diseases, BSR. Several studies focused on detecting *G. boninense*'s infection, assessing isolate aggressiveness, or deciphering oil palm's defence reaction during infection (Ho et al., 2014; Tee et al., 2013; Idris et al., 2004; Utomo et al., 2000). However, only limited information is available on this pathogen's spreading properties as well as its evolvability. Spreading properties encompass the reproduction mode (sexual vs. asexual), the dispersion ability of the propagules, or even the number of isolates effectively contributing to reproduction in a given population. Evolvability is the capacity for a given population to generate adaptive genetic diversity that will help in adapting to new environmental constraints. These biological characteristics are very important in the sense that they govern dynamic changes of the disease, and they should both be accounted for when designing efficient agricultural practice and developing a meaningful strategy for BSR-tolerant oil palm planting material. However, spreading characteristics and evolvability are also difficult to assess directly. A good strategy to evaluate these factors is to estimate population genetic parameters associated with genetic diversity, and population structure by means of an appropriate set of molecular markers.

Among many possible molecular markers, microsatellites, also called simple sequence repeats or SSRs, present very interesting properties. Microsatellites are tracts of repetitive DNA with small motifs (2–6 base pairs) repeated typically 5–50 times. They are characterized by a higher mutation rate than the rest of the genome (Brinkmann et al., 1998) and thus have a higher genetic diversity than other regions of the genome. Other advantages of SSRs include their moderate cost, the technical feasibility of their use on large samples, and their codominance and locus specificity (Jarne and Lagoda, 1996). This provides them with desirable properties for use in population genetics estimations and other demographic inference (Luikart et al., 2003; Cornuet et al., 1999; Michalakis and Excoffier, 1996). In this chapter, we describe the development of a *G. boninense*-specific SSR set from a draft genome assembly and its use in population genetic analysis.

2.6 Developing an SSR set

As shown by Dutech et al. (2007), the development of SSR is generally harder in fungi than in other groups. This difficulty could be due to the scarcity and short length of SSR in fungi genomes. Additionally, and contrary to what can be observed in plants, it is also generally hard to transfer SSR between fungal species of the same genus (Dutech et al., 2007). However, the increasing affordability and availability of sequencing data from next-generation sequencing technologies now enables access to large amount of sequenced data, from which it is possible to isolate SSR motifs.

In *G. boninense*, Mercière et al. (2015) combined 454 sequencing and Illumina data to produce a 63-Mb draft assembly that was used to identify and characterize all SSR loci. They then focused on a subset of these, in order to design primers and define amplification protocols to allow multiplexing. Accounting for SSR with perfect repeats and di- to hexanucleotide motifs only, Mercière et al. (2015) recorded a total of 2487 SSRs from the draft assembly. The SSR content (39 SSRs per Mb) of the *G. boninense* draft genome investigated is thus consistent with those published for other fungal species which ranges from tens to hundreds of SSR per Mb (Labbé et al., 2011; Karaoglu et al., 2005). It is also similar to the SSR content of the *G. lucidum* genome (37 SSRs per Mb) (Qian et al., 2012). While it was not possible to undergo marker development for the complete *G. boninense* SSR set, 145 of them were randomly selected for primer design. A preliminary step of *in silico* polymerase chain reactions allowed 35 of them to be discarded because of non-monolocus targeting. The remaining 110 SSR primers were then evaluated *in vitro* on a small subset of 5 *G. boninense* isolates: 17 primer pairs were finally retained according to their monolocus amplification pattern, polymorphism and the possibility to multiplex their amplification and genotyping. These 17 primers were used to study a collection of 107 *G. boninense* isolates from North Sumatra (Indonesia), Peninsular Malaysia and Sabah (part of Borneo), to validate their desired amplification and sufficient polymorphism level.

2.7 Deciphering *G. boninense* in Malaysia and North Sumatra

Malaysia and North Sumatra are the historical centres for large-scale cultivation of oil palm, and at the same time, for BSR development in Southeast Asia. Therefore, studying *G. boninense* genetic diversity in these particular regions is of key interest. Mercière et al. (2017) collected and genotyped an extensive sample of 311 isolates from Peninsular Malaysia (FELDA plantations) and North Sumatra (Socfindo plantations), and used 11 of the previously mentioned SSRs (Mercière et al., 2015) to investigate the various characteristics of their genetic diversity, in an attempt to decipher the biological processes that may have shaped them. It appeared that *G. boninense* exhibited a high level of genetic diversity (H_e = 0.651) with only a few duplicated genotypes. The five pairs of duplicated genotypes studied, originating from either Peninsular Malaysia or North Sumatra, were all collected from neighbouring trees, at a distance of about nine metres. These results clearly support the predominance of sexual reproduction in shaping global *G. boninense* diversity, confirming the works of Miller et al. (1999) and Pilotti et al. (2003). Additionally, this data enabled the estimation of the effective population size for the pathogen in this region. This was calculated as the number of distinct genotypes involved in breeding (about 50 000 as a rough estimate). The asexual spread from root to root appeared to be marginal, at least within the well-maintained plantations from which the samples were collected. Nevertheless, the importance of sexual reproduction has been highlighted by other authors (Rees et al., 2012; Pilotti et al., 2003; Miller et al., 1999), although those studies were limited by their geographical scope and the genetic marker used. *G. boninense's* sexual reproduction is mediated by basidiospores that are notoriously capable of large-scale dispersal (Rees et al., 2012; Hallenberg et al., 2001). This biological feature is responsible for gene flow over long distances, and for the absence of any genetic structure observed in the area encompassing North Sumatra and Peninsular Malaysia (Mercière et al., 2017). More particularly, these authors showed that *G. boninense* has a two-tier spreading pattern, with both a high capacity for dispersal over short distances (less than 2 km), and over long distances (between 500 and 700 km). Such a spreading pattern seems common to basidiospore-spread fungi as it was also identified in *Heterobasidion irregulare* (Garboletto et al., 2013).

2.8 Deciphering *G. boninense* in Southeast Asia

Besides Peninsular Malaysia and North Sumatra, BSR has been described in other regions of Southeast Asia, and in Africa. Studies were conducted in order to determine whether the development of BSR in these regions was caused by *G. boninense* genotypes closely related to those observed in Peninsular Malaysia and North Sumatra, or, on the contrary, by genotypes belonging to other *G. boninense* sub-populations, (or even due to other *Ganoderma* species). Mercière et al. (2017) genotyped an additional group of isolates using the same set of 11 SSRs previously used for Peninsular Malaysia and North Sumatra (Mercière et al., 2015). These isolates were collected in Thailand (Krabi, four isolates), Borneo (Sabah, 34 isolates), South Sumatra (7 isolates), Papua New Guinea (11 isolates) and Cameroon (32 isolates). In addition to the SSRs used, all the isolates were further confirmed with an internal transcribed spacer (ITS) sequence of *G. boninense* (Latiffah et al., 2002; Rees et al., 2012).

The diversity, as measured by the expected heterozygosity (Nei, 1987) is high, with the order of magnitude of North Sumatra (0.65) and Peninsular Malaysia (0.63), ranging from 0.57 (Papua New Guinea) to 0.62 (South Sumatra). According to El Moussadik and Petit (1996), the estimation of allelic richness buffering uneven sample sizes yielded similarly high values among locations, ranging from 3.4 (North Sumatra and South Sumatra) to 2.9 (Thailand). Based on the Bayesian clustering approach implemented in STRUCTURE software (Pritchard et al., 2000), Southeast Asia's *Ganoderma* diversity is structured in two main differentiated genetic groups (Fst = 0.13). The first group encompasses isolates from Thailand, Peninsular Malaysia, North Sumatra and South Sumatra. The second group mainly gathers isolates from Borneo and Papua New Guinea. A limited number of isolates (6) are classified as intermediate between these two groups. Finally, a significant phylogeographic signal (Hardy et al., 2003) could be detected between the two identified genetic groups, indicating low gene exchange between them. Although the analysis is still at its preliminary stage, this is an interesting discovery as it allows for the possibility of new hypotheses.

The use of SSR markers revealed that the *G. boninense* affecting oil palm in Southeast Asia is highly diverse, and subdivided into two distinct and geographically isolated sub-populations. These results may have important implications for oil palm improvement for tackling *Ganoderma*. Firstly, due to the high genetic diversity of the pathogen, associated with it's large effective population size and active sexual reproduction, one should be careful of the development of multigenic tolerance rather than monogenic total resistance, in order to design sustainable oil palm varieties. On the other hand, the subdividing of *G. boninense* in two Southeast Asian populations calls for more studies in order to better understand their differences, notably in terms of aggressiveness. Here, we have stressed the fact that human-mediated gene flows between the two *G. boninense* groups should be carefully avoided in order to prevent hybridization, possibly leading to the emergence of *Ganoderma* with increased aggressiveness. Finally, and before more knowledge on the characteristics of the *Ganoderma* sub-populations is gained, partially resistant oil palm varieties should be used, taking into account the genetic background of locally present *G. boninense* isolates (e.g. using SSR markers). The use of oil palm which has tolerance against both *Ganoderma* sub-populations will need to be fully ascertained.

3 Cellulolytic degradation as a possible mode of infection

Oil palm is susceptible to attacks from pathogenic fungi such as *Ganoderma* spp. which can cause rotting of the roots and basal stem of the standing palms. *G. boninense* among the *Ganoderma* spp. is capable of degrading the plant's lignocellulosic biomass of the cell wall.

The main components of lignocellulose are cellulose, hemicellulose and lignin (Sjöström, 1993). Studies on lignin-modifying enzymes from *Ganoderma lucidum* indicate that lignin component is the rate-limiting factor in the lignin degradation process (D'Souza et al., 1999). Deposition of lignin in the cell wall can serve as a barrier to microbial attack, because it provides strength and is a water-impermeable seal across cell walls in the xylem tissue. Lignin therefore, may play a major role in disease response mechanisms (Paterson, 2007).

The ability of *Ganoderma* spp. to mineralize lignin to produce carbon dioxide and water is remarkable. It is related to its ability to cleave the monomeric ring structures of the lignin monomers, although the physical properties of lignin are the product of aromatic heteropolymers synthesized from the phenylpropanoid aryl-C_3 units, coniferyl, synapyl and *p*-coumaryl alcohols, with at least 12 different types of linkages such as aryl-ether and carbon-carbon bonds (Boerjan et al., 2003).

Ganoderma spp. produces several types of extracellular oxidative enzymes that are related to the degradation of the lignin component of plant cell walls. For instance, manganese peroxidase and laccase in *G. lucidum* (D'Souza et al., 1999), lignin peroxidase in *G. applanatum* (Morgenstern et al., 2008; Martínez, 2002), and lignin peroxidase, manganese peroxidase and versatile peroxidase of other white rot fungi (Dashtban et al., 2010; Ward et al., 2004), are involved in the degradation of lignin.

Laccases are blue multicopper phenol oxidases, that oxidize various phenolic substrates via the reduction of oxygen to water, and also oxidize non-phenolic lignin (Bourbonnais and Paice, 1990). Laccases work with a wide range of substrates without cofactors, and they have wide applications in biotechnology (Upadhyay et al., 2016; Arora and Sharma, 2010). They are commonly used in feedstock industries (Sharma et al., 2013), textile industries (Couto et al., 2004) and soil bio-remediation (Nyanhongo et al., 2006). Laccases are produced in a wide range of organisms including bacteria, fungi, plants and insects. In fungi, laccases are involved in the degradation of lignin (D'Souza et al., 1999), whilst they are involved in the biosynthesis of lignin in plants (Sato et al., 2001).

4 Laccase gene discoveries

The genome of *G. boninense* was sequenced using Illumina and 454 sequencing technology for the discovery of microsatellite markers (Mercière et al., 2015). A draft genome sequence of 63 Mb was assembled, providing the starting genomic resources for laccase gene discoveries. *Ab initio* gene model prediction on this draft genome was performed with Augustus 2.6.1 (Stanke and Waack, 2003) using *Phanerochaete chrysosporium* as a training organism (unpublished results).

In order to discover laccase genes from the *G. boninense* draft genome *in silico*, Camus-Kulaidevalu et al. (2014) mined for the laccase genes in both the public database and the predicted gene models derived from the draft genome. In order to retrieve known fungi laccases, we searched the NCBI 'nr' protein database using keywords 'laccase' and 'fungi'. This resulted in 841 laccase protein sequences that were longer than 100 amino acids with methionine amino acid start codons, and which contained the protein sequence name 'laccase'. We analysed the essential sequence features of laccases available from the public domain, based on multiple sequence alignments of 841 protein sequences using MAFFT software (Katoh and Standley, 2013) using '-einsi' option to allow for large unaligned regions. We then used HMMER3 software (Mistry et al., 2013) to synthesize sequence profiles common to laccase alignment ('hmmbuild' module), and mined *G. boninense* predicted gene model database for putative laccase ('hmmsearch' module). Based on the full sequence score and *E*-value of 1.1^{e-63} (best fitting domain), 33 *G. boninense* gene models showed significant similarities to the laccase sequence profile based on 841 input fungus laccase alignment using HMMER software.

Among these 33 gene models fitting HMMER laccase pattern, 25 bore the four-domain laccase signature (Kumar et al., 2003). These 25 gene models displayed a predicted coding region length between 1473 and 1926 bp (between 491 and 642 amino acids). These gene models are distributed on seventeen scaffolds. Scaffold 1 bears three gene models with four-domain laccase signature; scaffold 49 bears three gene models with four-domain laccase signature; scaffolds 46, 149 and 197 bear two gene models each with four-domain laccase signature. The predicted intron number varies between 3 and 12.

Twenty-four gene models were predicted using TARGETP 1.1 (http://www.cbs.dtu.dk/services/TargetP) and 23 displayed a predicted peptide signal SIGNALP 3.0 (http://www.cbs.dtu.dk/services/SignalP). At least seven predicted laccase genes are expressed in *G. boninense* isolates, based on the sequence similarity search of 25 predicted gene models with four-domain laccase signature, against the transcriptome assembly (unpublished data) of *G. boninense* isolate cultured in potato dextrose agar plate. Our search for sequence similarities indicated that seven gene models showed strong similarity with assembled transcripts with a sequence similarity between 93 and 99% over more than 1300 bp in length.

In order to investigate the relationship of the 25 predicted *G. boninense* laccase genes with other fungi species, we aligned the putative laccases with other known fungal laccases from *Laccaria bicolor*, *Coprinopsis cinerea*, *Trametes villosa*, *G. lucidum* and *Phanerochaete chrysosporium* (in this latter case Multi-Copper Oxidase – MCO). These were retrieved from NCBI using MAFFT software (Katoh and Standley, 2013). The five species studied belong to basidiomycota, either from the polyporales order (*T. villosa*, *G. lucidum*, *Phanerochaete chrysosporium*) or from the agaricales order (*L. bicolor*, *C. cinerea*). We removed poorly aligned regions with gBlocks software (Castresana, 2000) and produced a phylogenetic tree (Fig. 4) with PhyML (Guindon et al., 2010) using default values for amino acid analysis.

Based on our analysis, predicted laccases from *G. boninense* are positioned in two groups. Gene models g9396 and g4264 are gathered with a *G. lucidum* and two *L. bicolor* laccases belonging to laccase *sensu lato* (Hoegger et al., 2006). More specifically, these two *L. bicolor* laccases are ferroxidases. The other 23 *G. boninense* predicted gene models gather in a large group solely composed of polyporales laccases, including all five *T. versicolor* laccases and 12 *G. lucidum* laccases. Interestingly, the seven laccase predicted gene models showing transcript evidence are located in the polyporales gene cluster.

In summary, Camus-Kulaidevalu et al. (2014) identified 25 gene models exhibiting the four domains with fungal laccase signatures, and the main characteristic of fungal laccases in terms of length, cellular addressing, signalling and intron number. For seven of these 25 laccase predicted gene models, we found transcript evidence supporting gene prediction. Our results suggest the existence of a specific group of polyporales *sensu stricto* laccases (Hoegger et al., 2006) for which ancient duplications occurred (Fig. 4). This group includes laccases from the white rot *G. lucidum*, *G. boninense* and *T. versicolor* but not *Phanerochaete chrysosporium*. Within the polyporales *sensu stricto* laccase group, the phytopathogenic *G. boninense* exhibit a noticeable position, with the specific expansion of some gene sub-family (e.g. gene model g6150, g580, g7800, g11265, g785), leading to a potentially doubled laccase copy number compared to its relative *G.*

lucidum. This important information allowed us to conduct further analysis for verification on lignocellulosic pathway, and the possibility of finding an inhibitor might provide a long-term solution such as systemic fungicide development in the future.

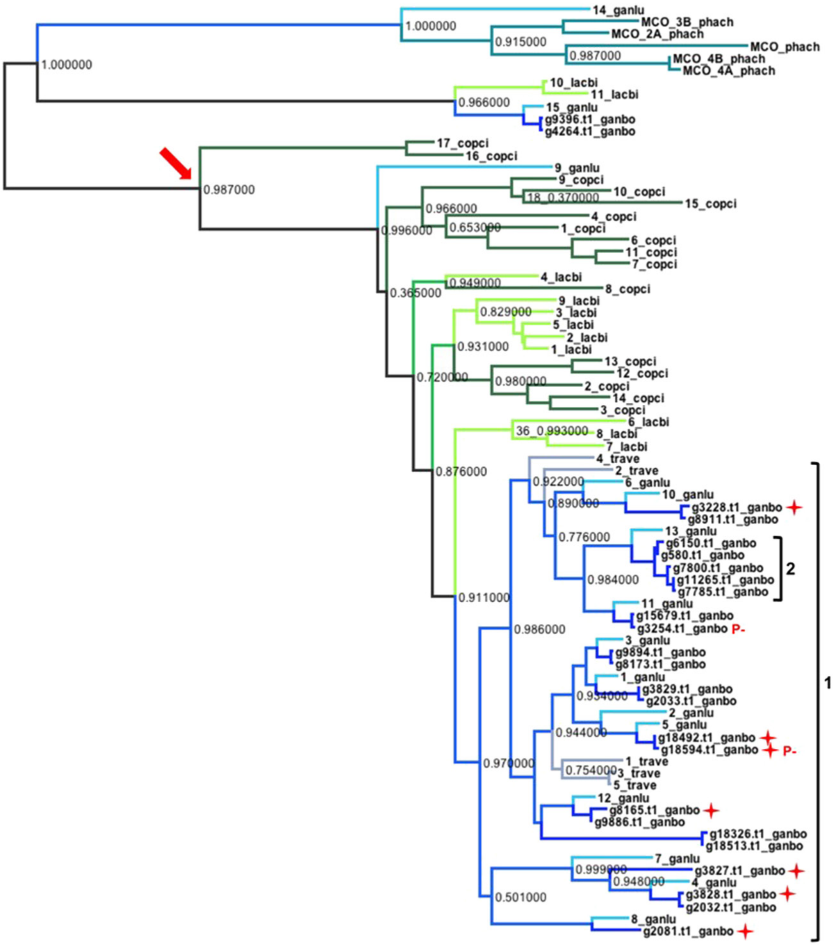

Figure 4 A phylogenetic tree for *G. boninense*-predicted laccases, and laccases of four other basidiomycetes species. The phylogenetic tree was obtained with PhyML (Guindon et al., 2010) using default values for amino acid analysis. It is rooted on the median point. ganbo: *G. boninense* predicted laccase gene models (electric blue), ganlu: *G. lucidum* (cyan), trave: *T. versicolor* (grey), phach: *Phanerochaete chrysosporium* (Turkish green), copci: *C. cinerea* (dark green), lacbi: *L. bicolor* (light green). Plain blue indicates branches specific to polyporales and plain green indicates branches specific to MCO: Multi Copper Oxidase. Branch support values were obtained with LRT SH-like test. A red arrow indicates *sensu stricto* laccases as defined by Hoegger et al. (2006). Bracket one underlines a laccase clade specific to polyporales order, and bracket two pinpoints a possible copy expansion in *G. lucidum*. Red star indicates *G. boninense* gene model with transcript match, and red 'P-' indicates *G. boninense* gene models with no peptide signal.

5 Developing partial resistance planting material against BSR

At present, there is no known oil palm planting material that is resistant to *G. boninense*. However, there are at least two commercial planting materials with partial resistance against BSR that have been released. In 2014, PT Socfindo successfully released 'DxP Socfindo Moderate Gano Resistant (MTG)' in Indonesia. In order to obtain the varieties of *Ganoderma*-partially-resistant seeds, the material is obtained from the genetic seed garden after passing through the census process. This is followed by a series of trials involving subjecting the materials in a *Ganoderma* nursery to a screening test (Idris et al., 2004; Breton et al., 2006), and accompanied by a miniature experiment in the field. Field tests were conducted in parental garden, seed garden and progeny trials.

In 2016, FELDA Global Ventures (FGV) of Malaysia released another partial resistance material against BSR namely 'Yangambi Ganoderma-Tolerant 1 (GT1)'. The approach used by FGV in developing GT1 is very much similar to methodology described before with the exception that planting materials were initially screened with a set of markers (Tan et al., 2011) targeting a disease resistance gene, before being subjected to *Ganoderma* nursery screening phase. The integration of molecular marker (with up to 70% accuracy) enabled FGV to fast track the screening of partially resistant materials.

6 *Fusarium* wilt

Fusarium wilt, also more commonly known as vascular wilt disease, is caused by *F. oxysporum* f.sp. *elaeidis*. It is a soil-borne disease and it was reported to enter its host (oil palm) through the roots and along the stele (Corley and Thinker, 2003). Wardlaw (1950) first reported it during a visit to Belgian Congo in 1946 where he observed a wilt disease in oil palm, and later isolated *F. oxysporum* from the necrosed vascular strands. Subsequently, other plantations in the African and South American continents such as Nigeria, Ivory Coast, Central Africa, Brazil and Ecuador have reported *Fusarium* wilt (van de Lande, 1983; Renard and de Franqueville, 1989; Flood et al., 1989). However, to date no *Fusarium* wilt disease has been reported in Southeast Asia.

In a review by Flood (2006), two disease syndromes were observed. The first syndrome is described as 'acute wilt' wherein the leaves dry out and die rapidly while retaining their original erect positions on the plant until broken off, usually several feet from the base, by wind action. As the disease progresses, the palm will eventually die within two or three months after this syndrome is observed. The second syndrome also known as 'chronic wilt' sees the palms remain alive for many months and even years, but becomes progressively stunted. This eventually leads to flattening of the crown due to the production of the youngest fronds in the crown which are often chlorotic. As in BSR, vascular wilt is also known to be a soil-borne disease and the main culprit of the infection is through contact with dead or infected tissue (Renard and de Franqueville, 1989).

Unlike BSR, it is actually possible to breed for resistance planting material against vascular wilt. It was reported that breeding programmes in Ivory Coast had been successful, with the introduction of resistant varieties that were able to reduce the disease incidence from an area as high as 30% to less than 3%. Rosenquist et al. (1990) reported that pure Dumpy Deli *dura* materials appeared to be immune against vascular wilt. Nursery screening was the initial tool used to conduct rapid screening and identification of potential resistant varieties. Prendergast (1963) was the first to develop a technique to screen for seedlings resistant to the disease at the nursery stage. Subsequently, a few researchers have adopted and modified the methodology (Flood et al., 1989; Renard et al., 1991). However, Corley and Tinker (2003) suggested that the best approach was described by de Franqueville (1984), where a wilt index system (percentage of wilt-infected plants divided by the mean wilt percentage of all progenies in a trial) first introduced by Renard et al. (1972), was used to calculate wilt severity. The modified wilt index system by de Franqueville (1984) involved transformation of percentages for individual plots. Data was statistically analyzed and progenies were only accepted as resistant if they had significantly lower losses than either the mean of the trial or standard crosses with known performance data.

7 Spear rot or bud rot

Spear rot, which was previously known as bud rot, is another important disease predominantly found in Latin America (Mariau, 2001). As the name of the disease suggests, it primarily affects spear leaves and the heart of the palm. Turner (1981) had suggested that the term 'spear rot' should be considered when the primary rotting affects the spear, while 'bud rot' should be considered for the disease primarily destroying unemerged leaves. The latter disease is usually fatal, while the former frequently non-fatal. The first published report of an oil palm plantation destroyed by bud rot in Latin America was from Suriname, where a 4-year-old plantation was completely destroyed in 1920 (Malaguti, 1953). Meanwhile, bud rot was also reported in Colombia and in 1964, complete destruction of an oil palm plantation (~2000 ha) in Turbo near the border of Panama (De Rojas and Ruíz, 1972).

There has been much speculation on the cause of bud rot disease with micro-elements deficiency such as boron (Ferweda, 1954). Observations made by Robertson (1960) in Nigeria suggested that there was an active pathogen involved, as susceptible palms had regular cycles of infection, and prevention by cutting off the spear could prevent the disease from recurring. Duff (1963) later suggested that bacterium of the genus *Erwinia*, similar to *E. lathyri* which was isolated from palm, was found in Congo.

A review by de Franqueville (2003), highlighted that there had been many bacterial and fungal pathogens, such as *Fusarium* and *Thielaviopsis* that were often isolated, but inoculation experiments with these pathogens could not be proven via Koch's postulates in healthy oil palms. It was only recently that *Phytophthora palmivora* had been demonstrated to be the causal agent of bud rot disease in Colombia (Drenth et al., 2013; Torres et al., 2010). Generally, initial visible symptoms such as the formation of small, water-soaked lesions in the leaflets at the base of the spear leaf, are usually followed by an increase in the number and size of the lesions. Sometimes, it is also associated with unusually wet weather, and long periods of continuous precipitation, accompanied by cloudy mornings and wet palm canopies (Martínez, 2009).

Fortunately, one of the most effective ways to overcome bud rot disease is through a genetic pool where resistant planting materials are to be planted in the epidemic area (Avendanõ and Garzon, 2013; Bastidas et al., 2007; Meunier, 1991). Planting materials such as interspecific hybrid crosses of *Elaeis guineensis* × *Elaeis oleifera* have been shown to give rise to desirable agronomic traits and reduced susceptibility towards bud rot. Crucially, it can provide potential options for disease control (Alvarado et al., 2013; Corley and Tinker, 2003). Torres et al. (2016) reported that if the disease is detected in the early stages, remedial action such as 'surgery' can be taken. This involves the removal of all of the affected tissue to just above the meristem, quick flaming of the exposed area to control any surviving spores, followed by the application of a mixture of bactericides, fungicides and insecticides to the exposed area. The same researchers also suggested that an integrated crop management system (cultivar selection, proper drainage, fertilization, monitoring, removal of infected tissues and destruction of tissues or palms), can effectively control bud rot disease to keep it to a minimum.

8 Future trends and conclusion

Although concerted efforts have been made to prevent various fungal infections in oil palm plantations, the ultimate long-term solution is to identify planting materials that are resistant to the respective fungus through a conventional or marker-assisted breeding approach. More importantly, an integrated disease management approach must be incorporated in tandem with the planting materials, as soil sanitation and integration of beneficial microbes that are antagonistic to the fungus are important for their long-term sustainability. In the future, diagnostic kits for both fungus identification and quantification of the virulence level of the fungus, could be used on-site for better plantation management to prevent the spread of fungal diseases

9 Where to look for further information

FGV's world class R&D and Agri-Services Cluster is anchored on five decades of research and development. The Cluster's key objective is to generate cutting-edge agri-business technologies to enhance operational performance and commercial utilization across all facets of FGV. The company's award-winning Yangambi oil palm planting material, which has 40 percent market share in Malaysia, is just one of R&D's innovative products. Besides this, FGV has launched other planting materials such as FGV 3-way and Yangambi GT-1 for niche markets. Our Research & Development centre is led by a team of highly specialized scientists. Its activities support internal growth across all Clusters. These involve improving the yield of selected agri crops through breeding, tissue culture agronomy, crop protection and sustainability. Other activities include the optimization of waste and by-products for use in generating new products with higher-growth, higher-margin industries, and the provision of high quality agro-based products and services. R&D and Agri-Services Cluster's focus on bio-molecular marker research has led to the pioneering of marker-assisted oil palm breeding and selection. For more information, please visit: http://www.feldaglobal.com/our-business/plantation/rd-services/.

CIRAD (French Agricultural Research Centre for International Development) is a public establishment (EPIC) under the joint authority of the Ministry of Higher Education, Research and Innovation and the Ministry for Europe and Foreign Affairs. Its activities concern the life sciences, social sciences and engineering sciences, as applied to agriculture, the environment and territorial management. Its work centres on several main topics: food security, climate change, natural resource management, reduction of inequalities and poverty alleviation. CIRAD works with its partners in southern countries to generate and pass on new knowledge to support agricultural development. It puts its scientific and institutional expertise at the disposal of policymakers in those countries and global debates on the main issues concerning agriculture. It also supports French scientific diplomacy operations. For more information, please visit: http://www.cirad.fr/en/.

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1 Chapter 1 Fungal diseases affecting oil palm

1 Introduction

Oil palm has proved to be the most efficient and productive oil crop, giving far higher

yields when compared to soybean, rapeseed and sunflower. As of October 2014, the

production of palm oil was reported at 53.67 million tonnes, compared to soybean at

41.66 million tonnes, rapeseed at 24.48 million tonnes and sunflower at 14.8 million tonnes

(www.oilpalmresearch.org). Based on the statistics obtained from the Malaysian Palm Oil

Board in 2015, Malaysia’s export of palm oil reached 17.31 million tonnes. The majority of

Malaysian palm oil was exported to India (3.25 million tonnes), China (2.84 million tonnes)

and the Netherlands (1.60 million tonnes). However, oil palm is also prone to attack by a

number of fungal diseases such as basal stem rot (BSR), Fusarium wilt (vascular wilt) and

bud rot disease. To date, only partial resistance materials have been identified for the BSR,

and we will be providing more insights into the BSR that is causing a major problem on

plantations particularly in Malaysia and Indonesia. Meanwhile, resistant planting materials

were found for the latter two fungal diseases.

In Southeast Asia, one of the most devastating diseases at the moment is BSR. The

disease was first described in 1915 in the Republic of Congo, West Africa (Wakefield, 1920). Thompson (1931) detected the disease infecting palms aged over 25 years in

Malaysia on old palms due for replanting. BSR disease, which is caused by the fungal

species Ganoderma boninense (Fig. 1), is the most serious disease affecting the oil palm

in Malaysia and Indonesia (Ariffin et al., 1989; Rao, 1990). The disease progresses slowly

and eventually causes the death of infected palms. The disease can infect all stages of the

oil palm, and palms infected at the early stage of their life cycle usually show no symptoms

until after they are more than 12 years old (Lubis, 1992).

2 BSR caused by Ganoderma boninense

Ganodermataceae are cosmopolitan basidiomycetes which cause white rot of hardwoods

such as oak, maple, maple, sycamore and ash by decomposing lignin, cellulose and related

polysaccharides (Hepting, 1971; Blanchette, 1984; Adaskaveg and Ogawa, 1990; Adaskaveg

et al., 1991, 1993). G. boninense Pat. is known to be the causal agent of BSR in oil palm (Ho

and Nawawi, 1985; Abadi, 1987; Khairuddin, 1993; Utomo, 1997; Soepena et al., 2000).

Figure 1 The presence of G. boninense mature fruiting body (basidiomata) found on an oil palm tree

showing basal stem rot disease.

Soepena et al. (2000) reported that in the second and third cycles of replanting oil

palms in the same place, the symptoms can appear as early as one to two years after

planting. A more acute G. boninense problem is likely to surface over the next few years

as the fungus increases its geographical range and virulence (Murphy, 2007). Singh (1991)

conducted a study aimed at quantifying yield losses based on fresh fruit bunch (FFB)

production and concluded that FFB production was adversely affected by the incidence

of the disease. Losses due to BSR are not only through the direct reduction in oil palm

numbers in stands, but also through a decrease in fruit bunch number and weight from

diseased standing palms (Fig. 2), as well as from those with sub-clinical infections (Turner,

1981). The disease can result in the death of more than 80% of the plants by the time that

they are halfway through their normal economic life and losses, reaching 30% have quite

frequently occurred (Turner, 1981).

2.1 Symptoms of Ganoderma disease

In young palms, the external symptoms of BSR normally include a one-sided yellowing,

or mottling of the lower fronds, followed by necrosis (Singh, 1991a). Ariffin et al. (2000)

reported that in cases of infection, the newly unfolded leaves were shorter than normal,

chlorotic, and the tips may be necrotic. As the disease progresses, palms may take on an

overall pale appearance, with retarded growth and spear leaves remaining unopened.

Similar symptoms are observed in mature palms, with multiple unopened spear leaves

and an overall pale leaf canopy. Often, when foliar symptoms are observed, it is found that at least one-half of the basal stem tissue has already been killed by the fungus. Infected

young oil palms normally die at 6–24 months after the first appearance of symptoms,

although mature palms can take 36 months to die.

Figure 2 Plantation with severe BSR disease with vacant planting spots in the field.

2.2 Possible sources of Ganoderma infection

There have been numerous theories on the possible source of Ganoderma infection

in oil palm. Oil palm stands were found to exhibit BSR symptoms at 10–14 years after

planting following the conversion of rubber plantations (Flood et al., 2000). Meanwhile,

a more widely accepted hypothesis proposes that Ganoderma attacks the root system

from second and subsequent replanting cycles of oil palm. Through a series of controlled

Ganoderma nursery trials, Rees et al. (2007, 2009b) clearly indicated that controlled root

infection leads to typical symptoms. Rees et al. (2007) showed that root infection in the

field originates from multiple, natural infections of different roots in a single palm. This

finding, which is consistent with results from Flood et al. (2005), indicated that infection of

the seedlings resulted from nearby colonized oil palms, with those seedlings nearer to the

colonized trunks becoming diseased more quickly than others.

More recent findings showed that basidiospores were involved in the development of

both manifestations (upper and basal) of stem rot (Rees et al., 2012). Authors reported that

basidiospores were produced in prolific numbers throughout the sampling period, with a

maximum release intensity during the evening, earlier than the midnight maximum release

reported by Ho and Nawawi (1986). This suggested a constant potential for inoculum to

colonize wounds and palm debris throughout the plantation (Rees et al., 2012; Cooper

et al., 2011). The idea that spores from fruiting bodies (basidiomata) were identified is not

new, as Lim and Fong (2005) and Utomo et al. (2005) had hypothesized the most likely

sources of inocula for further infection via root contact.

2.3 Studies of BSR caused by Ganoderma sp. in oil palm

BSR was found to be a significant constraint for the oil palm plantation industry (Miller

et al., 1999). In the subsequent year, Flood et al. (2000) stated that BSR has been a

serious disease of oil palm for over 80 years, with severe economic loss in both Malaysia

and North Sumatra (Indonesia). Bridge and Utomo (2005) suggested that Ganoderma

infections occur over a period of several years, which is much longer than the timescales

for other severe fungal plant pathogens (e.g. Fusarium oxysporum).

Ariffin et al. (2000) described how basidiomata develop at either the stem base, leaf

base, or infected root, with the location providing a guide to the diseased area inside

the palm. Abdullah's (2000) study on Ganoderma in coconut hypothesized a spread from independent secondary inocula, and their work did not support root-to-root spread and/or

airborne spore spread. In contrast, a review by Paterson (2007) suggested that roots were

thought to be the mode of spread. This idea, that infection results from contact between

healthy roots and diseased tissue remaining in the soil, appears to be widely accepted.

Interestingly, Bridge et al. (2004) mentioned that almost all isolates of G. boninense differed

from one another. Therefore, the author emphasized the importance of basidiospores, and

argued that ignoring this route of infection and the generation of new pathogen variation

would be a mistake.

2.4 Effects of BSR on Malaysia's oil palm plantations

Due to the scarcity of available arable land in Malaysia, and the implementation of new

land regulations on land use change, the expansion of oil palm plantations is now very

limited. Plantation companies have to deal with this limitation by embarking on intensive

replanting activities, including planting land that is heavily infected with BSR. Based on the

G. census conducted in Malaysia by Idris et al. (2011), 632 out of 1061 plantations (~60%)

have recorded BSR incidence.

It was estimated by the Federal Land Development Authority (FELDA) that 200 million

Malaysian Ringgit (US$45 million) had been lost due to the impact of BSR in the first

generation of oil palm planting in Malaysia (Sirrul et al., 2016). Astonishingly in the

same report, Ganoderma infection was found to be on the rise, as 264 plantations (61%)

were found to be infected with BSR disease in 2015. Through this census, where all the

FELDA's plantation schemes participated, BSR was observed in plantations two years after

replanting had been completed.

A field study was conducted by Sirrul et al. (2016) in order to compare the levels of

Ganoderma incidence between sanitation-windrowing palm debris (standard practice),

under-planting practices (Fig. 3), and sanitation, against non-sanitation areas. Through

these observations, it was found that plots practising under-planting showed a very high

incidence of Ganoderma, which was to be 110% higher than plots cultivated under standard

practice. The results, after eight years of the re-planting programme in the non-sanitation

area, recorded Ganoderma incidence at about 4.47–4.66%. In comparison, no Ganoderma

incidence was observed in areas where proper sanitation processes has been practised.

Therefore, under-planting is not recommended where oil palm replanting programme takes

place, although this method is commonly practised by the non-participating FELDA settlers.

The sanitation practice is currently being enforced in all plantations where BSR is recorded.

Figure 3 Scenario where under-planting is adopted in replanting areas, where old palms are not

removed to allow proper field sanitation to take place. New planting materials were planted close to

the dead palms which will eventually be culled by trunk injection (chemical). Image courtesy of Sirrul

Asrar Husain Fatimi (FGV R&D Sdn Bhd).

2.5 SSR genotyping of G. boninense strains (Southeast Asia and Africa)

G. boninense, a soil-borne basidiomycete, is the main causative agent of one of the more

devastating oil palm diseases, BSR. Several studies focused on detecting G. boninense's

infection, assessing isolate aggressiveness, or deciphering oil palm's defence reaction

during infection (Ho et al., 2014; Tee et al., 2013; Idris et al., 2004; Utomo et al., 2000).

However, only limited information is available on this pathogen's spreading properties as

well as its evolvability. Spreading properties encompass the reproduction mode (sexual

vs. asexual), the dispersion ability of the propagules, or even the number of isolates

effectively contributing to reproduction in a given population. Evolvability is the capacity

for a given population to generate adaptive genetic diversity that will help in adapting

to new environmental constraints. These biological characteristics are very important in

the sense that they govern dynamic changes of the disease, and they should both be

accounted for when designing efficient agricultural practice and developing a meaningful

strategy for BSR-tolerant oil palm planting material. However, spreading characteristics

and evolvability are also difficult to assess directly. A good strategy to evaluate these

factors is to estimate population genetic parameters associated with genetic diversity, and

population structure by means of an appropriate set of molecular markers.

Among many possible molecular markers, microsatellites, also called simple sequence

repeats or SSRs, present very interesting properties. Microsatellites are tracts of

repetitive DNA with small motifs (2–6 base pairs) repeated typically 5–50 times. They are

characterized by a higher mutation rate than the rest of the genome (Brinkmann et al.,

1998) and thus have a higher genetic diversity than other regions of the genome. Other

advantages of SSRs include their moderate cost, the technical feasibility of their use on

large samples, and their codominance and locus specificity (Jarne and Lagoda, 1996). This

provides them with desirable properties for use in population genetics estimations and

other demographic inference (Luikart et al., 2003; Cornuet et al., 1999; Michalakis and

Excoffier, 1996). In this chapter, we describe the development of a G. boninense-specific

SSR set from a draft genome assembly and its use in population genetic analysis.

2.6 Developing an SSR set

As shown by Dutech et al. (2007), the development of SSR is generally harder in fungi

than in other groups. This difficulty could be due to the scarcity and short length of SSR

in fungi genomes. Additionally, and contrary to what can be observed in plants, it is

also generally hard to transfer SSR between fungal species of the same genus (Dutech

et al., 2007). However, the increasing affordability and availability of sequencing data

from next-generation sequencing technologies now enables access to large amount of

sequenced data, from which it is possible to isolate SSR motifs.

In G. boninense, Mercière et al. (2015) combined 454 sequencing and Illumina data

to produce a 63-Mb draft assembly that was used to identify and characterize all SSR

loci. They then focused on a subset of these, in order to design primers and define

amplification protocols to allow multiplexing. Accounting for SSR with perfect repeats and

di- to hexanucleotide motifs only, Mercière et al. (2015) recorded a total of 2487 SSRs from

the draft assembly. The SSR content (39 SSRs per Mb) of the G. boninense draft genome

investigated is thus consistent with those published for other fungal species which ranges

from tens to hundreds of SSR per Mb (Labbé et al., 2011; Karaoglu et al., 2005). It is also

similar to the SSR content of the G. lucidum genome (37 SSRs per Mb) (Qian et al., 2012).

While it was not possible to undergo marker development for the complete G. boninense

SSR set, 145 of them were randomly selected for primer design. A preliminary step of in

silico polymerase chain reactions allowed 35 of them to be discarded because of non monolocus targeting. The remaining 110 SSR primers were then evaluated in vitro on a

small subset of 5 G. boninense isolates: 17 primer pairs were finally retained according to

their monolocus amplification pattern, polymorphism and the possibility to multiplex their

amplification and genotyping. These 17 primers were used to study a collection of 107 G.

boninense isolates from North Sumatra (Indonesia), Peninsular Malaysia and Sabah (part of

Borneo), to validate their desired amplification and sufficient polymorphism level.

2.7 Deciphering G. boninense in Malaysia and North Sumatra

Malaysia and North Sumatra are the historical centres for large-scale cultivation of

oil palm, and at the same time, for BSR development in Southeast Asia. Therefore,

studying G. boninense genetic diversity in these particular regions is of key interest.

Mercière et al. (2017) collected and genotyped an extensive sample of 311 isolates

from Peninsular Malaysia (FELDA plantations) and North Sumatra (Socfindo plantations),

and used 11 of the previously mentioned SSRs (Mercière et al., 2015) to investigate the

various characteristics of their genetic diversity, in an attempt to decipher the biological

processes that may have shaped them. It appeared that G. boninense exhibited a high

level of genetic diversity ($H_e = 0.651$) with only a few duplicated genotypes. The five

pairs of duplicated genotypes studied, originating from either Peninsular Malaysia or

North Sumatra, were all collected from neighbouring trees, at a distance of about nine metres. These results clearly support the predominance of sexual reproduction in shaping global G. boninense diversity, confirming the works of Miller et al. (1999) and Pilotti et al. (2003). Additionally, this data enabled the estimation of the effective population size for the pathogen in this region. This was calculated as the number of distinct genotypes involved in breeding (about 50 000 as a rough estimate). The asexual spread from root to root appeared to be marginal, at least within the well-maintained plantations from which the samples were collected. Nevertheless, the importance of sexual reproduction has been highlighted by other authors (Rees et al., 2012; Pilotti et al., 2003; Miller et al., 1999), although those studies were limited by their geographical scope and the genetic marker used. G. boninense's sexual reproduction is mediated by basidiospores that are notoriously capable of large-scale dispersal (Rees et al., 2012; Hallenberg et al., 2001). This biological feature is responsible for gene flow over long distances, and for the absence of any genetic structure observed in the area encompassing North Sumatra and Peninsular Malaysia (Mercière et al., 2017). More particularly, these authors showed that G. boninense has a two-tier spreading pattern, with both a high capacity for dispersal over short distances (less than 2 km), and over long distances (between 500 and 700 km). Such a spreading pattern seems common to basidiospore-spread fungi as it was also identified

in Heterobasidion irregulare (Garboletto et al., 2013).

2.8 Deciphering G. boninense in Southeast Asia

Besides Peninsular Malaysia and North Sumatra, BSR has been described in other regions

of Southeast Asia, and in Africa. Studies were conducted in order to determine whether

the development of BSR in these regions was caused by G. boninense genotypes closely

related to those observed in Peninsular Malaysia and North Sumatra, or, on the contrary,

by genotypes belonging to other G. boninense sub-populations, (or even due to other

Ganoderma species). Mercière et al. (2017) genotyped an additional group of isolates using

the same set of 11 SSRs previously used for Peninsular Malaysia and North Sumatra (Mercière

et al., 2015). These isolates were collected in Thailand (Krabi, four isolates), Borneo (Sabah,

34 isolates), South Sumatra (7 isolates), Papua New Guinea (11 isolates) and Cameroon (32

isolates). In addition to the SSRs used, all the isolates were further confirmed with an internal

transcribed spacer (ITS) sequence of G. boninense (Latiffah et al., 2002; Rees et al., 2012).

The diversity, as measured by the expected heterozygosity (Nei, 1987) is high, with the

order of magnitude of North Sumatra (0.65) and Peninsular Malaysia (0.63), ranging from 0.57

(Papua New Guinea) to 0.62 (South Sumatra). According to El Moussadik and Petit (1996), the estimation of allelic richness buffering uneven sample sizes yielded similarly high values

among locations, ranging from 3.4 (North Sumatra and South Sumatra) to 2.9 (Thailand).

Based on the Bayesian clustering approach implemented in STRUCTURE software (Pritchard

et al., 2000), Southeast Asia's Ganoderma diversity is structured in two main differentiated

genetic groups (Fst = 0.13). The first group encompasses isolates from Thailand, Peninsular

Malaysia, North Sumatra and South Sumatra. The second group mainly gathers isolates from

Borneo and Papua New Guinea. A limited number of isolates (6) are classified as intermediate

between these two groups. Finally, a significant phylogeographic signal (Hardy et al., 2003)

could be detected between the two identified genetic groups, indicating low gene exchange

between them. Although the analysis is still at its preliminary stage, this is an interesting

discovery as it allows for the possibility of new hypotheses.

The use of SSR markers revealed that the G. boninense affecting oil palm in Southeast

Asia is highly diverse, and subdivided into two distinct and geographically isolated sub

populations. These results may have important implications for oil palm improvement for

tackling Ganoderma. Firstly, due to the high genetic diversity of the pathogen, associated

with it's large effective population size and active sexual reproduction, one should be

careful of the development of multigenic tolerance rather than monogenic total resistance, in order to design sustainable oil palm varieties. On the other hand, the subdividing of

G. boninense in two Southeast Asian populations calls for more studies in order to better

understand their differences, notably in terms of aggressiveness. Here, we have stressed

the fact that human-mediated gene flows between the two G. boninense groups should

be carefully avoided in order to prevent hybridization, possibly leading to the emergence

of Ganoderma with increased aggressiveness. Finally, and before more knowledge on the

characteristics of the Ganoderma sub-populations is gained, partially resistant oil palm

varieties should be used, taking into account the genetic background of locally present

G. boninense isolates (e.g. using SSR markers). The use of oil palm which has tolerance

against both Ganoderma sub-populations will need to be fully ascertained.

3 Cellulolytic degradation as a possible mode of infection

Oil palm is susceptible to attacks from pathogenic fungi such as Ganoderma spp. which can

cause rotting of the roots and basal stem of the standing palms. G. boninense among the

Ganoderma spp. is capable of degrading the plant's lignocellulosic biomass of the cell wall.

The main components of lignocellulose are cellulose, hemicellulose and lignin (Sjöström,

1993). Studies on lignin-modifying enzymes from Ganoderma lucidum indicate that lignin

component is the rate-limiting factor in the lignin degradation process (D'Souza et al., 1999). Deposition of lignin in the cell wall can serve as a barrier to microbial attack, because

it provides strength and is a water-impermeable seal across cell walls in the xylem tissue.

Lignin therefore, may play a major role in disease response mechanisms (Paterson, 2007).

The ability of Ganoderma spp. to mineralize lignin to produce carbon dioxide and water

is remarkable. It is related to its ability to cleave the monomeric ring structures of the

lignin monomers, although the physical properties of lignin are the product of aromatic

heteropolymers synthesized from the phenylpropanoid aryl-C 3 units, coniferyl, synapyl

and p-coumaryl alcohols, with at least 12 different types of linkages such as aryl-ether and

carbon-carbon bonds (Boerjan et al., 2003).

Ganoderma spp. produces several types of extracellular oxidative enzymes that are

related to the degradation of the lignin component of plant cell walls. For instance,

manganese peroxidase and laccase in G. lucidum (D'Souza et al., 1999), lignin peroxidase

in G. applanatum (Morgenstern et al., 2008; Martıńez, 2002), and lignin peroxidase,

manganese peroxidase and versatile peroxidase of other white rot fungi (Dashtban et al.,

2010; Ward et al., 2004), are involved in the degradation of lignin.

Laccases are blue multicopper phenol oxidases, that oxidize various phenolic substrates

via the reduction of oxygen to water, and also oxidize non-phenolic lignin (Bourbonnais and Paice, 1990). Laccases work with a wide range of substrates without cofactors, and

they have wide applications in biotechnology (Upadhyay et al., 2016; Arora and Sharma,

2010). They are commonly used in feedstock industries (Sharma et al., 2013), textile

industries (Couto et al., 2004) and soil bio-remediation (Nyanhongo et al., 2006). Laccases

are produced in a wide range of organisms including bacteria, fungi, plants and insects. In

fungi, laccases are involved in the degradation of lignin (D'Souza et al., 1999), whilst they

are involved in the biosynthesis of lignin in plants (Sato et al., 2001).

4 Laccase gene discoveries

The genome of G. boninense was sequenced using Illumina and 454 sequencing

technology for the discovery of microsatellite markers (Mercière et al., 2015). A draft

genome sequence of 63 Mb was assembled, providing the starting genomic resources

for laccase gene discoveries. Ab initio gene model prediction on this draft genome

was performed with Augustus 2.6.1 (Stanke and Waack, 2003) using Phanerochaete

chrysosporium as a training organism (unpublished results).

In order to discover laccase genes from the G. boninense draft genome in silico, Camus

Kulaidevalu et al. (2014) mined for the laccase genes in both the public database and the

predicted gene models derived from the draft genome. In order to retrieve known fungi laccases, we searched the NCBI ‘nr’ protein database using keywords ‘laccase’ and ‘fungi’.

This resulted in 841 laccase protein sequences that were longer than 100 amino acids with

methionine amino acid start codons, and which contained the protein sequence name

‘laccase’. We analysed the essential sequence features of laccases available from the public

domain, based on multiple sequence alignments of 841 protein sequences using MAFFT

software (Katoh and Standley, 2013) using ‘-einsi’ option to allow for large unaligned

regions. We then used HMMER3 software (Mistry et al., 2013) to synthesize sequence

profiles common to laccase alignment (‘hmmbuild’ module), and mined G. boninense

predicted gene model database for putative laccase (‘hmmsearch’ module). Based on

the full sequence score and E-value of 1.1 e−63 (best fitting domain), 33 G. boninense gene

models showed significant similarities to the laccase sequence profile based on 841 input

fungus laccase alignment using HMMER software.

Among these 33 gene models fitting HMMER laccase pattern, 25 bore the four-domain

laccase signature (Kumar et al., 2003). These 25 gene models displayed a predicted

coding region length between 1473 and 1926 bp (between 491 and 642 amino acids).

These gene models are distributed on seventeen scaffolds. Scaffold 1 bears three gene

models with four-domain laccase signature; scaffold 49 bears three gene models with four-domain laccase signature; scaffolds 46, 149 and 197 bear two gene models each with

four-domain laccase signature. The predicted intron number varies between 3 and 12.

Twenty-four gene models were predicted using TARGETP 1.1 (http://www.cbs.dtu.dk/

services/TargetP) and 23 displayed a predicted peptide signal SIGNALP 3.0 (http://www.

cbs.dtu.dk/services/SignalP). At least seven predicted laccase genes are expressed in G.

boninense isolates, based on the sequence similarity search of 25 predicted gene models

with four-domain laccase signature, against the transcriptome assembly (unpublished data)

of G. boninense isolate cultured in potato dextrose agar plate. Our search for sequence

similarities indicated that seven gene models showed strong similarity with assembled

transcripts with a sequence similarity between 93 and 99% over more than 1300 bp in length.

In order to investigate the relationship of the 25 predicted G. boninense laccase

genes with other fungi species, we aligned the putative laccases with other known fungal

laccases from Laccaria bicolor, Coprinopsis cinerea, Trametes villosa, G. lucidum and

Phanerochaete chrysosporium (in this latter case Multi-Copper Oxidase – MCO). These

were retrieved from NCBI using MAFFT software (Katoh and Standley, 2013). The five

species studied belong to basidiomycota, either from the polyporales order (T. villosa,

G. lucidum, Phanerochaete chrysosporium) or from the agaricales order (L. bicolor, C.

cinerea). We removed poorly aligned regions with gBlocks software (Castresana, 2000)

and produced a phylogenetic tree (Fig. 4) with PhyML (Guindon et al., 2010) using default

values for amino acid analysis.

Based on our analysis, predicted laccases from G. boninense are positioned in two

groups. Gene models g9396 and g4264 are gathered with a G. lucidum and two L. bicolor

laccases belonging to laccase sensu lato (Hoegger et al., 2006). More specifically, these

two L. bicolor laccases are ferroxidases. The other 23 G. boninense predicted gene models

gather in a large group solely composed of polyporales laccases, including all five T.

versicolor laccases and 12 G. lucidum laccases. Interestingly, the seven laccase predicted

gene models showing transcript evidence are located in the polyporales gene cluster.

In summary, Camus-Kulaidevalu et al. (2014) identified 25 gene models exhibiting

the four domains with fungal laccase signatures, and the main characteristic of fungal

laccases in terms of length, cellular addressing, signalling and intron number. For seven of

these 25 laccase predicted gene models, we found transcript evidence supporting gene

prediction. Our results suggest the existence of a specific group of polyporales sensu

stricto laccases (Hoegger et al., 2006) for which ancient duplications occurred (Fig. 4).

This group includes laccases from the white rot G. lucidum, G. boninense and T. versicolor but not Phanerochaete chrysosporium. Within the polyporales sensu stricto laccase group, the phytopathogenic G. boninense exhibit a noticeable position, with the specific expansion of some gene sub-family (e.g. gene model g6150, g580, g7800, g11265, g785), leading to a potentially doubled laccase copy number compared to its relative G. lucidum. This important information allowed us to conduct further analysis for verification on lignocellulosic pathway, and the possibility of finding an inhibitor might provide a long term solution such as systemic fungicide development in the future.

Figure 4 A phylogenetic tree for G. boninense-predicted laccases, and laccases of four other basidiomycetes species. The phylogenetic tree was obtained with PhyML (Guindon et al., 2010) using default values for amino acid analysis. It is rooted on the median point. ganbo: G. boninense predicted laccase gene models (electric blue), ganlu: G. lucidum (cyan), trave: T. versicolor (grey), phach: Phanerochaete chrysosporium (Turkish green), copci: C. cinerea (dark green), lacbi: L. bicolor (light green). Plain blue indicates branches specific to polyporales and plain green indicates branches specific to MCO: Multi Copper Oxidase. Branch support values were obtained with LRT SH-like test. A red arrow indicates sensu stricto laccases as defined by Hoegger et al. (2006). Bracket one underlines a laccase clade specific to polyporales order, and bracket two pinpoints a possible copy expansion in G. lucidum. Red star indicates G. boninense gene model with transcript match, and red ‘P-’ indicates

G. boninense gene models with no peptide signal.

5 Developing partial resistance planting material against BSR

At present, there is no known oil palm planting material that is resistant to G. boninense.

However, there are at least two commercial planting materials with partial resistance

against BSR that have been released. In 2014, PT Socfindo successfully released ‘DxP

Socfindo Moderate Gano Resistant (MTG)’ in Indonesia. In order to obtain the varieties

of Ganoderma-partially-resistant seeds, the material is obtained from the genetic seed

garden after passing through the census process. This is followed by a series of trials

involving subjecting the materials in a Ganoderma nursery to a screening test (Idris et al.,

2004; Breton et al., 2006), and accompanied by a miniature experiment in the field. Field

tests were conducted in parental garden, seed garden and progeny trials.

In 2016, FELDA Global Ventures (FGV) of Malaysia released another partial resistance

material against BSR namely ‘Yangambi Ganoderma-Tolerant 1 (GT1)’. The approach used

by FGV in developing GT1 is very much similar to methodology described before with the

exception that planting materials were initially screened with a set of markers (Tan et al.,

2011) targeting a disease resistance gene, before being subjected to Ganoderma nursery

screening phase. The integration of molecular marker (with up to 70% accuracy) enabled

FGV to fast track the screening of partially resistant materials.

6 Fusarium wilt

Fusarium wilt, also more commonly known as vascular wilt disease, is caused by

F. oxysporum f.sp. elaeidis. It is a soil-borne disease and it was reported to enter its host

(oil palm) through the roots and along the stele (Corley and Thinker, 2003). Wardlaw

(1950) first reported it during a visit to Belgian Congo in 1946 where he observed a wilt

disease in oil palm, and later isolated F. oxysporum from the necrosed vascular strands.

Subsequently, other plantations in the African and South American continents such as

Nigeria, Ivory Coast, Central Africa, Brazil and Ecuador have reported Fusarium wilt (van

de Lande, 1983; Renard and de Franqueville, 1989; Flood et al., 1989). However, to date

no Fusarium wilt disease has been reported in Southeast Asia.

In a review by Flood (2006), two disease syndromes were observed. The first syndrome

is described as ‘acute wilt’ wherein the leaves dry out and die rapidly while retaining their

original erect positions on the plant until broken off, usually several feet from the base, by

wind action. As the disease progresses, the palm will eventually die within two or three

months after this syndrome is observed. The second syndrome also known as ‘chronic wilt’

sees the palms remain alive for many months and even years, but becomes progressively

stunted. This eventually leads to flattening of the crown due to the production of the

youngest fronds in the crown which are often chlorotic. As in BSR, vascular wilt is also

known to be a soil-borne disease and the main culprit of the infection is through contact

with dead or infected tissue (Renard and de Franqueville, 1989).

Unlike BSR, it is actually possible to breed for resistance planting material against

vascular wilt. It was reported that breeding programmes in Ivory Coast had been

successful, with the introduction of resistant varieties that were able to reduce the disease

incidence from an area as high as 30% to less than 3%. Rosenquist et al. (1990) reported

that pure Dumpy Deli dura materials appeared to be immune against vascular wilt.

Nursery screening was the initial tool used to conduct rapid screening and identification

of potential resistant varieties. Prendergast (1963) was the first to develop a technique

to screen for seedlings resistant to the disease at the nursery stage. Subsequently, a few

researchers have adopted and modified the methodology (Flood et al., 1989; Renard

et al., 1991). However, Corley and Tinker (2003) suggested that the best approach was

described by de Franqueville (1984), where a wilt index system (percentage of wilt-infected

plants divided by the mean wilt percentage of all progenies in a trial) first introduced by

Renard et al. (1972), was used to calculate wilt severity. The modified wilt index system

by de Franqueville (1984) involved transformation of percentages for individual plots.

Data was statistically analyzed and progenies were only accepted as resistant if they had

significantly lower losses than either the mean of the trial or standard crosses with known

performance data.

7 Spear rot or bud rot

Spear rot, which was previously known as bud rot, is another important disease predominantly

found in Latin America (Mariau, 2001). As the name of the disease suggests, it primarily

affects spear leaves and the heart of the palm. Turner (1981) had suggested that the term

‘spear rot’ should be considered when the primary rotting affects the spear, while ‘bud rot’

should be considered for the disease primarily destroying unemerged leaves. The latter

disease is usually fatal, while the former frequently non-fatal. The first published report of

an oil palm plantation destroyed by bud rot in Latin America was from Suriname, where

a 4-year-old plantation was completely destroyed in 1920 (Malaguti, 1953). Meanwhile,

bud rot was also reported in Colombia and in 1964, complete destruction of an oil palm

plantation (~2000 ha) in Turbo near the border of Panama (De Rojas and Ruíz, 1972).

There has been much speculation on the cause of bud rot disease with micro-elements

deficiency such as boron (Ferweda, 1954). Observations made by Robertson (1960) in

Nigeria suggested that there was an active pathogen involved, as susceptible palms had

regular cycles of infection, and prevention by cutting off the spear could prevent the

disease from recurring. Duff (1963) later suggested that bacterium of the genus Erwinia,

similar to E. lathyri which was isolated from palm, was found in Congo.

A review by de Franqueville (2003), highlighted that there had been many bacterial

and fungal pathogens, such as Fusarium and Thielaviopsis that were often isolated, but

inoculation experiments with these pathogens could not be proven via Koch's postulates in

healthy oil palms. It was only recently that Phytophthora palmivora had been demonstrated

to be the causal agent of bud rot disease in Colombia (Drenth et al., 2013; Torres et al.,

2010). Generally, initial visible symptoms such as the formation of small, water-soaked

lesions in the leaflets at the base of the spear leaf, are usually followed by an increase in

the number and size of the lesions. Sometimes, it is also associated with unusually wet

weather, and long periods of continuous precipitation, accompanied by cloudy mornings

and wet palm canopies (Martínez, 2009).

Fortunately, one of the most effective ways to overcome bud rot disease is through a

genetic pool where resistant planting materials are to be planted in the epidemic area

(Avendanõ and Garzon, 2013; Bastidas et al., 2007; Meunier, 1991). Planting materials

such as interspecific hybrid crosses of Elaeis guineensis × Elaeis oleifera have been shown

to give rise to desirable agronomic traits and reduced susceptibility towards bud rot.

Crucially, it can provide potential options for disease control (Alvarado et al., 2013; Corley

and Tinker, 2003). Torres et al. (2016) reported that if the disease is detected in the early

stages, remedial action such as 'surgery' can be taken. This involves the removal of all

of the affected tissue to just above the meristem, quick flaming of the exposed area to

control any surviving spores, followed by the application of a mixture of bactericides,

fungicides and insecticides to the exposed area. The same researchers also suggested that

an integrated crop management system (cultivar selection, proper drainage, fertilization,

monitoring, removal of infected tissues and destruction of tissues or palms), can effectively

control bud rot disease to keep it to a minimum.

8 Future trends and conclusion

Although concerted efforts have been made to prevent various fungal infections in oil

palm plantations, the ultimate long-term solution is to identify planting materials that are

resistant to the respective fungus through a conventional or marker-assisted breeding

approach. More importantly, an integrated disease management approach must be

incorporated in tandem with the planting materials, as soil sanitation and integration of beneficial microbes that are antagonistic to the fungus are important for their long-term

sustainability. In the future, diagnostic kits for both fungus identification and quantification

of the virulence level of the fungus, could be used on-site for better plantation management

to prevent the spread of fungal diseases

9 Where to look for further information

FGV’s world class R&D and Agri-Services Cluster is anchored on five decades of research

and development. The Cluster’s key objective is to generate cutting-edge agri-business

technologies to enhance operational performance and commercial utilization across all

facets of FGV. The company’s award-winning Yangambi oil palm planting material, which

has 40 percent market share in Malaysia, is just one of R&D’s innovative products. Besides

this, FGV has launched other planting materials such as FGV 3-way and Yangambi GT-1 for

niche markets. Our Research & Development centre is led by a team of highly specialized

scientists. Its activities support internal growth across all Clusters. These involve improving

the yield of selected agri crops through breeding, tissue culture agronomy, crop protection

and sustainability. Other activities include the optimization of waste and by-products

for use in generating new products with higher-growth, higher-margin industries, and

the provision of high quality agro-based products and services. R&D and Agri-Services

Cluster's focus on bio-molecular marker research has led to the pioneering of marker assisted oil palm breeding and selection. For more information, please visit: http://www.feldaglobal.com/our-business/plantation/rd-services/.

CIRAD (French Agricultural Research Centre for International Development) is a public establishment (EPIC) under the joint authority of the Ministry of Higher Education, Research and Innovation and the Ministry for Europe and Foreign Affairs. Its activities concern the life sciences, social sciences and engineering sciences, as applied to agriculture, the environment and territorial management. Its work centres on several main topics: food security, climate change, natural resource management, reduction of inequalities and poverty alleviation. CIRAD works with its partners in southern countries to generate and pass on new knowledge to support agricultural development. It puts its scientific and institutional expertise at the disposal of policymakers in those countries and global debates on the main issues concerning agriculture. It also supports French scientific diplomacy operations. For more information, please visit: http://www.cirad.fr/en/.

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2 Chapter 2 Diseases affecting oil palm

1 Introduction

Oil palm production is one of the most important agricultural activities in South American

and Central American countries, including Brazil, Colombia, Costa Rica and Ecuador, and

constitutes a key alternative for generating employment, income and foreign currency.

It is also considered strategic for national economies. In Asia (India) and Africa (Ghana,

Cameroon and Nigeria), oil palm is one of the most important oil-producing crops.

Diseases have been some of the most important constraints to oil palm production.

The oil palm disease-causing phytoplasmas that remain a major constraint presently were

first reported by Turner (1981). An early report of Phytophthora disease from Latin America

is from Alvarez (1998) and Sanchez et al. (1999). All of the major plant disease-causing

agents – fungi and phytoplasmas – cause economically important damage to oil palm

through large parts of the regions, countries and continents within which the crop is grown.

However, there are important differences in patterns of distribution. Indeed, it is important

to highlight here that these differences mean that there continue to be significant risks of

the spread of pathogens with a limited current distribution to parts of the world in which

they do not currently occur. Although many of the diseases of oil palm are most readily

spread through seed, several have important interactions with insect vectors. An important

feature of this interaction is that changes in abundance levels or patterns of distribution of

vectors can have important consequences for the transmission and geographical spread

of the pathogens. Since insects can be particularly sensitive to abiotic factors, such as

temperature and rainfall, this also means that present and anticipated climate changes will

have a significant impact on transmitted pathogens.

Oil palm diseases affect all parts of the plant: leaves, stem, flowers and roots, although

the most common symptoms are chlorosis and blights in leaves and soft or dry rot in the

roots. Losses caused by oil palm diseases vary greatly depending on the region, local

environmental conditions and oil palm variety. Overall, however, it is likely that more than a

third of global palm oil production, equivalent to several billion US dollars, is lost annually.

Control efforts have, therefore, become more important although much remains to be

done to improve and extend management efforts.

2 Oil palm basal stem rot (BSR) disease, Ganoderma spp.

2.1 BSR in Africa

In Africa, one of the most devastating diseases, called basal stem rot (BSR) disease, is

caused by the genus Ganoderma, a soilborne fungus that threatens the oil palm industry,

especially in Ghana, Nigeria and Cameroon. Elaeis guineensis (African oil palm) palms are

the main hosts for BSR disease.

Biology

The genus Ganoderma belongs to the class Basidiomicetes. Ganoderma spp. are referred to as white rot fungi that degrade lignin as well as other wood components. Mainly, three species of Ganoderma (G. boninense, G. zoanatum and G. miniatocinctum) are the cause of BSR disease (Naher et al. 2015). Ganoderma is characterized by basidiocarps, large, perennial and woody brackets that are lignicolous. The fruit bodies grow in a hoof-like form on the trunks of trees. They have double-walled, truncated spores with yellow-to brown ornamented inner layers (Hushiarian et al. 2013).

Studies of G. boninense have found that oil palm plantations have great diversity. The small ribosomal subunit RNA (in prokaryotes 16S and in eukaryotes 18S) gene is one of the most important molecular markers, with a range of applications in biodiversity screening, phylogenetic analyses and evolutionary studies (Meyer et al. 2010).

A phylogenetic study of Ganoderma using single-locus mt SSU rDNA led to dividing Ganoderma into six distinct monophyletic groups and indicated that complex situations related to the geographic region and the pathogen–host relationship must be considered as well as the phylogenetic relationships (Soon Gyu and Jung 2004).

Symptoms and effects on yield

The symptoms of BSR are decay of the bottom of the stem from where basidiocarps

emerge and, sometimes, also decay of the roots. Stem rotting restricts the uptake of water

and nutrients to the fronds, causing chlorosis. When the disease is more advanced, the

older fronds wilt and hang down to form a skirt around the trunk (Turner and Gillbanks

1974). Other observable symptoms are flattening of the crown and spear leaves that have

not opened. In the most severe cases, the stem might even fracture (Rees et al. 2012).

Once the plant dies, colonization of basidiomata can develop rapidly along the entire

trunk. In young palm, decay of the soft tissues of the stem occurs rapidly compared with

mature palm (Naher et al. 2015).

The disease can decrease the yield of infected palms by killing them or by reducing the

weight of the fresh fruit bunch in infected palms (Assis et al. 2016).

Epidemiology

Ganoderma spreads in the soil through roots and the air. Wind, rain and insects all

assist in carrying spores to wounds on trees, most commonly those that have been

cut. In particular, the Oryctes beetle (Turner 1981) and larvae of the Sufetula spp.

caterpillar play at least a small role in spreading Ganoderma spores (Genty et al. 1976).

Experiments in which an enormous number of Ganoderma spores were released in a

field but did not infect most trees (Ho and Nawawi 1986) have indicated that infected tissues in the soil are more likely to spread the disease to healthy roots than airborne

spores.

Control

Some control measures are used to minimize economic loss from the disease. Soil

mounding, in which soil is heaped around the trunk to a height of 75 cm, is an effective

technique to prevent BSR in oil palm. The technique may prolong the yielding life of oil

palm affected by BSR. Digging trenches around infected palms prevents mycelium spread

by root contact with healthy palms (Ho and Khairudin 1997; Naher et al. 2015). Fungicide

treatment is another approach to control BSR in oil palms. It is mainly used to protect

seeds from infection and to control BSR. Fungicides such as triadimefon, cycloheximide

and benomyl inhibited Ganoderma growth. But, they are not recommended. The use of

species of Trichoderma as biological control agents showed their potential antagonistic

effect in controlling other fungi (Soepena et al. 2000). The BSR was lower in a field

treated by Trichoderma harzianum than in an untreated field (Susanto et al. 2005). The

effect of isolates of Bacillus was tested on G. boninense growth on oil palm seedlings

(Suryanto et al. 2012) and resistant cultivars are alternative means to control BSR. The

use of resistant-planting material offers the best alternative to control BSR. Removing or destroying infected palms through sanitation remains one of the most important measures for controlling BSR.

2.2 BSR in Asia

In Asia, Indonesia and Malaysia produce 87% of the world’s total palm oil. Fungi that rot and kill oil palm could cost Southeast Asian countries USD 500 million a year (Ommelna et al. 2012). The BSR, a disease caused by G. boninense, is considered a serious threat to the oil palm industry in these countries. The BSR caused by Ganoderma spp. causes significant losses up to 80% on oil palm plantations in Southeast Asia (Susanto 2009).

Biology

BSR is caused by numerous species of the fungus Ganoderma. Pathogenic species for oil palm have a wide host range. In Southeast Asia, the BSR disease that is caused by the white rot fungi of the genus Ganoderma is the major disease affecting the oil palm industry.

Symptoms and effects on yield

Internal symptoms of BSR appear like brown rot marked by darker coloured bands. There are yellow transitional areas between healthy and diseased tissues. Small wide buttons of tissue mark the beginnings of Ganoderma sporophores. Typical bracket-shaped sporophores of Ganoderma showed a shiny upper surface and whitish border. Approximately 60% of the plantations in Malaysia reported diseased trees. In East Malaysia, the lack of good field training is a contributing factor for production losses (Murphy 2014). It has been reported that economic loss caused by G. boninense can reach USD 500 million (Ommelna et al. 2012).

Epidemiology

Survival and development in the soil vary between species. Soil type has been implicated with the pure structure of coastal clays, and the impermeable soil of marine origin is thought to lead to increased Ganoderma attack. High incidence has been associated with a high water table limiting rooting or where flooding occurs. Spread and infection can occur through roots (Cooper et al. 2011).

Control

There are sources of natural genetic disease resistance. Genetic resistance to BSR of oil palm is a major component of an integrated control strategy for the disease. Early detection of the level of resistance is of importance for the breeding and sustainability of this crop in Southeast Asia. A set of standard crosses was developed by both Socfindo and Lonsum to provide results from different trials using different Ganoderma isolates (Breton et al. 2009). Research efforts have focused on understanding the molecular defence responses in plant-pathogen interactions to find practical solutions to control the disease (Ho and

Tan 2015). Lignin structure modification by breeding could result in genetic resistance.

Candidate genes for breeding BSR resistance are sought in transcripts and proteins that

alter their expression upon infection (Ho and Tan 2015). Phytosanitary practices, biological

control with Trichoderma spp., and palm endophytes are practical solutions to manage the

disease (Mohammed et al. 2014). Trichoderma and its efficacy as a biocontrol agent of BSR

of oil palm have been reported by Ilias (2000).

Management of Ganoderma in peat soil in Indonesia was reported by Lim and Udin

(2010).

2.3 BSR in Central America

In Central America and northern regions of South America, Elaeis oleifera (Kunt, Cortez)

is known as the American oil palm. Elaeis oleifera populations grow along riverbanks,

tolerating shade and flooding, thus showing environmental adaptability (Corley and Tinker

2003). Colombia, Suriname and northwest Brazil are considered the species' centre of

origin (Ooi et al. 1981). Oil palm fruits are the richest plant source of provitamins A and E.

The genus Ganoderma is a major problem.

In the state of Pará, Brazil, the crop is often considered as an industrial crop, but in many

areas, it is a valuable smallholder crop (Feintrenie et al. 2010). Government policies favour

smallholder involvement in the oil palm industry.

Biology

Basidiocarps are clear to dark brown in colour with shiny texture. Basidiospores have a

truncated apex, in some cases with a ‘cap’, and free piles (dots in the upper part of the

basidiospore), with the width being thin to medium thick.

The morphological characteristics of basidiocarps identified the fungus within the genus

Ganoderma, subgenera Elfvingia and Lucidum.

Symptoms and effects on yield

In Colombia, BSR is considered the most important emerging infectious disease threatening

oil palm because of its direct effects, with a direct impact on yields. Symptoms include

multiple spear leaves, the oldest fronds wilt and hang down to form a skirt around the

trunk (Turner and Gillbanks 1974). In the most severe cases, the stem might even fracture

(Rees et al. 2012). The proliferation of adventitious roots is visible only when the internal

damage is in a very advanced state.

Disease symptoms were described on two plantations in El Copey, Cesar, in northern

Colombia.

Epidemiology

Airborne basidiospores are of high importance in the epidemiology of Ganoderma.

Control

Ganoderma was found on four plantations of the northern coast of Colombia and

eradication was recommended as a disease-control strategy.

The number of cases

reported was low.

Triazole triadimenol (Bayfidan) 250EC 2.5 g ia/palm by root absorption and PCNB 5 g

ia/palm by stem injection were used as chemical controls.

3 Oil palm dry basal rot disease, Thielaviopsis paradoxa

3.1 Dry basal rot disease in South America

Ceratocystis paradoxa (anamorph: Thielaviopsis paradoxa) is parasitic on a range

of economic and food crops and is the cause of dry basal rot, a limiting disease in oil

palm.

Biology

The pathogenic and genetic diversity of Thielaviopsis isolates from oil palms in Colombia,

Ecuador and Brazil was evaluated. A total of 164 strains of Thielaviopsis paradoxa were

characterized using pathogenicity tests, random amplified polymorphic DNA (RAPD)

markers and polymerase chain reaction (PCR) sequencing of the ITS region of 5.8 S

ribosomal DNA (Alvarez et al. 2012a).

Population structure analyses of the RAPD data suggested that most of the isolates

obtained in this study belonged to a single population. The genetic diversity of the isolates

from South America was intermediate and, therefore, Thielaviopsis paradoxa is likely to be

predominantly clonal compared with Ceratocystis species. Sporadic sexual reproduction

may occur for Thielaviopsis paradoxa, but is secondary to clonal reproduction. Data

on pathogen diversity will provide information on breeding strategies and population

structures (Alvarez et al. 2012a).

Symptoms and effects on yield

Dry basal rot, caused by the vascular pathogen Thielaviopsis paradoxa (teleomorph:

Ceratocystis paradoxa), can attack the stem (Fig. 1a), leaves and fruits, causing premature

fruit drop (Kile, 1993) (Fig. 1b).

The disease is characterized by dry rot of the bud tissue with necrotic lesions of different

colours (Buitrago and Nieto 1995).

It can be economically significant, for example, in northern Colombia, where 70% of the

plantations are affected (Tovar and Nieto 1998). It is also economically important in the

southern region of Bahia, Brazil.

Figure 1 (a) Oil palm inoculated with Ceratocystis paradoxa. (b) Transversal cutting of oil palm

inoculated with Ceratocystis paradoxa.

Epidemiology

This disease affects palms of any age and is prevalent in lowland areas where the average

annual rainfall is 2 500 mm/year or above.

Oil palm seeds are mostly free from Thielaviopsis paradoxa, so transmission through

seedlings is low and some other mechanisms of disease inoculum dispersal must be

postulated (Alvarez et al. 2012).

In this sense, the relatively frequent isolation of this pathogen from different plant tissues

of oil palm trees indicated to us that dispersal might be by airborne spores or by infected

harvesting and pruning equipment. Because old leaves of oil palms are carefully pruned

during their growth cycle, this second dispersal mechanism may be common, as it is in

other crops according to Kile (1993).

Control

Knowledge of the genetic and pathogenic diversity and population structure of Ceratocystis

paradoxa may help when designing effective control measures such as breeding for

resistance or biological and chemical control (Alvarez et al. 2012).

The association of Thielaviopsis paradoxa with different palm genotypes needs to be

studied in order to identify resistance sources.

3.2 Dry basal rot disease in Africa and Asia

In Africa, dry stem rot caused by Thielaviopsis can affect oil palms in commercial cultivars

grown in Cameroon and Nigeria (Tovar and Nieto 1998).

Biology

Oil palm Ceratocystis isolates from trunks, cut basal ends of leaf fronds and rotting palm

nuts were collected in Cameroon. The DNA was isolated with the CTAB protocol described

by Moller et al. (1992).

For the identification of Ceratocystis isolates, internal transcribed spacers ITS1 and ITS2 and intervening 5.8S rDNA of the ribosomal RNA gene cluster (ITS) were amplified with

PCR and sequenced. Additional genetic regions of the β-tubulin gene and TEF-1a were

sequenced (Mbenoun et al. 2014).

Multigene DNA phylogenics in combination with mating studies and careful

morphological examination revealed that the Ceratocystis complex includes more species

than the five described previously (Harrington 2009).

Symptoms

Disease symptoms are characterized by bud and trunk rots.

Epidemiology

In the future, a more comprehensive sampling of taxa with larger sample sizes for each

taxon may reveal more alternative hosts among, for example, grasses. Other challenges

within the field of lethal wilt (LW) epidemiology include the identification of insect vectors

(Bila et al. 2015).

Control

In West Africa, biological control of Ceratocystis paradoxa causing black seed rot in oil

palm sprouted seeds was accomplished by Trichoderma species.

Trichoderma viride, Trichoderma polysporum, Trichoderma hamatum and Trichoderma

aureoviride were used as potential biological agents for seed treatments against Ceratocystis

paradoxa causing black seed rot in oil palm sprouted seeds (Eziashi et al. 2006).

The emergence (survival) and the growth of oil palm seedlings from Trichoderma

species-treated oil palm sprouted seeds were significantly higher than the emergence and

the growth observed from the control treatment. Ceratocystis paradoxa-infested seeds

had 63% to 71% survival and average seedling height of 18.4 to 25.1 cm. Seeds without

pathogen had 100% survival with average seedling height of 38.2 to 46.5 cm. The effects

of the bioagents were similar or higher than the effects obtained from benlate solution.

Occurrence in Asia

Common spear rot (CSR), which is also known as crown disease, was first reported in

Indonesia in the 1920s. It has caused considerable losses in young oil palm plantings.

Symptomatic spear leaves were collected from oil palm plantations and farm plots in

South Sumatra, North Sumatra and Bangka-Belitung, Indonesia (Akino and Kondo, 2012).

In a study conducted by Akino and Kondo (2012), Koch's postulate experiments showed

that Ceratocystis paradoxa was able to infect wounded oil palm leaves causing a symptom

of extensive rotting similar to that found in the field. It was confirmed that Ceratocystis

paradoxa is one pathogen that is associated with CSR of oil palm in Indonesia.

4 Oil palm bud rot disease, Phytophthora palmivora

One of the pseudofungal diseases affecting oil palm is root rot caused by Phytophthora

species from the genus of plant-damaging oomycetes (Alvarez et al. 1998; de Franqueville

2003; Faparusi 1973). Phytophthora palmivora has been reported to attack oil palm

(Joseph and Radha 1975; Alvarez et al. 2010; Torres et al. 2016).

4.1 Biology

Oil palm bud rot (OPBR) disease is caused by the pseudofungus Phytophthora palmivora.

The sporangia of Phytophthora palmivora isolates from oil palm are papillate and

limoniform. In Colombia, the isolates were characterized by morphology light microscopy,

ELISA enzyme immunoassay, PCR and hybridization with a specific probe for Phytophthora

spp. (Alvarez 2007). A homogeneous and reproducible band of about 900 bp was obtained

with PCR (ITS1 and ITS4), which, when digested by restriction enzymes, showed an equal

pattern of bands for all isolates. The isolates thus belonged to one species. The RAPD

analysis revealed intraspecific genetic diversity, demonstrating a wide range of genetic

diversity in the pathogen population. Restriction fragment length polymorphism (RFLP)

analyses provided genetic evidence of a well-characterized group among isolates.

Phytophthora palmivora is characterized by oval and ellipsoid sporangia with a short

pedicel. The sporangia are obovoid, limoniform or ellipsoid and have tapered bases.

Phytophthora strains were examined for differences in morphology, pathogenicity and

DNA polymorphism. The strains were chosen to be diverse according to geographic origin.

Characterization of the strains by morphology was difficult because not all strains produce

fungal structures. The strains caused typical symptoms in oil palm, but varied in pathogenicity.

The DNA polymorphism was determined by both RFLP of the ribosomal ITS and 5.8S DNA

amplified by PCR. Restriction digest with HindI, of the product amplified for the ITS region,

showed three different restriction patterns that corresponded to three species, respectively.

Twenty random 10-mer primers were tested, and four gave reproducible bands. The results

suggested a high genetic diversity among the strains tested (Alvarez et al. 1999).

The PCR amplification of the ITS region followed by digestion with restriction enzymes

can be used to separate the species. A collection of Phytophthora strains obtained from

different regions in Colombia showed high morphological and pathogenic variations (Llano

et al. 2006). Phytophthora palmivora was identified as the most important species causing

bud rot in Colombia (Alvarez 2010; Torres et al. 2016). A Phytophthora sp. was isolated

from commercial plantations cultivated in Ecuador, Brazil, and Colombia showing typical

symptoms of bud rot. Pathogenicity was evaluated in 6- and 24-month-old palms under

controlled conditions in the greenhouse and in leaf fragments placed in humidity chambers.

Isolates of this Phytophthora sp. were found to be pathogenic on both 6 and 24-month-old

palms, and Phytophthora sp. was re-isolated from infected tissue, therefore fulfilling Koch's

postulates. Through PCR, the causal agent was identified using A2/I2 primers specific to the

genus Phytophthora, which amplified a 788-bp fragment located in the internal transcribed

spacer (ITS) region. The PCR product was digested with the restriction enzymes MspI, RsaI,

and TaqI, generating fragments that corresponded to P. palmivora. With the sequences

obtained, molecular beacon probes and primers specific to the species were designed. This

new method permitted timely, sensitive, and specific diagnoses of the pathogen (Alvarez

et al. 2010). In Colombia, isolate identifications were confirmed using an ITS marker. Host-

pathogen interactions were also studied under greenhouse conditions (Alvarez et al. 1998).

Inoculated 2-year-old oil palm variety Gunung Melayu, inoculated with the puncture

method at the base of the stem, showed symptoms 20–25 days after inoculation, starting

with chlorosis of the spear and flag leaf, followed by a dry necrosis (browning of the tissue)

in a progressive form (Sánchez et al. 1999) (Fig. 1).

The pathogen (Phytophthora spp.) was re-inoculated from the affected tissue, and its

identification was confirmed by morphology in culture medium and light microscopy.

Phytophthora spp. initially caused a yellowing or chlorosis of leaves, resulting in browning

or dry necrosis of the affected tissue (Alvarez et al. 2007).

4.2 Symptoms and effects on yield

OPBR symptoms are encountered where oil palm crops are poorly drained or on farmland

recently converted from humid forest and it can be difficult to determine the source of

primary infection. Bud rot initiated by primary-infecting pathogens is frequently exacerbated

by subsequent colonization by saprophytic species. Disease symptoms on spear and young

leaves are characterized initially by chlorosis and finally by necrosis (Fig. 2a) (Alvarez 2007).

In Colombia, up to 80% of the oil palm has been reported to be affected by bud rot,

whereas in southern India, production losses of 70% have occurred. Bud rot is a major

constraint to oil palm production in areas of the eastern plains and Tumaco in Colombia.

Bud rot has destroyed more than 70 000 ha of oil palm in the western and central oil

palm–growing regions of Colombia (Torres et al. 2016).

4.3 Epidemiology

Phytophthora species are spread through the use of seeds obtained from an infected plant.

Easy dispersion hinders management of the disease. Transmission also occurs through

infected soil, which is common in fields that are flooded. The pathogen survives in the

soil. Disease incidence is the highest during the rainy season, on humid soils. To prevent

introducing the pathogen into disease-free regions, a real-time PCR diagnostic method has

been developed to detect Phytophthora palmivora in infected tissues (Alvarez et al. 2010).

Phytophthora species attack oil palm plants, especially under favourable conditions

such as poor drainage, compacted soil and usage of infected seed.

4.4 Control

Strategies to control Phytophthora rot have focused on the use of resistant oil palm

hybrids. In a biological control strategy, Trichoderma harzianum and Trichoderma viride

reduced percentage infection and increased production.

Resistance to the disease is reported in the South American species Elaeis oleifera

(Elaeis melanococea) and hybrids between these and Elaeis guineensis.

Trials were carried out on oil palm plantations to evaluate the effect of induced resistance

to bud rot, applied in two ways: injection to the trunk below the meristem and absorption

by the roots. Phosphoric acid was used in concentrations of 25% and 40%, and the product

NF (phosphoric acid: 434 g/L P_2O_5 , and potassium hydroxide and potassium citrate:

Figure 2 (a) Necrosis on spear leaf and flag leaf in oil palm inoculated with Phytophthora palmivora.

(b) Negative control (inoculated with water).

403 g/L K_2O). Sterile water was used as a control. There were no significant differences

between injection to the trunk and root absorption. It was concluded that bud rot could

be controlled using inducers of resistance based on potassium and phosphorus, as part of

integrated management of the disease (Alvarez et al. 2003).

The most effective means of preventing infection and the spread of OPBR is by planting

disease-free seed. Strict quarantine and surveillance measures are required to prevent its

introduction to Asia or Africa. The use of resistant parental genotypes in breeding programmes

combined with phenotypic field selection under high disease pressure should enhance control.

The most economical solution for bud rot control in the medium and long term is the

incorporation of American palm resistance into commercial hybrid materials without

affecting the performance of commercial palm oil materials and preserving the quality of

the oil (Alvarez et al. 2007).

In advanced stages of the disease, the emerged outer part of the spear leaf looks totally

dry, while the white unemerged central tissues and the tissues above the meristem are

destroyed (Sarria et al. 2013). A final symptom is the destruction of the young tissue and

the meristem (Torres et al. 2016).

5 Oil palm vascular wilt disease, Fusarium oxysporum f.sp. elaeidis

In Africa, vascular wilt is the most destructive disease of oil palm. The disease was first

described in the Democratic Republic of Congo (Wardlaw 1946) and also has been

reported in Cote d'Ivoire, Nigeria, Ghana, Cameroon and Congo (Flood 2006).

In South America, the disease had been reported in Brazil (Van de Lande 1984) and

Ecuador (Renard and de Franqueville 1989). The disease has not yet been reported in

Malaysia or in Southeast Asia (Rusli et al. 2013).

5.1 Biology

Fusarium oxysporum Schlechtend.: Fr. f.sp. elaeidis Toovey is a soilborne fungus that

produces macroconidia, microconidia and chlamydospores. Chlamydospores allow

survival in plant debris and soil.

Flood et al. (1992) reported that all pathogenic isolates from Zaire were vegetatively

compatible with each other and were designated vegetative compatibility group (VCG) 0140,

while another VCG (0141) occurred in Brazil. Later, Mouyna et al. (1996) reported that South

American isolates were compatible with isolates from Ivory Coast and allocated to VCG 0141.

5.2 Symptoms

Disease symptoms are acute wilt in which leaves dry out and die rapidly while retaining their

original erect positions on the plant until broken off, usually several feet from the base, by

wind action. The disease progresses rapidly and palms die within two or three months.

Additional disease symptoms are characterized by chronic wilt in which the palm

remains alive for months or years and becomes progressively stunted. The older fronds

become desiccated and hang around the stem. These symptoms progress gradually,

with younger fronds becoming affected. The youngest fronds produced in the crown

remain erect, often chlorotic and reduced in size (stunted). The apex of the trunk may

be reduced in diameter (Flood 2006).

5.3 Effects on yield

Renard and de Franqueville reported substantial yield reductions (from 6 to 16%) in 6-year

old replanted palms when only a small per cent (2.5–5.5% of plants) actually showed external

symptoms. These authors attributed most of this yield reduction to 20–30% of palms that

were actually infected but appeared healthy (Renard and de Franqueville 1989).

5.4 Epidemiology

The pathogen is soilborne and spread is thought to occur through root contact with dead,

infected palm tissues (Renard and de Franqueville 1989). Palms killed by the pathogen

become sources of nutrients for adjacent palms and these too become infected (Corley

and Tinker 2003).

Contamination of oil palm seeds by the pathogen has also been reported, both on the

outside of seeds and the kernel surface. Spores can be carried on oil palm seeds on the

kernel surface.

Oil palm seeds are important in global breeding programmes, and there is a risk of

long-distance transmission on contaminated seeds. The possibility of contaminated seeds

giving rise to infected plants has been investigated (Flood 2006).

5.5 Control

The soilborne nature of the pathogen has made management of the disease difficult.

The use of Brachiaria as a cover crop and a cultural practice such as the removal and

burning of infected palms have been promoted. The disease can also be controlled

through better field management, e.g., disease incidence can be halved by planting new

palms at a distance of more than 2 m from old stumps. The application of potassium is

reported to reduce disease incidence. Breeding for resistance remains a practical long

term method of management for this disease. Breeding programmes such as those in

Ivory Coast have been successful, with the introduction of resistant varieties reducing

losses in some areas from 20 to 30% to less than 3%.

Screening trials in the nursery where palms are deliberately inoculated have been

introduced in several West African breeding programmes and generally correlate well

with field results (Renard and de Franqueville 1989).

Chemical and heat as seed treatments are measures to control the disease. In addition,

biological control with Trichoderma has been used (Flood 1994).

6 Oil palm phytoplasma diseases in South and Central America: lethal wilt disease (LWD)

Various groups and subgroups of phytoplasma have been reported to be associated with oil

palm diseases in Latin America (Alvarez et al. 2014) and Asia (Jones and Turner, 1979; Mehdi et

al. 2012). Also, a phytoplasma has been reported from oil palm in Mozambique (Bila et al. 2015).

Few phytoplasma groups have been reported to cause disease in oil palm. The diversity

of phytoplasma is reported to be low from South America (Candidatus Phytoplasma

asteris) and a similar number of groups are recognized from Southeast Asia (Candidatus

Phytoplasma asteris) and Africa (Candidatus Phytoplasma asteris and Candidatus

Phytoplasma palmicola). Only two subgroups have been identified as important pathogens

of oil palm in South America (Alvarez et al. 2014).

Phytoplasmas are mycoplasma-like organisms that are often mistaken for plant

pathogenic viruses. They are specialized bacteria that are obligate parasites of plants and

that infect phloem tissue. They are often difficult to diagnose and detect. Discovered

in the 1960s, phytoplasmas are pathogens that are becoming increasingly important in

Latin America and the Caribbean. The most important oil palm diseases associated with

phytoplasma infection are oil palm LWD and oil palm leaf stripe disease (LSD).

In this section, we will focus on LWD in South and Central America. Section 7 will then

focus on LSD, while Section 8 discusses the occurrence of phytoplasma diseases in Asia

and Africa.

The LWD has been reported in Colombia (Alvarez et al. 2014), Ecuador (Alvarez et al.

2013; Baer et al. 2013) and Brazil (Brioso et al. 2006; Montano et al. 2007). The LWD affects production and can cause severe economic loss. In Colombia, losses of more than

USD 85 million have been reported. The LWD is associated with phytoplasma group 16SrI

subgroup B (Alvarez et al. 2013).

Colombia is the major producer of oil palm (Elaeis guineensis Jacq.) in Latin America,

and the fifth-largest grower worldwide, which plays an important role in biodiesel markets

(Castiblanco and Mosquera 2011). Oil palm has become a paramount export crop and

source of employment for the national economy. However, its production has declined

by 7.1% since 2002, with a dramatic drop of 10% in northeastern Colombia (FEDEPALMA

2010). The cause of this decrease has been LWD (‘marchitez letal’ in Spanish) (Mejia de Los

Rios 2014). The LWD was reported for the first time in the Llanos Orientales of Colombia

in 1994. In Ecuador, the disease was reported for the first time in 2006 in the region of San

Lorenzo, Santo Domingo, Quevedo and Orellana, with total crop losses of 200 hectares

(Baer et al. 2013).

LW is present on the oil palm plantations (Pérez and Cayón 2010) of the Upía River

area, Palmar del Oriente (1994), Palmas del Casanare (1999), Palmeras Santana (2000) and

Palmeras del Upía (2002). The disease had decimated around 690 hectares and a total of

97 619 oil palms by 2010 (FEDEPALMA 2010; Mejia de Los Rios 2014).

The disease has been observed on Palmas Sicarare oil palm plantations in northern

Colombia (Elizabeth Alvarez, personal communication, 4 October 2016).

6.1 Biology

A preliminary study detected phytoplasmas in symptomatic plants in commercial crops

of the susceptible oil palm hybrid (Elaeis guineensis × Elaeis oleifera) (Alvarez and Claroz

2003) in Colombia.

Cell characteristics of phytoplasma were detected in sieve tube inflorescence phloem.

The phytoplasma structures observed were pleomorphic, comprising round, elongate,

dumbbell and ring-shaped elements, mostly 150–250 nm wide and 1000 nm long (Fig. 3).

The phytoplasma structures were limited only to phloem tubes and were never seen in

large quantities (Alvarez and Mejía 2005).

Nested PCRs primed by phytoplasma universal primer pair R16F2n/R2 resulted in the

amplification of 1.2-kb DNA fragments of the 16S ribosomal DNA, indicating that the

symptomatic oil palm plants were infected by phytoplasma (Alvarez 2006).

The RFLP analysis of the 1.2-kb 16S rDNA amplicons indicated that a phytoplasma

belonging to subgroup 16SrI-B (‘Ca. P. asteris’) was present in all symptomatic oil palm

plants. The RFLP patterns from the positive samples were indistinguishable from each

other and from phytoplasma reference strains belonging to subgroup 16SrI-B (Alvarez et al. 2014).

PCR assays with the rpF1/rpR1 primer pair amplified the expected fragment length of

about 1200 bp from 18 oil palm samples. RFLP analyses with four restriction enzymes

produced RFLP profiles that were identical to each other. These allowed a clear

differentiation of the two oil palm phytoplasma strains from those aster yellow (AY) strains,

phytoplasma from Colombia (Fig. 4).

More in-depth phytoplasma differentiation can be obtained by studying polymorphisms

in other gene sequences (Mitrovič et al. 2011).

Phytoplasma strains of the 16SrI group were detected and characterized by multigene

typing analysis based on four phytoplasma genes and distinguished from reference strains

(Bertaccini et al. 2014).

Figure 3 Transmission electron micrographs of phytoplasma cell of LWD. (a) Infected oil palm

inflorescences and (b) positive control (affected periwinkle).

The RFLP characterization of the groEL, amp and rp genes, together with sequence

data, distinguished the AY strain detected in Colombian oil palm samples from other AY

phytoplasmas used as reference strains (Alvarez et al. 2014).

The 16S rDNA is a valuable classification tool, but it is not always able to discriminate

phytoplasma strains. Multigene sequence analysis based on amp, groEL and rp genes indicated that they are useful molecular markers to follow up on the Colombian oil palm

epidemic (Mejĩa de Los Rios 2014).

The rpF1/rpR1 sequence from OP47 (1168 bp) was deposited in GenBank under

accession number KF434318 (Mejĩa de Los Rios 2014).

A real-time PCR assay was developed to detect and quantify a 16SrI phytoplasma

associated with oil palm LWD. A taqMan probe was designed for the microorganism,

based on the rp gene (16SrI phytoplasma). By qPCR, sensitivity increased from 100- to

1000-fold of that obtained from nested PCR (Alvarez et al. 2012).

In Ecuador, from 16 samples from Palmar del Río in Orellana with LW symptomatology,

amplification of the fragment of approximately 1430 base pairs in second nested PCR was

obtained, using universal primers reported previously by Alvarez (2006) and Smart et al.

(1996), associated with the presence of phytoplasma, whereas in none of the asymptomatic

plants was an amplicon obtained (Baer et al. 2013).

6.2 Symptoms and effects on yield

Symptoms of LW commonly first appear as vascular discolouration and leaf yellowing in

seven-year-old palms (i.e. flowering and fruiting). These symptoms are followed by leaf

Figure 4 Restriction fragment length polymorphism (RFLP) patterns of oil palm phytoplasma strains

OP45 and OP47 compared with several reference strains from periwinkle that were amplified with primers rpF1/rpR1 and digested with restriction enzymes TruI (a), TaaI (b), Hpy8I (c) and AluI (d). The

acronyms of the strains are described in Table 1. Markers: phiX174, phiX174 HaeIII digested; and

pBR322, pBR322 HaeI digested.

drying, wilt necrosis of infected tissues and eventual plant collapse (Fig. 5). Root necrosis

often accompanies leaf discolouration. Internal discolouration of trunk tissue may also

occur, but does not represent a distinctive symptom.

LW is potentially destructive because it spreads rapidly and causes plant death within 4

to 6 months after symptoms first appear (Pérez and Cayón, 2010).

In Colombia, the disease causes vascular discolouration and leaf yellowing when the

palm is mature. These symptoms are followed by leaf drying, wilt, necrosis of infected

tissues and eventual plant collapse (Alvarez et al. 2014).

Oil palm production in Colombia presented a sharp decline in the first six months of

2002, registering a fall of 7.1%. In the regional scenario, the area that most contributed

to this drop in production was the eastern region, where production decreased by almost

10%. An approximation of the losses incurred indicates that more than one hectare of

oil palm was eliminated per month (150–200 plants in an area of 4000 hectares, which is

equivalent to 0.34%) (Alvarez 2006; Alvarez et al. 2014).

LW-like symptoms were also observed in oil palms in Brazil affected by a disease known as ‘fatal yellowing’ (Brioso et al. 2006; Montano et al. 2007).

Figure 5 Oil palms in Colombia showing mild (a, severity score 2) and severe (b, severity score 4) lethal

wilt symptoms. Lethal wilt symptoms reported in oil palm in northern Colombia in young plants, and

leaf drying and leaf discolouration (c and d).

In Ecuador, the disease appears in both young plants and adult plants, after growing for

three to four years. The first disease symptoms are leaflet yellowing and drying, beginning

at the tips and edges, as can be seen in Fig. 6. The last part that reaches necrosis is the

spear leaf or meristem (Baer et al. 2013).

6.3 Epidemiology

Phytoplasmas are commonly transmitted by phloem-feeding Hemiptera vectors. These

include plant hoppers and leafhoppers of the genera Macrosteles, Euscelis, Euscelidius,

Scaphoideus and Cacopsylla (Weintraub and Beanland 2006). The microorganism first

multiplies in the intestinal cells of its insect vectors and subsequently in the hemolymph

after passing through the salivary glands. It infects internal organs such as the thoracic

ganglion and fatty bodies (lipids) (Kawakita et al. 2000). Transmission can also occur

through grafting and the parasitic plant Cuscuta. Phytoplasma disease is disseminated

through the movement of infected seeds. It has recently been reported that the leafhopper

Myndus crudus (Cicadellidae) is able to transmit it from infected plants to healthy plants

(Arango et al. 2011). In addition, Cortés et al. (2015) concluded that Haplaxius crudus

is the insect vector of the causal agent of LW. Further studies are required, however, to

determine how significant this vector transmission is as a factor in the field- and regional

level epidemiology of oil palm disease (Alvarez 2006).

LW spreads rapidly and causes plant death within 4–6 months after symptom onset

(Pérez and Cayón 2010).

6.4 Control

An effective method of controlling phytoplasma diseases is through preventing

infection by assuring the health and quality of seed. Improved quarantine procedures

are required to prevent long-range disease spread. A thermotherapy treatment has

been used in Colombia for cleaning oil palm seed. Use of a resistance inducer (Kendal)

produced an increase in yield and reduced disease incidence (Elizabeth Alvarez, pers.

Figure 6 Yellowing and drying of leaflets with lethal wilt. To the left, the initial stage; to the right, the

advanced stage.

comm., 3 October 2013). Accurate and rapid diagnosis is a key component of disease

management strategies, and nested PCR and real-time PCR amplification assays have

been developed to allow specific detection of the phytoplasma causing LWD from field

collected samples (Alvarez et al. 2003; Alvarez and Mejía

2005; Alvarez and Pardo 2012).

Endophytic communities associated with healthy and phytoplasma-diseased plants

were described through cultivation-dependent and -independent methods, allowing the

identification of putative biocontrol agents. Although the mechanisms of phytoplasma–

endophyte interaction are not clear, preliminary experiments in controlled conditions

reported a mitigation of phytoplasma-associated symptomatology mediated by

endophytes (Bianco et al. 2013).

Tetracycline antibiotics have been found to cause remission of symptoms in a number

of diseases of suspected phytoplasma aetiology (Alvarez 2006). Tetracycline therapy

produces only a temporary remission of disease before symptoms reappear (McCoy 1972;

Agrios 1997).

In the Colombian eastern plains, the control strategy against LW includes establishing

leguminous cover crops in order to avoid the presence of grass; scouting fields on a

weekly basis in order to guarantee early detection of palms diseased with LW; immediately

destructing diseased oil palms and applying insecticide to palms surrounding the diseased

palms for preventing LW spread. Additionally, insecticide application was introduced

during the season of the year when the population of Haplaxius crudus was very high.

Results show that after a year of using the control strategy for LW, its incidence and development rate both declined: by 67% on IRHO and by 64% on Golden Hope material

(Cortés et al. 2015).

7 Oil palm phytoplasma diseases in South and Central America: leaf stripe disease (LSD)

The LSD has been reported in Colombia (Alvarez et al. 2014). Oil palm samples including

leaf tissue, embryo and germinated seeds were obtained at Sicarare and Unipalma

plantations.

7.1 Biology

Disease samples including rachis, petiole, basal part of the bulb, leaf half, leaf base,

meristem, leaflets and roots from African palm plantations located in the eastern plains of

Colombia were evaluated (Table 1). Table 1 Phytoplasma groups detected in LSD oil palm samples Tissue Phytoplasma group Root 16SrI Frond base 16SrI Meristem 16SrI Apical base 16SrI

Amplification of the 16S rDNA gene with universal primers M1/M2 showed a fragment

of approximately 500 bp (Fig. 1). The DNA amplifications correspond to disease samples

including roots, leaf base, meristem and apical base (Table 1).

The RFLP patterns were compared with those reported by Contaldo (2012) (Fig. 7).

Additionally, seed embryo tissue samples from African palm plantations located in the

eastern Colombian plains were evaluated (Table 2).

Amplification of the 16S rDNA gene with M1/M2 universal primers showed a 500-bp fragment (Fig. 8).

The 16Sr gene of ribosomal DNA was amplified by nested PCR using universal and

specific primers: P1/Tint, R16F2n/R2 (Lee et al. 1995) and M1/M2 (Gibb et al. 1995).

Positive controls correspond to X disease 16SrIII group. Amplification of the 16S rDNA

gene using M1/M2 universal primers showed a 500-bp fragment (Fig. 9). Positive samples

were digested with MseI.

Sequence analysis of the 16Sr gene was carried out for the identification and classification

of phytoplasma.

A high level of homology (99%) was obtained with sequences of the 16SrI (‘Ca. P.

asteris’) group. The Blastn-assisted alignment revealed that the nucleotide sequences of

the 16SrDNA gene of the phytoplasmas detected in samples 6492, 6497 and 6498 were

similar to those of GenBank accessions KC009838, KC243397 and KC808147.

7.2 Symptoms

Symptoms are characterized by stunting, yellow streaking of the leaves and a marked

reduction in fruit and stalk size (Fig. 10), which progress to no fruit production in the final

Figure 7 Amplified DNA fragments with M1/M2 primers. Lanes 23, 30, 35 and 20 correspond to leaf

base tissue, meristem, apical base and diseased roots, respectively, and lanes 87 and 89 correspond

to seed samples 6577 and 6876, respectively. Lanes C1, C2, C3 and C4 correspond to positive controls of 16SrI phytoplasma. The lanes labelled 16SrIII-L CS correspond to a positive control of

cassava phytoplasma group III and the lane labelled negative control corresponds to PCR product

without DNA (HyperLadder TM II).

stages. Pale or bright yellow streaks on the leaf midrib are also observed (Alvarez, 2013).

The described symptoms are similar to the ones reported by Ammar et al. (2005) in date

palms in Egypt.

7.3 Epidemiology

The disease is transmitted by an insect vector. The insect vector transmitting the disease

has not been identified yet. The disease could be disseminated by an infected seed.

Transmission studies to confirm the vector of the phytoplasma causing LSD in Colombia

are required.

Research on phytoplasma–insect vector interaction is needed for the development of

strategies to control LSD.

7.4 Control

The effectiveness of resistance inducers was confirmed on oil palm plantations in Sicarare,

northern Colombia (Alvarez et al. 2012b, 2013).

The use of resistant germ plasm is the best strategy to manage the disease. Phytoplasma

disease-free seed is another strategy to control LSD. Table 2 Phytoplasma groups detected in LSD oil palm embryo seed samples Sample no. Source Phytoplasma group 83 Seed raceme 6874 U = 735 C 5:20 16SrI 87 Raceme 6577 U = 8030 5:20 16SrI 89 Raceme 6876 U = 707 C 5:20 16SrI

Figure 8 Amplification of DNA with M1/ M2 primers. Lanes 82, 83, 87, 89 and 86 correspond to seed

samples 6874, 6577 and 6876, respectively. Lane 16SrIII-L CS corresponds to a positive control and

lane negative control corresponds to PCR product without DNA. Lanes with the letter M indicate the

molecular weight marker 100 bp (HyperLadder TM II).

8 Oil palm phytoplasma diseases in Asia and Africa

8.1 Phytoplasma diseases in Asia

In Asia, LWD is associated with phytoplasma 16SrI subgroup B. AY phytoplasmas have

been detected through RFLP analyses of nested PCR-amplified fragments corresponding

to the phytoplasma. Oil palm disease phytoplasmas indicated the presence of strains all

related to the 16SrI group. Sequence analyses of partial 16S rDNA fragments showed

that phytoplasmas have 99% similarity with Candidatus Phytoplasma asteris (Alvarez et

al. 2014). Phytoplasma-associated symptoms include leaf yellowing, reduction in fruit and

stalk size, stunted growth, wilting and severe or slow decline (Mehdi et al. 2012). The

LWD reduces yield, and, in India, the disease causes yield losses in clonally propagated

oil palm (Elaeis guineensis Jacq.) in the district of West Godavari, Andhra Pradesh (Mehdi

et al. 2012). Similarly, oil palm plantations in Malaysia were affected in Banting, Selangor

(Nejat et al. 2009).

Figure 9 Amplification of DNA from germinated palm seed with primers M1/M. Lanes 6492-1, 6492-2, 6497-1, 6497-2, 6498-1 and 6498-2 correspond to positive samples. Lane 16SrIII-L CS corresponds to a

positive control, phytoplasma group III, and lane negative control corresponds to PCR product without

DNA (HyperLadder TM II).

Figure 10 (a and b) Leaflets showing yellowish lines running parallel to veins. (c) Fruit bunch with low

fruit production.

Spear rot disease (SRD) of oil palm was reported on plantations of Kerala (Kochubabu

and Nair 1993; Nair and Kochubabu 2000). Oil palm stunting (OPS) disease was reported

in oil palms from Andhra Pradesh, India, and was found associated with 16SrI-B subgroup

Ca. P. asteris-related strain (Azadvar et al. 2012).

Oil palm is one of the most important oil-producing crops in India. The area cultivated

each year is 121 128 ha, of which more than 85 000 ha is grown in Andhra Pradesh

(Directorate of Oil Palm Research 2010).

In Malaysia, the phytoplasma infecting oil palm belongs to the same 16SrXIV

phytoplasma group (Nejat et al. 2009). The same authors also reported another novel

phytoplasma species infecting oil palm.

Biology

A single occurrence of what seems to be a different phytoplasma from that occurring in

coconut and other palm species has been recorded in an oil palm planting in the West New

Britain area of Papua New Guinea, suggesting that oil palm is susceptible to infection by one type of phytoplasma (Turner 1981). Molecular confirmation and the interrelationship

of phytoplasmas associated with diseases of palms in southern India were reported by

Kochubabu et al. (2014).

Leaf samples of symptomatic oil palms were collected, and the presence of

phytoplasma was confirmed by nested PCR using universal phytoplasma-specific primer

pairs P1/P7, followed by R16F2n/R16R2 for amplification of the 16S rRNA gene, and

semi-nested PCR using universal phytoplasma-specific primer pairs SecAfor1/SecArev3,

followed by SecAfor2/SecArev3 for the amplification of a part of the secA gene (Mehdi

et al. 2012).

Analysis of 16S rDNA sequence of the phytoplasma associated with stunting of oil palm

in Andhra Pradesh, India, revealed its similarity with 16SrI AY group phytoplasma.

The RFLP pattern derived from in silico analysis of R16F2n/R16R2-primed sequence of

16S rRNA of OPS phytoplasma using the iPhyClassifier tool assigned the OPS phytoplasma

to subgroup B of 16SrI group phytoplasma.

Samples of 28 SRD-affected oil palms from three locations in Kerala and one in

Karnataka were collected after assessing disease severity. A phytoplasma presence in

symptomatic oil palm was confirmed by nested PCR. The presence of phytoplasma group

16SrXI was determined. Comparison of the ~1.2-kb sequences of two oil palm SRD strains

from Wayanad and Kollam (accession numbers KM593237 and KM593241) with other

phytoplasma sequences in GenBank revealed that the phytoplasma associated with SRD

of oil palm had a 16S rDNA sequence identity of 99–100% with sugarcane grassy shoot

phytoplasmas (KJ792743 and KJ435292).

Symptoms and effects on yield

Phytoplasmas are known to induce symptoms that are quite variable and consist of leaf

yellowing, reduction in fruit and stalk size, stunting, wilting and severe or slow decline.

Symptoms found in the West New Britain area of Papua New Guinea were some necrosis

of the oldest fronds and foliage colour in general was chlorotic, in marked contrast with

the dark green appearance of the remainder of the planting (Turner 1981).

In India, severe stunting symptoms were observed in clonally propagated oil palm in

the district of West Godavari, Andhra Pradesh. In Kerala and Karnataka, phytoplasma

symptoms of yellowing of the inner whorl of leaves and rotting of spears in oil palm were

observed. The SRD of oil palm and OPS disease associated with phytoplasma have been

described (Kochubabu 1989; Azadvar et al. 2012).

In Malaysia, oil palm samples were collected from spear leaves of six 2-year-old

seedlings showing yellowing and necrosis symptoms in a nursery in Banting, Selangor.

A phylogenetically distinct oil palm phytoplasma shared 99% similarity with EU371934

(periwinkle) and EU498727 (coconut) (Nejat et al. 2009).

Epidemiology

The LW has no known vector, but spread is known to be mediated by the use of seed

obtained from infected fields.

In view of the cross-transmission of phytoplasmas associated with LW by Proutista moesta

and dodder in Kerala (CPCRI 1995) and the capability of insect vectors (leafhoppers)

such as Aphrodes bicincta and Euscelis incisus in transmitting more than one group of

phytoplasmas, the possibility of cross-transmission of other groups (16SrXIV; 16SrI-B) of

phytoplasmas by Proutista moesta is very much present (Kochubabu et al. 2014).

Control

Identification of alternative hosts is essential to develop sustainable control strategies. The

varieties that were shown to be resistant to lethal yellowing in the Caribbean region did

not show the same degree of resistance in Africa (Bila et al. 2015).

8.2 Phytoplasma diseases in Africa

The LWD in Africa was associated with phytoplasma.

Biology

Elaeis guineensis is an alternate host of coconut LYD phytoplasma in Mozambique.

Out of 28 plants sampled, one positive PCR for 16S rRNA gene primers was achieved on oil palm samples. A higher ratio of PCR-positive samples with both 16S rRNA and secA

gene primers was achieved on Elaeis guineensis palm tree samples collected using the

stem boring method.

Symptoms and effects on yield

In the district of Nicoadala, African oil palm (E. guineensis) exhibiting symptoms of a skirt

shaped brown discolouration (necrosis) of mature and spear leaves (Fig. 11) was associated

with a phytoplasma disease.

Epidemiology

Transmission of phytoplasma between different host species was observed in Malaysia,

where the causal agent of coconut LY-type diseases was also observed in oil palm (Nejat

and Vadamalai 2010).

Challenges within the field of LYD epidemiology include the identification of insect

vectors (Bila et al. 2015).

Control

One disease management strategy is the removal and burning of symptomatic trees.

Removed palms must be replaced by resistant varieties. However, identifying resistance to

the palm phytoplasma in Africa has proven challenging (Bila et al. 2015).

9 Conclusion, summary and future trends

9.1 Conclusion

Major oil palm diseases are limited to certain continents: Fusarium in Africa, Bud Rot in

Latin America and Ganoderma in SE Asia. In various regions of the world, the existence

of soils that are in some way inhospitable to Fusarium wilts has prompted exploration of

biotic and abiotic mechanisms of disease suppression. The association between Fusarium

wilt suppression and environmental factors is typically related, in part, to the effects of

these factors on the soil microbiota, members of which may compete directly with or

release toxins against the pathogen or incite plant host defence responses (Baker and

Cook 1974). A natural biological control system of Fusarium-suppressive soils could

explain why vascular wilt disease is not present in Malaysia. Alkaline soils generally are less

conducive to Fusarium wilts of many crops (Jones et al. 1989), which is thought to explain

why the disease does not limit seed production in Denmark. Another theory regarding

the mechanisms of Fusarium wilt suppression achieved with soil limestone application

Figure 11 African oil palm (Elaeis guineensis) exhibiting skirt-shaped brown discolouration of the

older leaves.

is that Ca provided by the limestone is beneficial for plant defence responses, because

Ca fortifies cell wall structure by cross-linking pectins and is involved in cellular defence

signalling (Marschner 1995).

Rusli et al. (2013) investigated the possibility of Fusarium oxysporum-suppressive soils in

Malaysia in order to explain the non-appearance of this vascular disease there and possibly to reveal other potential biocontrol agents. The explanation as to why Malaysia has not yet attained the disease is likely to revolve around the soil properties, in particular the microflora. This review reported that greater disease severity based on visual symptoms occurred in autoclaved soils and compost than in untreated soils when oil palm seedlings were artificially infected with Fusarium oxysporum.

Given the limited genetic basis exploited in plantations, natural sources of variation existing in oil palm are low and have led studies to exploit the different sources of variation in order to increase the oil palm genetic diversity. Genetic diversity of oil palm has been narrowed due to the limited number of founder lines used in the breeding population. Broadening the genetic base would help increase the oil palm yield (Mayes et al. 1997).

9.2 Summary

Diseases have been documented as one of the primary constraints to oil palm production. Phytoplasma and fungal pathogens cause important yield losses where oil palm is grown. Some of these pathogens and the diseases that they cause are only partially characterized and understood, and many research gaps still need to be addressed. Progress is limited in the management of oil palm diseases.

In this chapter, we have presented information on oil palm diseases and their causal agents. Several of these are of key importance now. In Latin America, LWD and LSD continue to spread through oil palm-producing areas in Colombia. The significance of this threat has increasingly been recognized by the research, plant protection and extension communities within the country. This and other related strategies from oil palm stakeholder institutions are paving the way for an increased commitment to developing effective, affordable and durable solutions to this problem. In Latin America, great progress has been made in recent years in understanding the pathogen interactions that give rise to the devastating LWD. Moreover, experience gained in researching phytoplasmas associated with this condition is having a powerful effect on new research being conducted on a related pathogen that is causing LSD in the eastern plains (Llanos Orientales) in African oil palm, pertaining to Unipalma and Sicarare. This highlights the importance of one of the most important themes in the management of oil palm diseases, which is the prevention of pathogen spread between countries and continents through the vigorous application of phytosanitary protocols. It is essential that human and technical capacity to enforce phytosanitary controls be greatly strengthened to ensure that all oil palm stakeholders are fully informed of the risk of introducing diseases carried by oil palm seed between territories and continents.

9.3 Future research on diseases discussed in this chapter

- The physical size of the oil palm genome is two-thirds of the maize genome and four times the size of the rice genome. A complete sequencing of the palm genome would help in understanding the key genes affecting disease resistance.
- Multi-parental populations are promising tools for identifying quantitative disease resistance loci. The multi-parental population design allowed us to identify quantitative disease resistance loci among an extended genetic diversity, and to test their effects in various genetic backgrounds, which should enhance the transferability of results and the sustainability of the selected resistances.
- The selection of varieties resistant to a combination of diseases will be essential for multi-criteria improvement, as Ganoderma is found throughout the oil palm cultivation area, combined with other devastating diseases like the Fusarium wilt in Africa and bud rot in South America. Hence, the global genetic architecture of disease resistance in oil palm needs to be investigated, especially potential trade-off effects related to different pathogens, as shown for other species. The multi-parental population and the implemented quantitative trait loci (QTLs) mapping approach provide powerful tools for investigating such global genetic architecture of disease resistance in oil palm (Tisne et al. 2017).
- The use of metabolomic tools such as liquid chromatography–mass spectrometry/ mass spectrometry (LC–MS/MS) profiling technology holds great promises for investigating and understanding metabolism associated with root metabolome (Nurazah et al. 2016). The LC–MS/MS method developed for profiling and identifying oil palm root metabolites can also be used as a model for developing a reliable tool towards distinguishing tolerant palms to oil palm disease such as BSR.
- Identifying metabolites associated with resistance promises development of biomarker tools for screening of oil palm resistant to G. boninense. In addition, understanding resistance mechanisms at the metabolome level helps breeders better understand resistant gene function and pyramid suitable resistant gene in elite variety.
- Transcriptome of oil palm roots treated with a causal agent of BSR, G. boninense using a cDNA microarray approach. This information contributed to our understanding of the defence mechanisms of oil palm in response to G. boninense, the future development of molecular markers for marker-assisted breeding and screening of oil palms that are tolerant to G. boninense (Tee et al. 2013).
- Approaches to the phytosanitary management of oil palm health: strict quarantine regulations on the importation of oil palm

seeds in order to prevent introduction of these destructive diseases.

10 Where to look for further information

Societies involved in oil palm disease study

American Phytopathological Society (APS). http://www.apsnet.org/Pages/default.aspx

International Society for Plant Pathology (ISPP). http://www.isppweb.org/index.asp

Information sources about plant disease

CABI. http://www.cabi.org/isc/

Plantwise Knowledge Bank. http://www.plantwise.org/KnowledgeBank/Home.aspx

Organizations involved in oil palm disease research

Centro Internacional de Agricultura Tropical (CIAT). www.ciat.org

Oil Palm Research Institute (OPRI) of Ghana. www.csir.org.gh

Council for Scientific and Industrial Research (CSIR). www.csir.org.gh

Colombian Oil Palm Research Center (CENIPALMA). www.cenipalma.org

Indonesian Oil Palm Research Institute (IOPRI). www.iopri.org

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3 Chapter 3 Insect pests affecting oil palms

1 Introduction

The oil palm is a food source for a large number of actual and potential insect pests. The

increasing international movement of material is also introducing new insects. Populations

of these invasive insects can grow rapidly in new areas where there are no natural enemies

and cause sudden and spectacular outbreaks. However, less than 10% of the thousand

arthropods that live on palm plantations have been recognised as serious pests for cultivated

palm species. Indeed, Lespesme (1947) reported that insects cause very little damage to

wild palms. However, as soon as the oil palm is cultivated on a large scale, it becomes

more susceptible to pest attack as pest pressure increases. The rapid and exponential

increase in cultivated oil palms over the last 50 years (Rival and Levang, 2013; FAOSTAT,

2015), especially in the form of large-scale monocultures, has favoured outbreaks of several

species which have been able to colonise new areas and have acquired pest status (e.g.

Oryctes rhinoceros in Southeast Asia and Oryctes monoceros in Africa). Pest outbreaks also

occur when there is an imbalance in the biocenosis (ecological community), mainly due to

poor cultivation practices and intensive spraying with contact insecticides.

All types of herbivorous arthropods can be found on oil palms, including polyphagous species that also feed on other plant taxa or specialised species which can only develop on plants in the family Arecaceae. These insects attack all niches offered by the oil palm: fronds, sap, stipe, roots, inflorescences and fruits. Like all palm species, the oil palm has unique anatomical and physiological traits, characterised by rapid growth from a single meristem from which the stem, fronds and inflorescences develop, forming a large amount of tissue that is rich in water and nutrients (Cohen, 2017).

Oil palm insect pests include borers which dig galleries and feed on fresh tissue in the meristem (Coleoptera: Scarabaeidae and Lepidoptera). Pests include weevils (Coleoptera: Curculionidae), leaf-eating caterpillars (Lepidoptera), some mites (Acari), sap-feeders (Hemiptera), long-horned grasshoppers (Orthoptera) and stick insects (Phasmatidae). Species belonging to other Lepidoptera families (Crambidae, Satyriidae, Lymantriidae and Psychidae) are also important oil palm pests. The range of species attacking the oil palm differs between continents (the plant is found in South America, Africa, Asia and the Pacific Islands).

Many species from the Scarabaeidae family are serious oil palm pests in their adult form, whereas in other species (families Curculionidae and Chrysomelidae), damage is caused by their immature stages. Borers are by far the most difficult group to manage but, although the large-scale use of insecticides has been successful, many of these products

have been, or are being, banned.

The Lepidoptera are the largest group of pests attacking coconut, date and oil palms,

with about 240 species. Among the most damaging caterpillars are several species of

Limacodidae, leaf eaters that attack unfolded spears and folded fronds. Other species are

miners which bore into fronds, flowers, fruits, stems, nursery seedlings and roots (Mariau,

2001). When the harmful stage of the insect pest can be accessed easily as it is living on

the palm (such as defoliators or sap-feeders), any natural or chemical control measure can

be effective. The situation is totally different when the caterpillar, larva or adult lives inside

the plant (leaf miner or borer). Several control methods are discussed in this chapter, some

of which are still being improved.

A selection of the main insect pests found in oil palm plantations in Latin America, West

Africa, Southeast Asia and the Pacific is presented in this chapter, which was not designed

to update existing reviews, but to serve more as an overview of the main types of oil palm

pests (23 species) that have been selected from the most damaging groups to illustrate

the relationships between oil palm plants and herbivorous arthropods. This chapter is

designed for practical use and intended for growers, agronomists, students, extension

officers and any stakeholders interested in sustainable oil palm cultivation. Readers will find descriptions and high-quality photographs which should help them identify species.

It also provides useful information compiled during field work and from literature reviews

(Lepesme, 1947; Bedford, 1980; Mariau, 2001; Howard et al., 2001; Bedford, 2013). For

convenience, the pests we describe are classified according to the part of the palm that

they target, fronds, meristem, roots or fruit bunches, and some general features of their

habitual behaviour that have practical implications for their control are discussed.

In terms of pest control, Desmier de Chenon (1989) has studied the relationships between

host-parasitoid-predator-entomopathogen and alternative hosts to encourage specific

natural enemies and prevent unnecessary and ineffective chemical treatments. Careful

application and selective use of insecticides can prevent any adverse effect on beneficial

insect populations (Kamarudin et al., 1998). The development of integrated pest management

(IPM) programmes to control oil palm pests (bagworm, rhinoceros beetle, nettle caterpillar,

bunch moth) in Malaysia has been reviewed by Ariffin and Basri (2000). Control measures are

only effective when an IPM system is adopted. This includes a combination of several factors:

a comprehensive surveillance system; farming practices such as retaining some selected

nectariferous plants/planting legumes in the field; the timely use of predators, parasitoids

and pathogens; and the appropriate use of specific insecticides (Lay, 1996).

2 Insect pests of oil palm fronds

2.1 Lepidoptera: Limacodidae

Palms (Arecaceae) are the main host for the Limacodidae family, some 68 species of which

have been recorded to be found in Asia, particularly in Southeast Asia (Cock et al., 1987), 20

species in tropical South America and 6 in Africa. These are polyphagous species, commonly

known as nettle caterpillars. Only six species (four from Southeast Asia, one from South

America and one from Africa) of the 32 that cause severe defoliation, as mentioned by Mariau

(1999), are illustrated in this section. They have been selected according to the probability of

outbreaks and the severity of the damage to the oil palm (Fig. 1). The species Thosea vetusta

and Susica malayana are also illustrated, although significant outbreaks remain rare.

The life cycle of the nettle caterpillar takes from 2 to 3 months (60 days on average for

Setora nitens and Darna trima; 104–129 days for Latoia viridissima) according to Mariau et al.

(1981, 1991). These caterpillars display some characteristic bright colours and a large number

of stinging bristles (hence the name nettle caterpillar or slug caterpillar) (Fig. 2, 3, 5–11).

The use of viruses to control outbreaks has been described by Philippe et al. (1997).

Various diseases that affect these caterpillars have been listed by Entwistle (1987), and

the importance of natural enemies and their potential use in IPM strategies was reported by Desmier de Chenon (1989). Up-to-date biological controls involving natural enemies

Figure 1 Defoliation due to Limacodidae outbreak in Indonesia © Laurence Ollivier.

are not commonly used during pest outbreaks in plantations, but there is a real potential

for managing outbreaks using biological controls, rather than pesticides. Developing

biological tools to control Limacodidae would be a good strategy, as successful biological

control benefits all, without cost. Potential types of biological control for particular regions

are summarised below:

2.1.1 Limacodidae from Southeast Asia (Indonesia) (Mariau, 1999) • Thosea vetusta Walker (Fig. 2): Thosea vetusta Walker (Hymenoptera: Ichneumonidae) is the most common parasite to attack caterpillars. • Susica malayana Hering (Fig. 3) caterpillars are affected by pathogens and parasitoids (Fig. 4). • Darna diducta Snellen (Fig. 5) is found in Thailand, Malaysia and Indonesia, and parasitised by Hymenoptera [Braconidae Apanteles aluella and the hyperparasitoid Aphanogmus manila, Rogas sp. (hyperparasitoid)]; Eulophidae Neoplectrus clavatus; Ichneumonidae (Buysmania oxymora); and Diptera (Tachinidae Chaetexorista javana, Palexorista solennis). • Darna trima Moore (Fig. 6) has been found in Malaysia and Indonesia and four Hymenoptera families have been recorded as parasitic: Braconidae (Apanteles aluella and the hyperparasitoid Aphanogmus manila, Apanteles sp., Formicia penang and Rogas sp.); Eulophidae (Platyplectrus orthocraspedae); Chalcididae (Brachymeria lasus (hyperparasitoid)); Ichneumonidae (Buysmania oxymora); and the Diptera Bombyliidae Systropus roekpei and Tachinidae Chaetexorista javana. • Setora nitens Walker (Fig. 7) is found in Malaysia and Indonesia. Four Hymenoptera families are parasitic: Trichogrammatidae (Trichogrammatoidea thoseae); Braconidae {Fornicia ceylonica, Fornicia sp., Apanteles parasae, Meteorus sp., Spinaria spinator, Rogas sp. [Brachymeria lasus, n.r. (no record), hyperparasitoid, triraphis]}; Ichneumonidae (Buysmania oxymora, Chlorocryptus purpuratus, Goryphus mesoxanthus, Theronia orientalis, Xanthopimpla sp.); and Eurytomidae (Eurytoma sp., hyperparasitoid).

Figure 2 Thosea vetusta © Laurence Ollivier.

Figure 3 Healthy Susica malayana © Laurence Ollivier.

Figure 4 Susica malayana affected by entomopathogens or parasitoids © Laurence Ollivier.

Figure 5 Darna diducta © Laurence Ollivier. • Caterpillars are susceptible to diseases and parasitism (Fig. 8a and b). • Setothosea asigna Van Eecke (Fig. 9a and b) is found in Malaysia, Indonesia and the Philippines. Hymenoptera families have been recorded to attack Setothosea asigna: Braconidae (Rogas sp., Spinaria sp., Fornicia sp., Fornicia ceylonica); Ceraphronidae (Aphanogmus manila, hyperparasitoid); Eulophidae [Euplectromorpha nr. (no record) bicarinata, Metaplectrus solitarius]; Ichneumonidae (Chlorocryptus purpuratus, Goryphus sp., Theromia orientalis); Trichogrammatidae (Trichogrammatoidea thoseae), and Diptera: Tachinidae (Chaetexorista javana). In 1980-81, a cytoplasmic polyhedrosis virus was occasionally reported to be found on Setothosea asigna, along with caterpillars displaying disease symptoms of the B. nudaurelia type, although it was impossible to say whether the two diseases were associated (Desmier de Chenon et al., 1988; Sinuraya, 1989). • Caterpillars can also be affected by some unidentified pathogens (Fig. 10).

Figure 6 Darna trima © Laurence Ollivier.

Figure 7 Setora nitens © Laurence Ollivier.

Figure 8 (a, b) Setora nitens affected by entomopathogens © Laurence Ollivier.

Figure 9 (a, b) Healthy Setothosea asigna © Laurence Ollivier.

Figure 10 Setothosea affected by unidentified pathogens © Laurence Ollivier.

2.1.2 Limacodidae from South America (Ecuador) (Mariau, 1999; Genty, 1972) • Sibine fusca Stoll (Fig. 11): Various species of Hymenoptera attack Sibine fusca, including: Braconidae [Cotesia sp. nr. (no record) glomerata (Elasmus maculatus, Conura immaculata, hyperparasitoids]; Ichneumonidae [Casinaria sp. (Palmistichus elaeisis, Conura immaculata, Conura camescens, Conura biannulate, hyperparasitoids), Baryceros sp. Diptera: Tachinidae (Palpexorista coccyx] and Bombyliidae (Systropus nitidus) also. • Caterpillars were also found to be predated by entomopathogens (Fig. 12). Epizootic infection by a very aggressive virus has been observed in Sibine fusca caterpillars, with high levels of mortality in the early stages (Genty and Mariau, 1975). Cases of attack by densonucleosis virus were also described by Meynadier et al. (1977).

2.1.3 Limacodidae from Africa (Gabon) (Mariau, 1999) • Latoia viridissima Holland (Fig. 13) is found in Western and Central Africa. Four Hymenoptera families attack Latoia viridissima: Braconidae (Apanteles sp., Rogas sp.); Eulophidae (Tetrastichus spp. nr. balteatus); Chalcididae (Brachymeria sp. and Chrysis spina); Ichneumonidae (Coccygodes coccyx), and two Diptera (Tachinidiae Palexorista sp. nr. (no record) moyneana, and Bombyliidae Systropus pelopeus). • Figure 13 shows caterpillars affected by a possible entomovirus. Latoia viridissima is affected by various other viruses: a picornavirus was identified by Fedière et al. (1990) during an outbreak, a nuclear polyhedrosis baculovirus was detected by Kouassi et al. (1991) and a ribovirus was studied by Zeddam et al. (1990). Larval and pupal stages of Latoia viridissima are also attacked by a number of parasitoids (Igbinosa, 1988). • In most of the species studied, population levels are naturally controlled by parasitism (by Hymenoptera: Braconidae and Eulophidae and Diptera: Tachinidae), but Hemiptera predators also play an active role (Mariau, 1999). Virus pathogens have been reported to play a major role in regulating populations during outbreaks (Mariau, 1999), although this effect remains largely underexploited. Small, free viruses have also been detected in South America and West Africa (Desmier de Chenon et al., 1988).

Figure 11 Sibine fusca © Laurence Ollivier. • Sex pheromone components have been identified in Darna trima (Sasaerila et al. 2000a), Setothosea asigna (Sasaerila et al., 1997) and Setora nitens (Sasaerila et al., 2000b) and these have enabled effective bait traps to be developed to monitor limacodid pest populations in Asian oil palm plantations. However, these cannot be used for mass trapping.

2.2 Lepidoptera: Erebidae

In this section, which focuses on the Lymantriidae, we only discuss two species: • Calliteara horsfieldii Saunders, 1851: that damages the leaves of adult palms • Dasychira inclusa Walker that damages leaves in young plantations and nurseries

Apart from Orgyia turbata Butler (Corbett and Dover, 1927), which causes severe

defoliation of young palms, other species such as Dasychira mendosa Hubner (Wood,

1968), Euproctis semisignata Walker (Abraham and Remamong, 1976), Euproctis linta

Moore (Mariau et al., 1991) and Laelia venosa Moore (Wood, 1968) are considered to

be secondary pests of the oil palm. These species are characterised by numerous long

hairs.

Figure 12 Sibine fusca with pupae of Hymenoptera parasitoids © Laurence Ollivier.

Figure 13 Latoia sp. in Gabon © Kevin Fernandez.

Calliteara horsfieldii Saunders, 1851 affects oil palms in Southeast Asia, particularly in

Indonesia (Mariau et al., 1991). This caterpillar displays the yellow dorsal hairs typical of

this genus and tufts at the front (Fig. 14), and its life cycle takes 1.5 months (Mariau et al.,

1991). Calliteara horsfieldii is a polyphagous lepidopteran (Pholboon, 1965; Browne,

1968; Barlow, 1982; Kuroko and Lewvanich, 1993; Hutacherern and Tubtim, 1995; Chey,

1996) and the caterpillars affect the leaves in adult oil palm plantings where they cause

major, though not spectacular, defoliation.

This insect is a typical pest, which can appear in sudden outbreaks that can be

prevented from having a severe economic impact through natural control or chemical treatments. It seems that these populations are resident in some plantation blocks and are capable of causing repeated outbreaks. Larval excrement on the ground shows that the foliage is actively being consumed by healthy caterpillars, and early caterpillar detection enables treatment to be planned before the final larval stage starts to transform into a chrysalis. The leaf-eating caterpillars' cocoons can be observed on the undersides of leaves and the chrysalides are covered in white silk. Cocoons remain on the foliage, and it is essential to check the effectiveness of any chemical treatment so that they do not form a population reservoir (diapause) which can often cause an outbreak at a later date.

Two tachinid dipterans were found to keep population levels down (Mariau et al., 1991) and natural control was observed in the field prior to chemical treatment in Indonesia (possibly due to a cytoplasmic polyhedrosis virus). Infected caterpillars are soft and pink in colour (Fig. 15) and immobile, or move very little, when handled. Their cuticle is fragile and breaks easily, allowing a yellowish and particularly foul-smelling liquid to leak from the body. Further investigation is required to identify a natural biological control method using a virus.

Dasychira inclusa Walker (Mariau et al., 1991): The caterpillars affect leaves in nurseries and young oil palm plantings (Fig. 16) and their life cycle takes 51–57 days.

They attack the upper epidermis, then right through the lamina. A hymenopteran

scelionid parasitises the eggs, while Apanteles sp. (a braconid) and Diptera: Tachinidae

attack the caterpillars.

Figure 14 Healthy caterpillar © Laurence Ollivier.

2.3 Lepidoptera: Cambridae

Furcivena rhodoneuralis Hampson damages oil palm leaves in West Africa (Fig. 17). The

caterpillar is very mobile (Fig. 18) and its life cycle takes approximately seven weeks (Mariau

et al., 1981). The limbs of the leaflets are perforated along the main nervure (main vein);

they are rectangular in shape, one to five times longer than they are wide. Defoliation

due to young caterpillars (<5 mm in size) is negligible compared to that recorded during

the last two weeks of the caterpillar stage, which can account for more than 90% of

the damage observed. These caterpillars cause similar damage to Coelaenomenodera

lameensis and these two pests might not be differentiated from each other as both can be

found on oil palm leaflets. Ten successive cycles (seven weeks/cycle) during which more

than 45 caterpillars per lower leaf are counted are believed to cause at least 10% of the

damage. Populations do not usually consist of many individuals for very long, suggesting

that a natural biological control could be reducing population levels.

Figure 15 Caterpillar affected by virus © Laurence Ollivier.

Figure 16 Dasychira inclusa caterpillar © Laurence Ollivier.

Figure 17 Damage on leaves due to Furcivena rhodoneuralis in Ghana © Laurence Ollivier.

Figure 18 Furcivena rhodoneuralis caterpillar © Laurence Ollivier.

2.4 Lepidoptera: Psychidae

The two main species are: • Mahasena corbetti • Metisa plana

They are known as bagworms and leaf-eating caterpillars in Southeast Asia. They are

serious oil palm pests, but several other species of Psychidae can also cause damage (for

example, Clania sp. in West Papua).

2.4.1 Mahasena corbetti Tams 1928

This is a polyphagous pest found throughout Southeast Asia (Lepesme, 1947; Kalshoven,

1950) and the caterpillar attacks oil palm leaves of all ages. In an early stage, the caterpillar

builds a bag made of leaf fragments stuck to a mass of silky threads which it secretes

(Fig. 19) and it then develops into this bag. This helps the pest use the wind to disperse

over large areas (Syed et al., 1974). The female imago remains vermiform and never

escapes from its sheath (Fig. 20). Fertility is very high (up to 3000 eggs/adult) and the life

cycle of this species takes about four months (Mariau et al., 1991).

Figure 19 Mahasena corbetti eating leaflets © Laurence Ollivier.

Eight parasitoids are common to both of these psychid species, while seven are associated only with Metisa plana and three only with Mahasena corbetti in Peninsular Malaysia (Kamarudin et al., 1996). The list of parasitoids and predators is quite substantial for all the developmental stages except the eggs (Tiong, 1979; Mariau et al., 2001; Syed et al., 1974). IPM with a granulosis virus (Syed and Saleh, 1998) has been used, and a sexual pheromone emitted by the females has been isolated (Rhainds et al., 1997).

Injecting the trunks of mature palms with systemic chemicals is a viable option, and there are many advantages to trunk injection, the main one being its compatibility with IPM practices. The technique is specific to a target insect species, so natural predators are spared and can still proliferate. The use of appropriate trunk injection techniques, the right choice of chemicals and equipment, and a resistance management strategy all contribute to an effective control (Hean, 2000).

2.4.2 Metisa plana Walker

The caterpillar of this species mainly damages mature oil palms, and its morphology and biology are similar to those of Mahasena corbetti. The larval sheath is attached to the leaflets by a hooked filament (Fig. 21). Natural enemies of the bagworms that attack oil palms in eastern Malaysia have been described by Sankaran and Syed (1972), and Wahid and Kamaruddin (1993) found that Metisa plana was attacked by primary and secondary

parasitoids and a predator.

2.5 Lepidoptera: Nymphalidae

The caterpillar of Amathusia phidippus Linnaeus, 1763 attacks oil palm leaves in the nursery

and on mature palms at any developmental stage. These caterpillars have a gregarious

behaviour. The life cycle takes two months (Wood, 1968; Lever, 1979). Early instars have

three black spots (Lever, 1979) and caterpillars grow to about 90 mm long at the end of

their development. They develop long and numerous hairs (Fig. 22a and b) which are not

urticarial. The main natural enemies of this insect are several species of tachinid dipterans,

Figure 20 Mahasena corbetti extracted from the bag © Laurence Ollivier.

including Pamexorista solennis and Exorista sorbillans (Kalshoven and van der Laan, 1981),

and a chalcid hymenopteran (Mariau et al., 1991). Removing the insects by hand as soon

as they are seen is the most effective control measure (Mariau et al., 1991).

2.6 Lepidoptera: Saturnidae

Automeris liberia Cramer, 1779 damages oil palm foliage in Colombia, Ecuador,

Venezuela, Brazil and Peru (Genty et al., 1978) and the caterpillar is especially harmful to 1-

to 3-year-old palms. It is also reported to be a highly polyphagous species (Howard et al.,

2001; Cock, 2005). The caterpillar is green in colour with a bold white lateral stripe with purplish-red borders, and it is very urticate (Fig. 23). The length of the life cycle is unknown

(Genty et al., 1978). As they are an occasional pest on oil palms, Automeris (Automeris

Liberia) are usually effectively controlled by natural enemies which include Braconidae,

Ichneumonidae and Tachinidae.

Figure 21 Metisa plana sheath © Laurence Ollivier.

Figure 22 (a) Amathusia phidippus caterpillars - young caterpillars © Laurence Ollivier. (b) Amathusia

phidippus caterpillars – last stage caterpillars © Laurence Ollivier.

3 Coleoptera Curculionidae

Coelaenomenodera lameensis Berti and Mariau (1999) is considered to be the most

harmful hispine pest in West Africa, displaying disease symptoms of the B. nudaurelia

(Nudaurelia B virus) including Cameroon (Jacquemard, 2011; Jolivet et al., 2004) (Fig. 24).

Larvae mine the leaflets (Fig. 25). Outbreaks cause significant defoliation to the oil palm,

which affects crop yields for 2–3 years. Coelaenomenodera lameensis attacks were found

to cover thousands or even tens of thousands of hectares of Elaeis guineensis in most

countries (Cachan, 1957). Research into this species is ongoing due to its economic

importance. The life cycle takes about 95 days (Morin and Mariau, 1970). Preliminary

observations in the field showed that different levels of damage, based on the type of

defoliation, depended on the genetic origin of the oil palm (Philippe, 1977, 2003; Coffi, 2006, 2014; Beaudoin-Ollivier et al., 2015).

Rational methods of chemical control have been proposed (Mariau and Philippe, 1983;

Philippe, 1990a,b), but chemical control depends on the size of the infested area and

the type of plantation. In areas of sizes up to 500 ha, adult pests were controlled most

efficiently by spraying Evisect S (Thiocyclam hydrogen oxalate) (Coffi, 2014). The pesticide

Figure 24 Coelaenomenodera lameensis adult and galleries © Laurence Ollivier.

Figure 23 Automeris liberia © Laurence Ollivier.

is very efficient, so only few treatments are required. Parasitoids include three species that

infest the eggs and four species that live on the larvae and pupae (Jolivet et al., 2004).

Local parasitoids are not effective (Mariau and Morin, 1972).

The survival of Coelaenomenodera lameensis has been studied in relation to the physical

characteristics of different oil palm populations originating from breeding programmes

(Beaudoin-Ollivier et al., 2015). No significant difference in the average number of eggs

laid and the average hatching percentage was found between Elaeis oleifera and Elaeis

guineensis populations. A highly significant difference was evidenced at the transition

stage from first and second larval instars into third and fourth larval instars: the percentage

of individuals passing to third and fourth larval instars reached 87% for Elaeis guineensis of La Mé origin, whereas it was only 0–2.8% for two Elaeis oleifera breeding populations

(Beaudoin-Ollivier et al., 2015).

Breeding populations can be classified according to the positive or negative influence they

for different oil palm breeding populations is required to identify genetic resistance to insect

pests. The effect of certain compounds in the leaflets on larval mortality, which might inhibit

Coelaenomenodera lameensis feeding behaviour, also requires further investigation.

4 Orthoptera Pyrgomorphidae

Zonocerus variegatus (Linnaeus, 1758), or the stink locust, is widespread in West Africa,

but infection has not been reported in Gabon (Chiffaud and Mestre, 1990). The adult has a

very distinctive appearance due to its bright colours (red, green and yellow) (Fig. 26). This

aposematic colouration warns off possible predators. The complete life cycle takes 10–11

months (Mariau et al., 1981). Z. variegatus is a polyphagous species that has been recorded

on Elaeis guineensis (Brunel and de Grégorio, 1978; Copr, 1982; de Grégorio and Brunel,

1977; Hartley, 1967; Jerath, 1965; Koman, 1983; Mayné, 1914; Page, 1978; Steedman,

1988; Mariau et al., 1981) and Elaeis sp. (Appert, 1957; Lepesme, 1947; Mayné, 1917).

Elaeis guineensis is included on the list of the main cultivated plants eaten by

Z. variegatus (Chiffaud and Mestre, 1990). Damage includes severe defoliation, mainly of

young palms, by the imagos and larvae (Fig. 26 and 27). The larvae strip the upper surface

of the leaflets, leaving the lower epidermis. We observed a few specimens on young palms

under three years of age in both Ghana and Gabon in 2016. The economic importance of

Figure 25 Coelaenomenodera lameensis last instar larvae outside of the gallery © Laurence Ollivier.

Z. variegatus has increased over the last 30 years, and the leaf eater has become a threat

in both forest and preforest areas (Chiffaud and Mestre, 1990). Following major changes

in their environment, pest populations may increase locally and create new damage foci.

The insect’s two main enemies are the dipteran Blaesoxipha filipjevi Rohdendorf, 1928

(Sarcophagidae: Miltogramminae) and the fungus Entomophaga grylli Fresenius, 1858.

Blaesoxipha filipjevi parasitises the imago and may be an important cause of reduction in

the number of eggs laid by the female. Development is optimised in areas with favourable

hygrometric conditions. Entomophaga grylli attacks all the developmental stages of the

insect pest except the first stage. Other parasites or diseases of Z. variegatus that have a

low impact are cited by Chiffaud and Mestre (1990).

A push-pull strategy using attractive plants such as Ageratum conyzoides can be used,

and the attractive plant can also be used to detect and monitor Z. variegatus before an

outbreak. Solanum verbascifolium, Chromolaena odorata and coffee clones IRCC 181 and

202 were found to be attractive to Z. variegatus in Ivory

Coast (Coulibaly et al., 1988, as published in Chiffaud and Mestre, 1990). Small populations can also be controlled by hand picking. Controlling Z. variegatus is innocuous, environmentally safe and inexpensive.

Figure 26 Zonocerus variegatus imago in Ghana © Laurence Ollivier.

Figure 27 Zonocerus variegatus larva in Ghana © Laurence Ollivier.

5 Insect pests of the oil palm meristem

5.1 Coleoptera Scarabaeidae

5.1.1 Oryctes rhinoceros

Oryctes rhinoceros (Linnaeus, 1758), or the rhinoceros beetle, is native to India and Indonesia, and it is a major pest of both indigenous and imported palms in Southern and Southeast Asia and the western Pacific Islands (Corley and Tinker, 2016; Howard et al., 2001). The adult attacks soft tissues located inside the growing point (Fig. 28), and this often kills young palms, although rarely mature ones. The tightly folded young fronds inside the bud are damaged, resulting in a characteristic and symmetrical loss of wedge shaped sections of tissue on both sides of the rachis, which are easy to see later on, when the fronds have expanded. The growing point is also damaged and this strongly affects further growth of the palm (Fig. 29). The beetle has been observed attacking oil palm fruit bunches by boring into the stalk (Ponnamma et al., 2001). Its lifespan ranges from 4 to 10 months, and the larvae feed on and develop in organic woody material, dead palm trunks

and softwood logs (Fig. 30). Immature stages are also found in empty fruit bunches which

are used in the field as a natural potassium fertiliser (Fig. 31). Ecological studies were

undertaken by Cumber (1957) in Western Samoa in 1957, and several other surveys were

then published by Peterson (1977), Bedford (1980) and Young (1986).

It is likely that IPM could control Oryctes rhinoceros populations if the appropriate

combination of methods is used. According to the zero-burning policy guidelines issued

by ASEAN in 2003, dead oil palm trunks should not be left standing to rot in the field when

replacement palms are planted. Felled palms in replanted areas must be shredded, and

the resulting woodchip spread in a single layer to destroy the breeding sites provided by

the dead palms (Fig. 32).

Insect control is based on the use of a cover crop that is grown on the palm woodchip and

acts as a vegetative barrier. It also relies on the manual collection of larvae from breeding

sites before replanting and the removal of adults feeding in galleries burrowed in the

Figure 28 Oryctes rhinoceros adult © Laurence Ollivier.

Figure 29 Young oil palm affected by Oryctes rhinoceros attacks © Laurence Ollivier.

Figure 30 Abundant last instar larvae of Oryctes rhinoceros in a breeding site © Laurence Ollivier.

young palms. These are satisfactory methods of reducing

Oryctes rhinoceros populations

(Fig. 33) and fishing nets are also used to protect patrimonial oil palms used in breeding

programmes (Fig. 34) (Moore and Quitugua, 2014). The use of insecticides (cypermethrin

and lambda-cyhalothrin) is recommended, with the frequency of application depending

on the age of the palm.

There have been many attempts to design biological control strategies, and some

success was achieved with a baculovirus strain (Oryctes rhinoceros nudivirus OrNV)

which was spread by infecting and releasing adults (Huger, 2005; Prasad et al., 2008;

Bedford, 2013). However, Jackson et al. (2005) pointed out that population control has

diminished over time and suggested that efforts should focus on the genetic selection and

dissemination of effective virus strains.

Figure 31 Empty fruit bunches as source of Oryctes rhinoceros breeding sites © Laurence Ollivier.

Figure 32 Pieces of old oil palm stems spread as a layer © Laurence Ollivier.

Figure 33 Hand-picking of Oryctes adult from young palms © Laurence Ollivier.

Figure 34 Fishing net to protect patrimonial oil palms © Laurence Ollivier.

The aggregation pheromone ethyl 4-methyloctanoate, produced by Oryctes rhinoceros

males, is commercially used in the field and captures a large number of insects of both

sexes (Hallett et al., 1995; Kalidas, 2014). However, there is no evidence that mass trapping can control pest proliferation satisfactorily (Bessou et al., 2017). The pheromone

trap remains a useful tool to detect areas newly affected by Oryctes rhinoceros and to

monitor the spread of the pest (Fig. 35a and b). The fungus Metarhizium anisopliae is

an effective biopesticide against immature stages of the insect, and it can be spread by

adult stages (Fig. 36) and used in combination with pheromone traps (Cik Mohd Rizuan

Figure 35 (a) PVC traps © Laurence Ollivier. (b) Bucket trap © Laurence Ollivier.

Figure 36 Oryctes rhinoceros adult infected by M. anisopliae © Laurence Ollivier.

et al., 2016). The effect of predators (such as scoliid wasp parasites) on eggs, larvae

and pupae is not thought to be significant. Studies into the management of this insect

pest in Malaysia (Manjeri et al., 2014) are still ongoing, and recent advances have been

published (Bedford, 2013, 2014).

5.1.2 Scapanes australis

Scapanes australis (Boisduval, 1832) is economically important and is a serious impediment

to the establishment of commercial palm plantations in Papua New Guinea (Bedford,

1976; Waterhouse and Norris, 1987; Beaudoin-Ollivier et al., 1999). The adults cause

similar damage in young palms to Oryctes spp. (Bedford, 1976) (Fig. 29). The male bears

three prothoracic horns (Fig. 37) and emits an aggregation pheromone (Prior et al., 2000;

Rochat et al., 2000).

5.2 Coleoptera Dryophthoridae

Palm weevils, Rhynchophorus spp. are Coleoptera: Curculionidae syn. Rhynchophoridae.

They are characterised by an elongated rostrum (‘snout’) with small mandibles at the distal

end. Most palm-associated weevils are polylectic and have a wide range of hosts within

the Palmae/Arecaceae, and sometimes within other monocotyledons such as sugar cane

(Gramineae/Poaceae), banana (Musaceae) and pineapple (Bromeliaceae).

Rhynchophorus spp. are considered to be major pests of coconut palms in tropical

regions of the world (Wattanapongsiri, 1966), and the main species found on the oil palm

are Rhynchophorus palmarum, Rhynchophorus bilineatus and Rhynchophorus phoenicis

(Fig. 38). Their entire life cycle lasts 3 to 6 months. Larvae are apodous and move

peristaltically, tunnelling into the crown and stem (Fig. 39).

Larval stages are protected from most predators, parasites and external environmental

factors while devouring all or some of the inside of the host. The tissues around the

growing point begin to decay as the late-instar larvae destroy the apical meristem and

the palm may be killed (Fig. 40) (Giblin-Davis and Howard, 1989). The external symptoms

Figure 37 Male of Scapanes australis in Papua New Guinea © Laurence Ollivier.

of the attack have been described as similar to those of

Fusarium wilt: the leaves show

gradually increasing signs of chlorosis and fracture in strong winds.

The adults live on wounded palms and they are usually cryptic, taking refuge between

petiole bases, unopened inflorescences, floral peduncles and sites of damage caused by

larval feeding in the crown and/or stem of the palm, where they oviposit. Rhynchophorus

palmarum is a pest of African oil palms and, in addition to causing direct damage, these

palm weevil larvae can be vectors of lethal, nematode-borne red ring disease or chronic

little leaf of palms. Pheromone traps are used to control populations in oil palm plantations

(Fig. 41).

Rhynchophorus bilineatus infestations are endemic in Papua New Guinea, and

Rhynchophorus bilineatus is a secondary pest once Scapanes australis has damaged the

plant. Infestation results in the death of the palm. Rhynchophorus phoenicis is known to

attack the African oil palm in Africa (Fig. 38b and 40), and it is interesting to note that

palm weevil larvae are the insects most widely eaten by humans (Howard et al., 2001).

Pheromone trapping is widely used to detect and monitor Rhynchophorus phoenicis,

Rhynchophorus bilineatus and Rhynchophorus palmarum (Rochat et al., 1993a,b).

Figure 38 Rhynchophorus sp [(a) R. palmarum; (b) R. phoenicis] © Laurence Ollivier.

Figure 39 Larvae of Rhynchophorus phoenicis © Laurence

Ollivier.

6 Insect pests of the oil palm root system

Sufetula sunidesalis Walker (a root miner) is a lepidopteran of the Crambidae family which

attacks the root systems of oil palms in Indonesia. Pest pressure is higher in oil palm

plantations on peat soils than on mineral soils. The species has been described by several

authors (Desmier de Chenon, 1975; Wahyu et al., 2001) and the characteristics of the

caterpillar are detailed in Fig. 42 and 43.

The adult is nocturnal, using ferns surrounding palms as shelter during the day, and the

eggs are laid in peat soil near the palms. Palms with young aerial roots are particularly

susceptible to Sufetula sunidesalis attack (Lavogez, 2012) (Fig. 44). The highly mobile

caterpillars attack the apex of the primary roots to feed and develop. They can colonise

and attack several roots which, once destroyed, generate a new apex near the point of

attack. In a severe infestation, primary roots undergo repeated attacks which force the

palm to continually renew its root apices (Fig. 45).

This phenomenon has already been described in coconut palms, where it causes an

imbalance in energy distribution to the detriment of the fruit bunches and considerably

reduces potential yield (Bonneau et al., 2004, 2007). Observations made at two sites in

the Indonesian provinces of Riau and North Sumatra in 2010 have made it possible to estimate the level and dynamics of Sufetula spp. attacks on oil palm primary roots. After

Figure 40 Palm killed by Rhynchophorus phoenicis attack © Laurence Ollivier.

monitoring for one year, results show the degree of damage caused to the oil palm root

system on the plot level. The dynamics of the attacks varied according to the planting date

(Beaudoin-Ollivier et al., 2011).

Phytosanitary methods involving the massive use of pesticides on very fragile soils and

ecosystems are clearly inadvisable (Bessou et al., 2017). Removing all the vegetation that

provides shelter to adult Sufetula sunidesalis has had positive results in coconut plantations

(Bonneau et al., 2007), but these practices were found to generate high labour costs.

An agroecological alternative would be to manage the level of the water table carefully

so that an area affected by an Sufetula sunidesalis outbreak can be quickly flooded to

prevent the caterpillars from completing their life cycles (Bessou et al., 2017). This is one

of the Roundtable on Sustainable Palm Oil (RSPO) recommendations for management of

oil palm plantations on peat soils.

Figure 41 Use of pheromone trap to catch Rhynchophorus palmarum in Ecuador © Laurence Ollivier.

It is important to understand the behaviour and chemical ecology of Sufetula

sunidesalis by studying the insect’s mating behaviour. Studies on the relationship

between the caterpillar/moth and host plant have identified two different molecules

which could possibly constitute a kairomone emitted by root apices (Lavogez, 2012;

Bessou et al., 2017). Indigenous nematodes which can kill Sufetula sunidesalis caterpillars

have also been discovered in Indonesia (Lavogez, 2012), and these results now serve

as a foundation for different hypotheses for the integrated management of Sufetula

sunidesalis.

7 Insect pests of oil palm bunches

Castnia daedalus Cramer is a large lepidopteran of the Castniidae family (Fig. 46a). The

caterpillars are trunk borers and they are harmful for oil palm fruit bunches and bases of

the petioles in tropical South America (Venezuela, Suriname, Guyana, northeast Brazil,

Colombia, Ecuador and Peru). The whole life cycle is completed in the stem and takes

410–441 days (Genty et al., 1978). Caterpillars feeding on the fruit bunches can cause

considerable production losses and they also dig large cavities under the stem apex that

kill the palm. At the end of their development, the huge caterpillars (10 cm long) migrate

to the periphery of the stem and make a large fibrous cocoon (Fig. 46b).

This pest can be controlled by following best cultivation and hygiene practices (Schuiling

and van Dinther, 1980), and adults can be netted during periods of high moth density

and cocoons collected from the leaf axils as additional control measures. Ooencyrtus

Figure 42 Last instar caterpillars © Laurence Ollivier.

af. calpodicus is a hymenopteran in the Encyrtidae family and is a parasitoid for C.

daedalus eggs (Ruiz and Korytkowski, 1979). Eggs are also attacked by ants of the genera

Odontomachus, Pheidole and Iridomyrmex. A nodavirus has also been identified, but its

effect is still unknown (Mariau, 2001).

Figure 43 Details of caterpillars © Laurence Ollivier.

Figure 44 Aerial roots susceptible to Sufetula sunidesalis attacks © Laurence Ollivier.

Figure 45 Successive reiterations due to Sufetula sunidesalis attacks © Laurence Ollivier.

Figure 46 (a) Castnia daedalus imago © Laurence Ollivier. (b) Castnia daedalus cocoon © Laurence

Ollivier.

8 Future trends and conclusion

This chapter describes only a few representative examples of oil palm pest species which

can commonly be found both on young and mature palms in smallholders' plots and

agro-industrial plantations. For more detailed information about these insects, the reader

should refer to the reviews published by Lepesme (1947), Mariau (2001), Howard et al.

(2001) and Bedford (2013).

In April 2011, 26 oil palm companies were granted RSPO certification (14 in Indonesia,

10 in Malaysia, 1 in Papua New Guinea and 1 in Colombia) and the area certified reached

857 000 ha (Jacquemard, 2011). RSPO Principle 4 covers the

‘use of appropriate best

practices by growers and millers’ and criterion 4.5 states that ‘Growers should apply

recognised IPM techniques, incorporating cultural, biological, mechanical and physical

methods to minimise the use of chemicals. Native species should be used in biological

control where possible’.

According to Sipayung et al. (1989), it is important to understand the various factors

involved in the natural biological control of oil palm pests in order to maintain or restore

an appropriate environmental balance in the plantation. Several flowering weed species,

such as Euphorbia prunifolia, Ageratum conyzoides and Turnera subulata, are maintained

and/or actively planted in oil palm fields to encourage parasites and predators (Syed and

Shah, 1977) (Fig. 47). A fauna/flora combination which provides food and resting sites for

adult parasitoids and predators amongst the palms and along roadsides, where it does not

compete with the crop, is always advisable (Delvare and Genty, 1992).

Oil palms should be examined regularly (Morin and Philippe, 1978) and monthly

inspections are required for young palms, due to their greater susceptibility to insect

damage. Inspections can be less frequent for plantations over four years old. The objectives

are to measure the extent and severity of infestation and to determine whether insecticide

treatment is required until the pest population returns to normal. There is a natural balance

between pests and their enemies; so a small amount of leaf damage might sometimes be

seen without any significant effect on palm growth and development. Severe problems

only arise when this balance is disturbed.

Figure 47 Nectariferous plants introduced in Indonesia © Laurence Ollivier.

Key measures consist of setting up a network to monitor accidental pest introductions,

adopting suitable quarantine and hygiene practices when importing planting material,

detecting any changes in the plantation as soon as possible (agronomic practices or

products used) and continuously investing in up-to-date staff training. Insects can be

trapped using synthetic attractants to detect and monitor new pests, but any trapping

strategy should aim to reduce population levels. It is essential to understand the pest's

dispersal capacity to effectively combine existing trapping methods and biological

controls to achieve a sustainable reduction in pest populations.

Although the use of phytosanitary products is sometimes unavoidable, it must be

limited as much as possible because of their environmental impact, and these products

must be used in accordance with best practice recommendations. The use of these

compounds must only be tolerated in emergency situations where the choice of actions

is limited: the selection of a suitable pesticide must take into account its biodegradability

rate with respect to local legislation and the RSPO Principles and Criteria. The method

of application (trunk injection, or using viruses, entomopathogenic fungi, nematodes,

bacteria, predators or parasitoids which are specific to the pest) is also of paramount

importance to the agroecological impact of these chemical treatments.

The use of smart IPM methods, adapted to local conditions, is a sensible way to achieve

RSPO certification while complying with sustainable development criteria, to the shared

benefit of the plantation environment and the people who work in it.

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5 Chapter 5 The integrated management of bud rot disease and Phytophthora palmivora in oil palm

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6 Chapter 6 Advances in disease-resistant oil palm varieties

1 Introduction

There are many known pests that can damage the oil palm (Corley and Tinker,

2016). Although some cases of limited difference between varieties may occur, such

discrepancies have been poorly documented and no specific breeding work has been

undertaken to generate pest-resistant varieties. However, it is remarkable that interspecific

hybrids (E. oeifera × E. guineensis) are generally less appealing to pests as compared to

E. guineensis varieties. We will only consider resistance to diseases in this chapter.

2 Key issues

2.1 Usefulness of genetic resistance for disease control

An almost exhaustive list of diseases affecting the oil palm was given by Turner (1981);

this book is a still a reference for oil palm phytopathologists, although some newer

considerations or findings are missing (Corley and Tinker, 2016). Although some bacteria,

virus and phytoplasmas can cause serious damage, fungus is generally the most frequent

cause of disease.

Genetic resistance may exist for most diseases, but has been observed only for a

limited number of pathogens (Table 1). In addition, before embarking on a disease

resistant breeding programme, one has to take into consideration the severity of the damage as well as the availability of simple and economically viable control

methods based on field practices or the limited use of chemicals. Indeed, breeding

programmes aimed at selecting for genetic resistance have been undertaken only for

Table 1 Oil palm diseases for which genetic resistance has been observed

Disease Stage Genetic resistance (Reference) Control

Cercospora (Fungus) Mainly prenursery and nursery Durand-Gasselin personal communication Agricultural practices and chemical control

Curvularia

(Fungus) Mainly prenursery and nursery Nouy and Durand-Gasselin personal communication (Fig. 1, Table 2) Agricultural practices and chemical control

Blast

(Phytoplasma is suspected,

transmitted by Recilia

mica) Mainly prenursery and nursery de Franqueville (1999, 2001) Agricultural practices (mainly) and chemical control of the vector

Leaf mottle/Mancha anular.

(Very likely a virus

transmitted by an insect

(Sogatella?)) Nursery and young age Claude Louise personal communication (Table 3) Agricultural practices (mainly) and chemical control of the vector

Fusarium wilt (fusariosis)

(Fungus) Field adult age (> 5 year), rarely in young age Bachy and Fehling, 1957; Franqueville and de Greef, 1988) (Fig. 2) Agricultural practices (limited effect). Breeding for resistance

Ganoderma basal or upper

stem rot

(Fungus) Field adult age (> 5 year), rarely in young age Akbar (1971); Franqueville et al. (2001) (Fig. 2) Agricultural practices. Breeding for resistance

Bud rot

(Very likely Phytophthora

palmivora as primary

agent) Field any age For E. oleifera x E. guineensis: Turner (1981) For E. guineensis: Franqueville, (2003); Amblard et al. (2009) (Fig. 2) Agricultural practices (limited effect). Breeding for resistance

Figure 1 Susceptible and highly resistant crosses to Curvularia (Thailand, © T. Durand-Gasselin).

Fusarium wilt, upper or basal stem rot caused by Ganoderma, and for various forms

of bud rot.

Fusarium oxysporum f. sp elaeidis is a soilborne and biotrophic fungus. It is an imperfect

fungus, that is, its sexual reproductive stages have never been observed and it produces

conidia and chlamidospores (Flood, 2006). It is probably one of the reasons why the

genetic diversity of F. oxysporum f. sp elaeidis is so limited (Mouyna et al., 1996).

The Ganodermataceae family are basidiomycota fungi. Within the Ganoderma genus,

the predominant species, G. boninense, appears to be the most aggressive (Cooper et al.,

2011). In Africa, G. ryvardense has been reported to be the cause of basal stem rot (Kinge

and Mih, 2011). G. boninense is a soilborne fungus and a polypore which bears double

walled basidiospores. Spores give rise to monokaryonic mycelium which eventually

mate to generate dikaryons if they are sexually compatible (Pilotti et al., 2002). Pilotti

Table 2 Levels of resistance to Curvularia among Deli progenies at eight-month-old nursery

stage (from Nouy, pers. com.)

Deli origin	Cross	Intensity of Curvularia damage
A	A 1	Obvious within cross disjunction between affected and healthy palms
A	A 1	Obvious within cross disjunction between affected and healthy palms
B	B 1	High incidence
B	B 2	High incidence
B	B 3	No damage
C	C 1	No damage
D	D 1	High incidence
D	D 2	High incidence
D	D 3	Extremely high damage

Table 3 Effect of Pisifera 1 in the protection of crosses from leaf mottle (mancha anular) (two-year-old palms, Ecuador). Pisifera 1 is compared to other pisiferas while using the same Deli mother palm. Results are given as index mean (from six genetic trials which have more than 14% incidence of the disease, Louise pers. com.)

Mother palm	Father palm: Other pisifera	Father palm: Pisifera 1	Comment
Deli 1	126 (2 cross)	5 (2 cross)	25 times less
Deli 2	67 (2 cross)	8 (1 cross)	8 times less
Deli 3	119 (2 cross)	21 (1 cross)	6 times less
Deli 4	130 (3 cross)	22 (1 cross)	6 times less
Deli 5	157 (2 cross)	27 (1 cross)	6 times less
Deli 6	112 (3 cross)	50 (3 cross)	2 times less
Deli 7	138 (2 cross)	97 (1 cross)	1.5 times less

has conducted studies on the genetic variability of Ganoderma within plantations, using

RAPD, concluding that genetic variation was very high even within small plots (Pilotti et al.,

2003). Mercière et al. (2015) developed SSR markers from G. boninense which will allow

interesting diversity studies of G. b. in Asia in comparison with Africa and probably with

America. G. boninense is a necrotrophic fungus.

Bud rot seems to be associated with Phytophthora palmivora (Sarria et al., 2008, 2016;

Torres et al., 2010). In its early stages, many of the symptoms caused by P. palmivora in

oil palm have been reported to be typical of Phytophthora diseases in general (Torres

et al., 2016). In later stages, saprophytic microorganisms might be able to develop,

leading to a variety of symptoms (Franqueville, 2003; Louise et al., 2015; Torres et al.,

2016). Phytophthora palmivora is an oomycete which is often classified as a fungus-like

microorganism, but this class is now included in stramenopiles. It produces abundant

sporangia which generate zoospores. Sexual reproduction between compatible mating

types leads to oospores and chlamydospores which provide the main way P. palmivora

survives naturally. Even if P. palmivora has a soilborne phase, it cannot be classified as a

soilborne disease but rather as a biotrophic fungus. Genetic diversity of Phytophthora was

found to be generally high, although the various pathogen strains might show only limited

diversity (Maroa et al., 2017).

2.2 Resistance sustainability

The perennial nature of the oil palm makes disease-resistance the focal point of breeding strategies. Van der Plank (1963, 1968) first developed the concept of horizontal resistance, which is expected to be multigenic, and of vertical resistance, which is expected to be single-gene based. The former – being non-race/strain-specific resistance – is expected to be sustainable, the latter being specific and non-sustainable. This concept has evolved with the understanding of gene–gene interactions between host and pathogen and the description of some mechanisms of partial resistance. Indeed, Robinson (2006) refined that concept although it is of great interest to understand how specific resistance can evolve towards non-specific resistance (McDonald and Linde, 2002). Roux et al. (2014) proposed that plant disease resistance is intrinsically dual, thus combining both a qualitative-like and a quantitative-like behaviour. These authors also consider that our knowledge on the determinants of qualitative resistance represents only the ‘tip of the iceberg’. Breeders will have to deal with this lack of knowledge and must bear in mind that things are not as

Figure 2 Field evidence of genetic resistance differences (a) Fusarium wilt, (b) Ganoderma Basal Stem Rot and (c) Bud Rot, respectively, in Côte d’Ivoire, Indonesia and Ecuador, © Google Earth.

‘black and white’ as stated in the 1960s. Nevertheless, it provides an interesting framework for breeders, and breeding for partial resistance is certainly the way to go.

It is probably useful to share here the meaning of some useful words, following the recommendations from the International Seed Federation (ISF) (https://www.euroseeds.eu/system/files/publications/files/esa_12.0605.pdf). Indeed, ISF encourages plant pathologists and breeders to make a clear distinction between immunity, resistance and susceptibility. Immunity is when a plant is not subjected to any attack and is generally race/strain-specific. Resistance is the ability of a plant variety to restrict the growth and development of a disease. Resistances are generally non-specific. Immunity usually (though not always) results from a gene–gene interaction between the plant and the pathogen and it can be overpassed. For oil palm, the breeder's strategy will aim at selecting for multiple defence genes involved in (partial) resistance, also called quantitative disease resistance (Roux et al., 2014). This selection strategy will favour sustainable non-specific resistance to a larger diversity of isolates of the pathogens, rather than specific resistance. It is important to note that consequently selecting plants for multiple partial disease resistance will result in varieties that exhibit some disease symptoms but will be more efficient in limiting their number. In line with these recommendations the authors ranked resistances into different levels: highly resistant, intermediate resistant or susceptible varieties. The term 'tolerance' should be avoided for this purpose as it should be used only to describe the ability of a

variety to endure abiotic stresses.

2.3 Simple modelling of disease development

Understanding how a disease develops is of great importance in order to predict its

evolution and consequently its possible damage. To this end, the development of

mathematical models can be of great help. It is not a simple question as each single

parameter has to be part of the equation. A non-exhaustive list of parameters could be as

follows: % of infected host, % of healthy palms, % of remission, gain of immunity after the

first infection or not (could be partial), transmission mode (air, contact or soil), etc. As an

example, remission does exist in Fusarium wilt (Franqueville and Diabate, 1995) or Bud

rot, but it has never been described for basal stem rot (Ganoderma). Bud Rot outbreaks

generally occur during or just after a heavy rainy season and so some climatic parameters

should be incorporated into the models.

One advantage of the mathematical models is that they enable the calculation of the

threshold of epidemic take-off, and thus can encourage planters to adopt strict agronomical

practices to keep the disease incidence below a given threshold (Jacquez, 1996).

One of the questions which must be addressed by both phytopathologists and breeders

is how to describe a disease in the field or after artificial inoculation. Should it be a binary notation (infected/non-infected, alive/dead)? Should the intensity or severity of the damage be taken into account? Should we observe external symptoms only or both internal and external ones?

Two reflections may help address these questions. The first will be to ensure that the observation method does not bypass a potential defence barrier of the plant. For example, if you inoculate a petiole with Fusarium, you may bypass barriers that prevent the fungus from entering the roots. The second is the cost/benefit ratio of the experiment. An observation that is difficult to operate and does not significantly improve the discrimination power of the screening should not be upheld.

For breeding purposes, simple binary models which are close enough to real-life observations may be sufficient. As an example, Fig. 3 shows some data from a trial planted in 1983 in Ecuador for Bud Rot monitoring together with simulated data using the classic logit function. The figure shows that the function does not describe precisely the early stage of the disease, although it is very difficult to clearly differentiate the different types of materials at this stage. During the epidemic stage it is important to analyse the data when the maximum differences between varieties do occur (after 17 years in that case). At a younger age, only susceptible materials can be distinguished and conversely at a later age, only the most resistant are evidenced. Another very important point, at least for field

observations, is to know the maximum percentage of infected palms that the disease will

induce. This can be done only at the end of the trial: 100% for susceptible varieties and

around 50% for the moderately resistant ones in the present case (Fig. 3).

In most cases, our experience shows that the maximum level of discrimination is reached

when the percentage of infected palms in a trial averages 30% or more.

Three different varieties are analysed, namely very susceptible (pink); susceptible (blue);

and modertaely resistant (orange).

2.4 Agricultural practices

Agricultural practices and genetic resistances are building blocks of Integrated Pest

Management (IPM). The economic efficiency of agricultural practices is also part of the

picture as it will impact dramatically the sustainability of oil palm cultivation.

The very first point is to take into account what happened during the previous

generation. For Fusarium wilt, the success of a replantation is linked to the phytosanitary

situation of the previous generation, including the severity of the disease (Franqueville and

Renard, 1988). Singh (1991) collected data from different fields infected by Ganoderma

and underlined the importance of the previous crop on the development of Ganoderma

infection, coconut being one of the worst.

In the case of replantation, the distance to the previous palm is of tremendous

importance for Fusarium wilt (Renard and Franqueville, 1991) as well as for basal stem

rot caused by Ganoderma (Flood, 2000). However, this is not the only infection gate as

Ganoderma dispersion occurs through root to root infection (Tuner, 1965); a result which 0 10 20 30 40 50 60 70 80 90 100 1 3 5 7 9 11 13 15 17 19 21 I n c i d e n c e % Year 0 10 20 30 40 50 60 70 80 90 100 1 3 5 7 9 11 13 15 17 19 21 23 Simulation

Figure 3 Changes in Bud Rot incidences as monitored for 23 years in trial SHGP 1, Ecuador (planting

1983) (left) and simulation of the data using a logit adjustment (right).

was confirmed by Flood et al. (2000) using bait palms. These authors confirmed that bait

palms were infected by the same Ganoderma strain as the source palm (Fig. 4).

From an experiment conducted in Costa Rica, Albertazzi et al. (2009) hypothesised that

Bud Rot development can be related to some deterioration of the whole plant due to poor

root development which led to the possible development of the disease. The authors

recommend improvement of drainage, avoidance of soil compaction and taking into

account the fertilisation regime.

2.5 Early screening test

Most of the time, it is preferable to control diseases by agricultural practice or

reasonable chemical treatment when possible. The development of early screening tests will obviously help. Prendergast was the first to propose an early screening test

for Fusarium wilt resistance in oil palm in 1963 and Arrifin for Ganoderma (Arrifin et al.,

1995). The two methods were nursery tests that were later refined as pre-nursery tests

(Renard et al., 1972; Breton et al., 2006) which allowed implementation of much more

extensive work.

In oil palm, early screening tests have been developed for two patho-systems, namely

Fusarium and Ganoderma, and they are now used as routine tools. The recent finding

that Phytophthora is the major causing agent of Bud Rot may lead to the development of

another early screening test in the coming years; however, this work might be complicated

by interaction with secondary opportunist pathogens. To be useful, an early screening test

must comply with a set of characteristics described in the following paragraphs.

2.5.1 Index scores and trial comparison

When screening for resistance to disease, one of the difficulties is to compare the

results from one trial to another or to compare field results with those generated by

the early screening method. It is difficult to compare percentage of incidence per se

as environmental conditions are always different. This has led phytopathologists to

work on an index score. This has been defined by Renard et al. (1972) and refined by

Franqueville (1984). The idea is to give a score of 100 to the mean of the trials and to

Figure 4 Infected adult palm and bait palms could be infected by the same Ganoderma strain (from

Durand-Gasselin et al., 2015).

compare all progenies to that mean. A score of 120 means that 20% more plants were

infected as compared to the mean, and logically a score of 80 means that 20% fewer

plants were infected. Such index scoring is not a perfect method, although it can be

used to compare data from one trial to another as long as the trials (and therefore the

mean of the trial) represent a subset of material with a comparable range of resistance.

Otherwise, one has to connect the trials using a set of standard crosses which should

be included in all the tests. The number of standard crosses to be used is linked to the

required level of precision for comparison.

2.5.2 Repeatability

An early screening test must be repeatable: indeed, from one test to another, one must

be able to find the same result. Using index scores, Franqueville was able to provide very

early results for Fusarium nursery tests (Franqueville, 1984) and Durand-Gasselin (2015)

provided an example (Table 4) of Ganoderma early screening tests.

2.5.3 Host-pathogen interaction

As we are looking for non-specific (partial) resistances, it is important to check if significant

interaction between isolates and oil palm progenies exists.

When using two different strains

of Fusarium and 52 progenies to study inheritance of Fusarium wilt resistance, Meunier et al.

(1979) concluded there was no interaction between strains and progenies. From preliminary

data, Durand-Gasselin et al. (2015) reported similar results for Ganoderma (Table 5).

2.5.4 Precision

Unfortunately, even if a sizeable number of plants are used (e.g. 100 to 200), the precision

of early screening tests will be weak (Renard et al., 1972). This is linked to the binary nature Table 4 Performance of two crosses which have been repeatedly included in various tests. The resistant cross is consistently classified as resistant when the susceptible one is classified as susceptible or very susceptible Trial Susceptible cross Resistant cross Test 1 143 89 Test 2 98 73 Test 3 101 75 Test 4 102 72 Test 5 102 77 Test 6 112 78 Test 7 143 82 Test 8 144 85 Test 9 152 89 Test 10 121 89

of the observation which participates in making such tests a burden (Renard et al., 1972).

Idris et al. (2004) showed data from nursery tests, using 40 palms per progeny, in which

40% infected palms were not significantly different from 22.5% (Idris et al., 2004). Field

tests are even weaker in terms of accuracy. Flood et al. (1989) were able to distinguish

differences in resistance between clones through a refined protocol and very precise

monitoring (Flood et al., 1989), but such a protocol has not yet been generalised and

correlation with field data still remains to be assessed.

2.5.5 Additivity

For breeders, it is important to know the nature of the observed variation which can be linked to either genetic or non-genetic effects (environmental factors, field practices,

etc.) or to the interaction between the two. Genetic effects arise from either additive,

dominance or epistasis variation, the former being the most helpful for breeding.

Meunier et al. (1979) highlighted the predominant role of additive effects in Fusarium

wilt resistance. Later, de Franqueville and de Greef (1988) also used an additive model to

explain field resistance to Fusarium at the Binga plantation. Durand-Gasselin et al. (2015)

reported the same observation for Ganoderma in field experiments as in pre-nursery early

screening tests.

2.5.6 Correlation between field and early screening tests

The concern of phytopathologists and breeders is that any early screening test may not be

well correlated to the behaviour of the palms in the field. As an example, using a simple

test on the leaf petiole may bypass some resistance mechanisms that may arise in the

roots or around the roots (Diabaté et al., 1990). It is probably one of the reasons why early

screening tests have been developed using whole living plants. Such a system is not easy

to implement and further systems such as the one proposed by Mepsted et al. (1995) were

based on rachis inoculation. Further efforts are required to make it fully operational, to

ensure that the test is correlated with field results for all genotypes. This has been a great concern for all the teams working on early screening tests.

Table 5 Interaction between Ganoderma isolates (strain) of various levels of aggressiveness and 6 progenies of various degrees of resistance: A and B being the most resistant progenies, F being the most susceptible followed by E, D and C

Isolate (aggressiveness)	Progenies A	B	C	D	E	F
V (+)	1	2	5	4	3	6
W (++)	1	2	3	5	6	4
X (+)	2	1	3	5	4	5
Y (+)	1	2	3	6	4	5
Z (-)	2	1	4	3	6	5

For Fusarium wilt, Renard et al. (1972) from the IRHO group published the first attempt to establish a correlation between pre-nursery tests and field results which was later confirmed by Franqueville and Diabate (1995), whereas Franqueville undertook similar observations for the Unilever group (Franqueville, 1984). An illustration of this relationship was published by Franqueville et al. (2011) and provided in Fig. 5.

For Ganoderma, the very first report on the relationship between field results and pre nursery tests was presented by Purba et al. (2012), and additional data were later published by Durand-Gasselin et al. (2015). More experiments are needed to reach the same level of confidence as obtained for Fusarium wilt.

3 Achievements in improving genetic resistance to oil palm diseases

3.1 Fusarium wilt resistance

3.1.1 Sources of Fusarium wilt resistance

The Nigerian Institute for Oil Palm Research ranked its material for resistance to Fusarium wilt. Indeed, more than 300 progenies were assessed and results show that two palms of Calabar origin bear significant resistance to Fusarium, namely

32.364T and 32.3005T; the former

being well known for its outstanding general combining ability (GCA) for yield, despite the

fact that it shows an extremely rapid vertical growth. Conversely, the palm 4.1811T from

Aba population was identified as very susceptible to the disease (Rajagopalan et al., 1978).

At the research station of Unilever and Sipef in Binga (Zaire now Congo RDC),

Franqueville and de Greef (1988) described the 69 MAB palm as being very resistant. This

palm is from pure Djongo origin, and it is worth highlighting that the palm1212A of the

same origin displays high susceptibility. This palm originates from the self-pollination of 0 5 10 15 20 25 30 35 40-49 50-59 60-69 70-79 80-89 90-99 100-109 110-119 >120
% F u s a r i u m w i l t i n p l a n t a t i o n
Pre-nursery Index

Figure 5 Relationship between pre-nursery index and the degree of resistance in the field (from

Franqueville et al., 2011).

the palm 16R which is moderately susceptible. Two relations of palm1212A, namely palms

1245A and 1342A, were crossed and the Fusarium wilt resistance of two palms resulting

from that cross was assessed: one was significantly resistant and the other significantly

susceptible. Again, it is clear that within-origin variability is high.

When the French research institute IRHO assessed a large part of its collection, it found

sources of resistance in most of the tested population (Renard et al., 1980). As an example,

parents from Deli origin were ranked from highly resistant (mean index of 85 for DA300D,

from 16 tests) to very susceptible (mean index of 141 for LM412D from 18 tests). The same

result was found within the La Mé population and the Yangambi/Sibiti population where

the index range was 58 to 120 and 86 to 131, respectively. In the same paper, the authors

reported the only known attempt to assess Fusarium wilt resistance of the interspecific

hybrid Elaeis oleifera x Elaeis guineensis. Also E. o. populations from Brazil appeared

to transmit susceptibility to the hybrids. Several populations from Colombia or Central

America have a genetic factor that transmits extremely high resistance (at least during

early screening pre-nursery tests, as the connection with field data has not been reported

yet). Further information was provided by Durand-Gasselin et al. (2000) and again high

variability within the population was highlighted.

Therefore, it is not surprising that the combination of parents from two origins will

generate highly variable resistances to Fusarium wilt depending on the resistance of the

parents. Among Deli x La Mé crosses reproduced through self-pollination of the parents

(Jacquemard et al., 1981), the DA115D x LM2T cross showed an average index of 79

(excellent resistance), whereas LM407D x LM451T index was 132 (poor resistance). Such a

huge genetic variation for resistance to Fusarium was also found among palms belonging to

the same progeny, even when this progeny results from a selfing of a unique palm (Fig. 6).

Such results were used by the breeders to develop commercial material carrying

moderate-to-high resistance to Fusarium wilt. In Cameroon, Pamol has developed

Fusarium wilt-resistant material based on Binga results, and Cerapah did the same based

on IRHO results (Ngando et al., 2012). 0 5 10 15 20 25 30 65 70 75 80 85 90 95 100 105 110 115 120 125 130 N u m b e r o f p a l m s Resistant Index Susceptible

Figure 6 Fusarium wilt resistance assessed among 94 relations within the family LM2T self. Palms with

an index over 110 are clearly susceptible; each parent has been tested more than 20 times.

A very convincing outcome of breeding for Fusarium wilt resistance has been presented

by Franqueville and Diabaté (1995). The authors described the evolution of the cumulative

incidence of Fusarium wilt in a semi-commercial plantation (4000 ha). The incidence is the

mean for the entire plantation, all ages gathered. This plantation, called Dabou, was one

of the most impacted plantations in Africa. Indeed in 1964, 33% of the palms were sick.

The policy of the company was to thoroughly replant palms using progenies which had

been assessed to be resistant through early screening tests. In 1992, the incidence was

found to be negligible and in addition most of the remaining cases were furtive as palms

recovered rapidly from the disease (Franqueville, pers. com.) (Fig. 7).

Phytopathologists and breeders have been able to select highly resistant material which has dramatically improved the sanitary status of plantations in Africa. Such a high

level of protection has been achieved that hardly any material affected by the disease

can now be found. Such a success story is the result of five decades of continuous

work conducted by different research teams in Nigeria, Congo, Cameroon, Ghana, Côte

d'Ivoire and Benin.

3.2 Ganoderma basal/upper stem rot resistance

Malaysia and Indonesia are the countries in which Ganoderma stem rot causes the most

damage. Most of the reports and achievements regarding selection for Ganoderma

resistance originated from research conducted in these two countries despite the fact that

Ganoderma has been detected and described as pathogenic in some parts of Africa for

quite a long period (Congo (RDC) and Cameroon).

Akbar et al. (1971) first reported that pure Deli material was more susceptible to

Ganoderma stem rot than Deli x Yangambi material. The susceptibility of Deli material as

a whole was later confirmed by Durand-Gasselin et al. (2005).

Idris et al. (2004) published initial results from an early screening test conducted

in the nursery. Table 6 displays a summary of these results for which we have gathered 0 6 4 6 6 6 8 7 0 7 2 7 4 7 6 7 8 8 0 8 2 8 4 8 6 8 8 9 0 9 2 10 20 30 40 % V a s c u l a r w i l t (C u m u l a t e d) Planting year

Figure 7 Decrease in vascular wilt (Fusarium o.) incidence over the years in Robert Michaud plantation

(4000 ha, Dabou Côte d'Ivoire).

performance by origin. Here again, the pure Deli material is the most susceptible, whereas

African materials are more resistant. Among them, Avros material seems to transmit a

higher susceptibility as compared to pure Nigeria or Cameroon material. It is worth noting

that the appellations 'Cameroon' or 'Nigeria' are far from being representative of the entire

countries. This work is based on a few palms from those origins only. In the same work,

three crosses of pure E. oleifera (originating from Colombia and Honduras) were found to

be susceptible as well as one interspecific cross between E. g. and E. o.

Setiawati et al. (2010) described the very interesting work carried out by Sumatra

Bioscience (also well known as Lonsum) to screen their own genetic material in the field

and in pre-nursery. From early results in the field, showing that the average percentage

of palms infected by Ganoderma was around 10%, the authors were able to identify clear

sources of susceptibility among some material from Congo, while one origin from Lobe

research station (Cameroon) was found to be highly resistant. In addition, from early results

from a multilocal field trial, the authors underlined, as already pointed out by different

papers, the susceptibility of Deli material, whereas Binga x Pobè crosses (Congo, Benin)

proved to be the most resistant material.

In the same paper, an important set of trials conducted in pre-nursery is presented. The first

work was to define a set of standard crosses ranking from susceptible, moderately resistant to

highly resistant crosses. This set of crosses was used to connect 35 pre-nursery trials that led

to the evaluation of 217 progenies from 69 different breeding origins. Four of those origins

were represented by more than 5 crosses: it is worth noting that Deli x Avros crosses showed

an intermediate level of resistance between pure Avros crosses and pure Deli crosses (Table 7). Table 6 Results from nursery test screenings of 19 progenies, grouped by origin (adapted from Idris et al., 2004) Origin No. of tested progenies % of dead palms Pure Deli 3 36.7 (Nigeria or Cameroon) x Avros 6 25.4 Deli x Avros 4 24.4 Pure Nigeria 2 21.3 Pure Cameroon 4 15.6 Table 7 Average % of infected seedlings in four origins represented by more than five crosses in pre-nursery tests (Adapted from Setiawati et al., 2010) Type of crosses % of infected seedlings Avros x Avros 14 Deli x Avros 18 Deli x Deli 23 ‘Binga’ (Congo) 24

In addition, 65 from the 217 studied crosses were also evaluated in the field. As expected,

the correlation was poor, because of i) the low accuracy of field monitoring, especially in

fields where the number of planted palms is low; and ii) the fact that the disease in the

field has yet to express its maximum. Nevertheless, results clearly showed that susceptible

crosses in pre-nursery tend to be susceptible or moderately resistant in the field and rarely

resistant (1 out of 16). Furthermore, the resistant palms in nursery were either resistant or

moderately resistant in the field, and were found to be rarely susceptible (1 out of 16). The

results for moderately-resistant crosses were of course less clear (Table 8).

In 2015, Durand-Gasselin et al. presented outputs of research work in North Sumatra

with the Socfindo planting company. A range of 368 commercial crosses were evaluated in

pre-nursery. To this end, Deli x La Mé or Deli x Yangambi crosses were planted in an almost

complete factorial design (Table 9). In such assessment, it is normal that Deli origins and

La Mé or Yangambi origins share the same mean, despite the fact that pure La Mé or pure

Yangambi material is generally more resistant than pure Deli.

Table 8 Distribution of 65 families according to their degree of resistance expressed in the field and in the nursery (Setiawati et al., 2010)

Number of families		Field		
		Susceptible	Medium	Tolerant
N u r s e r y	Susceptible	6	9	1
	Medium	9	14	10
	Tolerant	1	10	5

Table 9 Observed index in pre-nursery tests of a set of crosses organised in a factorial design. Five Deli

(A group) origins were used as female parents and five La Mé or Yangambi (B group) origins as male

parents (adapted from Durand-Gasselin et al. 2015)

Origin	la Mé A	la Mé B	la Mé C	Yangambi A and A’	Yangambi B	Average	
Deli A	82 (36 tests)	88 (23 tests)	99 (22 tests)	109 (58 tests)	114 (13 tests)	98	Moderately resistant
Deli B	90 (5 tests)	86 (16 tests)	122 (12 tests)	107 (8 tests)	107 (8 tests)	102	Moderately resistant
Deli C	95 (13 tests)	107 (8 tests)	–	105 (10 tests)	129 (5 tests)	109	Susceptible
Deli D	86 (20 tests)	103 (13 tests)	102 (9 tests)	139 (11 tests)	122 (10 tests)	110	Susceptible
Deli E	97 (11 tests)	118 (12 tests)	115 (15 tests)	125 (22 tests)	117 (8 tests)	114	Susceptible

Average 90 Resistant 102 Moderately resistant 109 Susceptible 117 Susceptible 118 Susceptible General mean: 107

The range of partial resistance was greater for La Mé and Yangambi (from 90 to 118) as

compared to Deli (from 98 to 114); this result is in line with the genetic diversity of Deli

origin which is smaller than African origins (Cochard et al. 2009). Among the three studied

La Mé origins, one was clearly more resistant than the others (Origin la Mé ‘A’). The best

results were obtained when crossing the two best La Mé origins (A and B) with the most

resistant Deli origins (A and B). The average index of such crosses was 86 (in bold in

Table 9), indicating that this material has 20% fewer affected palms than the mean of the

trials (Index of 107). On the other hand, when crossing the two worst Deli origins with the

two Yangambi origins, we observed 20% more infected palms (Index of 127) (in italics in

Table 9). This result is in line with the predominant additive inheritance of partial resistance

to Ganoderma.

Because of the predominant additivity inheritance, the authors have undertaken some

work to assess the female origins (most of them being of pure Deli origin, A group) as well as

male origins (most of them being of pure La Mé or Yangambi origin, B group) using testers.

This work allowed the authors to rank 16 different female origins (16 pure Deli and 1 Deli

x Angola) and 12 different male origins (9 pure La Mé and 3 pure Yangambi). Each origin is represented by different crosses (Fig. 8).

In addition, the authors illustrated some within-origin variation. As an example, the Deli I

origin is represented by 14 crosses, each of them having been tested 15 times on average

(from 5 to 34) (Fig. 9). It is worth observing that the range of resistant palms within this

origin is almost as wide as those obtained within Deli origin. This kind of observation is

very useful for breeders as they can expect to find resistant material in a majority of origins.

In this example, the best family, which was assessed 11 times, originating from a moderate

resistant Deli origin (Deli I) appeared as good as the best-performing Deli origin (Deli A).

Of course this is just an example as one can find an even better family within the Deli A

origin.

In the same paper, field results were presented. Results obtained from a dedicated

factorial design were found to provide similar results as those performed in pre-nursery

(results not shown here) that also illustrate the additive inheritance of Ganoderma partial

resistance.

It has been possible to calculate the GCAs for Ganoderma partial resistance of many

parents of crosses involved in genetic trials planted in North Sumatra in an area affected by

Ganoderma (480 crosses with at least 72 palms planted per cross). The analysis by parent

Figure 8 Estimated index for different A (female parent) or

B (male parent) group origins. Number of

studied progenies within each origin is given in brackets (from Durand-Gasselin et al., 2015).

did not give significant results because of the limited number of palms per progeny and

relatively low Ganoderma incidence among the trials (around 10%). Nevertheless, regrouping

the parents in five classes for female (A group) from −2 (susceptible) to +2 (resistant) and for

male (B group) according to their partial resistance to the disease gives the clearest picture

(Table 10). Crosses between resistant parents showed fewer than 5% Ganoderma infection in

the field (in bold in Table 10) as compared to 10.7% for the whole experiment.

The authors have identified commercial planting material which showed some

intermediate resistance to Ganoderma and originates from the combination of the best

Deli dura parents, with Pisifera palms originating from the best La Mé family.

This planting material has been tested in nursery in its original form (without use of test

crosses). To this end, parents taken from selected families coming from three of the best

Deli origins (Deli E, F and I) were crossed to parents from the La Mé A family. The resulting

progenies showed very low indexes, thus confirming their estimated levels of resistance

(Table 11).

It is important to underline that genetic resistance, while of major influence, is only one

facet of any IPM strategy aimed at controlling Ganoderma disease.

Impressive research work carried out in Malaysia and Indonesia, the main achievements

of which are presented here, has led to the generation of commercial planting material

(varieties) which express moderate resistance to basal/upper stem rot caused by

Ganoderma. There is no doubt that within a few years and step by step, this resistance will

be improved to a highly resistant level. Partial resistances are expected to be sustainable

and the genetic progress achieved here is of great value for many stakeholders in the

plantation sector. However, planters must continue to use any combination of agronomic

practices (Flood et al., 2000) together with resistant varieties through integrated

management of the disease.

Figure 9 Estimated index for 14 families of Deli I origin. The number of tests performed for each family

is given in brackets.

3.3 Bud rot resistance

For long the aetiology of Bud rot has remained unclear. It is only recently that Bud rot has

been associated with P. palmivora (Torres et al., 2010), although it remains very difficult

to inoculate the pathogen and trigger the disease. Nevertheless, based on field results,

some achievements were published a few decades ago for interspecific hybrids E. oleifera

x E. guineensis and more recently for pure E. guineensis material.

3.3.1 Bud rot resistance of interspecific hybrids E. oleifera x E. guineensis

Bud rot caused massive losses at the La Arenosa estate (Turbo region) in Colombia during

the 1960s. In 1981, Turner reported that Elaeis oleifera x Elaeis guineensis interspecific

crosses planted in 1968 were spared by the disease (Renard and Quillec, 1984). The same

resistance was observed in Suriname; indeed, Van de Lande described a small plot of

interspecific hybrids that had survived the disease. This plot was planted in 1978 at Victoria

estate, Suriname (Van de Lande, 1986) and was still intact by 2007 (Corredor pers. com.). Table 10 Average percentage of Ganoderma infection for 480 crosses planted in Aek Loba Timur genetic block (North Sumatra) as grouped by origin and class of resistance. Parents are ranked from −2 to +2 according to the GCA values for Ganoderma resistance trait. In bold are the crosses with good resistance behaviour Class B Group Average−2 −1 0 + 1 +2 A Group −2 17.1 8.3 18.9 15.2 5.8 15.3 −1 12.9 – 13.4 8.6 7.1 10.9 0 12.4 20.1 11.1 10.7 6.4 11.0 +1 14.7 8.2 8.9 8.7 2.0 9.8 +2 10.1 9.2 4.6 7.3 4.0 6.1 Average 13.3 15.9 10.9 10.4 5.5 10.7 Table 11 Nursery testing of the intermediate resistant commercial varieties for Ganoderma resistance. Results are given as mean index and number of tests Group A origin Group B origin Origin La Mé A Deli I x La Mé A 85 (11 tests) Deli F x La Mé A 88 (7 tests) Deli E x La Mé A 71 (34 tests)

In the Tumaco region (Colombia) many plots of old O x G hybrids (Sinu x Yangambi origins)

planted in the 1970s developed resistance to the disease (Durand-Gasselin et al., 2009).

One can probably qualify the interspecific varieties as being highly resistant. Franqueville

(2003) found Bud Rot symptoms affecting sporadically interspecific hybrids in Ecuador. It is

only when the disease is very active and highly aggressive that interspecific material can be significantly affected and some palms may not survive (Franqueville, pers. com.). The

Cenipalma team confirmed this result for the Coari x La Mé interspecific hybrids for which

the degree of severity of the disease hardly reached the severity degree of two out of

five (Avila-Diazgranados et al., 2016), including one cross that seemed to be free of the

disease.

Interspecific hybrids may not yield as much as E. guineensis by up to 30% (Franqueville,

2003), although much better results have been obtained in the Llanos region of Colombia

(Zambrano, 2004). The drawback of this type of material is that it has to be hand-pollinated,

a disadvantage that is somewhat compensated for less frequent harvesting rounds (Corley,

2016) and simpler pest management (Herrera, pers. com.). Finally, yield is no longer an

issue (Durand-Gasselin, 2010; Amblard, 2010), and planters' investments are strongly

protected against Bud Rot when using the interspecific hybrid.

3.3.2 Bud rot resistance of E. guineensis crosses

For a long time there were thought to be no differences in resistance to Bud Rot between

pure E. guineensis materials planted in America (Chinchilla-López, 2010). However, two

teams have shown since then that E. guineensis may express partial resistance to Bud

Rot.

Unipalma (Unilever) reported that some material, planted in

1991 near Puerto

Wilches in Colombia, showed promising partial resistance in regions which were

devastated by the disease (Cadavid, 2013) (Fig. 10). The author undertook further

research in order to confirm this result in different plantations in Colombia with

Figure 10 Unipalma material partially resistant to Bud Rot (left) and susceptible material (right) (from

Cadavid, 2013).

genetically-related material and very early results showed a similar trend (Cadavid,

2013).

The CIRAD/PalmElit team reported results from a set of trials. At first, material showing

partial resistance in the field was identified and an example is given in Fig. 2. An attempt

was made to confirm that result by comparing some promising material against six other

materials (trial SHGP 8) (Louise, 2016). A subset of this trial is presented in Fig. 11, which

shows the evolution of the incidence of Bud Rot from the date of planting (2/2000) until

the stabilisation of the disease evolution (end of 2013) for three types of material. Origin

1 was the most resistant and around 50% of the palms were decimated by the disease.

Because of the presence of a majority of susceptible material, we have to keep in mind

that the pressure of the disease was very important throughout the monitoring period.

Without such an intense inoculum pressure, the results could have been much better.

Nevertheless, we found that such partial resistance did not provide sufficient protection.

There are also some differences between the two most susceptible materials, indicating

that some partial resistance of small effect does exist and it is worth cumulating it with the

strongest one.

In a similar trial (SHGP 9) the same origins were represented by a set of 7 or 8 crosses.

Significant but variable resistance to Bud Rot was evidenced in all origins (Louise, 2016).

Figure 12 illustrates the observed variability for 3 crosses of each origin as presented in Fig. 11.

It is the hope of breeders that selecting that best progenies within a given origin will

lead to significant genetic progress. This seems to be the case within the best origin

(Origin 1) for which the best cross (C1) showed only 32% of infected palms as compared

to 52% for the mean of the origin (Fig. 13).

Early results confirmed that the most resistant material to Bud Rot in a given location

is also the best in other locations. Louise (2016) concluded that such results are promising

Figure 11 Comparison of the partial resistance of three different types of material in Shushufindi,

Ecuador. Adapted from Louise (2016).

and he estimated that within a few years, resistant E. guineensis materials with intermediate

resistance to Bud Rot will be commercially available in Ecuador.

4 Conclusion

During the past decade breeding for resistance to diseases obviously became a main

objective for breeders. Breeding for yield remains of course a long-term target, although

both account for the global sustainability of the oil palm industry but in a slightly different

Figure 12 Comparison of the partial resistance of three crosses per type of material at nine years in

Shushufindi, Ecuador. Adapted from Louise (2016).

Figure 13 Comparison of the partial resistance of seven crosses within origin 1 at nine years old in

Shushufindi, Ecuador (Adapted from Louise, 2016).

way. Indeed, planting material, which expresses resistance to a disease, protects the

planter's investment, whereas yield enhances his resources.

Oil palm is a perennial crop and, as a consequence, the number of generations in a given

period is limited. For breeders the crop is not as agile as an annual crop. Three to four

decades are spent in order to obtain some durable protection against F. oxysporum. After

two decades of hard work, phytopathologists and breeders are able to generate planting

material with intermediate resistance to basal/upper/stem rot caused by Ganoderma. For

Bud Rot, the most devastating disease, we have been lucky to find a pre-existing strong

resistance in the interspecific hybrid. Resistances in pure E. guineensis material were

rare, but at least two teams have generated some solid hopes that at least intermediate

resistances will become exploitable soon.

Such findings have been possible thanks to long-running and steady work undertaken

by research institutions and R&D centres from private plantation companies. One of the

main challenging issues will be to combine resistances in order to face more than one

disease at the same time. In Africa, especially in the Congo basin and in Cameroon, some

plantations are facing damage caused by Fusarium as well as Ganoderma. Spear rot-like

diseases do exist in Asia, and they may become epidemic in this region one day (Corredor,

pers. com.).

Such a target will be very likely attained because of the diversity evidenced within most

oil palm origins, as long as the breeders accept working with a broad genetic base. Two

examples can be given to illustrate that point. There is a famous palm named Deli E206

(from Elmina Estate in Malaysia) which is also known as the dumpy palm because of its

short stipe and larger girth. This palm is known to be resistant to Fusarium wilt (Rosenquist,

1985), but it is highly susceptible to Ganoderma (Franqueville, pers. com.). On the contrary,

the La Mé palm LM2T, whose resistance to wilt is well documented (Durand-Gasselin,

2000), has also been found to be a promising source of resistance to Ganoderma (Durand

Gasselin, 2005). It is for this reason that breeders need a broad genetic base for their

breeding programme.

Should planters face compromise on yield when using materials that are resistant to

diseases? This question does not have an easy answer. Of course, the yield of interspecific

hybrids used to be lower than that of normal E. guineensis commercial materials, but

this is no longer the case. A possible answer to that question is that most of the planting

material that was identified to be resistant to diseases during the first step of selection

in the field was commercial material: as a consequence, disease-resistant materials do

originate from excellent material.

The sustainability of partial resistance is very likely to be confirmed. Such resistances

are the bottom line of breeders’ work. The fact is that no example of total immunity has

yet been reported. Even the highly resistant interspecific hybrids or the highly resistant

Fusarium wilt materials can be affected by Bud Rot or fusariosis when planted under high

pressure of an aggressive strain of the pathogen.

The development of early screening tools for resistance to Fusarium and to Ganoderma

has enhanced the efficiency of our research work. Nonetheless, before using it, it has

proven pivotal to assess some of their main properties: repeatability, precision, low or

no host–pathogen interaction, and connection with field data. Breeders will also assess

the inheritance of the resistant traits, which have been found to be mainly an additive

transmission, at least for resistance to Fusarium and

Ganoderma.

Last but not least, planters must not solely rely on genetic resistance to disease.

Partial resistance is part of IPM strategies and any field practice that helps to limit the

presence or the development of the inoculum will also limit the number of affected

palms.

Today, planters benefit from oil palm varieties that effectively protect their plantation from

Fusarium wilt and Bud Rot and can provide some moderate protection against Ganoderma.

The highest level of protection against Bud Rot relies on interspecific hybrids – which need

assisted pollination – and on pure E. guineensis varieties with moderate resistance, which

have been made available recently. As researchers pursue their efforts, there is no doubt

that new incremental progress will be steadily achieved.

5 Future trends

At first, efforts must be made to simplify and improve the existing early screening tests

and an evaluation of the current resistance screening methods is needed (Kull et al., 2003).

Nevertheless, one will have to comply with the specifications described earlier in this

chapter, particularly avoiding bypassing possible defence mechanisms. For Bud Rot, it

is worth underlining the tremendous efforts made by Cenipalma (Colombia) to artificially

duplicate the disease caused by P. palmivora in the greenhouse. Without any doubt this work will help in developing a very sought-after early screening test.

Because of its perennial character, the oil palm is unlikely to become a model plant.

Nonetheless, any tool that will help to save time will have a huge impact because of this

perennial character.

For a long time the work of phytopathologists and breeders has focused on total

resistances which were expected to provide plants with a sort of immunity (Dodds and

Rathjen, 2010). Despite the fact that immunity has been of huge help to farmers, the risk

that pathogens will overcome such resistance remains high, and thus, partial nonspecific

resistances are needed as they have been proved to be very durable. Some in-depth

understanding of the genetic patterns of such resistance is needed, and despite the

diversity of situations and the complexity of research questions, new knowledge is being

generated (McDonald and Linde, 2002; Roux et al., 2014).

Breeders have been using partial resistance for decades, but their work will certainly

be more relevant if they can integrate such knowledge in their practice. An intermediate

situation will be the use of molecular markers as the detection of QTLs is particularly suitable

for partial resistance. Historically, the need for specific experiments has slowed down such

research, and in addition the inaccurate data available to assess genetic resistance led to

the detection of weak QTLs (Cochard, pers. com.). Recent work has generated new hopes;

identifying QTLs using the information given by a broad set of relatives. The fact is that oil

palm pedigree is relatively well documented and this knowledge can help to detect QTLs

in nonspecific genetic trials (Tisné et al., 2015).

It might be the case that some strong resistance factors exist, for example, resistance of

interspecific hybrid to Bud Rot, and in this case it might be relatively easy to trace those

using molecular markers. This will help the introgression of such traits from E. oleifera

– which is the source of that strong resistance – into E. guineensis through backcrossing.

Now that annotated oil palm genome sequences have been made available, we will be

able to discover gene sequences of great interest in durable disease resistance, and new

genome editing tools can also be used (CRISPR/Cas9).

6 Tribute to Hubert de Franqueville

This chapter is dedicated to the memory of Hubert de Franqueville, our oil palm

phytopathologist colleague, who dramatically passed away in November 2015. He

certainly should have been the co-leading author of this chapter. Our remembrance is

not only because Hubert was a great colleague, a friend with whom we shared good

and bad times, but also because we have been continuously building bridges between

pathologists and breeders' knowledge. The work of our team has gained in relevance because of these bridges: taking into account the constraints of the oil palm, the constraints

of the phytopathologists and those of the breeders who have made our research much

more meaningful. Hubert and I built a strategy to breed for disease resistance which is

summarised hereafter.

To breed for disease resistance, we will have to face many challenges, each in interaction

with the other. In addition to numbers, just taking into account the first-order interactions

already deliver a very complicated picture.

The factors correlated to disease resistance may be related to the following.

The disease itself:

- the type of pathogen: fungi, phytoplasmas, bacteria, viruses, etc;

- the genetic diversity of the pathogen which is generally linked to its sexual cycle and reproduction mode;

- its propagation: in the soil (for soilborne pathogens), in the air, spores quantities and viability, through vectors (for phytoplasmas, nematodes, etc); and

- the pathogen can be either biotrophic or necrotrophic (sometimes hemibiotrophic), which will obviously lead to different responses from the host.

The host:

- annual or perennial crop, and obviously, the perennial character of oil palm is a key factor;

- the genetic diversity of the host; and

- the age of the host is also a key factor. Diseases occurring at the seed, pre-nursery or nursery stage could be easier to control as the acreage involved is much smaller than for field diseases.

The environmental factors:

• climatic conditions, such as the length of dry season, rainfall and temperature;

• soil receptivity and soil infectivity;

• soil microflora or micro fauna; and

• agricultural practices, which are human-dependent, can affect drainage, cover plants or spore transmission.

Accurate knowledge or observations about the pathogen will obviously help breeders

to develop resistant varieties. Of course, the identification of the disease is highly

desirable even if breeding can in principle (but with great difficulties) be initiated

without it. As soon as they have identified a pathogen which could be potentially

linked to a disease, phytopathologists will make best efforts to comply with Koch’s

Postulates.

Evidence of field genetic resistance is of great help, at first to consolidate the idea that

breeding could be efficient, and later to confirm in the field that selected resistant varieties

are behaving as expected.

Resistance to diseases can be either total or partial and this point has been

discussed. Whatever the type of resistance, the challenge is to develop – together with

phytopathologists – an early screening test. Ideally, an early screening test should be

repeatable, manageable as a routine tool for breeders (high throughput) and as fast as

possible. It is also important to check if significant interaction between isolates inducing a given disease and oil palm progenies exists. Last but not least, the early screening test has to be straightforward and highly correlated to field resistance.

The inheritance of resistance to a given disease also needs to be assessed. First, one has to understand that while moving from one generation to another, the additive effects are passed to the offspring, whereas interactions (non-additive effects) have vanished. Under some conditions, non-additive effects can be retained for seed production. Oil palm breeding is still in its early stages; therefore we can expect that additive effect will be largely predominant.

Having in hand most of this knowledge and tools, breeders and phytopathologists will be able to develop oil-palm-resistant varieties to several diseases. The impracticality of obtaining within a short period of time a sufficient number of generations of oil palms is a major constraint. This leads to devising long-term strategies that will have to consider the durability of the resistance as the main objective. For the same reason, the number of traits that can be addressed is very limited: breeding for sustainable resistance to only one disease is such a burden that to date has not been reasonable to undertake a breeding programme for resistance to a disease that can be controlled by any agricultural practice.

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7 Chapter 7 Bioactive compounds in oil palm

1 Introduction

Bioactive compounds in plants are defined as substances that elicit pharmacological or

toxicological effects in humans and animals. They are typically secondary metabolites

produced by the plant in addition to the primary metabolites such as amino acids,

proteins, carbohydrates and lipids required for growth and development. Unlike primary

metabolites which participate in nutrition and essential metabolic processes within the

plant, secondary metabolites are considered non-essential for sustaining life but crucial

for the survival of the producing organism (Hadacek, 2002). They influence ecological

interactions between plants and their environment and are often involved in defence

mechanisms to protect the plant against biotic and abiotic stresses. They are ubiquitous

in plants on account of their important protective biological functions. The oil palm being

a tropical crop is exposed to high temperature and intense sunlight that result in the

generation of reactive oxygen species that elicit oxidative stress responses. The palm

has thus evolved cellular and metabolic processes and produces bioactive compounds

as protective measures against the ravages of the weather as well as the surrounding

ecosystem. While plants are the prime source of bioactive compounds for drug discovery and development of functional foods and nutraceuticals, supply of these compounds is often curtailed by the low content and limitation in supply. The tremendous productivity of the oil palm and the abundance of cultivated palms on a global scale, however, provide an abundant source of lipid- and water-soluble bioactives. A major environmental advantage of palm bioactives is that they are readily available products of palm oil milling and refining processes. This can play a key role in value addition and improved sustainability of the oil palm. The palm fruit which represents one of only a few oleaginous fruits is poised to play an increasingly substantiated role in nutrition and health, not only through the delivery of important dietary fats but also its distinct bioactive compounds.

2 Lipid-soluble bioactives

The oil palm mesocarp yields an orangish red oil commonly known as crude palm oil (CPO). CPO is bestowed with a bouquet of minor components constituting 1% of its total content (Goh et al., 1985; Choo et al. 2000, 2004a,b,c; Choo, 2000). Although small in amount compared to the major lipid components, these minor components are of nutritional value and confer important health benefits.

The major fat-soluble phytonutrients and/or bioactives in palm oil include carotenes, tocols (tocopherols and tocotrienols), squalene, sterols, phospholipids (better known as lecithin) and coenzyme Q 10 (also known as ubiquinone)

(Goh et al. 1985; Hamid et al. 1995;

Choo et al. 2000, 2004a,b,c; Choo 2000; Lau et al. 2006a). The compositions of these

phytonutrients, together with other minor components of CPO, are shown in Table 1.

2.1 Carotenes

Palm oil gets its orangish red colour from carotenoids. It is the richest source of natural

plant carotenoids in retinol (provitamin A) equivalent among all the edible oils and fats

(Hamid et al., 1995; Choo, 2000; Latip et al., 2000) – contains 15–300 times more retinol

(provitamin A) equivalent than carrot, green leafy vegetables and tomato. The carotenoids

have a large content of β-carotene, which also occurs in other vegetable oils, such as

olive, corn, sunflower and soybean oil (Choo et al., 1999; Cabrini et al., 2001; Ranalli and

Demattia, 1997; Ranalli et al., 1997). Table 1 Concentrations of minor components in CPO Component Concentration (ppm) Carotenoids 500–700 Tocopherols and tocotrienols 600–1000 Sterols 326–527 Phospholipids 5–130 Triterpene alcohols 40–80 # Methyl sterols 40–80 # Squalene 200–500 Aliphatic alcohols 100–200 Ubiquinones 10–80 Aliphatic hydrocarbons 50 # Estimated. Source: Goh et al. (1985).

The carotenoids in palm oil comprise carotenes and xanthophylls (Ranalli et al., 1999).

While the carotenes are hydrocarbons, the xanthophylls contain at least one oxygen

moiety. The main carotenes α- and β-carotene and their contents, as well as the contents

of other carotenes, differ in CPO and the residual oil obtained from palm pressed fibre

(palm pressed fibre oil, PFO), with the largest difference in lycopene (Goh et al., 1985;

Choo et al., 1996; Tay et al., 2001). The content of lycopene is much higher in PFO than

CPO. Table 2 shows the composition of the individual carotenes in CPO and PFO as

reported by various researchers, while their structures are depicted in Fig. 1 (Tan et al.,

1986; Yap et al., 1991; Sundram et al., 1989; Tay and Choo, 2000a).

Carotene content increases with fruit ripening and is highest in ripe palm mesocarp oil

(Sambanthamurthi et al., 2000; Tay and Choo 2000b; Sundram et al., 2003). Much less

is known about the chemistry of xanthophylls in palm oil, although a few compounds

such as dehydroretinal, ξ-carotene-dione and β-carotene-5,6-epoxide isomers have been

reported (Tan, 1987).

It has been documented that palm carotenes exhibit beneficial properties, such as

anti-cancer and antioxidative effects (Yap et al., 1991; Ashfaq et al., 2001; Murakoshi).

Carotenes are known to be potent antioxidants and anti-cancer agents (Britton, 1995;

Spiller, 2004; Nesaretnam et al., 2002; Sundram et al., 1989; Tay and Choo, 2000a).

Continual assessment of palm carotenes on breast cancer cells revealed their ability

to inhibit the growth of new cancer cells (Nesaretnam, 2000, 2007a). Studies have

shown that mice fed with palm carotenes were protected against DNA damage in bone

marrow and had better survival following X-ray irradiation

(Umegaki et al., 1997). α- and

β-carotenes have been proven to be provitamin A, and protect the cells against free

radical damage as well as xerophthalmia, or night blindness, in humans (Umegaki et al.,

1997; Dimascio et al., 1989; Ziegler, 1989; Ziegler et al., 1996a,b; Sundram et al., 1989;

Tay and Choo, 2000a). Table 2 Individual carotenes as percentage of total carotenes in CPO and PFO Carotene CPO (%) PFO (%) Phytoene 1.27 11.87 Phytofluene 0.06 0.40 β-Carotene 56.02 30.95 α-Carotene 35.06 19.45 cis-α-Carotene 2.49 1.17 ξ-Carotene 0.69 7.56 γ-Carotene 0.33 2.70 δ-Carotene 0.83 6.94 Neurosporene 0.29 3.38 β-Zeacarotene 0.74 0.37 α-Zeacarotene 0.23 Trace Lycopene 1.30 14.13 Source: Choo et al. (1996). P h y t o e n e P h y t o f l u e n e z c a r o t e n e N e u r o s p o r e n e L y c o p e n e a c a r o t e n e b c a r o t e n e g c a r o t e n e b z e a c a r o t e n e a z e a c a r o t e n e F i g u r e 1 M o l e c u l a r s t r u c t u r e s o f c a r o t e n e s i n p a l m o i l .

Rabbits fed diets enriched in palm carotenes were found to have different carotenes

in varying amounts in their plasma and organs, mainly the liver and adrenal glands. Most

of the supplemented α- and β-carotenes were metabolized to retinal and retinyl esters,

and mainly stored in the liver and, to a lesser extent, pancreas. Small amounts of other

carotenes – phytoene, phytofluene and ξ-carotene – were present in the rabbit plasma

and organs. The contents of retinal and retinyl esters in the liver of rabbits fed a diet

supplemented with palm carotenes were 3× and 30× times higher, respectively, than in

the rabbit groups not fed palm carotenes, suggesting that palm carotenes are converted

to retinal and retinyl esters in vivo.

2.2 Tocopherols and tocotrienols

The generic name 'tocopherol' was derived from the Greek words, 'tokos', which means

offspring and 'pherein' meaning to bear, with 'ol' appended to indicate the phenolic

hydroxy group (Tay and Choo, 1999). Tocopherol was first isolated and named by Evans

et al. (1936). The trivial name 'tocotrienol' was introduced by Bunyan et al. (1961) to

represent vitamin E homologues with an unsaturated isoprenoid side chain.

Natural tocols comprise eight individual components which are classified into two

homologous series: tocopherols and tocotrienols. Tocotrienols differ from tocopherols in

having three unsaturated bonds at the side chain.

The tocols in palm oil consist of both tocopherols and tocotrienols. Oil palm is unique

as it contains natural tocotrienols, which are rarely found in other vegetable oils, the

exception being rice bran oil (Table 3) (Tay and Choo, 2000b; Bunyan et al., 1961). There

are 600–1000 ppm and 2000–4000 ppm tocols, in CPO and PFO, respectively (Goh et al.,

1985; Tay et al., 2001; Sundram et al., 1989; Tay and Choo, 2000a; Qureshi et al., 2000;

Choo et al., 2003a, 2005a; Lau et al., 2006a,b, 2008; Ng et al., 2004a).

Table 3 Tocol contents in vegetable oils (ppm) Vegetable oil Tocopherol Tocotrienol Totalα-T β-T γ-T δ-T α-T 3 β-T 3 γ-T 3 δ-T 3

Coconut 5 – – 6 5 1 19 – 36

Corn	112	50	602	18	-	-	-	-	782
Cottonseed	389	-	387	-	-	-	-	-	776
Olive	51	-	-	-	-	-	-	-	51
Palm	152	-	-	-	205	-	439	94	890
Peanut	130	-	216	21	-	-	-	-	367
Rice bran	324	18	53	-	236	-	349	-	980
Safflower	387	-	174	240	-	-	-	-	801
Sesame	12	6	244	32	-	-	-	-	294
Soyabean	101	-	593	264	-	-	-	-	958
Sunflower	487	-	51	8	-	-	-	-	546

Source: Ng et al. (2004a).

All tocols have the same chroman structure and a side chain. However, as mentioned earlier, the tocopherol side chain is saturated whereas tocotrienols have three unsaturated bonds in the side chain. The difference between the individual tocopherols and tocotrienols in palm oil is in the positions they are methylated. Of the eight tocol isomers, four are reportedly present in palm oil – α-tocopherol (α-T), α-tocotrienol (α-T$_3$), γ-tocotrienol (γ-T$_3$) and δ-tocotrienol (δ-T$_3$) (Tan et al., 1986; Ng et al., 2004a,b), in varying amounts with γ-T$_3$ being the dominant (Sundram et al., 1989; Tay and Choo, 2000a; Ng et al., 2004a; Choo et al., 2005b; Gapor et al., 1981), while α-T is more abundant in residual oil obtained from palm pressed fibre (PFO) (Tay et al., 2001). Table 4 shows the composition of tocols in CPO and PFO with their molecular structures in Fig. 2. Choo et al. (2004a) detected tocopherols in the developing fruit mesocarp as early as four weeks after anthesis.

The vitamin E activity in palm oil is largely mediated through γ- and δ-tocotrienols. Many

studies have found that palm vitamin E possesses antioxidant properties in scavenging free

radicals which have been linked to cancer risk (Ong and Goh, 2002; Spiller, 2004; Tomeo

et al., 1995; Yurttas and Addis, 2001; Yu et al., 2008; Maniam et al., 2007; Nesaretnam

et al., 2007a; Das et al., 2005). It was also reported that tocols in palm oil inhibit human

platelet coalescence and improve glycaemic control in vivo (Holub et al., 1989; Hornstra,

1988; Wan Nazaimoon and Khalid, 2002). In addition, palm tocols were also found to

exhibit anti-cancer properties (Ashfaq et al., 2001; Nesaretnam, 2000; Nesaretnam et al.,

1992, 1995, 1998, 2007b, 2008; Chan and Chan, 2003; Goh et al., 1994; Guthrie et al.,

1993; Sylvester and Sumit, 2003; Wong et al., 2009; Li et al., 2010).

α-Tocotrienol was found to inhibit glutamate-induced activation of phospholipase A 2

and conferred neuroprotection (Khanna et al., 2005, 2010). Another isoform, γ-tocotrienol,

has also been found to exhibit neuroprotection (Mishima et al., 2003). δ-Tocotrienol was

able to protect mouse and human hematopoietic progenitors from gamma irradiation (Li

et al., 2010). γ-Tocotrienol, on the other hand, inhibited pancreatic tumours and sensitized

them to gemcitabine treatment by modulating the inflammatory microenvironment

(Kunnumakkara et al., 2010). Palm tocotrienols have been found to exhibit anti-angiogenic

potential in vitro (Miyazawa et al., 2004). δ-Tocotrienol is also required for normal vitamin

D metabolism in female rats (Norazlina et al., 2005).

2.3 Sterols

Sterols are found in most plants and are easily recognizable by their common steroid

structure. The phytosterols in palm oil differ only in the side chains from Carbon 12 of

the main steroid structure. There are ~1050 ppm sterols in olive oil with the campesterol:

stigmasterol ratio being 2.2:5.7 (Cabrini et al., 2001; Ranalli and Demattia, 1997; Ranalli Table 4 Individual tocols as percentage of total tocols in CPO and PFO Tocol CPO (%) FPO (%) α-Tocopherol 22 61.1 α-Tocotrienol 20 15.4 γ-Tocotrienol 46 18.0 δ-Tocotrienol 12 5.5 Source: Choo et al. (1996).

et al., 1997). In CPO, sterols are present at 250–620 ppm, but in higher content (4000–

6500 ppm) in PFO (Goh et al., 1985; Choo et al., 2003b, 2004b; Tay et al., 2001; Ng et al.,

2004b).

Several investigations have been carried out on the occurrence of sterols in palm

oil. The main sterols in CPO and PFO are β-sitosterol, campesterol, stigmasterol and

cholesterol, together with traces of avenasterol and brassicasterol (Goh et al., 1985; Choo

et al., 2003a,b; Lau et al., 2005). As the amount of cholesterol in palm oil is very low, it can OH O OH O OH O HO H 3 C H 3 C H 3 C H 3 C CH 3 CH 3 CH 3 CH 3 CH 3 CH 3 O HO CH 3 O g-tocopherol a-tocopherol a-tocotrienol g-tocotrienol d-tocotrienol

Figure 2 Molecular structures of tocols in palm oil.

be considered ‘cholesterol-free’. The composition of the individual sterols in palm oil is

depicted in Table 5 and their molecular structures are given in Fig. 3.

Sterols are converted to steroid derivatives such as β-sitosterol, which have reportedly

beneficial hypocholesterolemic effect (Sundram et al., 1989; Tay and Choo, 2000a;

Farquhar, 1996; Hedtmann et al., 1988; Yankah and Jones, 2011). However, most of the

sterols in CPO are removed during the refining process. Table 5 Individual sterols as percentage of total sterols in CPO and PFO Sterol Content (%) CPO PFO β-Sitosterol 60 59 Campesterol 13 22 Stigmasterol 24 18 Cholesterol 3 1 Source: Choo et al. (1996).

HO HO

HO HO b-sitosterol Stigmasterol Campesterol Cholesterol

Figure 3 Molecular structures of major sterols in palm oil.

Plant sterols are similar in structure to dietary cholesterol but are not absorbed by the

human gastrointestinal tract. They can thus inhibit the absorption of dietary cholesterol

and enable its removal from the body. Plant sterols exert a positive effect on blood lipid

profiles by significantly reducing total and LDL cholesterol.

2.4 Ubiquinones

Coenzyme Q compounds have a quinone structure with a side chain of varying isoprene

units as shown in Fig. 4. The difference in chain length distinguishes one coenzyme Q

from another. Coenzyme Q 10 , for instance, has the basic quinone ring with 10 isoprene units in its side chain. Coenzyme Q 10 is a natural compound in the human body where

it is a potent antioxidant combating the ageing process (Sundram et al., 1989; Tay and

Choo, 2000a; Beyer, 1989; Kagan and Quinn, 2001; Lenaz, 1985b; Lipshutz et al., 2002;

Mellons and Tappel, 1996; Kueper et al., 2008; Ooe and Fujii, 2008; Takada et al., 2009;

Blatt et al., 1999). With age, the biogeneration of coenzyme Q 10 becomes less active. It is,

therefore, increasingly taken as a health supplement. About 10–80 ppm coenzyme Q 10

and 5 ppm coenzyme Q 9 were detected in CPO (Lau et al., 2006a; Sundram et al., 1989;

Tay and Choo, 2000a; Miettinen and Vanhanen, 1994; Tan and Kuntom, 1994; Hazura

et al., 1995; Ng et al., 2009). However, only coenzyme Q 10 has been reported in red

palm oil (18–25 ppm) (Tan, 1987). Ng et al. (2006) reported the presence of coenzyme

Q 9 in the developing palm mesocarp as early as four weeks after anthesis. However, its

concentration slowly diminishes as the fruit matures. As with other antioxidants, coenzyme

Q compounds are light and heat sensitive. It was reported that coenzyme Q 10 helps in

angina relief (Tran et al., 2001). Angina is the pain or discomfort experienced when blood

flow to the heart is restricted. Coenzyme Q 10 has also been attributed for boosting the

immune system as well as lowering high blood pressure and, thus, reducing the risk of

heart attack (Sundram et al., 1989; Tay and Choo, 2000a; Kagan and Quinn, 2001; Lipshutz et al., 2002; Lenaz, 1985b; Wyman et al., 2010; Sinatra, 1998; Yamamura, 1985; Nafeeza

and Kang, 2005).

Recent studies found that coenzyme Q is able to slow the functional decline in

neurodegenerative diseases such as Parkinson’s and Huntington’s disease (Ferrante

et al., 2002; Shults et al., 2002; Beal, 1999). Supplementation of coenzyme Q with

vitamin E has been shown to reduce the circulating markers of inflammation (Wang

et al., 2004).

Coenzyme Q can be extracted from natural sources as well as produced synthetically

(Lipshutz et al., 2002). The difference in activity, if any, between natural and synthetic

coenzyme Q is yet to be studied. O O O O CH 3 H 3 C H 3 C CH 3 C H 2 H n n = 1, 2, 3, 4 …. Figure 4 Molecular structure of coenzyme Q.

2.5 Squalene

Squalene was first discovered in shark liver oil and is also found in many marine organisms

(Lau et al., 2003; Ackman et al., 2000; Deprez et al., 2000). It is known to be an intermediate

in the cholesterol biosynthesis (Tay and Choo, 2000b; Kayama and Mankura, 1998;

Barrowman et al., 1989). It is also found in CPO (Tan et al., 1986; Lau et al., 2005; Miettinen

and Vanhanen, 1994; Berger, 2005; Tan and Kuntom, 1993). The molecular structure of

squalene is shown in Fig. 5.

There are 200–500 ppm squalene in CPO, and even higher in

PFO (500–1000 ppm) (Lau et al., 2005; Gapor and Hazrina, 2000; Gapor et al., 2000b, 2009; Gapor, 2002; Chua et al., 2007). Squalene is also extracted from palm fatty acid distillate (PFAD) (Gapor and Hazrina, 2000; Gapor et al., 2000, 2009; Gapor, 2002; Chua et al., 2007). Squalene possesses slight antioxidant activities and is able to retard the degradation of unsaturated fatty acids at high temperature (Rao and Achaya, 1970). It is also beneficial to health in helping body cells renew themselves and in boosting the immune system (Carlson et al., 2000).

Squalene is also an excellent emollient, or conditioning agent, in cosmetics (Gasparaoli et al., 1998; Kaiya, 1990). For pharmaceutical applications, squalene is converted to squalane as the saturated derivative has greater oxidative stability, and is better as a carrier for lipid-soluble drugs. It is also used as bactericide, intermediate for the manufacture of organic chemicals, rubber chemicals, aromatics and surfactants.

Studies have shown that squalene has some effect in chemoprevention of cancer (Rao et al., 1998; Smith, 2000). In recent years, squalene has been used in the preparation of vaccine against flu (Beck et al., 2010).

Besides squalene, there are numerous other shorter aliphatic and aromatic hydrocarbons in palm oil. Some of them are the natural constituents of palm oil, but some may be oxidation, or degradation, products.

2.6 Phospholipids and glycolipids

The chemistry of palm oil is complex as it contains many compounds with different

behaviours. The more commonly known minor components are divided into non-polar,

for example, carotenes, tocols and sterols, and polar types, for example, phospholipids

and glycolipids. PFO has relatively high amounts of phospholipids (Choo et al., 2002a,b,

2004b).

Phospholipids in palm oil have gained considerable attention due to the suspected

deleterious effect of phosphorus on oil quality. Most of the phosphorus in palm oil is

present as inorganic rather than as organic phospholipids. There are 20–80 ppm

phospholipids in CPO. Choo et al. (2004b) isolated and identified several of them –

phosphatidylcholine (better known as lecithin), phosphatidylinositol, phosphatidylamine

and phosphatidylethanolamine. Table 6 shows the phospholipids present in CPO.

Phospholipids in palm oil were reported earlier by Goh (1984) and Goh et al. (1985).

1 6 10 19 23 15

Figure 5 Molecular structure of squalene.

Choo et al. (2004b) also reported ~46 800 ppm phospholipids in the ethanol extract

of PFO with the major ones being phosphatidylcholine, phosphatidylethanolamine,

phosphatidylglycerol and phosphatidic acids.

Preliminary studies indicate 1000–3000 ppm glycolipids in CPO (Kulkarni, 1991a,b).

They include monogalactosyl diacylglycerols, digalactosyl diglycerides and esterified steryl

glycerides (Lau et al., 2006a, 2008; Kulkarni, 1991a,b). Both phospholipids and glycolipids

are removed during the refining of CPO through degumming, washing, phosphoric acid

treatment and absorption by clays or earths.

Both phospholipids and glycolipids constitute important components of cellular

membranes, which possess unique structures with both lipophilic and hydrophilic

functionalities. Palm phospholipids have been found to act synergistically with tocols

to exhibit powerful antioxidative effects (Choo et al., 2009). In addition, phospholipids

are essential for the biosynthesis of acylglycerols in plants (Dybing and Craig, 1969;

Tremolieres and Lepage, 1971).

3 Water-soluble bioactives

3.1 Phenolics

Phenolic compounds are a large class of plant secondary metabolites, showing a diversity

of structures. All phenolic substances have in common an aromatic ring with one or more

hydroxyl substituents. Several thousands of phenolic compounds have been classified

based on their basic chemical configuration, for example, number of phenol rings, and

into various subclasses based on specific substitutions or functional derivatives in the basic structure including glycosylation, esterification and polymerization. Phenolic compounds

thus range from those with relatively simple structures, for example phenolic acids,

through polyphenols such as flavonoids that have the characteristic C6–C3–C6 backbone

structure (structural variations in the three rings of flavonoids characterize different types Table 6 Individual phospholipids as percentage of total phospholipids in CPO Phospholipid Percentage (%) Phosphatidylcholine 36 Phosphatidylethanolamine 24 Phosphatidylinositol 22 Phosphatidylglycerol 9 Diphosphatidylglycerol 4 Phosphatidic acid 3 Lysophosphatidylethanolamine 2 Phosphatidylserine Trace Lysophosphatidylcholine Trace Source: Goh (1984).

of flavonoids) to polymeric compounds based on these different classes (Harborne, 1998).

Phenolic acids can be further divided into two main types, benzoic acid and cinnamic

acid derivatives with C1–C6 and C3–C6 backbones respectively. The majority of plant

phenolics exist as glycosides with different sugars and acylated sugars at various positions

of the phenolic structure. The degree of hydroxylation, the methylation pattern of the

aromatic rings and the glycosylation pattern all influence the physical and physiological

properties of phenolics.

Phenolic compounds are important for the quality of plant-based foods: they are

responsible for the colour of fruits, juices and wines; are substrates for enzymatic browning;

and are also involved in flavour properties. Phenolic-rich diets have been linked to numerous

health benefits. The phenolic ring and hydroxyl substituents of these compounds confer antioxidative properties, as they are able to capture free radicals by donating hydrogen

atoms or electrons. However, the bioactivity of phenolics extends well beyond the

modulation of oxidative stress and may involve their interaction with cellular signalling

pathways and associated machinery that regulate cell activities under both normal and

pathological conditions. Their biological activities may also be associated with their

capacity to chelate metals, inhibit lipoxygenases, inhibit nitrosation and modulate certain

cellular enzyme activities as well as endocrine function. For example, soya isoflavones affect

endocrine properties by interacting with oestrogen receptors (Kuiper et al., 1998). Nitric

oxide (NO) bioavailability influences insulin-stimulated glucose uptake and vascular tone

(Grassi et al., 2005). There is scientific evidence that phenolics exert significant vascular

protection because of their antioxidant properties and increased NO bioavailability.

Whilst much attention has been paid to lipid-soluble bioactives of oil palm, the

description of water-soluble bioactives, namely palm phenolics, has been relatively recent.

Sambanthamurthi et al. (2008,2011a) described the presence of phenolics with potent

antioxidant and bioactive function in the vegetation liquor of oil palm milling. Being water

soluble, these phenolic compounds enter the aqueous waste stream and are discharged as

palm oil mill effluent (POME). Sambanthamurthi et al.

(2008, 2011a) developed a process

for the recovery of phenolic-enriched extract, which they called oil palm phenolics (OPP)

by diverting the aqueous stream before it is discarded as waste. MS-coupled HPLC and

NMR confirmed the presence of several phenolic acids. OPP contains p-hydroxybenzoic

acid and three isomers of caffeoylshikimic acid as major phenolic compounds that accord

a unique signature profile to the extract (Sambanthamurthi et al. 2011a). Figure 6 shows

the HPLC profile of OPP. It also contains protocatechuic (PCA), caffeic, vanillic, ferulic and

other phenolic acids in addition to soluble fibres, sugars and minerals. Table 7 shows the

major phenolic components in OPP. An important non-phenolic component of OPP is

shikimic acid.

Caffeoylshikimic acid

Caffeoylshikimic acid is an ester of caffeic acid and shikimic acid. It is an intermediate

of the lignin biosynthesis pathway and not commonly found in nature. The date palm,

Phoenix dactylifera, is one of the few plants reported to contain this phenolic compound,

the 3-O-caffeoylshikimic acid isomer being one of the key enzymatic browning substrates

(Maier et al, 1964). 3-, 4- and 5-O-caffeoylshikimic acids are also known as dactilyfric,

isodactylifric and neodactylifric acid, respectively. They are among the resistance factors

of date palm roots against Fusarium oxysporum (Modaffar et al., 2000; Hassni et al., 2004). It would be interesting to investigate if they act as resistance factors in the oil palm.

Caffeoylshikimic acid is a minor constituent of the leaves of Vaccinium species – bilberry

(Vaccinium myrtillus L.), hybrid bilberry (Vaccinium x intermedium Ruthe L.) and lingonberry

(Vaccinium vitis-idaea L.) (Hokkanen et al., 2009); Yerba mate (Ilex paraguariensis L.); and

green tea (Camellia sinensis) (Bastos et al. 2007). More recently, Chideha et al. (2014)

reported the presence of high levels of 5-O-caffeoylshikimic acid in Solanum somalense

leaf which are used in Djibouti for its medicinal properties. Caffeoylshikimic acid makes up

more than half of the total phenolic content of OPP. Palm vegetation liquor, from which

caffeoylshikimic acid (as a constituent of OPP) is extracted, is thus the largest known

source of this bioactive compound. Caffeoylshikimic acid is relatively similar in structure

to caffeoylquinic acid (also known as chlorogenic acid), which also exists in three isomer

forms, namely 3-, 4- and 5-O-caffeoylquinic acids. Both are esters of caffeic acid. The only

difference between shikimic acid and quinic acid is a double bond in the ring structure

of shikimic acid, which is removed by the presence of an additional hydroxyl group in

quinic acid. Figure 7 shows the molecular structures of caffeoylshikimic and caffeoylquinic

acids. Several health benefits associated with the consumption of chlorogenic acid have

been documented including reduced incidence of type 2 diabetes (Salazar-Martinez et al.,

2004; Ranheim et al., 2005), cardiovascular disease (Ranheim et al., 2005) and anti-cancer

Figure 6 HPLC profile of OPP. Table 7 Major phenolic components in OPP Phenolic compounds Concentration (mg/kg) Mean SD Range Protocatechuic acid 600 100 400–800 p-Hydroxybenzoic acid 7000 1000 5300–8600 Caffeoylshikimic acid (total of 3 isomers) 10 800 2400 7700–15 100 Total major phenolics 18 400 2900 13 800–24 300 Gallic acid equivalents 18 200 1700 15 700–21 300 Source: Sambanthamurthi et al. (2011a).

properties (Tanaka et al., 1990). They also have anti-inflammatory (Santos et al., 2006) and

antibacterial properties (Lou et al., 2011; Karunanidhi et al., 2013). Green coffee is a major

source of chlorogenic acid (3-, 4-, and 5-caffeoylquinic acids). OPP extracts exhibit several

health benefits (see Section 2.3) similar to those of chlorogenic acid. The three isomers of

caffeoylshikimic acid may be responsible in part at least for these benefits.

Para-hydroxybenzoic acid

After caffeoylshikimic acid, para-hydroxybenzoic acid is the next most abundant phenolic

acid in OPP. Also known as 4-hydroxybenzoic acid, it is an isomer of 2-hydroxybenzoic

acid commonly known as salicylic acid, which is used for the production of aspirin. Para

hydroxybenzoic acid is an important substrate for the preparation of its esters parabens,

which are used as preservatives in cosmetics and ophthalmic solutions. The coconut,

Cocos nucifera, and the acai palm, Euterpe oleracea, are rich sources of 4-hydroxybenzoic

acid. It is also present in cloudy (unfiltered) olive oil and blueberries.

Protocatechuic acid

Another important phenolic compound in oil palm is PCA (3,4-dihydroxybenzoic acid).

PCA has been shown to have strong in vitro and in vivo antioxidant activity. It is an

active component of traditional Chinese herbal medicines (Li et al., 2011) and present

in most edible plants used in folk medicine (Liu et al., 2004). A wide range of potential

pharmacological benefits has been attributed to PCA. These include anti-inflammatory,

anti-diabetic, anti-cancer, cardioprotective, hepatoprotective, antibacterial and antiviral

activities (Kakkar and Bais, 2014). PCA is found in a multitude of berries including blueberry,

strawberry, mulberry, cranberry and gooseberry. It also occurs in Olea europaea (olives),

Hibiscus sabdariffa (roselle), Vitis vinifera (white wine grapes), wine, honey and soybean.

It is also a breakdown product of anthocyanin and may be considered the bioavailable

form of anthocyanins.

Based on a human feeding trial, Vitaglione et al. (2007) suggested that the phenolic acid

degradation product, PCA, was a major metabolite of anthocyanins.

Caffeic acid

Caffeic acid (3,4-dihydroxycinnamic acid), identified as a component of OPP, has been

established to have multiple health benefits. Coffee is the primary source of this phenolic compound. It is an active component of propolis extract and widely distributed in several

plants. There is extensive evidence from in vitro and in vivo studies to confirm that it has

Figure 7 Molecular structures of caffeoylshikimic acid and caffeoylquinic acid.

antioxidant, anti-inflammatory, anti-carcinogenic, immuno-modulatory and antimicrobial

activities (Kang et al., 2009; Touaibia et al., 2011; Rodríguez-Vaquero et al., 2015).

3.2 Shikimic acid

An interesting metabolite found in OPP is shikimic acid (3,4,5-trihydroxy-1-cyclohexene

1-carboxylicacid) (Sambanthamurthi et al., 2010). Shikimic acid itself is not a phenolic

compound, as it does not contain an aromatic ring. It is a cyclohexene but is a precursor in

the biosynthesis of aromatic compounds including phenolics. The benzene ring, which is

the basic element of all aromatic compounds, is synthesized in plants and microorganisms

through the shikimic acid pathway. Shikimic acid derivatives have wide use in agriculture as

herbicides and antimicrobial agents as they can inhibit the shikimic acid pathway in plants

and bacteria without negative consequences in animals and humans, as the pathway

does not exist in animals. Important bioactivities of shikimic acid have been documented.

These include anti-inflammatory, anticoagulant, antithrombotic, antibacterial and antiviral

properties (Estevez and Estevez, 2012). Besides its bioactive properties, shikimic acid is also essential in the synthesis of related bioactive compounds in the pharmacological

industry (Estevez and Estevez, 2012). It is an important substrate for the industrial

synthesis of the antiviral drug oseltamivir, which is used for the treatment H1N1 influenza

and against all strains of influenza virus. Shikimic and its derivative, triacetylshikimic acid,

have anti-inflammatory properties through inhibition of COX-1 and COX-2 activities,

and also reduction of platelet aggregation and blood clot formation (Huang et al., 2002;

El-Seedi et al., 2003). Shikimic acid in combination with quercetin was reported to have

immunomodulatory effects by regulating the secretion of interleukin-6 and interleukin-8,

which mediate lymphocyte recruitment and activation (Bertelli et al., 2008). In addition,

shikimic acid derivatives are important in agriculture as herbicides and as antibacterial

agents as they can block the shikimate pathway in plants and bacteria without adverse

effects towards mammals. Currently, the main source of shikimic acid is the Chinese star

anise (Illicium verum) but the abundance of vegetation liquor from palm oil mills is an

attractive reliable source of shikimic acid.

4 Bioactive properties of OPP

4.1 Antioxidant potential of OPP

It has been established that free radicals and related reactive oxygen and nitrogen species,

ROS/RNS, play a key role in the pathogenesis of numerous diseases and disorders. OPP has been demonstrated to have potent antioxidant activity based on its high efficacy in

scavenging 2,2-diphenyl-1-picrylhydrazyl (DPPH), a stable free radical (Sambanthamurthi

et al., 2011a). The antioxidant potential of OPP results from the ability to donate hydrogen

atoms and scavenge free radicals. Antioxidant and radical scavenging activities increase

with the level of hydroxylation of the phenolic substance (Rice-Evans et al., 1996).

Caffeoylshikimic acid, the major phenolic acid of OPP, has four hydroxyl groups, thus

accounting for the powerful antioxidant activity of OPP. The other phenolic compounds in

OPP such as hydroxybenzoic acid and PCA would also be expected to contribute to the

antioxidant activity observed and in fact may have a synergistic effect.

4.2 Cardioprotective effect of OPP

Atherosclerosis is the main cause of morbidity and mortality worldwide. Oxidation of LDL is

a key initial event in the development of atherosclerosis (Steinberg et al., 1989). Oxidized

LDL induces complex inflammatory and immunologic reactions in the endothelial cells

of the vascular wall. Uptake of oxidized LDL by macrophages and smooth muscle cells

leads to the formation of cholesterol-rich foam cells and development of fatty streaks, a

principle event in early atherosclerosis. Phenolics inhibit LDL oxidation by scavenging free

radical species or sequestering metal ions (Salah et al., 1995; Bernatova et al., 2002), thus protecting against cardiovascular disease. The resistance of LDL to oxidation is positively

correlated to the severity of coronary atherosclerosis in human subjects (Regnstrom et al.,

1992). Sambanthamurthi et al. (2011a) showed that OPP inhibited Cu-mediated oxidation

of human LDL in a dose-dependent manner in vitro, suggesting potential efficacy against

atherogenesis. Wine, cocoa and green tea have also been shown to inhibit LDL oxidation

(Frankel et al., 1995; Osakabe et al., 2002; Yang and Koo, 2000).

Rabbits on a high-fat, cholesterol-rich atherogenic diet were reported to have extensive

fibrous and fatty plaques and fatty streaks in their aortas. However, rabbits on the same diet

supplemented with OPP had significantly decreased fatty streaks and fatty plaques and

more lesion-free areas. This observation indicated bioactivity and bioavailability of OPP

in providing nett protection against the development and progression of atherosclerosis

(Sambanthamurthi et al., 2011b). Gene expression studies (Leow et al., 2013a) showed

that the atherogenic diet resulted in oxidative stress, inflammation and increased turnover

of metabolites and cells in the liver, heart and spleen. OPP, however, attenuated/reversed

these effects and increased unfolded protein response in the liver, upregulated antioxidant

genes in the heart and reduced antigen presentation and processing in the spleen. OPP

also returned antioxidant activity in the serum to normal levels. Che Idris et al. (2014)

studied the protective effects of OPP and tocotrienol-rich vitamin E singly or in combination

against atherosclerosis in a rabbit model fed an atherogenic diet. The results confirmed

that while OPP and tocotrienol-rich vitamin E individually reduced the development of

atherosclerotic lesions, OPP in combination with tocotrienol-rich vitamin E conferred the

highest protective effect. The effect was not additive but synergistic.

Numerous plant compounds such as wine (Bernatova et al., 2002), tea (Grassi et al.,

2008), coffee (Suzuki et al., 2006) and soy isoflavones (Chin-Dusting et al., 2004) improve

vascular function in whole animals and human subjects by producing vasodilation.

OPP induces vascular relaxation via endothelial NO, a key endogenous vasodilator in

maintaining cardiovascular homeostasis as evidenced in an ex vivo study with isolated

vascular preparations (Sambanthamurthi et al., 2011a). OPP also decreased blood pressure

in an NO-deficient rat model of hypertension confirming the in vitro observations and

indicating its direct effect on the endothelial NO synthase system (Sambanthamurthi et al.,

2011b).

4.3 Anti-diabetic effects of OPP

Polyphenols have been established as powerful antioxidants that can ameliorate

type 2 diabetes through multiple mechanisms. These include anti-inflammatory and immunomodulatory effects, modulation of glucose-induced oxidative stress, inhibition of

carbohydrate hydrolysing enzymes such as α-amylase and α-glucosidase and inhibition

of glucose absorption as well as preserving vascular functions in diabetic complications.

The potency of phenolic compounds on carbohydrate metabolism and glucose

homeostasis has been studied in vitro, in animal models and human intervention trials

(Bahadoran et al., 2013). Anderson (2008) reported that cinnamon phenolics improved

insulin sensitivity in vitro and in human subjects with type 2 diabetes. Individuals with

the metabolic syndrome who consumed an aqueous extract of cinnamon had improved

parameters including fasting blood glucose, systolic BP, percentage body fat and lean

body mass compared with the control group. Mulvihill et al. (2009) provided evidence that

naringenin attenuated hyperinsulinaemia and dyslipaemia in LDL receptor null mice with

diet-induced insulin resistance.

OPP has been shown to protect against early type 2 diabetes characterized by

hyperglycaemia and hyperlipaemia in a rat model (Nile rat, Arvicanthis niloticus) that

spontaneously develops diabetes on a high carbohydrate diet. As in humans, the model

used typically exhibits elevated glucose, total cholesterol, triacylglycerol, liver and kidney

weights, fatty liver and depressed HDL as markers for type 2 diabetes and the metabolic syndrome. The animals on OPP showed significant decrease in glucose levels and all

the criteria for diabetes (Sambanthamurthi et al., 2011b). Bolsinger et al. (2014) further

demonstrated that OPP mitigated several aspects related to hyperglycaemia in the Nile

rat without any toxic effects.

4.4 Anti-tumour effects of OPP

OPP was shown to have anti-cancer properties in both in vitro and in vivo studies. It effected

dose-dependent growth arrest and cell death of various cell lines including human lung

carcinoma, oestrogen receptor-positive human breast adenocarcinoma and mouse IgA

secreting myeloma cell lines (Sekaran et al., 2010). OPP was shown to reduce tumour

growth in BALB/c mice injected with myeloma cells. Gene expression studies indicated

that OPP inhibited tumour growth in the mice by inducing a G1/S phase arrest in the cell

cycle (Sambanthamurthi et al., 2011b). Other phenolics including hydroxytyrosol (Fabiani

et al., 2002), resveratrol (Joe et al., 2002), genistein (Raffoul et al., 2006) and luteolin (Lim

et al., 2007) have also been reported to inhibit tumour growth of several cancer cell lines

by inducing cell cycle arrest. A point of interest is that several of the genes that were

significantly changed in expression by OPP were also found to be differentially expressed,

but in the opposite direction, in colorectal tumour cells that were resistant to a combined chemotherapy of 5-fluorouracil, folinic acid and irinotecan (Sambanthamurthi et al., 2011b). This suggests that OPP may sensitize cancer cells towards chemotherapy and may enhance cytotoxicity in cancer cells when used in combination with chemotherapeutic agents. Several cytokines including the chemokine CXCL12 and interleukin IL-6 are known to be important mediators of advanced metastasis and significantly contribute to the lethal phenotype (Loberg et al., 2007). CXCL12 was significantly downregulated in tumours of mice treated with OPP suggesting that OPP played a role in reducing the aggressiveness and metastatic potential of these tumours (Sambanthamurthi et al., 2011b).

Time course microarray analysis on spleens following injection of J558 myeloma cells in mice indicated that the immune response of tumour-bearing mice given OPP was lower than that in control mice, thus implying delayed inflammation in response to OPP (Leow et al., 2013b). Cholesterol biosynthesis genes were upregulated and inflammatory genes were downregulated in the livers, further suggesting attenuation of systemic inflammation and cachexia. These effects correlated with the delayed in vivo development of syngeneic tumours in mice given OPP (Leow et al., 2013b).

OPP suppressed proliferation of cells in two pancreatic cancer cell lines (PANC-1 and BxPC-3) in a dose-dependent manner (Ji et al., 2015). The anti-proliferative, apoptotic (programmed cell death) and anti-metastatic properties of OPP were confirmed based

on evidence of cell cycle arrest in the S phase, induction of apoptosis associated with

decrease in survivin and Bcl-XL expressions and increased expression of cleaved caspase-3,

caspase-9 and PARP. Its anti-metastatic effects were confirmed based on decreased

expressions of vascular endothelial growth factor and MMP-9.

Tannic acid, a water-soluble phenolic abundant in Chinese herbal medicines and tea,

inhibits CXCL12 and this may explain its anti-inflammatory, anti-tumour properties (Chen

et al., 2003).

4.5 Role of OPP in neuroprotection and improved cognitive function

Mice supplemented with OPP showed superior cognitive and spatial learning skills based

on their performance in a water maze. They also exhibited better motor function and

coordination based on their performance on a rotarod (rotating rod where the rotating

speed is gradually increased). Gene expression analysis indicated that OPP upregulated

genes involved in brain development and activity, such as the signalling genes under

the control of the brain-derived neurotrophic factor. OPP also downregulated genes

involved in inflammation. The cognitive and motor function enhancement is thus

attributed to the neuroprotective and anti-inflammatory properties of the extract

(Leow et al., 2013c). Similar results were reported by van

Praag et al. (2007), where

supplementation of C57BL/6 mice with catechins resulted in upregulation of genes

involved in learning and downregulation of genes associated with inflammation.

Furthermore, genes involved in focal adhesion, notably the beta-actin gene that

encodes a cytoskeletal protein that is elevated in the brains of patients with Alzheimer’s

disease and in reactive glia were downregulated by OPP (Leow et al., 2013c). Similar

observations were made by Deshane et al. (2004) in the brains of mice that were

supplemented with a grape seed extract enriched with proanthocyanidins. Wang et al.

(2006) also showed that moderate consumption of Cabernet Sauvignon attenuated

Abeta (amyloid beta-protein) neuropathology in a mouse model of Alzheimer’s disease

while Hartman et al. (2006) reported that pomegranate juice decreased amyloid load

and improved behaviour in a mouse model of Alzheimer’s disease. Haque et al. (2006)

also reported that long-term supplementation of green tea catechins in rats significantly

improved spatial cognition in rats and also lowered reactive oxygen species in the

hippocampus of the brain.

4.6 Protective effect of OPP against mitochondrial dysfunction

It is increasingly evident that several chronic diseases including ageing, diabetes,

cardiovascular diseases and neurodegenerative disorders such as Alzheimer's,

Parkinson's and Huntington's disease are related to mitochondrial dysfunction (Swerdlow,

2011; Reddy, 2008; Victor et al., 2009). Mitochondrial dysfunction is characterized by

diminished efficiency in the electron transport chain and entry of metabolites into the

mitochondria and decreased synthesis of high-energy molecules such as adenosine-5′

triphosphate. The nucleotide reverse transcriptase inhibitor 3′-Azido-3′-deoxythymidine

(AZT) is a common component of combination anti-HIV regimens to treat HIV/AIDS.

However, prolonged use of this antiviral results in accumulation of mitochondrial

mutations and mitochondrial dysfunction. Oxidative stress and damage has been

postulated to be one of the reasons for this toxicity. Osborne et al. (2014a) reported that

OPP mitigated AZT-induced mitochondrial genotoxicity (mutagenesis) as well as dose

dependent cytotoxicity in cultured HepG2 cells. Three regions of the mitochondrial

genome studied (HV2, CO2 and ND1) had 35% of the number of mutations observed in

cultures treated with AZT alone and co-treatment of AZT with OPP increased cell survival

by up to 350%. It was confirmed that the effects were not because of degradation

or inactivation of AZT by OPP. The discovery offers a potential method of mitigating

AZT-induced mutations and related contraindications of prolonged AZT use with OPP supplementation. Osborne et al. (2015) also went on to show that oxidative damage

was only a minor contributor to AZT-induced mutations. Instead, most of the mutations

(80%) arose from AZT-induced mitochondrial DNA polymerase errors suggesting that

OPP preserved DNA polymerase fidelity or prevented possible AZT-induced alterations

in cellular nucleotide pools that could lead to errors in mitochondrial DNA polymerase.

Natural supplements have been used in the treatment of chronic disease resulting from

mitochondrial dysfunction (Nicolson, 2014). Osborne et al. (2014b) described the use of

OPP for the prevention and treatment of mitochondrial dysfunction and DNA damage,

especially in vulnerable populations, such as the aged and individuals being treated with

AZT and other drugs.

4.7 Multiple effects of OPP and safety

While the positive outcomes of OPP observed in the multiple studies described are

mainly attributed to phenolic compounds, it is most likely that a combination of bioactives

such as shikimic acid and soluble fibres worked in synergy with the phenolic compounds

and played a key role in the effects observed. It is pertinent to bear in mind that the

OPP extract in its entirety conferred the outcomes. The potent effects conferred by this

combination of water-soluble bioactives present an opportunity for the formulation of

functional foods and nutraceuticals. As OPP is a newcomer to the bioactive scene, it is imperative that its safety is ensured. Toxicological and teratological studies confirmed that it is safe for consumption (Sambanthamurthi et al., 2011a). A Phase 1 human intervention trial (Syed Fairus, pers. comm.) also showed that consumption of OPP had no serious adverse effects.

5 Bioactives in different palm sources

Bioactives such as carotenes, tocols, sterols, coenzyme Q, squalene and phospholipids are present in the oil palm fruits as early as 4 weeks after anthesis. On pressing the fruits for palm oil, these phytonutrients, being oil-soluble, are extracted with the oil (CPO). However, CPO is not the only source of palm phytonutrients. These compounds also end up in various products/by-products in the different stages of oil palm milling and refining processes. CPO, when further processed to downstream products, transfers some of these phytonutrients to the end products, which then also become good sources of palm phytonutrients.

5.1 Oil palm milling

Crude palm oil

The main source of lipid-soluble palm bioactives is derived from CPO, following the milling of fresh fruit bunches. Apart from the Elaeis guineensis, E. oleifera (the American oil palm) and the hybrids of E. oleifera and E. guineensis are a rich source of phytonutrients

(Latip et al., 2000; Tan et al., 1986; Choo et al., 2002b, 2005a; Kulkarni, 1991; George and Arumughan, 2006; Tan et al., 2007). E. oleifera oil is especially rich in carotenes, tocols and sterols, more so than E. guineensis. Tables 8–10 depict the concentration of carotenes, tocols and sterols present in different species and varieties of oil palm.

Palm pressed fibre

Palm pressed fibre is the residue of the oil palm fruit mesocarp after pressing for oil. The fibre is normally burnt as fuel to generate electricity for mill operation. These fibres still contain about 5–6% residual oil as the single pressing in the milling process does not completely remove the oil from the fibre. The residual oil can be extracted using solvent or other extraction technology such as supercritical fluid extraction. The oil obtained from the fibre contains much higher concentration of phytonutrients than CPO (Goh et al., 1985; Tan et al., 1986; Choo et al., 2005a; Lau et al., 2006b, 2008). Phospholipids are the major phytonutrients present in PFO, and their concentrations are more than 300-fold that of CPO. The detailed phytonutrient profile in PFO is depicted in Table 11.

Vegetation liquor

The palm oil milling process generates an aqueous stream known as vegetation liquor as a by-product. Vegetation liquor is derived primarily from the sterilizer condensate and centrifuge sludge and usually discarded as POME. About 2.5–3.5 m^3 of vegetation liquor

is generated for every tonne of CPO produced. Malaysia generates about 45 million

tonnes of vegetation liquor annually while global output exceeds 100 million tonnes.

Fresh fruit bunches are typically sterilized using high pressure steam (120 to 140°C at 40

psi) to soften the fruits, enable the separation of the fruit from bunches and inactivate

enzymes that hydrolyse the oil and cause fruit deterioration. The steam extracts the water

soluble components of the fresh fruit bunches which then enter the sterilizer condensate.

A substantial amount of water is added during the clarification step of palm oil milling

to separate the oil from oil-water-sludge emulsion. The oil is skimmed off while the

sedimented fraction (centrifuge sludge) enters the aqueous stream and discarded as

POME. Like the sterilizer condensate, the centrifuge sludge is a rich source of water-soluble

phytonutrients. Sambanthamurthi et al. (2008) developed a process whereby the fresh

vegetation liquor from the sterilizer condensate and centrifuge sludge are centrifuged in a

three-phase high-speed decanter to remove debris and residual oil and the middle water

phase passed through a series of filters to produce a phenolic-enriched filtrate termed

OPP, whcih contains among others, soluble fibres, sugars and shikimic acid in addition to

phenolics. The sterilization process ensures that polyphenol oxidases are inactivated and the phenolics are bioactive. While the heat-sensitive phenolics may have been inactivated,

the extraction process selectively enriches for highly stable phenolics. The phenolics in

OPP are thus highly stable. T a b l e 8 I n d i v i d u a l
c a r o t e n e s i n m e s o c a r p o i l s f r o m E . g
u i n e e s i s a n d E . o l e i f e r a a n d t h e i r h
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e n e s E . g u i n e e s i s (E . G) , % E . O l e i f e
r a (E . O) E . G × E . O A l b e s c e n s F i b r e T e
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u r c e : C h o o e t a l . (1 9 9 9) . T a b l e 9 C o n
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f e r e n t p a l m v a r i e t i e s a n d s p e c i e s a
n d t h e i r h y b r i d s a s p e r c e n t a g e o f t o
t a l t o c o l s E . g u i n e e s i s (E . G) E . o l e
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3 3 8 2 1 2 7 2 8 2 2 3 1 3 1 1 6 . 2 γ T o c o t r i e n o
l 4 5 3 2 4 0 5 4 4 2 4 9 5 1 5 1 2 4 . 0 δ T o c o t r i e
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- 1 6 0 0 8 0 0 - 1 7 0 0 7 0 0 - 9 0 0 7 0 0 - 9 0 0 2 5 0 0 - 4 0 0 0 S o u r c e : C h o o e t a l . (1 9 9 9) . T a b l e 1 0 C o m p o s i t i o n o f s t e r o l s i n m e s o c a r p o i l s f r o m d i f f e r e n t o i l p a l m s a s p e r c e n t a g e o f t o t a l s t e r o l s E . g u i n e n s i s (E . G) E . o l e i f e r a (E . O) E . G x E . O A l b e s c e n s F i b r e o i l T e n e r a (T) P i s i f e r a (P) D u r a (D) E . O x P E . O x D E . O . D x β S i t o s t e r o l 6 0 5 4 5 5 6 4 5 9 6 1 5 8 7 0 5 8 . 5 C a m p e s t e r o l 1 3 1 7 2 5 1 9 2 0 2 2 2 0 2 0 2 2 . 3 S t i g m a s t e r o l 2 4 2 2 1 4 1 5 1 6 1 3 1 9 8 1 8 . 0 C h o l e s t e r o l 3 7 6 2 5 4 3 2 1 . 2 T o t a l (p p m) 2 5 0 - 6 2 0 1 5 0 0 - 2 0 0 0 2 0 0 0 - 2 5 0 0 3 5 0 0 - 4 0 0 0 1 1 0 0 - 1 2 5 0 1 2 0 0 - 1 4 0 0 7 0 0 - 8 0 0 5 0 0 - 6 0 0 5 0 0 0 - 6 3 0 0 S o u r c e : C h o o e t a l . (1 9 9 9) .

5.2 Palm oil refining

Palm fatty acid distillate

CPO is refined either physically or chemically for use. Chemical refining is carried out

by neutralizing the fatty acids using an alkali. The process yields refined, bleached

and deodorized palm oil with PFAD produced as a by-product. PFAD is also rich in

phytonutrients, especially tocols, squalene and sterols (Gapor, 1993, 2002; Gapor et al.,

1993, 2000, 2009; Ahmad et al., 2009; Gapor and Hazrina, 2000).

Gapor et al. (2000) found 2128–13 505 mg/kg squalene in PFAD, more than 10x

the amount in CPO, and these sterols have since been successfully extracted as pure

crystals).

Red palm oil

Palm phytonutrients – carotenes, tocols, coenzyme Q and sterols, are largely preserved

in red palm oil, a premium oil. In normal refining of CPO, the carotenes and tocols are

largely removed/destroyed. A new refining process that retains the carotenes and tocols

in the end product (red palm oil/olein) has since been introduced. In commercial red palm

olein (CRPo), the average carotene content is ~665 ppm, tocols 717–863 ppm, sterols

325–365 ppm and coenzyme Q 18–25 ppm (Sundram et al., 1989). Commercial red palm

oil products, marketed under the trade name 'CAROTINO', are produced using PORIM/

MPOB technology (Ong and Goh, 2002).

Today, the products are sold in more than 15 countries, providing the much needed

nutrients to consumers. The nutritional information on red palm oil is shown in Table 12.

Red palm oil like standard palm oil is free from harmful trans-fatty acids. The carotenes,

tocols and coenzyme Q in red palm oil act as antioxidants scavenging oxygen free

radicals, and are hypothesized to play a protective role in cellular ageing, atherosclerosis

and cancer prevention. The natural carotenes in red palm oil provide provitamin A that is

readily converted to vitamin A in the body in accordance with its requirements. Synthetic

vitamin A can be toxic in excess.

In a storage stability study of CRPo over 12 months under the typical conditions in

Malaysia, the carotene level remained stable with only a minor drop in tocols at the end of

the period (Sundram et al., 1989; Tan, 1987).

Due to its nutritional benefits, red palm oil has wide applications in the food, healthcare

and skincare industries. The oil can be incorporated in biscuits, breads, cakes, noodles, Table 11 Concentrations of phytonutrients in CPO and PFO Phytonutrient CPO (ppm) PFO (ppm) Carotenes 500–700 4000–6000 Tocols (tocopherols and tocotrienols) 600–1000 2000–4000 Sterols 326–527 4000–6000 Squalene 200–500 500–1000 Phospholipids 5–130 37 000–40 000 Source: Choo et al. (1996).

margarine (as colourant), frying oil, mayonnaise, salad dressings, health foods and skincare

products (Benade, 2001). It not only provides natural ingredients, but also adds value to

the products by improving their health and nutritional attributes.

The bioavailability of beta-carotenes from red palm oil and synthetic beta-carotene

is similar (Van Het Hof, 1999). However, red palm oil is a better choice as it contains

a bouquet of carotenoids rather than just a single carotene. In a study, mothers and

children in Burkina Faso experienced a 40% fall in vitamin A deficiency after one year

of taking red palm oil (Zagre et al., 2002). The taste and appearance of red palm oil

prepared dishes are readily acceptable. Primary school children in South Africa who

consumed four CAROTINO red palm oil biscuits a day had significantly higher serum

retinol (Stuijvenberg et al., 2000). In studies, pregnant women supplemented with red

palm oil had significantly higher alpha- and beta-carotenes in their plasma and breast milk

(Canfield et al., 2001). A separate study by the National Institute of Nutrition in Hanoi, Vietnam, showed that CAROTINO red palm oil supplementation significantly improved serum retinal and Hb levels in rural children under five years of age. The haemoglobin level of the red palm oil supplemented group was as high as in those given vitamin A capsules (Nguyen et al., 2001). A vitamin A intervention programme was carried out in Gansu Province, China, where biscuits made from red palm oil were given to school children. Through this programme, the incidence of vitamin A deficiency was reduced from 21.6% to 6.1% (MPOB, unpublished data). Table 12 Nutritional contents per serving of 15 mL and 100 mL commercial red palm oil 15 mL 100 mL Energy 510 kJ 3400 kJ Protein 0 g 0 g Total fat 14 g 92 g • Monounsaturated 52.5 g • Polyunsaturated 25.3 g • Saturated 14.3 g Cholesterol, carbohydrate, dietary fibre Nil Sodium Carotenes • β-carotene (provitamin A) 0.80 mg • α-carotene (provitamin A) 0.61 mg 100% • Other carotenes 0.34 mg 40% Natural vitamin E 10 mg 100% (Tocopherols and tocotrienols) 0.50 mg Natural vitamin K 1 mg Coenzyme Q 10 * 1 kJ = 0.24 kcal. Source: http://www.carotino.com.

5.3 Other downstream products: palm oil methyl esters (palm biodiesel)

Palm oil methyl esters (palm biodiesel) are derived from esterification/transesterification of CPO with methanol (Choo et al., 1993; Ong et al., 1992). The mild conditions (temperature <70 ˚ C and under atmospheric pressure) of the reaction largely conserve the phytonutrients, which are retained in the palm biodiesel from where they can be recovered before it is burnt as fuel. The phytonutrients are recovered as a dense, thick semi-liquid termed as phytonutrient concentrate.

5.4 Oil palm leaf

The oil palm leaf is a rich source of polyphenols. Runnie et al. (2003) showed that

oil palm leaf extracts contain 8% higher polyphenol content on a dry weight basis

than green tea. Its main phenolics mirror several catechins contained in green tea,

namely catechin (0.30%), epigallocatechin gallate (0.28%), epigallocatechin (0.08%),

epicatechingallate (0.05%), epicatechin (0.01%) and their glycosides (Jaffri et al.,

2011a), and may thus be a potential inexpensive source of such catechins (Mohamed,

2014). Alcoholic extract of oil palm leaves was reported to contain 24.3 mg gallic

acid equivalent (GAE)/g dry weight of total phenolic content (Tan et al., 2011). The

antioxidant capacity of oil palm leaf extract was shown to be higher than those

of papaya shoot, green chilli and lemon grass in vitro (Abeywardena et al., 2002).

Jaffri et al. (2011b) demonstrated anti-hypertensive and cardioprotective effects of

oil palm leaf extract in NO-deficient rats. Abeywardena et al. (2002) reported that

polyphenol-enriched extract of oil palm (E. guineensis) fronds promotes vascular

relaxation via endothelium-dependent mechanisms and Tan et al. (2011) reported

that the leaf extract reduced hyperglycaemia and lipid oxidation in streptozotocin

induced diabetic rats. Palm leaf extract also inhibited Cu 2+ -mediated oxidation of low-density lipoprotein (Salleh et al., 2002). Supplementation of the oil palm leaf extract to healthy volunteers over a 2-month period resulted in significant cognitive enhancement based on computer-assisted cognitive tests that assessed spatial visualization ability and processing speed. Supplementation of the oil palm leaf extract conferred neuroprotection to NO-deficient rats via systemic and cellular modulations that eventually enhanced neuron survival (Mohamed et al., 2013).

6 Future trends

While the oil palm offers a whole array of promising bioactives with potential health benefits, mechanistic studies are required to establish their long-term benefits. As is the case for most plants, much of the scientific evidence on the beneficial effects of palm bioactives is drawn from in vitro or animal studies. While human intervention studies have been carried out on various aspects of palm carotenes, tocotrienols and OPP, more intervention studies are needed to confirm the whole spectrum of effects of the bioactives in vivo. Also, the doses applied in most animal experiments are high and translations of doses in humans are necessary. Efficacy and toxicity tests will also be intensified. Future research will also involve identification and improvement of the bioactive compounds individually and in combination. Allopathic medicine generally employs purified single compounds while alternative or traditional medicine uses multiple combinations of compounds working in synergy. There may be an increasing trend in this direction as society moves towards natural bioactives as these may have fewer side effects compared to single pure compounds. Advanced delivery systems are important for optimal efficiency of bioactives. Liposomes, hydrogels, virosomes, microspheres and miniature implants are examples of superior delivery systems that are increasingly being used and improved upon to deliver active molecules to target sites.

7 Conclusion

In view of the importance of palm oil phytonutrients, extensive research has been carried out to discover bioactives and authenticate their biological activities. Extracting palm phytonutrients from various products of oil palm, such as palm oil, PFO, PFAD and palm oil mill waste has been carried out with success. Today, palm phytonutrients are available for various applications, such as in the food and non-food industries, cosmetics, nutraceuticals and pharmaceuticals. Valorization of by-products of the oil palm industry to harness value-added bioactives decreases the environmental burden and fulfils the triangle of sustainability – economy, society and environment. The harnessing of valuable phenolic compounds from the waste stream of oil palm milling is one such example.

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8 Chapter 8 Palm oil and health

1 Introduction

Nutrition is a major factor in maintaining good health. A well-balanced diet is a key factor,

with the total fat intake and the distribution of fatty acids being particularly important.

Saturated and unsaturated fatty acids must be present in correct proportions. Palm oil

is rich in saturated fatty acids, accounting for half its total fatty acid content. Western

diets are high in saturated fatty acids (SFAs), which come mainly from animal sources

(dairy and meat). Saturated fatty acids can increase total and LDL cholesterol in the blood

stream (atherogenic lipoprotein fraction (Mensink et al., 2003). Unsaturated fatty acids,

particularly polyunsaturated fatty acids, may decrease both total and LDL cholesterol

(Mensink et al., 2003). It has been believed for half a century that saturated fatty acids are

responsible for atherosclerosis, because of their effect on blood cholesterol (Vartiainen

et al., 2010). However, during the last decade, this has been the subject of considerable

controversy (Astrup et al., 2011).

This chapter examines the composition of palm oil, its exact content of fatty acids and their

position on the glycerol molecule which may modify the biological effect. Several published

studies of clinical trials on the effect of palm oil on blood cholesterol and lipoprotein are

reviewed. The role of diet and palm oil on other biological markers of cardiovascular risk are discussed. This chapter will focus on the role of fatty acid intake (particularly of saturated fatty acids) on cardiovascular and coronary heart disease through the more recent epidemiological studies. Various epidemiological studies concerning the role of palm oil on coronary heart disease morbidity and mortality are explored. The role of palm oil in dietary fat intake will be presented. Finally, its place in a well-balanced diet is considered, as the physical properties of palm oil have enabled the limitation of processes such as partial hydrogenation and thus the reduction of trans-fatty acids in Western diets.

2 Palm oil composition and properties

2.1 Fatty acids (May & Nesaretnam, 2014)

Palm oil belongs to the family of solid fats, together with kernel oil, coprah oil, cocoa butter and karite oil. It is a vegetable oil obtained from the fruit of the palm tree (Elaeis guineensis), while kernel oil is extracted from the seed of the palm fruit.

Crude (red) palm oil is obtained from the mesocarp (outer pulp) before the refining process. It is produced in palm oil mills by pressure. Fractionation and refining of the crude palm oil then takes place to obtain palm olein and superolein, which are fractions less rich in palmitic acid, the main palm oil fatty acid.

Crude palm oil may be directly used for culinary purposes in the countries where it is produced (mainly Western Africa and Brazilian Nordeste), but its global use is based on

the fractionated and refined oils.

Palm oil is composed of saturated and unsaturated fatty acids in almost equal

proportions. The main fatty acid is palmitic acid (C16:0), which accounts for 44% of the

total fat content. Lauric acid (C12:0) and myristic acid (C14:0) are lacking. The second

main fatty acid is oleic acid (C18:1n-9), which accounts for 39% of the total fat content

and is a monounsaturated fatty acid. Polyunsaturated fatty acids account for 10% in

the form of linoleic acid (C18:2 n-6). The typical fatty acid composition of palm oil is

presented in Table 1.

The fatty acids are attached to a glycerol molecule and their distribution is specific to

palm oil. Sn-1 and Sn-3 are located on the extremities of the glycerol molecule and Sn-2

is on the middle of the glycerol molecule. In palm oil, more than 87% of the unsaturated Table 1 Fatty acid composition of palm oil g/100g • Saturated fatty acids 44–55 < 10:0 0 Lauric acid C12:0 0 Myristic acid C14:0 0.5–2 Palmitic acid C16:0 39.5–47.5 Stearic acid C18:0 3.5–40 • Monounsaturated fatty acids 38–45 Oleic acid 36–40 • Polyunsaturated fatty acids 9–12 Linoleic acid 9–12 Alpha linolenic acid < 0.5

fatty acids are located in the Sn-2 position while only 7-11% of the palmitic acid is located

in the Sn-2 position.

In the digestive process, pancreatic lipase and colipase hydrolyse the Sn-1 and Sn-3

fatty acids which become free, while the Sn-2 fatty acid will remain attached to the glycerol as a 2-monoacylglycerol (2-MAG). In the presence of calcium, a fraction of the free long-chain saturated fatty acid (palmitic acid) precipitates as calcium soaps, which are excreted and not absorbed. However, the 2-MAG, which is mainly unsaturated, is well absorbed for re-synthesis of a new triacylglycerol (triglycerides) and incorporation into chylomicrons.

2.2 Other components (Sundram et al., 2003)

The minor components of palm oil are divided into two groups. The first group comprises fatty acid derivatives such as partial glycerides which are saponifiable. These do not occur in significant amount in good-quality oils. The second group is found in the unsaponifiable fraction. These consist mainly of sterols (phytosterols), triterpene alcohols, tocopherols and tocotrienols, phospholipids, chlorophylls, carotenoids and volatile flavour components such as aldehydes and ketones.

The pigmentation of palm oil depends on its maturity. Two classes of natural pigments occurring in crude palm oil are carotenoids and chlorophylls. Crude palm oil is the richest natural source of carotenoids. The carotenoid content of crude palm oil, which is responsible for its red colour, ranges from 500 to 2000 mg/kg. However after refining and de-colouration, this content will be much lower (10 mg/kg).

As with all vegetable oils, palm oil contains tocopherols and tocotrienols, which are fat-soluble vitamin E isomers. Together with rice bran and corn oil, palm oil is rich in

tocotrienols. Crude palm oil contains 20–30% of tocopherols and 70–80% of tocotrienols,

up to 600–1000 mg/kg. Refining reduces the level to 350–630 mg/kg. Heating and

repeated deep frying can reduce 90% of the tocotrienols content.

2.3 Physical properties (Ong and Goh, 2002)

Due to its high level (50%) of saturated fatty acids (mainly palmitic acid), palm oil has

specific physical properties. As it is solid at room temperature (20˚C) it has increased

utility in the food-processing industry. Its solidity is mainly due to its high melting point

(36–38˚C). Palm stearin has a higher melting point (50–55˚C) while that of olein palm is

lower (19–21˚C). The uses for these different fractions may therefore differ.

Because of its low level of poly- and monounsaturated fatty acids, palm oil is stable and

is not easily oxidized. This stability is advantageous in cooking or frying.

There are three processes for improving the hardness and stability of vegetable oils:

i) dividing into a solid fraction (soft stearin or hard palm stearin) and a non-solid fraction

(olein) – this is a natural physical process; ii) interesterification, which is a process modifying

the distribution of fatty acids on the glycerol molecule (which has been the most widely

used for many years); and iii) hydrogenation – total hydrogenation adds hydrogen to all the double bonds of the unsaturated fatty acids, which then become totally saturated;

partial hydrogenation adds hydrogen to a part of the double bonds. However, this process

induces the generation of trans-fatty acids on the remaining double bounds. Unfortunately,

trans-fatty acids have adverse effects on lipoprotein metabolism and therefore lead to

cardiovascular risk (Mozaffarian and Clarke, 2009).

3 Effects of palm oil on cardiovascular risk markers

3.1 On fasting lipids and lipoproteins (Sundram, 1997; Lecerf, 2013; Fattore et al., 2014)

Because palm oil contains 50% saturated fatty acids (44% from palmitic acid), it has been

considered harmful for the metabolism of both lipids and lipoproteins. However, lauric and

myristic acids, which are the main cholesterol-raising fatty acids, are present only in trace

amounts in palm oil, while palmitic acid has a much weaker cholesterol-raising potential.

Moreover, in the three principal triglyceride species of palm oil, palmitic acid is located

at the alpha-position (Sn-1 and Sn-3) on the glycerol molecule. Palm oil also consists of

half unsaturated fatty acids (40% monounsaturated and 10% polyunsaturated fatty acids,

mainly oleic acid and linoleic acid, respectively). It is therefore necessary to conduct good

clinical randomized studies comparing palm oil, or its fractions, with other vegetable oils.

Several studies have been made to assess the effect of different oils on cholesterol and

lipoproteins (Bautista et al., 2001; Choudhury et al., 1995; Jensen et al., 1999; Müller et al., 1998; Ng et al., 1991; Pedersen et al., 2005; Sundram et al., 1992; Tholstrup et al., 2011; Vega-López et al., 2006; Wood et al., 1993; Zhang et al., 1997).

Total cholesterol is not a good marker of cardiovascular risk, except for severe dyslipidaemia. LDL cholesterol is clearly associated with atherosclerosis in epidemiological studies, and this has been confirmed through interventional studies with cholesterol lowering diet or drugs. The underlying mechanisms are now clearly known: when LDL lipoprotein goes through the endothelial, the unsaturated fatty acids of the esterified cholesterol may be oxidized. The oxidation of LDL depends also on the antioxidant content of LDL particles, the size of LDL (small dense LDL is more readily oxidized), and finally the level of HDL cholesterol. A low HDL concentration is associated with higher cardiovascular risk. One of the explanations is the anti-oxidative role of para-oxonase, an enzyme carried by HDL.

It has been established that saturated fatty acids increase LDL cholesterol blood concentration and also HDL cholesterol concentration. However, there is no evidence of the protective effect of high HDL cholesterol, or of the increase of low HDL cholesterol.

Finally, it is also important to consider the role of blood triglycerides concentration because each increase in triglycerides is inversely associated to lower HDL cholesterol and higher

small dense LDL.

Several studies have been performed over many years comparing oils and fats, both

hydrogenated and non-hydrogenated. The majority of these are well-conducted (double

blind, controlled-randomized) studies. However, there is a heterogeneity due to the level

of the total fat intake and/or to the dietary cholesterol intake and/or to the linoleic acid

intake. For this reason, these results were analysed, taking into account the percentage of

fat in the global diet (Lecerf, 2013). Of course, the observed effects will also depend on

the oils or fats compared.

In the case of a low or moderate fat diet (≤27–30%), as in Malaysia, palm oil or its

fraction induces a lower LDL cholesterol (or apolipoprotein B) than other solid oils or

saturated fatty acid rich fats. There are no differences in total, LDL and HDL cholesterol

concentrations between palm oil and olive oil. When compared to peanut oil, the LDL

cholesterol is lower and the HDL cholesterol is slightly higher. Some studies have been

conducted in order to compare partially hydrogenated oils (rich in trans-fatty acids) with

palm oil: it was found that palm oil induces a higher HDL cholesterol concentration and

lower LDL cholesterol concentration. An interesting study (French et al., 2002) has shown

that palmitic acid does not cause an increase in blood cholesterol when the linoleic acid intake is higher than 4,5% of total energy intake.

In the case of a normal fat intake (35–40%, which is the French recommendation), palm

oil has a similar or better effect on HDL cholesterol and a similar or less favourable effect

on LDL cholesterol than olive oil, and a more favourable effect than butter or partially

hydrogenated fat. In the case of a very high fat diet (>40%) palm oil causes a higher LDL

and total cholesterol concentration than sunflower oil.

Another review was published (Fattore et al., 2014) with a meta-analysis of dietary

intervention trials. Comparison of palm oil diets with diets rich in stearic acid (C18:0),

monounsaturated and polyunsaturated fatty acids showed significantly higher total

cholesterol, LDL cholesterol, apolipoprotein B, HDL cholesterol and apolipoprotein A-I.

However, the unfavourable effects of palm oil on total and LDL cholesterol compared

with monounsaturated and polyunsaturated fatty acids disappeared when young

people (≤30 years of age) were considered. Moreover, these effects were attenuated

in normocholesterolaemic subjects and were abolished in patients whose level of total

energy derived from dietary fat was lower. This is probably why the impact of palm oil may

differ between Asian and Western countries. Most of the lipid and lipoprotein markers

were significantly lower when compared with diets rich in myristic/lauric acid (butter for instance). Finally, the comparison of palm oil rich diets with diets rich in trans-fatty

acids showed significantly higher concentrations of HDL cholesterol and apolipoprotein

A-I and significantly lower concentrations of apolipoprotein B, triacylglycerols and total

cholesterol/HDL cholesterol.

3.2 On post-prandial plasma lipids and lipoproteins (Lecerf, 2013; Mukherjee and Mitra, 2009)

It has been established that the post-prandial hyperlipidaemia is more atherogenic than

the fasting state. But the body is more often in the post-prandial state (except during the

second part of the night). Lipid and lipoprotein post-prandial metabolism has been widely

studied. In some of these studies, the response was the same with palm oil, trans-fatty acid

fat or animal fat (lard), or with palm olein, olive oil or coconut oil. Another study showed a

lower response with lard than with palm or olive oil, and with palm oil than with olive oil.

It seems that long-chain saturated fatty acids are less quickly absorbed than long-chain

unsaturated fatty acids, mainly when these are located in the Sn-1 and Sn-3 position on

the glycerol molecule, but the global area under the curve of plasma triglycerides is the

same.

3.3 Effects on other cardiovascular risk markers (Sundram, 1997; Lecerf, 2013; Mukherjee and Mitra, 2009)

Cardiovascular diseases may not be reduced merely to the atherosclerosis process,

which partially, but not totally, implies cholesterol and lipoprotein metabolism. Severe

cardiovascular events may also be due to thrombosis, which occurs when there is platelet

aggregation as soon as the rupture of a vulnerable inflammatory atherosclerosis plaque

occurs. The post-prandial triglycerides-rich lipoproteins increase stimulates the factor

VII implied in the coagulation steps and in the thrombosis state. Probably because the

post-prandial lipid response between tested oils are similar, the thrombotic activity

of palm oil showed no difference when compared to other oils. A study showed a

more favourable effect of palm oil when compared to a trans-fat diet on fibrinolysis.

Other studies have shown that palm oil has a favourable or no effect on platelet

aggregation.

Some studies have been conducted on fasting or post-prandial inflammatory markers

such as C-reactive protein or cytokines, and these showed no difference between the

tested oils.

Although the beneficial role of carotenoids is well known, they are present only at a low

level in refined palm oils. Their benefits are more evident in crude red palm oil in which the

tocotrienols content remains high after refining, but decreases dramatically after intensive

heating or repeated frying. Tocotrienols have beneficial properties, partly due to having a

more powerful antioxidant effect than tocopherols, and must be considered in the overall assessment of a healthy diet.

4 The health impacts of saturated fatty acids

4.1 Saturated fatty acids and coronary heart disease

Since ecological studies were conducted in the 1960s by Ancel Keys (Keys et al., 1986),

it has been thought that saturated fatty acids were deleterious to health, leading to

cardiovascular risk and coronary heart disease morbidity. However, several misinterpretations

have been pointed out, particularly the fact that fatty acids are also a marker of dietary

patterns, but may not be implied in the pathogenesis of the disease (Astrup et al., 2011).

Highly saturated fatty acids have an effect, along with dietary cholesterol, although not

exclusively, on blood cholesterol, elevating LDL cholesterol and HDL cholesterol. They

differ from trans-fatty acids which increase both, and polyunsaturated fatty acids which

decrease LDL cholesterol. Moreover, not all saturated fatty acids have the same effect on

blood lipids. Stearic acid (C18:0) does not increase LDL cholesterol, while palmitic acid,

myristic acid and lauric acid do. The Nurses' Health Study (Hu et al., 1999) has specifically

addressed the relationship between dietary saturated fatty acids with differing carbon

chain lengths and ischaemic heart disease. The cohort showed a moderately increased

risk of ischaemic heart disease for all longer-chain saturated fatty acids (lauric acid through

stearic acid), whereas for short to medium-chain saturated fatty acids (butyric through

capric acid) no associations with ischaemic heart disease were observed. However, the

relationship between cholesterol and cardiovascular disease is complex and also depends

on overall diet and the lifestyle. In the 25-year follow-up from the Seven Countries Study

(Kromhout, 1999), the relationship between blood cholesterol and coronary heart disease

mortality was mainly observed in Western countries and not in Mediterranean societies.

However, dyslipidaemia, particularly familial dyslipidaemia, and metabolic syndrome must

be corrected by diet and drug therapy.

In 2010, a first meta-analysis of 16 prospective (not ecological) studies was published

(Siri-Tarino et al., 2010a), which did not show any association between saturated fatty acids

and ischaemic heart disease.

4.2 Prevention of cardiovascular disease and cerebro-vascular disease

An update of the meta-analysis, including four additional prospective cohort studies as

well as a meta-analysis of a selection of 12 cohort studies, did not observe any association

with a non-significant relative risk (de Souza et al., 2015). However, the negative role of

trans-fatty acids on cardiovascular mortality and type 2 diabetes was confirmed.

There is controversy about secondary prevention studies. Few of these are recent and

many show bias in their methodology. In most cases, the tested diets consisted of a decreased intake of saturated fatty acids and an increase of polyunsaturated fatty acids.

Some, such as the Oslo Diet Heart Study (Hjermann et al., 1981), showed a spectacular

reduction of the occurrence of new coronary events. However, a considerable number of

the subjects also stopped smoking; the mean level of blood cholesterol was initially very

high; and soy bean oil and fish, rich in omega-3 fatty acids, which are polyunsaturated-rich

foods, were added to the diets. Three other studies (Strandberg et al., 1991; Ramsden

et al., 2013; Ramsden et al., 2016) did not find evidence of any deleterious effect or

increase in cardiovascular mortality or morbidity long after the end of the studies. Although

post hoc analyses are interesting, they are mostly questionable: harmful effects occur

when there is too high an increase of omega-6 polyunsaturated fatty acid intake with very

high P/S levels (Polyunsaturated/Saturated). Where there is a reduction in saturated fatty

acids combined with a moderate increase of polyunsaturated fatty acids, including omega

3 and omega 6 unsaturated fatty acids, there is a beneficial effect in secondary prevention

(Ramsden et al., 2013).

4.3 The sources of saturated fatty acids

A new approach has recently been developed to aid in understanding the discrepancy

between dietary intakes and predicted impairment with regard to cardiovascular risk, and the non-deleterious effect of saturated fatty acids. The focus was on the food sources of saturated fatty acids: first in the MESA study (de Oliveira Otto et al., 2012) and then in a subgroup of EPIC study (Praagman et al., 2016). These studies have clearly shown that saturated fatty acids provided by meat products are associated with high cardiovascular risk, whereas saturated fatty acids provided by dairy products are associated with a reduction of this risk. This is probably due to other nutrients or components which are directly involved in a protective or harmful effect in these foods, through specific mechanisms. These include the atherogenic TMAO production from the metabolism of carnitine-containing meat by the microbiote and the beneficial effect of calcium, certain specific fatty acids (conjugated linoleic acid or rumenic acid for instance, or short chain fatty acids), probiotics or functional peptides in dairy products. Finally, it should be noted that fats are not consumed separately.

There is therefore some interaction between fat and carbohydrate intakes while protein intake is almost stable. When saturated fatty acids decrease, carbohydrates and/or sugar increase. But it has been well known for more than fifteen years that carbohydrates induce a higher blood concentration of triglycerides, a lesser HDL cholesterol concentration and mainly small dense LDL particles which are oxidized and atherogenic (Siri-Tarino et al., 2010b) (Siri-Tarino et al., 2015).

4.4 Epidemiological studies on palm oil and cardiovascular risk

Unfortunately there are very few available studies in this area and none are of adequate

quality.

The first is an ecological study (Zhang and Kesteloot, 2001) about mortality data in Hong

Kong and Singapore between 1963 and 65, compared with 1993–5, using Spain, Japan

and the United States as reference countries. Mortality and food consumption data were

obtained from the WHO and FAO respectively. The authors observed a higher increase

of ischaemic heart mortality in Singapore when compared to Hong Kong, and differences

in dietary habits, including a higher consumption of coconut and palm oil in Singapore.

However, no relationship can be drawn from ecological studies: the same mistake was

made during the 1960s with the Seven Countries Study. These are not individual data, and

significant differences exist between the lifestyles of the studied populations.

The second study was conducted by Campos and Baylin (Kabagambe et al., 2005). This

is a large population-based incident case-control study. The studied cases were survivors

of a first acute myocardial infarction (2111 subjects) and were matched to an equal

number of randomly selected population controls. In order to validate the dietary intake,

adipose tissue profiles of essential fatty acids were assessed. It was found that palm oil

users were more likely to have a myocardial infarction than users of soybean oil (OR 1,33)

or other cooking oils (OR = 1,23 non-significant), but these patients did not differ from

users of soybean oil with a high trans-fatty acid content (OR 1,14). Compared with palm

oil users, linoleic acid and alpha linolenic acid were higher among users of soybean oil.

Unfortunately, case-control studies have significant bias and cannot prove any relationship

between the diet observed and the disease due to a lack of chronology. However, it has

been established that in secondary prevention for coronary heart disease, higher alpha

linolenic and linoleic intakes are beneficial (Virtanen et al., 2014; Wu et al., 2014). There is

no information about the amount of oil consumed.

The third study (Chen et al., 2011) is also an ecological study which analysed the deaths,

stroke mortality and ischaemic heart mortality of adults aged 50 and older in 23 countries.

The increased rates of mortality between 1980 and 1997 were examined, as well as the

per capita consumption of palm oil and cigarettes, and the per capita Gross Domestic

Product. In developing countries, for every additional kilogram of palm oil consumed per

capita annually, the ischaemic heart mortality rates increased by 68 deaths per 100 000,

whereas stroke mortality rates increased by 19 deaths per 100 000, but this was non

significant. For historically high-income countries, changes in ischaemic heart disease and

stroke mortality were found to be smaller (17 and 5 respectively). Unfortunately, as with

the Zhang and Kesteloot study, no link between a single fact and health can be drawn,

although global lifestyle and dietary pattern changes cannot be ignored.

It is useful to remember that in countries such as Malaysia and Indonesia, where palm

oil is traditionally used for cooking, the coronary heart disease mortality rate is still low,

probably because the global diet is poor and the incidence of obesity is low. Given the

globalization of food habits and the rapid rate of urbanization in such countries, it is of

paramount importance that serious cohort studies on the health effect of the consumption

of palm oil as the almost unique source of vegetable fat are undertaken.

The fourth study (Basu et al., 2013) is a calculation of the potential effect of a palm oil

tax on hyperlipidaemia and cardiovascular disease mortality in India. A 20% excise tax

on palm oil purchases was studied over the period 2014–23 through a micro-simulation

model of mortality. The model was used to project future mortality due to myocardial

infarction and stroke as well as the potential effect of a tax on food insecurity accounting

for the effect of increased food prices. A 20% tax on palm oil purchases was expected to

avert approximately 363 000 deaths from myocardial infarction and stroke over the 2014–

23 period out of a total of 36.6 million expected deaths (a 1.3% reduction in cardiovascular deaths) if consumers did not substitute other oils to compensate for their reduced palm oil consumption. A total of 421 000 deaths were expected to be averted if there was a substitution with increased polyunsaturated fats. The calculation of the estimated relation between changes in the consumption of various oils and changes in total cholesterol was drawn from the Keys' formula (Keys et al., 1965). Although the relationship between LDL cholesterol (not total cholesterol) and cardiovascular disease is well established, the link between saturated fatty acids and cardiovascular risk and mortality is not. So this extrapolation cannot be considered as being valid.

5 Palm oil consumption

5.1 Estimating the consumption of palm oil

For many years there was no accurate data on palm oil dietary intakes, only indirect data about apparent consumption obtained through economic data (importation-exportation). However, it may be estimated at the level of 2.7 g/d/pers in France in 2009. Recently, the annual CCAF study conducted in France by CREDOC was made available (CREDOC, 2013). This is a dietary survey conducted on a sample of 2500 representative adults and 900 young adults and children (3–18 years) with a three-day dietary record. All information on food composition was accurately obtained from industry. The daily palm oil consumption was found to be 2.8 g/d/pers and is slightly higher in younger people (3.4 g/d/pers). For

the 90th percentile, the intake may reach more than 6.5 g/d/pers in adults and more than

7.5 g/d/pers in children and young adults. This represents an average of 1.4 g of saturated

fatty acids. It is useful to keep in mind that the total fat daily intake in France is 75 g/d and

that the French recommended dietary intakes for saturated fatty acids is 12% of the total

fat intake (ANSES, 2011), which represents 27 g of saturated fatty acids.

5.2 A place for palm oil in a balanced diet

The importance of a global well-balanced diet with healthy foods must be kept in mind.

In Western countries, palm oil fractions are included in processed foods such as biscuits,

snacks, confectionery, cakes, pastry, chips, fried foods, crackers, desserts and ice cream–

consumption of which should be limited. These foods are also often rich in sucrose, fats

and salt and poor in fibre. They replace healthier foods such as fruit, yogurt, legumes,

vegetables and whole grains in the diet. Palm oil is not a ‘bad’ oil as it contains half

saturated and half unsaturated fatty acids, but it is relatively poor in linoleic acid, and

does not provide alpha linolenic acid. Although it contains tocotrienols (refined oil no

longer contains carotenoids), its polyphenol content is much lower than that of olive

oil. It is therefore advisable to use a wide variety of oils for cooking, salad dressing or baking.

Since its introduction 20 years ago, particularly in Western countries such as France,

palm oil has made possible a dramatic reduction in the use of partially hydrogenated

vegetable oils in the agrofood industry (and thus the consumption of trans-fatty acids).

The subsidiarity principle should be applied to its use: if other solutions are possible, they

should be pursued; if not, palm oil may be used.

Finally, it remains important to limit those food products which contain fat, sugar and

salt in excess and to promote a varied diet.

6 Further trends in research

The negative role of saturated fatty acids is no longer recognized in all studies. This does not

mean, however, that their consumption can be increased without adverse effects, nor that

a good balance between fatty acids is unnecessary, but that a sufficient polyunsaturated

linoleic and alpha linolenic acids intake is important for cardiovascular health.

Furthermore, two strands of information are lacking. The first is the specific role

of saturated fatty acids according to their sources. We know that saturated fatty acids

from meat products and from dairy products have opposite effects, probably due to the

presence of protective components in dairy products and to negative components such

as carnitine in meat. So one explanation is that saturated fatty acids are not implied in cardiovascular risk although they increase LDL (and HDL) cholesterol and that they are only a marker. Another explanation is that the total profile of fatty acids originating from food products are different despite some similarities.

The second is the lack of available prospective cohort studies designed to measure the impact of palm oil consumption on cardiovascular risk which take into account the whole diet, risk factors and lifestyle patterns.

7 Conclusion

Palm oil is increasingly used throughout the world. It is a solid oil due to its high content of saturated fatty acids, mainly palmitic acid. Half its fatty acids are unsaturated. Saturated fatty acids are specifically located on Sn-1 and Sn-3 (on glycerol), which diminishes their intestinal absorption. Crude palm oil is also rich in carotenoids, and has a high tocotrienols content, but the refining processes greatly decreases the concentration of carotenoids, while heating and frying lowers the concentration of tocotrienols. Fractioning makes it possible to obtain more or less solid fractions dedicated to various industrial uses. This has enabled the removal of trans-fatty acids through the interruption of partial hydrogenation of vegetable oils. Due to its fatty acid composition, palm oil is not only a solid oil but also stable and heat resistant with low oxidization ability.

Palm oil may increase blood cholesterol concentration by increasing LDL cholesterol

and HDL cholesterol concentration. But these effects are modest and smaller than those

observed in vegetable oils rich in trans-fatty acid. They are also close to that observed in

olive oil. Because polyunsaturated fatty acids decrease LDL cholesterol, comparison with

oils such as soy, sunflower or corn oil is less favourable. Palm oil has no clearly deleterious

effect on other cardiovascular parameters involved in thrombosis or risk factors. Although

the oldest ecological studies, undertaken in the 1960s, suggested that saturated fatty

acids were responsible for coronary heart disease, the meta-analysis of prospective

studies does not confirm that view, and show no relationship between the two. However,

secondary prevention for ischaemic heart disease requires an increase in omega 3 and

omega 6 polyunsaturated fatty acids.

No consistent epidemiological study has been performed on the effect of palm oil

on cardiovascular risk. Poor methodology in the available studies makes it impossible

to confirm a deleterious effect, and further good epidemiological studies are necessary.

Finally, the consumption of palm oil remains very low in Western countries such as France

and represents a small part of fat and saturated fatty acid intakes. However most of the

foods containing palm oil are not particularly healthy and need caution in order to limit their consumption. Moreover the promotion of a diversity of oils for dressing and cooking

and the encouraging of a well-balanced diet are important. In the agrifood industry the

subsidiary principle must be applied.

8 Where to look for further information

need to conduct a good epidemiological study on the role of palm oil in health. Indeed,

there is a lack of data on the effect of palm oil consumption on cardiovascular disease in

both developing and developed countries. Any study must be prospective with a large

cohort of subjects, initially without cardiovascular disease, and with a follow-up of more

than 10 years. All confounding factors must be taken in account. Dietary intakes must be

determined at the beginning of the study and during the follow-up. It would therefore be

necessary to know the exact food consumption and to be able to distinguish exactly the

sources of fatty acids in the diet, and not only in the final composition. It will require some

effort to obtain that information.

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9 Chapter 9 The nutritional value of red palm oil

1 Introduction

Palm oil is now the most widely consumed vegetable oil worldwide (Mba et al., 2015).

For one, its cost is low compared to other oils. The main consumers of palm oil are China,

India, Indonesia and the European Union; their demand is entirely met by imports since

they do not produce palm oil. Additionally, the nearly solid state of palm oil at room

temperature makes it a good substitute for hydrogenated oils widely used until recently

in the food industry and which contain undesirable trans-fatty acids. The ban on trans

fat in several countries including Canada and the United States, because of adverse

cardiovascular effects similar to saturated fat, drives the rapid global shift in consumption

from soybean oil to palm oil (Global Industry Analysts, 2015).

There is a great deal of confusion regarding the nutritional value and health effects of

palm oil. The controversy and conflicting views still continue on whether or not palm oil is

atherogenic. Based on current evidence, it would appear that palm oil has both favourable

and unfavourable effects. The nutritional and health properties of palm oil depend not

only on the amounts consumed and the other components of the diet, but also on the

extent of processing and on the fractions considered. The crude (red) palm oil (RPO) is very distinct from the refined product and its high content of antioxidants including vitamin E

and provitamin A may be responsible for health benefits that are no longer present in the

refined oil as more than half its antioxidants have been destroyed. The health aspects

of palm oil were discussed in previous chapters. It is suspected that several publications

may have tended to be positively biased due to the fact that the palm oil industry has

been very active at sponsoring research, as reported in two large systematic reviews and

meta-analyses (Fattore et al., 2014; Sun et al., 2015). The primary focus of the present

chapter is on the nutritional value of crude RPO, primarily as a source of vitamin A.

2 Nutritional composition of palm oil

The nutritional composition of palm oil and its fractions is summarized in Table 1. First,

palm mesocarp oil has to be distinguished from palm kernel oil, the latter being much

more saturated than the former, 80% versus 40%–50%, respectively. We will only refer

to palm fruit oil in this chapter. Palm (fruit) oil consists of 94%–98% triglycerides. Myristic

acid (1%), stearic acid (4–5%) and palmitic acid (42–47%) make up the saturated fatty

acid component in addition to monounsaturated oleic acid (37–41%) and polyunsaturated

linoleic acid (9–11%). Although it is not as saturated as coconut oil, palm oil is still at the

top of the list when it comes to saturation.

Although palm oil and animal fat have similar saturated fat content, the positional

distribution of fatty acids in triglycerides is different: 70% of the palmitic acid in palm oil is

in the sn-1 and sn-3 positions, whereas the majority of palmitic acid in animal fat is in the

sn-2 position (Zhao et al., 2005). Fatty acids in the sn-2 position might have an enhanced

absorption (Hunter, 2001), and thus some researchers have suggested that the palmitic

acid in palm oil may be less hypercholesterolemic and atherogenic than that in animal

Table 1 Nutritional composition of crude and refined palm oil and its fractions (per 100 g) Palm kernel oil Crude (red) palm oil Refined palm oil Olein Stearin

Lauric acid (12:0) 47.8 0.0 0.2 0.2 –

Myristic acid (14:0) 16.3 1.2 1.0–1.5 1.0–1.5 1.0–2.0

Palmitic acid (16:0) 8.5 39.5 42.0–47.0 38–42 47–74

Stearic acid (18:0) 2.4 4.0–5.0 4.0–5.0 4.0–5.0 4.0–6.0

Oleic acid (18:1) 15.4 43.4 37.0–41.0 40.0–44.0 16.0–37.0

Linoleic acid (18:2) 2.4 12.2 9.0–11.0 10.0–13.0 3.0–10.0

Linolenic acid (18:3) – 0 0.4 0.4

Total saturated fatty acids 82.1 44.4 49.9 45.9

Total monounsaturated fatty

acids 15.4 55.6 39.2 54.1

Total polyunsaturated fatty

acids 2.4 10.5

Total carotenes (μg/g) – 500–700 (90% α- and β-carotene) *
12

Tocopherols and tocotrienols

(vitamin E) (µg/g) - 600–1000 (73% tocotrienols, 27% tocopherols) ~50% loss 643

Sources: Sambanthamurthi et al., 2000; Edem, 2002; O'Brien, 2004; Boon et al., 2013.

*Physical or chemical refining entails a nearly total loss of carotenoids, but a technology exists to produce a refined

RPO retaining 80% of carotenoids and 85% of tocols (Mayamol et al 2007).

fat (Ebong et al., 1999). A more recent study found that palmitic acid in the sn-2 position

could decrease postprandial lipaemia in humans (Sanders et al., 2011).

The resulting two components of the palm oil fractionation is palm olein (liquid) and palm

stearin (solid). The fatty acid composition of palm olein is approximately 45% saturated

fat and 54% unsaturated fat. The main saturated fatty acids are 40–44% palmitic acid and

4–5% stearic acid. The unsaturated fatty acids are 43% oleic acid and 12% linoleic acid.

Technological advances in palm oil fractionation have allowed to further separate olein

fractions (Boon et al., 2013).

Palm oil tends to be perceived negatively because it is highly saturated (and because of

the environmental impact of the large plantations). However, this is somewhat balanced

by its high content of provitamin A carotenoids, vitamin E and other antioxidants as well

as phytosterols, at least in the crude RPO. The antioxidants contribute to the oil stability,

as well as to its nutritional and health benefits, alleged or real (Oyewole and Amosu, 2010).

One characteristic of crude palm oil is its high content in vitamin E (tocopherols and

tocotrienols), with a total content ranging from 600 to 1000 ppm. It is actually the highest

food source of tocotrienols. The tocopherol/tocotrienol ratio is usually around 20%, whereas

it is roughly reversed in palm oil. Compared to other oils, palm oil also has a high proportion

of tocopherols and tocotrienols in relation to its unsaturation. The ratio of total vitamin E

(tocopherols and tocotrienols in ppm) to polyunsaturated fatty acids (PUFA expressed in %)

is about 50, while it is only 19 for soybean and 12 for sunflower oils. The combined effects

of high tocopherols and tocotrienols, and low PUFA, could explain why palm oil would

present a greater oxidative stability, for instance, in frying (Gibon et al., 2007).

Crude RPO also represents the highest natural source of carotenoids (500–2000 ppm).

β-carotene predominates and represents with α-carotene about 90% of the total carotenoids.

Additionally, these provitamin A carotenoids of RPO are highly bioavailable because of the

absence of a vegetable matrix and the presence of fat (Cottrell, 1991). In terms of vitamin A

activity (expressed in retinol activity equivalents [RAE]), RPO provides 15 800 µg and carrots

1000 µg per 100 g (Scrimshaw, 2000). Unfortunately most of the carotenoids in palm oil

are destroyed during the refining process, giving rise to colourless products (Gibon et al.,

2007). Crude oils are refined to remove all impurities and undesirable odour, flavour and

colour, but at the same time the process destroys more than half its natural antioxidants.

One of the modified refining processes developed by the Palm Oil Research Institute of

Malaysia procures a refined RPO (Carotino®) with a light pink colour but which has retained

80% of the carotenoids, 85% of the tocols and 65% of the phytosterols (Mayamol et al.,

2007). It is unfortunate that this technology is not more widely applied, particularly in areas

where vitamin A deficiency is a problem while palm oil is produced, notably in West Africa

and in India. The cost of the technology is possibly among main deterrents.

Elaeis guineensis is the principal variety of oil palm. It is originally from tropical Africa

and it is the most widely cultivated, not only in Africa but also in Asia and Indonesia.

E. oleifera is native of South America. Hybrids could have increased oil unsaturation,

carotene, tocopherol and sterol content (O'Brien, 2004), but they are little produced.

3 RPO as a source of provitamin A carotenoids

Vitamin A deficiency is still widespread in several African and Asian regions, where it is

responsible for excess morbidity and mortality particularly among young children, even in

the absence of the ocular manifestations of the deficiency. Preformed vitamin A or retinol

can be obtained from animal products (such as liver, eggs, dairy products) or as provitamin

A carotenoids in some plant products, including orange flesh fruits and vegetables. RPO

is the highest plant source of provitamin A carotenoids, and, as mentioned previously, its

vitamin A bioactivity is very high. The provitamins are absorbed and partly converted into

retinol. Various combinations of fortification, supplementation and dietary diversification

strategies are used to control vitamin A deficiency, but periodic supplementation with high

dose vitamin A capsules is still a major component of child survival strategies in African

and Asia countries where the deficiency is widespread. Promoting the production and

consumption of RPO where feasible and preventing its overheating appear as a logical,

although neglected strategy to prevent vitamin A deficiency. In sub-Saharan Africa, where

oil palms originated, RPO is traditionally consumed in some but not all areas, while vitamin

A malnutrition persists.

Table 2 lists the safe level of vitamin A intake in various age-sex groups, expressed in

RAE, the corresponding β-carotene needed, and, in the last column, the amount of RPO

required to meet the recommended daily intake. It is seen that, roughly equating 1 g RPO

with 1 ml, from two to four teaspoons of RPO would meet the daily recommended intake

of vitamin A. Even consuming small amounts of RPO can therefore go a long way towards

meeting daily requirements for vitamin A.

Table 2 The amount of RPO needed to meet the FAO/WHO recommended intakes of vitamin A

Subpopulation	Recommended safe intake (RAE, µg) 1	β-carotene (µg) 2	RPO (g) 3
Children			
0–6 months	375	4500	9.0
7–12	400	4800	9.6
1–3 years	400	4800	9.6
4–6	450	5400	10.8
7–9	500	6000	12.0
Adolescents			
10–18 years	600	7200	14.5
Adult women			
19–65 years	500	6000	12.0
65+	600	7200	16.4
Pregnant women	800	9600	19.2
Lactating women	850	10200	20.4
Adult men			
19–65 years	600	7200	14.5
65+	600	7200	14.5

1 Source: FAO/WHO.

2 Based on a conversion factor of 12 µg β-carotene for 1 µg of RAE.

3 Average value of 500 µg of β-carotene for 1 g of RPO.

Several trials and quite a few programmes showed vitamin A efficacy and effectiveness

of RPO in children and in women. In a systematic review (Rice and Burns, 2010), ten key

intervention trials of RPO used as daily supplement, in-home fortificant or in fortified food programmes were analysed. These trials were conducted in Indonesia, Honduras, Papua New Guinea, Tanzania, India, South Africa and Burkina Faso. Except for the studies in Papua New Guinea, Tanzania and Burkina Faso, the RPO was from Malaysia or Indonesia, the largest producers of palm oil in the world. All these studies reported positive effects, whether on serum or on milk retinol levels. In an Indian village, for example, 8 g of RPO daily for 15 days proved as effective as a single high-dosage retinol supplement on vitamin A status of schoolchildren (Mahapatra and Manorama, 1997). In South African poor schoolchildren aged 5–11 years, RPO- and β-carotene-fortified biscuits resulted in similar serum retinol increases (Van Stuijvenberg et al., 2001). The RPO-fortified biscuit is now commercialized and available on the South African market. In Tanzania (Lietz et al., 2001) and in Honduras (Canfield et al., 2001), RPO supplementation trials during pregnancy and lactation showed beneficial effects on vitamin A status of mothers and infants. In the Honduras study, RPO was found to be as effective as β-carotene supplements in this regard. The RPO studies that we conducted in Burkina Faso over a 10-year period are detailed below as case study.

There are at least two published reports of successful RPO fortification of staples. In a district of Tanzania, RPO was incorporated in cassava flour on a pilot basis in villages

representing three agro-ecological zones with high rates of vitamin A deficiency (Mosha

et al., 1999). Out of five villages, two served as controls. At the end of the 20-month

programme, most mothers had reportedly adopted the innovation and were preparing

the mix at home. The prevalence of low plasma retinol decreased from 53% to 8.5% in

pilot village children, while remaining above 50% in the control villages. Plasma retinol of

pregnant and lactating women increased by 12.6% in the pilot villages and only by 3.5%

in the control villages. However, in the absence of meta-analysis of the data for all these

studies, the average resulting effect on serum (or milk) retinol cannot be ascertained.

Other applications of RPO that were not assessed for their impact on vitamin A status

are mentioned in the review by Rice and Burns (2010), including its use as ingredient in

lipid-based ready-to-use therapeutic food (RUTF) and as fortificant in commercial baked

foods, as well as in condiments or salad dressings. It was also tested when added to

other cooking oils, for instance, in Brazil. In India, a blend of oil including 6–12% RPO was

found to be palatable, with no objectionable taste or smell of the food, although the oil

was coloured in red (Rao, 2000). In Burkina Faso, we also tested blends of RPO with local

vegetable fats as described below. More recent advances have been the development of high-carotene varieties of maize, sweet potatoes and cassava, as well as the genetically modified ‘golden rice’.

It is now common practice to fortify refined palm oil (or other vegetable oils) with retinyl palmitate as a source of preformed vitamin A to compensate for the loss of provitamin A carotenes during processing. Such fortification programmes are considered highly cost effective and they have been used successfully in various parts of the world with sugar, monosodium glutamate or wheat flour as vector foods. The feasibility of using as natural fortificant β-carotene from RPO as alternative strategy to address vitamin A deficiency was reviewed (Souganidis et al., 2013). While β-carotene may be as effective as retinyl palmitate to improve vitamin A status, the challenges of fortification with RPO-derived β-carotene include its unfavourable colour, taste and odour, as well as the lower stability to high temperatures of β-carotene compared to retinyl palmitate. Additionally, the RPO fortification cost would be roughly 40 times higher than that of retinyl palmitate (Souganidis et al., 2013). It is also reminded here that RPO is not only a high source of vitamin A (and fat), but also of several other healthful antioxidants including non-vitamin A carotenoids (lutein and lycopene) and vitamin E (tocopherols and tocotrienols), which are lost during refining. The health effects of these antioxidants were discussed in previous chapters.

4 Case study: RPO in Burkina Faso

This case study describes the rationale, the objectives and the activities of the three distinct phases of the RPO project. The results, lessons learned and challenges are then discussed.

4.1 Project background and history

The role of RPO for reducing vitamin A deficiency in Africa was considered underexploited (Solomons, 1998), and the possible nutritional and economic benefits for Sahelian countries were, and continue to be, little recognized. The idea for our project stemmed from the observation that refined palm oil could be found even in remote locations of the Sahel. Burkina Faso is probably the only country where the feasibility and impact of introducing RPO on a commercial basis in non-consuming population groups could be tested, because some RPO is produced in the western part of the country, although in still limited quantities. Besides, preliminary market studies had shown that the production of RPO could be considerably increased in Burkina Faso and that it could indeed generate profit.

The studies that our team conducted with institutional partners in Burkina Faso between 1998 and 2008 were intended to demonstrate the feasibility and nutritional impact of stimulating the production and consumption of RPO. Increasing RPO production, distribution and consumption indeed bears potential as part of overall strategies to increase vitamin A intake, in Burkina Faso and in surrounding Sahelian areas as well. The

RPO project in Burkina Faso was developed on a small scale, although the initial intent

was to scale it up if the initial phases proved successful. It is unique in that a new demand

for RPO was created by social marketing and was used as driver for local production. It

involved the development of oil palm orchards by women, and improved oil extraction

methods and the expansion of local markets to generate nutritional, women's income

and even environmental benefits as palm trees are known to consolidate the land of river

banks. RPO was posited as a food 'fortificant' for the nutritional benefit of mothers and

children primarily, as RPO is costly in the Sahel and as it is highly concentrated in vitamin

A. Several papers on this project were published (Delisle et al., 2001, 2003, 2004; Zagré

et al., 2002, 2003, 2004; Zeba et al., 2006).

The three phases of the project are described below, before commenting on the results

and perspectives.

4.1.1 Phase I: 1999–2002

The purpose was to demonstrate that it was feasible to introduce locally produced RPO on

a commercial basis, and that it was effective in improving the vitamin A status of women and

young children. The Burkina Faso Association of Home Economists (ABESF) was the main

field partner and the research was conducted in collaboration with the French Institute for

Research and Development (IRD). Field promotional activities were conducted by home

economists after appropriate training in social marketing, in a pilot zone (north-central part

of the country) where RPO is not part of food habits. RPO was purchased by the project

from women in south-western Burkina Faso, and other women were retailing it in the

intervention sites. Promotional activities included using the media, plays and testimonies

at village level, demonstrations and tasting of RPO-fortified dishes, and contests among

villages. RPO promotion was also coupled with vitamin A capsule distribution during

National Immunization and Micronutrient Days in order to bring the population to make

the connection between food (and not only capsules) and the prevention of vitamin A

deficiency. The impact was assessed in a random sample of 210 mother-child pairs whose

vitamin A status was assessed based on serum retinol levels before the beginning of the

project and two years later.

4.1.2 Phase II: 2002–2004

The second phase of the RPO project pursued the same initial goal, that is, to improve

vitamin A status of vulnerable groups via the purchase and consumption of RPO produced

right in Burkina Faso, but it was carried out on a larger scale and involved a wider range of

partners. Additionally, more emphasis was given to strengthening the RPO production and commercial distribution system. The intervention zone was extended to five provinces,

whereas Phase I took place in only one province. A school component was introduced,

and school meals were fortified two to three times a week with 15 ml of RPO per child

in a total of 41 schools in three provinces. In one province, RPO-fortified snacks were

first offered in schools before school canteens were operational. The formulations were

developed by ABESF and were very well appreciated. In all cases, teachers, parents and

communities were closely involved, and training for appropriate handling of RPO was

provided to cooks and to school managers.

In one of the provinces participating in the RPO fortification of school lunch, a randomized

controlled trial was carried out, with eight primary schools randomly assigned to RPO,

eight to supplementation with vitamin A capsules and eight served as controls. Serum

retinol was measured before the intervention in October and in the same children exactly

12 months later (to avoid a seasonality effect). The vitamin A capsule group received a

200 000 IU capsule before the school break, in July of the same school year. Serum retinol

was again measured when school resumed in October.

During Phase II, RPO production groups benefited from training, in Bénin and in Burkina

Faso, in order to improve the extraction techniques, to learn simple management tools and to contribute to setting up the RPO commercial distribution system through direct connections with wholesale outlets established in the main city of the five provinces.

Women's groups extracting the oil went from four at the beginning of Phase II to eight by the end with an average of 25 women per group. The groups formed a union of RPO producers around the pioneer group in the main producing village. A local organization involved in supporting rural enterprises funded the purchase of oil extraction equipment and the construction of a shed for RPO storage; it also provided support on technical and managerial matters.

4.1.3 Phase III: 2006–2008

This phase was limited to the RPO production zone of south-western Burkina Faso owing to limited funding. The activities were carried out in close collaboration with Oxfam-Québec, the NGO in charge of the intervention proper for this phase of the project. The objectives were to improve vitamin A status of mothers and children by promoting the consumption of RPO and to further strengthen the RPO production and marketing efforts as a means of procuring additional income for women (Oxfam-Québec, 2008).

The research activities conducted by our university team were: (1) to assess vitamin A status and RPO consumption and production among women of reproductive age in the RPO-producing area of Burkina Faso; (2) to assess the quality of RPO samples from Burkina

Faso and samples coming from neighbouring countries as available in Burkina Faso; and

(3) to test the technical feasibility and consumer acceptance of blends of RPO with either

peanut oil or shea butter at various concentrations. The underlying hypotheses were that

women's vitamin A status would be better in the RPO production area than in non-producing

areas, that the RPO produced in Burkina Faso with project support would be of high quality,

and that mixtures of RPO with other traditional fats would be well accepted by women

and their family. The research components included baseline data on RPO consumption

and vitamin A status of women as well as on the quality of the RPO from local production.

A total of 150 mothers randomly selected in 15 villages of the RPO-producing areas were

interviewed twice over a ten-month period. Their vitamin A status based on serum retinol

was assessed in the first survey round. An additional ten women from the main production

village were interviewed to better assess their experience with RPO production.

4.1.4 Phase IV: 2008–2011

This phase was planned to consolidate the previous achievements, to increase RPO

production and consumption and to undertake a comprehensive evaluation of the

health, income and environmental effects of the RPO project. This was to be a critical

phase to ensure the sustainability and scaling-up of the production and consumption of

RPO beyond the production zone to contribute to vitamin A status improvement and to

women's income. The project was to be scaled up further to set the stage for a national

RPO programme as part of the vitamin A strategy. The health, agriculture and social

sectors of the government of Burkina Faso were all mobilized and gave their support to

the approach. The expected duration of Phase III was three years. However, in spite of

the positive results of the previous phases and after several proposals to various potential

funding agencies, the funding was not secured. RPO apparently continues to be produced

locally and palm orchards are growing but no evidence of the beneficial effects and costs

could be generated and our dream of positing RPO as a major component of the vitamin

A strategies in the whole region of sub-Saharan Africa had to be dropped.

Before discussing the effects of the RPO project, we summarize the main outputs below: • A total population of 1.3 million was reached through community activities, the school component, R&D activities and media-based promotion of RPO in five provinces of Burkina Faso; • The more intensive community-based RPO strategy in one province reached 26 villages, for an estimated direct target of 20 000 women and under-five children; RPO retailing committees were trained (150 persons); • 6400 pupils aged 6–10 years in 41 schools of three provinces, the teachers and the parents were reached by the school component involving RPO-fortified meals and community mobilization. Some 76 school canteen cooks and at least 76 teachers were trained in adequate handling, storage and portioning of RPO in schools; • The number of RPO production women's groups went from 4 to 8 (~25 women per group), and the production was around 4200 liters for 2003 and 2004; 330 women producing or selling RPO received training and were given an opportunity to generate some additional income.

Information on the number of palm tree planted and on their oil yield once they began to be productive is unfortunately not available.

4.2 Effects on vitamin A status of women and children under five

We could demonstrate the feasibility and effectiveness of increasing production and

consumption of local RPO. In the north-east pilot area where RPO was not previously

available or consumed, nearly half the women purchased and consumed RPO after two

years of social marketing of the product. This was based on a random sample of 210

mother-child pairs who were surveyed at the beginning of the project and then 24 months

later. Highly significant improvements of the vitamin A status of women and children were

observed: the prevalence of low serum retinol (<0.7 µmol/L), while remaining high, went

from 85% to 67% in children, and from 62% to 28% in mothers. The prevalence of low

serum retinol remained high particularly among children in spite of the fact that they had

received a vitamin A capsule six months before the beginning of the RPO project. This

shows the importance of mixed strategies for the control of the deficiency which can

include supplementation, food-based approaches and public health measures to reduce

infection. The reduction of the prevalence of vitamin A deficiency was more marked among

women, which strongly suggests that other factors of the deficiency are at work in children,

particularly recurrent infections. It was noted that in mothers as well as in children, the

most deficient were also the ones whose vitamin A status improved the most, which tends

to confirm that provitamin A carotenoids are better utilized in deficient subjects.

Among schoolchildren included in the controlled trial, the prevalence of low serum

retinol was significantly reduced with both the RPO and the vitamin A capsule, as shown

in Fig. 1. Although the baseline prevalence of vitamin A deficiency was much lower in

the control schools, which was unexpected, mean serum retinol varied little in the control

group, whereas it increased sharply in the RPO and the vitamin A capsule groups. This trial

in schools confirmed that vitamin A deficiency was also widespread at school age and that

Figure 1 Serum retinol changes in primary schoolchildren exposed to HPR or high-dose vitamin A

supplements compared with control subjects.

an average of 51 RPO-fortified meals over a school year was as effective as one vitamin A

capsule to improve vitamin A status, besides RPO being well liked by children. Through

RPO fortification of school meals two to three times/week, it can be assumed that 34% of

the pupils were protected from vitamin A deficiency, based on the observed reduction of

low serum retinol from 47% before the school intervention to 13% one year later.

RPO was also successfully integrated into a local infant cereal mix and in nutrition

rehabilitation centres, although this was only done on a pilot basis and there was no

assessment of impact.

At the beginning of Phase III of the project in the RPO production zones, it was found

that the vitamin A status of RPO-producing women was significantly better, with only

5.9% showing low serum retinol (<0.7 µmol/L), compared with 20.8% in non-producing

women (and 62% initially among women of the pilot intervention area of Phase I of the

project). Although there was a tendency for RPO-producing women to report better socio

economic conditions, RPO production was the only significant variable in the logistic

regression of vitamin A status. The odds ratio for low serum retinol was 0.28 (CI 0.09–0.79)

in RPO-producing women compared to non-producers. Mean intakes of total vitamin A

as well as preformed retinol were significantly higher among RPO-producing than non

producing women, which suggested that not only RPO but also other sources of vitamin A

were consumed in higher amounts among the former compared with the latter.

4.3 Quality of the RPO

Throughout the project, producing high-quality RPO and using labour-saving equipment

were sought. During Phase II, RPO samples from Burkina Faso (n = 4, including two

from RPO project) and nine imported samples from Togo, Côte d'Ivoire and Ghana were

analysed for chemical properties, microbiological quality and content of provitamin A.

An expert tasting panel assessed the organoleptic quality of seven samples (four from Burkina and one randomly selected sample per import country). All 13 samples were again analysed 8 months later, and 5 were again tested 12 months after the initial analyses.

The results varied widely, whether in terms of chemical, microbiological or nutritional quality. There was no relationship between organoleptic quality rating by the taste panel and the other aspects of quality of the RPO samples, not even their acidity. All except one imported sample were adequate from a bacteriological standpoint, and the bacterial counts went down with time, likely owing to increasing acidity. The initial provitamin A carotenoid results confirmed that in spite of the high variance, RPO is a concentrated provitamin A source, providing more than 100 µg RAE per gram.

4.4 RPO as a food fortificant

Other approaches for promoting RPO consumption were tested and found very successful during Phase II. In a nutrition rehabilitation centre (CREN) close to the capital city of Ouagadougou, introducing RPO in the rehabilitation meals encouraged the mothers to purchase some RPO to continue using it at home (Delisle, unpublished results). RPO was also tested as a fortificant for Misola®, a locally prepared complementary food (weaning mix), with the local unit of fabrication in one province. It proved technically feasible to add 4-5% RPO without changing the process except for a slight reduction in groundnut

content, and the mothers and children liked it very much. RPO fortification of Misola on a

broader scale could therefore have been considered if the RPO project had been sustained.

Blends of RPO with either groundnut oil or shea butter were tested among women

because mixing RPO with other local fats and oils may encourage its consumption without

changing cooking practices. The response was positive for both mixes. The taste of RPO

was found more acceptable when mixed with either fat and there was no technical problem

with mixing RPO with these other fats and oils. The tests were first conducted in the RPO

pilot project area and, for that reason, we suspected that exposure to the RPO project

may have introduced some bias. The study was therefore repeated in a non-RPO area with

50 women (in charge of kitchen) randomly selected in the five neighbourhoods of a town

located 20 km away from the capital city of Ouagadougou. Following the initial interview

of all women on their perceptions and use of fats and oils in general and RPO in particular,

12 women were retained for two focus groups, one on RPO mixed with peanut oil and

the other one on RPO mixed with shea butter. In each case, two different concentrations

of RPO were presented for evaluation and tasting. The women were then given samples

of the two mixtures (prepared with them) at the preferred

RPO concentration for trial with their family. A final individual interview of these women was conducted 15 days later in their home. The results showed that the mixtures were feasible and acceptable in terms of colour, texture, taste and culinary use. Only one woman (out of 12) reported a negative response. The mixtures with a lower RPO concentration (10%) were preferred. The mixture of RPO with peanut oil was better rated than that with shea butter, and was considered preferable to using RPO alone in various preparations. The women appeared ready to prepare the mix again and they would even be willing to pay ~10% more for the mix already prepared. Blending RPO with peanut oil therefore appeared as an interesting strategy to promote RPO consumption.

4.5 Effects on women’s income and empowerment

During Phase III, there was particular emphasis on capacity building of women as producers and consumers. RPO production increased, and women extracting the oil formed a producers’ group (500 women in five subgroups); they had planted dwarf palm trees and were even given literacy and business training. Women producers were trained in palm orchard and RPO management as well as advocacy, along with literacy training. Several community workers were trained to carry social marketing campaigns for the promotion of RPO consumption.

According to the survey (Bougma, 2008), RPO-producing women perceived several advantages to the activity: RPO availability for consumption (88%), potential source of income (54%), and savings to attend to other needs (18%). The negative aspects were that it is physically demanding (49%) and time consuming (20%). In Tin, the village where the extraction unit is located, the 11 respondents (out of 20 in the unit) producing RPO were highly satisfied with the extraction material making the process easier; they wanted to remain members of the production group, and they reported that RPO production was a source of income, whether used for investment by the group or shared among members. Unfortunately, our plan to thoroughly assess the health and income effects of RPO production and distribution could not materialize since Phase IV was not funded.

4.6 Perspectives

The ‘scaling-down’ of the project rather than its scaling-up prevented an adequate assessment of the approach. It may even have had a negative effect in communities previously exposed to the pilot project. It would have been critical to thoroughly evaluate the process, outcomes and impact of the approach, as there are few projects based on local agriculture, focusing on women, and potentially benefiting micronutrient health and women’s income. It is unfortunate and indeed difficult to understand that this natural oil, which is now even promoted as ‘natural’ or ‘health food’ in the West, has raised until now

so little enthusiasm among international decision-makers and donors.

As underlined by Rice et al. (2010), there are several barriers to expanding and scaling

of RPO and policies, and programmes and resources to fund such vitamin A initiatives.

Consumer acceptance may be an issue where populations are unfamiliar with RPO, but

not in Africa. Even if RPO is not produced locally, most African populations know RPO

and it is a prestige food in some cultures. The quality, shelf life and cost of RPO remain

challenges, however, in non-producing areas. Sustained investments in local palm oil

production in Africa have been advocated (Skurtis et al., 2010), and it should have been

possible to encourage the use of the improved RPO-extracting technology in order for

the oil to retain its vitamin A activity and other oxidants, thereby contributing to improved

nutritional health and even contribution to income in Burkina Faso and neighbouring

Sahelian countries. As aptly stated by an eminent nutritionist (Solomons, 1998), RPO

should have become the logical substitute for vitamin A capsules in Africa.

5 Conclusion

Crude RPO is the highest and most bioavailable plant source of vitamin A in the form

of carotenoids, primarily α- and β-carotenes. Palm oil is nearly 100% fat and it is 50%

saturated, whether crude or refined; it may therefore contribute to overweight as well as nutrition-related chronic diseases such as cardiovascular disease or diabetes (Mensik, 2016). However, RPO may have important health benefits because of its high provitamin A, vitamin E and other antioxidant content. Furthermore, unlike Malaysian plantations, palm trees growing in the wild and small plantations in Africa are not detrimental to the environment. The project in Burkina Faso showed that RPO was effective in improving the vitamin A status of women, under-five children and school-age children, that it is well accepted by the population which is also willing to purchase the product, and that there is income generation for women producing RPO. The project also confirmed the high vitamin A content of RPO, its safety, the motivation of women to engage in RPO extraction as source of food and income and the prospective value of blending RPO with peanut oil as a means of increasing the use of RPO (and the intake of vitamin A). The project was deemed successful and the results impressive in spite of its small scale, but it proved impossible to get further funding to scale up the initiative and mount the distribution system.

6 Future trends

Implementation research would now be needed during a 'revitalization' phase of the RPO project in Burkina Faso. Additionally, various RPO commercial distribution strategies

should be tested for their economic sustainability. Another area for promising research is

on the adoption of the improved technology for processing palm oil without destroying its

antioxidants – enabling factors and barriers.

Research on potential cost-effectiveness of RPO-based interventions has been

advocated because such data are missing (Rice et al., 2010). However, cost-effectiveness

comparisons between RPO (and other food diversification) interventions, vitamin A

capsule supplementation and food fortification may not be appropriate and indeed

work against RPO (and other food diversification schemes) as these are more expensive

for less spectacular results on vitamin A status. RPO-based projects have benefits other

than vitamin A status, and these benefits are not taken into account in cost-effectiveness

studies, for instance, the income effects and the effects on local agriculture and the anti

erosion effects. For this reason, cost-utility evaluation or, even better, separated costs

and consequences are to be preferred in order to also take into account the benefits

other than nutritional. RPO production and distribution should be researched in inclusive

evaluation schemes.

7 Where to look for further information

The Micronutrient Forum: www.micronutrientforum.org

Roundtable on Sustainable Palm Oil: http://www.rspo.org

Carotino ® website:

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10 Chapter 10 Life cycle assessments of oil palm products

1 Introduction

Quantifying environmental impact is becoming a requirement for agricultural commodity

chains. Given the various pollution risks (e.g. eutrophication, global warming, ecotoxicity),

and the opportunities to mitigate those risks (e.g. increasing nitrogen utilisation efficiency,

nutrient recycling, carbon sequestration to reduce global warming), it is crucial to apply

models and tools that allow for the identification of best practices in order to reduce

the environmental impact of agriculture. It is particularly crucial for increasingly important

crops such as oil palm that may impact the environment both during cultivation and due

to land use change (LUC) for new plantations.

Over the last 20 years, the area of oil palm plantations has increased drastically. The total

productive area reached 18.7 Mha in 2014 compared with 7.5 Mha in 1994, according to

FAO 1 . This expansion was particularly remarkable in Indonesia and Malaysia, where the

productive areas increased by a factor of two and seven, respectively, over the same time

period 1 . Oil palms have the highest oil yield per hectare and palm oil can be used for

various purposes. Given the growth of the world's population and the consequent growing

demand for food and fuel, the increase in oil palm production is expected to continue,

albeit at a slower pace than over the last decade (OECD and

FAO, 2013). This increase

is also expected to extend to other developing or emerging countries in Africa and Latin

1. http://www.fao.org/faostat consulted on 28 January 2017.

America, where governments are promoting palm oil development in order to alleviate

poverty and increase energy security (Pirker et al., 2016).

Over the last decade, life cycle assessment (LCA) has become the worldwide standard

for reporting environmental product declarations (ISO 14025 Type III Environmental

Declarations) and the baseline model behind various greenhouse gas (GHG) calculators

(BIOGRACE 2 , GREET 3 , CCaLC 4) and GHG certification schemes (European Commission,

2009, BSI 2008, ISCC 5). Initially developed in the 1980s to assess the environmental

impact of industrial products and services, such as packaging, life cycle approaches

were rapidly applied in increasingly diverse contexts urging for the development of

harmonised guidelines. In the 2000s, the framework and methodological aspects of

LCA were standardised through international norms (ISO 14040 series 2000-2006),

particularly through the structuring and formalisation work led by SETAC 6 . LCA has

been applied to agricultural commodities primarily for the purpose of assessing various

environmental impacts and trade-offs, for example, bioenergy chains compared with fossil

ones. Adaptation of the LCA framework to agricultural products requires scientific and methodological developments that are still ongoing and represent specific challenges for

tropical perennial crops such as oil palm (Basset-Mens et al., 2010; Bessou et al., 2013;

Bellon-Maurel et al., 2013).

In this chapter, first we briefly present LCA modelling principles and methodological

steps, and then review the results from published LCA and GHG assessments of palm

oil products. Finally, we discuss the available information on the environmental impact of

palm oil and remaining challenges regarding LCA development and applications to palm

oil products.

2 LCA principles and methodology

LCA is based on two fundamental principles. Firstly, environmental burdens are gathered

throughout the commodity chain or ‘life cycle’, from raw material extraction (‘cradle’)

to the end-of-life of products or services (‘grave’). Secondly, environmental impacts are

quantified with respect to a functional unit (FU), either a product quantity (one kilo, one

car, etc.) or a usage or service [hours utilised, tonne-kilometre (tkm), etc.]. The entire life

cycle of a product has to be taken into account so that local environmental improvements

at one production stage or in one location do not result in a problem shifting to another

stage or location (Jolliet et al., 2010). Similarly, the comparison of two or more products

or services, based on the same FU, is paramount in order to identify all environmental

impacts of every compared product, which enables decision-makers to avoid hidden

problem shifting. Finally, LCA assesses environmental performance across numerous

impact categories, such as climate change, acidification or ozone layer depletion. Such a

multi-criteria approach does not focus on any one impact but rather pinpoints the relevant

impacts and their origins at given production stages. This holistic approach enables

identification of trade-offs and makes decision-making more transparent.

2. http://www.biograce.net/home consulted on 28 January 2017.

3. https://greet.es.anl.gov/consulted on 28 January 2017.

4. http://www.ccalc.org.uk/consulted on 28 January 2017.

5. http://www.iscc-system.org/consulted on 28 January 2017.

6. SETAC: Society of Environmental Toxicology and Chemistry, one of the most important international scientific organisations dealing

with structural issues of life cycle assessment (Jolliet et al., 2010).

LCA employs a four-stage methodology (ISO 14040 series 2000–2006):

- definition of the objectives and boundaries of the system to be studied from the beginning to the end of the chain;

- inventory of mass and energy flows used within the system and those released into the environment;

- characterisation or modelling of impacts based on the inventory; and

- interpretation of the results.

Definition of the study objectives (stage 1) implies definition of the FU and the scope of the system processes to be assessed: for example, the LCA of FU = 1 t fresh fruit bunch (FFB) includes accounting for all burdens from all processes, from raw material extraction up to the harvest of FFB at the edge of the palm block, in the relative proportions needed to produce 1 t of FFB. The flows (resources used and substances emitted) are inventoried (stage 2) according to the technical specificities of the studied system. Effects of resource use and emissions generated are quantified and grouped into a limited number of impact categories (stage 3), which are expressed as problem-orientated indicators (global warming potential, eutrophication potential, etc.) or damage-orientated indicators (human health, biotic and abiotic resources, etc.). The respective indicators are calculated based on a linear model (Eq. 1):

$$I_P = \sum_{i}^{n} m_i \cdot CF_{i,P} \quad (1)$$

where:

I_P is the indicator for the potential impact P,

m_i is the mass of the substance i contributing to the potential impact P,

$CF_{i,P}$ is the characterisation factor for the contribution of substance i to the potential impact P.

This linear model – a simplification of actual environmental impact mechanisms – does not usually account for local medium sensitivity or threshold effects; hence, LCA impacts are potential and not actual impacts. The interpretation of results (stage 4) is achieved

considering uncertainties related to all the previous steps. LCA allows for the identification

of environmental impact hot spots, process impact contributions and potential trade-offs

between impact categories or process stages.

For example, the impact on climate change is calculated by taking into account an

inventory of all GHG emissions per unit product. The emissions are then aggregated

into a single impact indicator (global warming potential or climate change) using IPCC's

model, which characterises what happens to GHGs in the atmosphere and their relative

contributions to the global greenhouse effect. Characterisation factors in the case of

climate change are expressed in CO_2 equivalent (CO_{2e}) based on mass.

Despite the intuitive methodological stages and well-documented guidelines, LCA

implementation poses some problems because of insufficient data or scientific knowledge,

which gives rise to a number of uncertainties, notably when inventorying field emissions

and characterising final impacts. Several characterisation methods exist that provide

varying environmental profiles, that is, a set of potential impact indicators. In the following

section, we review palm oil LCA results, which are available in the literature, without further

discussion regarding the underlying issues for LCA implementation. The challenges for

LCA implementation to oil palm products are then discussed in detail, that is, stage by

stage, in Section 4.

3 Results of LCA applied to oil palm products

3.1 Oil palm LCA studies

Several full or partial LCAs of oil palm products have been published over the last

20 years, with a drastic increase in publication rate over the last ten years (Fig. 1). A

review of the Web of Science 1975–2017 database provided 106 publications related

to palm LCA, with a large proportion of the published LCA studies focusing on palm

oil-based bioenergy. Energy Fuels is the top research field covered, concerning almost

40% of the literature (Fig. 2), and Biomass & Bioenergy and Applied Energy are among

the top five journals (Fig. 3). These publications were notably motivated by the debate

on potential net advantages of biofuel compared with their fossil fuel equivalents and

the subsequent release of the European Directive on Renewables (2009/28/EC), which

details sustainability criteria including minimum GHG savings compared with the use of

fossil fuels. Hence, most of the published palm oil-based LCA studies focused on GHG

(or climate change impact) and energy balance (or fossil resource depletion) (Manik and

Figure 1 Published items during each year over the last 20 years from the Web of Science (February

2017). Searching terms were TOPIC: (palm NEAR/1 oil) AND TOPIC: (lca OR ‘life cycle assessment’

OR 'life cycle' OR 'lifecycle'); the total output included 248 items, some were then withdrawn due to a

mistake in the Web of Science KeyWords Plus. The final item count was 106 publications.

Halog, 2013; Bessou et al., 2013). A small number of published LCA have actually looked

over the available panel of environmental impacts provided by LCA methodology. In the

following sections, we first review environmental information on palm biofuel and then

focus on palm oil LCA.

3.2 Environmental impact of palm oil-based bioenergy

Most LCA studies on palm oil-based bioenergy have been conducted in Malaysia and

Thailand (with 29% and 12% of the total 106 recorded items, respectively); the few

remaining predominantly cover Indonesia (more recent publications), Brazil, Colombia

and Cameroon. The large majority of these studies assessed the cradle-to-grave (well

to-wheel) system boundary of palm methyl ester (PME), that is, including all processes

from background input production (e.g. fertiliser manufacture) up to the vehicle tank,

assuming total combustion or including engine efficiency to calculate final energy and

GHG indicators.

The two main energy indicators commonly used are the Net Energy Ratio (NER = output/

input) and the Net Energy Gain or Balance (output-input). Although the common LCA

Figure 2 Published items classified according to their research topics, that is, Web of Science

Categories.

Figure 3 Published items classified according to journal titles.

indicator for energy use is usually expressed in total used fossil resource equivalents,

these indicators give an approximation of the environmental impact in terms of fossil

resource depletion. Energy indicators may include or exclude co-products depending

on the allocation ratios or whether system expansion was applied. Results vary greatly

among studies (with a mean NER value of approximately 2.9) notably regarding yields,

the handling of co-products, the inclusion or exclusion of capital goods (infrastructure)

and discrepancies in terms of transport scenarios. Despite some differences, all studies

highlight the great importance, in terms of energy costs, of both the agricultural production

of palm oil feedstock and transesterification. The oil extraction stage at the mill shows low

energy requirement in comparison due to the internal recycling of co-products for energy

purposes. During the agricultural stage, the upstream production of fertilisers and fruit

transport are the most energy-intensive steps. The upstream production of methanol is

the main contributor to the energy costs of both industrial phases; however, if bioethanol

replaced methanol, the NER could be improved up to ~3.6 (Papong et al., 2010).

GHG balances also vary greatly among studies and the main influencing factor is whether

LUC is accounted for or not, as the type of previous land use determines the final GHG

balance. The mean GHG balance (Fig. 4), accounting for various LUC scenarios, reaches

40 g CO_2e /MJ (9 g CO_2e /MJ without LUC), but is multiplied tenfold when peatland forest is

converted to palm plantations (in the upper range of the min-max values). Net savings of

GHG are possible when palms are planted on degraded lands or grasslands, and depend

Figure 4 Comparison of LCA results on palm biodiesel (PME) based on data collected in Manik and

Halog 2013: Mean GHG balance and minimum and maximum values with or without including land

use change (LUC).

upon the existing carbon stock of previous land uses. Compared with fossil fuels, palm

biodiesel is disadvantageous in terms of GHG if peatlands are converted or if tropical

forests are cleared and the palm plantation lasts less than a century (Reinhardt et al., 2007).

Otherwise, GHG savings ranging between 55% and 89%, compared with fossil diesel, can

be achieved (Wicke et al., 2008; Pleanjai et al., 2009; Thamsiriroj and Murphy, 2009; Achten

et al., 2010). Besides LUC, the main GHG sources are fertilisers (70–90% in field emissions,

10–30% emissions at the manufacturing site), methane emissions from the treatment of

palm oil mill effluent (POME) when methane is not captured and the transesterification

process (methanol and electricity) (Pleanjai et al., 2009;

Thamsiriroj and Murphy, 2009;

Achten et al., 2010; Choo et al., 2011).

Moreover, not all studies that include LUC use the same methodology to calculate GHG

impact, which hinders any comparison. The major calculation parameters that vary are the

carbon stocks accounted for (considered biomass compartments and amount of carbon

released/stored) and the time frame for amortisation (Wicke et al., 2008; Hansen et al.,

2014). Some of the studies that do not include LUC-related GHG emissions directly in

the balance give information on the carbon debt or payback time 7 together with other

results. This carbon debt varies between 8 and 169 years for palm biodiesel with mean

and median values of 54 and 43 years, respectively (Fargione et al., 2008; Wicke et al.,

2008; Pleanjai et al., 2009; Achten et al., 2010; de Souza et al., 2010; Harsono et al., 2012).

It is important to note that GHG accounting methodologies adopted by regulators within

existing biofuel directives can also differ quite substantially. These regulations impose

thresholds of minimum GHG emission reductions that biofuels must achieve, relative to

fossil fuels, to show compliance. The adoption of a well-to-wheels LCA-based accounting

perspective within regulations helps to ensure that such policies lead to actual reductions

in global emissions as opposed to shifting the burden to a different economic sector or

geographical region. Despite this, there are still many regulations today that continue to

mandate the use of biofuels in transport without imposing a minimum GHG emissions

reduction criterion, and therefore risk worsening global GHG emissions by forcing the

substitution of fossil fuels with a biofuel that can potentially have higher emission intensity

(Abdul-Manan et al., 2015).

Two of the most advanced biofuel regulations currently available are the EU's Renewable

Energy Directive (RED) and the US Renewable Fuels Standard 2 (RFS2). The EU's RED

requires biofuels to initially achieve a minimum reduction of 35% GHG emission, which is

then increased to 50% for new plant installations operating from October 2015, and 60%

for all biofuels effective from 2018 (European Commission, 2015). The US RFS2 stipulates

that for a biofuel to be granted 'renewable fuel' status, it has to demonstrate a minimum

GHG emission reduction of 20% (EPA, 2010). Although these regulations both adopt an

LCA approach, the detailed GHG accounting methodologies they relied on are in reality

very different, which prohibits any direct comparison.

An important distinction between the US RFS2 and the EU's RED is the way they take LUC

into account. Presently, both regulations require the incorporation of direct LUC (dLUC)

effects when accounting for biofuel GHG emissions. dLUC is the direct alteration of lands

by the farmers themselves to produce biofuel crops. Indirect LUC (iLUC) is the unintended change of land use worldwide, typically from carbon-rich non-agricultural land to carbon

poor agricultural land, in response to economic pressures arising from the increasing

7. Years needed to recover the carbon loss due to LUC based on the annual GHG savings allowed by biofuel when displacing fossil

fuel (Fargione et al., 2008; Gibbs et al., 2008).

demand for biofuels. iLUC requires a sophisticated economic modelling of global supply

and demand of lands worldwide and how they respond to economic pressures. Today,

both regulators acknowledge the importance of iLUC in terms of GHG emissions and its

potential influence on reducing GHG from biofuels. The US RFS2 and the California Low

Carbon Fuels Standard have included iLUC GHG penalties in their regulatory LCA, while

policymakers in the EU opted for a virtual control of iLUC through limiting the maximum

amount of conventional first-generation biofuels, like palm biodiesel, to be claimed under

the EU’s RED (Abdul-Manan, 2017), thus assuming that first-generation biofuel feedstocks

are more likely to drive iLUC.

Using their respective methodologies, both the US RFS2 and the EU’s RED have provided

estimated reduction potentials of GHG emissions for palm biodiesel. Under the EU’s RED

framework, the GHG savings potential for typical palm biodiesel processes without and

with methane capture are 36% (54 g CO_2e /MJ) and 62% (32 g CO_2e /MJ), respectively.

These values exclude dLUC, which operators need to estimate to show compliance.

However, according to the EU's RED sustainability criteria, no dLUC should occur after 1

January 2018 at the expense of lands with high carbon stock or high biodiversity value.

In comparison, the GHG emissions reduction potential for palm biodiesel under RFS2 has

been estimated to average approximately 17% (76 g CO 2e /MJ); this value includes both

dLUC and iLUC. The large difference between the regulatory values in the EU and the

United States are attributable to the methodological distinctions, including the treatment

Although the control of GHG emissions is a major issue in biofuel regulations, they also

include further pass-or-fail sustainability criteria such as elements relating to the protection

of land with high conservation value, prevention of habitat loss, fair and equitable treatment

of workers and communities and so on. Only GHGs are quantified using an environmental

LCA approach in spite of the much wider potential for the use of LCA techniques in

biofuel sustainability impact assessments. The scientific literature details many studies

which evaluate other environmental impacts of biofuel production (Achten et al., 2010;

Puah et al., 2010; Arvidsson et al., 2011; Silalertruska and Gheewala, 2012). These studies

concomitantly highlight the important contribution of the agricultural phase to other impact

categories, for example, eutrophication and acidification potentials, carcinogens and

respiratory inorganics. Fertilisers which leak into the environment contribute significantly to

eutrophication and acidification. The use of biodiesel in engines also adds to the potential

impact of eutrophication and acidification (Arvidsson et al., 2011), and contributes

significantly to the impact category of respiratory inorganics (Puah et al., 2010).

3.3 Environmental impact of oil palm fruits and palm oil

LCA studies on palm fruits and oil are less numerous than those focusing on palm

biodiesel, but they globally cover more impact categories and provide more details on

the agricultural phase (Yusoff and Hansen, 2005; Reijnders and Huijbregts, 2008; Zulkifli

et al., 2009; Vijaya et al., 2010; Schmidt, 2010; Stichnothe and Schuchardt, 2011). A few

studies also focus on GHG assessment (Chuchuoy et al., 2009; Choo et al., 2011; Kaewmai

et al., 2012; Bessou et al., 2014).

As expected, the main contributors to the GHG balance of crude palm oil (CPO) are the

same as for palm biodiesel, except transesterification, with LUC and peat oxidation being

critical and potentially overwhelming drivers (Schmidt, 2007; Reijnders and Huijbregts,

2008; Zulkifli et al., 2009), followed by methane emissions from the treatment of POME

and fertiliser-related emissions, notably N_2O field emissions (Schmidt, 2007; Choo et al.,

2011; Chase et al., 2012; Bessou et al., 2014). Nevertheless, the impact of POME can be significantly reduced if biogas is captured at the mill level (Chavalparit et al., 2006;

Choo et al. 2011; Bessou et al., 2014; Harsono et al., 2014) or, to a lesser extent, if raw or

partially treated POME are injected into a composting process for organic residues (Singh

et al., 2010; Stichnothe and Schuchardt, 2010).

In a pilot application of palm GHG (RSPO GHG calculator, Chase et al., 2012) on mills in

Southeast Asia and Latin America, the average GHG balance was 1.67 t CO 2e /t CPO and

ranged from −0.02 to +8.32 t CO 2e /t CPO (Bessou et al., 2014). Of the mills not supplied

by a peat area, land clearing, POME methane emissions and fertiliser-related emissions

accounted for 41–80%, 15–35% and 3–19% of total GHG emissions, respectively. The

impact of fossil fuel use was not significant (0–5% and 0–2% of total emissions at the field

and mill levels, respectively). Such a low impact was due to the low mechanisation level

in the plantations and the recycling of numerous residues providing heat and power to

operate the mill (with the potential production of excess electricity). Most field fuel use is

dedicated to FFB transport; hence, the impact of fuel use may vary greatly according to

FFB harvesting logistics.

Published GHG balances (or the climate change impact indicator) range between −0.55

and 24 t CO 2e /t CPO with median values around 1–2 t CO 2e /t CPO when LUC is applied to mixed previous land uses and less than 10% peatland, and methane is not captured

(Reijnders and Huijbregts, 2008; Schmidt, 2010; Choo et al., 2011; Bessou et al., 2012).

Looking at the other impact categories, the agricultural phase remains the main

contributor, except for human toxicity or respiratory inorganics impact categories, which

are mainly caused by boiler emissions (Stichnothe and Schuchardt, 2011; Bessou et al.,

2012). Mill emissions can also contribute to eutrophication which is driven by the emission

of nitrogen and phosphorus compounds. The main eutrophication factors at the agricultural

stage are nitrate leaching, and phosphorus and nitrate run-off. Other N-compound

emissions also contribute to acidification and photochemical ozone impact categories.

While palm oil generally performs worse than other oil crops on climate change impact,

when LUC occurs and leads to carbon loss from previous land use (e.g. in the case of

deforestation or peat oxidation), palm oil can perform better than rapeseed oil with regard

to eutrophication, acidification, ozone depletion and photochemical ozone impacts when

effective management is in place (Schmidt, 2010).

4 Challenges in building LCA of oil palm products

4.1 Issues at the Goal and Scope level

The Goal and Scope steps of the first stage of LCA are critical as they define the validity

domain of the final outputs. The boundary of the studied system must be delineated in order to ensure that all potential environmental impacts linked to the investigated product

or service are taken into account. At the same time, there might be trade-offs needed

between an exhaustive system assessment and gathering representative and consistent

data. Iterative adjustments from stage-to-stage are often needed to carry out a robust LCA.

Being a perennial crop, oil palms last for at least 25 years in the field, during which time

the crop stand goes through different development phases. The whole life cycle of oil palms

includes the nursery stage (three months in pre-nursery and nine months in the main nursery),

the early growing stage of immature non-productive palms (2–3 years) in addition to the

productive harvest period (Stichnothe et al., 2014). Palm trees older than 25–28 years old

(depending on planting material and site conditions) are often too high for harvesting to be

kept longer in the field. The early growing stages account for 10–15% of the entire plantation

cycle. These long and partitioned cycles require specific management, which usually combines

long-term management strategies and short- or medium-term adjustments. Moreover, it also

implies complex and evolving interactions with the ecosystem, which can affect the potential

performance of the crop and management efficacy. Nevertheless, in most published studies,

only the productive area of the plantation and the associated FFB yield are considered. Given

the potential significant contribution of the early stages and the variability in practices and performances throughout the long productive period, the modelling choices to account or not for the whole perennial cycle can influence LCA results (Bessou et al., 2016). Hence, when defining the goal and scope of an oil palm product LCA, attention should be paid to the whole perennial cycle in order to produce representative results. Considering the whole growing cycle is particularly relevant for nitrogen losses (Pardon et al., 2016a) and hence for the life cycle inventory (LCI).

Another peculiar aspect of perennial compared with annual crops is the potential importance of changes in carbon stocks (Mithraratne et al., 2008). Henson showed that mature oil palms on coastal soil in Malaysia generated a net carbon fixation of 11 t ha^{-1} y^{-1} based on the eddy covariance technique (Henson, 1999). This fixation rate varies depending on the plantation age and management, and it does not represent an actual net carbon fixation in the biosphere. Indeed, a large proportion of the assimilated carbon is exported to the oil mill (Melling et al., 2010).The temporary storage of carbon in oil palm stipes might improve the GHG balance of palm plantations (Lam et al., 2009), but there is no generally accepted method for quantifying temporary carbon storage (Levasseur et al., 2012). The most generally used and reproduced guidelines are those from IPCC (IPCC, 2006). Further guidelines developed on the same basis, such as PAS2050 (BSI, 2011) or

the European Renewable Directive (European Commission, 2009), all consider potential

carbon storage in biomass as long as it represents a stable stock at equilibrium for at

least 20 or 25 years. The way stocks are calculated and changes are modelled varies

considerably across methods and published studies. Whether or not oil palm plantations

are a net sink or source of carbon depends on the soils, climate, cultivation and residue

management practices; however, the history of the site, especially LUCs (Melling et al.,

2005, Melling et al., 2010), may significantly affect the GHG balance of end products such

as palm biodiesel (see Section 3.1). Defining if and how LUC should be included in the

LCA is a crucial parameter in the goal and scope definition of the LCA of palm products.

4.2 Issues related to LCI data collection

Specific quantified LCI data, for example, history of LUCs, influence of plantation

management practices, nitrogen budget of oil palms, residue treatment, etc., are frequently

missing, which is a current issue in tropical crop LCA (Basset-Mens et al., 2010). In the oil

palm sector, the lack of representative data is accentuated by the concomitant lack of

detailed institutionalised agricultural census for certain key producing countries and the

great diversity in oil palm practices observed in the field (Lee et al., 2014; Moulin et al.,

2016). Current knowledge regarding the influence of different management practices on the plantation and/or the palm oil mills varies from fragmented to non-existent. Examples include nutrient management, water level management on peat soils, pest control, residue treatment (empty fruit bunches (EFB), POME and nutshells), energy efficiency in oil mills, to name just a few. This critical lack of data persists despite the recent growing number of LCA studies driven by environmental concerns notably due to the expansion of oil palm areas.

LUC and peat oxidation lead to severe damage to the environment in terms of both biodiversity loss and GHG emissions. The proper identification of LUCs, from the type and extent of land cover, and subsequent land use fluxes and related emissions is therefore critical. Assessing the impact of oil palm area expansion requires the identification of LUCs and LUC impacts, as well as the impact of oil palm land use, for example, the impact on soil or carbon sequestration. Impacts of land use and LUCs are highly sensitive to soil type and climate conditions so that site or region-specific assessment is required to adequately cover this aspect. The development of region-specific LCI methods is hampered by the lack of regional and site-specific data. Moreover, there is still a lack of consensus on the methodology to address LUC history, carbon stock accounting, fluxes and therefore a lack of adequate and representative site-specific data sets.

Over the past 20 years, 95% of the Indonesian palm oil production area has been located

in Sumatra and Kalimantan, and palms have been increasingly cultivated on peatlands

(Afriyanti et al., 2016). Tropical peatlands store a huge amount of carbon, roughly 7000 t

C ha −1 in below-ground biomass (Moore et al., 2013) and are highly vulnerable to natural

and human disturbance. Under normal weather conditions, peatland in Indonesia is almost

entirely waterlogged, which must be drained via hydrological engineering prior to oil

palm planting. The water level is the main control for GHG fluxes from tropical peat soils.

Crouwenberg et al. (2010) calculated emissions of at least 9 t CO 2 ha −1 y −1 and considered

that to be a conservative estimate, because the role of oxidation in subsidence and the

increased bulk density of the uppermost drained peat layers are insufficiently quantified

(Couwenberg et al., 2010). The decomposition of biomass due to the lowering of the water

table levels also goes along with nitrous oxide emissions. Despite dedicated research

(Melling et al., 2007; Jauhiainen et al., 2012a,b) and recent guidelines (IPCC, 2013),

there is still considerable uncertainty on the impact of various water level management

practices on peat emissions and on the various direct and indirect fluxes and impacts of

peat cultivation; hence, LCI for oil palm plantations on peat soil are not comprehensive.

Nitrogen losses in agroecosystems are a major environmental and economic issue.

Indeed, agroecosystems receive approximately 75% of the reactive nitrogen created

by human activity (Galloway et al., 2008; Galloway et al., 2013). In oil palm plantations,

nitrogen fertilisation is a common practice that is associated with water pollution risks and

GHG emissions (Corley and Tinker, 2008; Choo et al., 2011; Comte et al., 2012), notably

nitrous oxide, a very potent GHG [8]. Furthermore, fertilisers constitute 46–85% of plantation

field costs (Caliman et al., 2001; Goh and Härdter, 2003; Silalertruksa et al., 2012). Oil palm

plantations have three main peculiarities affecting nitrogen dynamics in a way that differs

from other cropping systems: the long duration of the growing cycle, the marked spatial

heterogeneity and the large internal fluxes and pools of nitrogen. Substantial losses of

reactive nitrogen can occur during the immature phase, when palms are still young and

legume cover is vigorous; as well as during the mature phase in areas with sparse or no soil

cover; or where high amounts of organic and mineral fertilisers are applied (Pardon et al.,

8. Nitrous oxide has a global warming potential 298 times greater than carbon dioxide on the same mass basis (IPCC, 2007).

2016a). Pardon et al. investigated several models to estimate nitrogen losses of oil palm

plantations; most of the models indicated substantial losses at the early growing stage of

oil palms. On average, 31% of nitrogen losses occur during the immature growing phase

(Pardon et al., 2016b), which is frequently not taken into account in an LCA of oil palm

plantations (see Section 4.1). The greatest uncertainty involves the loss of nitrogen via

the emission of gaseous nitrogen compounds (N_2O, NO_x, N_2, NH_3) (Pardon et al., 2016a).

Reactive nitrogen emissions contribute to several environmental problems, such as climate

change, eutrophication or acidification. The lack of precise estimation of the nitrogen

compounds released into the environment thus causes a great deal of uncertainty in the

associated impact categories, emphasising the need for representative and robust LCI

data on nitrogen fluxes as far as possible.

The management of organic residues from palm oil mills is paramount to emission

reduction and nutrient recycling (Stichnothe and Schuchardt, 2010, Kaewmai et al., 2013).

Given the diversity of residues generated by the production of palm oil (EFB, fibres,

shells, etc.) and their respective large amounts (e.g. POME), there are very diverse ways

to reuse these products via various processes and potential impacts. One cubic metre

of POME treated in conventional open ponds can generate up to 12 m^3 of methane

emission, equivalent to approximately 200 kg CO_{2e}. Biogas production from improved

POME treatment is associated with a highly favourable GHG budget (Bessou et al.,

2014). A worst-case scenario is dumping EFB, causing GHG emissions equivalent to

1000 kg CO_2e t^{-1} (Stichnothe and Schuchardt, 2011; Langeveld et al., 2016). POME and

EFB can also be co-composted, which can lead to emission reductions as well as benefits

to soil quality (Stichnothe and Schuchardt, 2010). Indeed, EFB are generally applied back

to the plantation to maintain soil fertility through increasing the organic matter content

(Saletes, 2004, Carron et al., 2015). The application of palm oil mill residues back to the

field may not only reduce GHG emissions but also preserve resources as it reduces the

demand for mineral fertilisers. The impact of compost or EFB on soil quality, as well as

upstream emissions during the various composting processes, are still poorly quantified.

Further data collection is needed to better account for these practices within both LCI and

life cycle impact assessment (LCIA).

4.3 Challenges in impact pathway characterisation

The development of several LCIA methodologies has created confusion partly due to

differing results even for some midpoint or endpoint indicators. Several areas/indicators

(soil property change, ecotoxicity, biodiversity, etc.) are still under development and

consequently not fully ready for general use.

Land use causes various chemical, physical and biological changes to soil properties and

functions such as life support or nutrient cycling. Despite recent developments by the LCA

community (Milà i Canals et al., 2007; Oberholzer et al., 2012; Garrigues et al., 2013; Saad et al., 2013; Bos et al., 2016), there is currently no comprehensive impact assessment of the various branches of the cause–effect chains implemented in LCIA. In particular, impacts related to co-variations in the associated physico-chemical and biological soil properties and soil functions are hardly addressed in LCIA. Moreover, physical and chemical changes of surface and soil have further effects on flora and fauna and hence affect biodiversity within and above the soil. The accounting of land use and LUC impacts is critical for oil palms given the issue of area expansion and the peculiarities of oil palm as a perennial crop, that is, the long-term cultivation cycle with constant land cover and biomass accumulation, and the deep rooting system of the plant (see Section 4.1). In addition, practices related to the recycling of residues back to the field may also influence soil quality (see Section 4.2). Comprehensive impact pathways to relate the long-term trends and the influence of practices on the temporary storage of soil carbon, improvement of soil quality and protection from soil erosion are not currently part of the LCIA (Stichnothe and Schuchardt, 2011) as the existing level of knowledge impedes the modelling of all potential correlated processes and impacts. To design the best environmentally friendly scenarios of residues and global plantation management, the proper modelling of impact on soil is crucial.

The modelling of land use impacts on biodiversity is also considered a priority in LCA.

Biodiversity can be considered at different levels, namely ecological diversity (ecosystems),

population diversity (species) and genetic diversity (genes). The quantification is complex

and many diverging approaches have been proposed in an expanding literature on the

topic (Curran et al., 2016). Biodiversity loss can be linked to four midpoint indicators

(land use, ecotoxicity, acidification and eutrophication) but also to the endpoint indicator

'Natural Environment'. Curran et al. (2016) evaluated the performance of 31 models to

assess the biodiversity loss from both the LCA and the ecology/conservation literature.

The authors concluded that there is room for improvement and suggested working on

a 'consensus model' by the weighted averaging of existing information to complement

future development (Curran et al., 2016). Currently, there is no agreed and harmonised

approach which addresses how to quantify the spatially distinct environmental impacts of

LUC in palm oil-producing countries.

Spatially explicit methods are needed in LCA in order to accurately quantify impacts

of products and processes. Chaudhary et al. (2015) used the countryside species–area

relationship to quantify regional species loss due to land occupation and transformation

(Chaudhary et al., 2015; de Baan et al., 2015). These authors combined regional characterisation factors with vulnerable scores to calculate global characterisation factors.

Oil palms grow in tropical areas and tropical biomes have higher characterisation factors

than those of boreal biomes mainly because of their higher species richness per area.

Finally, dry peat soils are prone to subterranean fires, which smoulder and emit thick white

smoke laden with hazardous particles (Goldstein, 2016). Such fires in Indonesia became an

international health concern in 2015, enhanced by long and intense drought periods related

to a severe El Niño episode occurring in the region; a similar catastrophe occurred in 1997.

Such fires cause smog, haze and respiratory problems as far away as Malaysia, Singapore and

the Philippines. Those were obviously extreme events that, by definition, have the potential

to cause considerable health and other environmental impacts but whose occurrence is

rare. The frequency, intensity and persistence of such extreme events are still important

characteristics for deriving characterisation factors, for example, for human toxicity. Such

information requires dedicated modelling work in combination with LUC and climate models.

4.4 The challenge of interpreting results

Results have to be discussed with respect to the particular goal and scope of the study,

which in turn also define data requirements but also the limitation of the analysis.

Describing the consequences of modelling choices, such as total or productive plantation area, LCI models (IPCC, crop model, etc.), time period (year, plantation cycle or several plantation cycles) considered and so on, is crucial, as all such factors can influence the results. The spatial dimension is given by the scope of the study, for example, a specific plantation, a particular region or national production. The obtained results are only valid for the system under investigation. Although this may seem obvious, results are frequently generalised without proper evidence.

Palm oil mills are multi-output systems and the difficulty is quantifying and identifying which product contributes to the emissions. System subdivision is not feasible as palm kernels cannot be obtained separately. System expansion is possible but difficult to interpret and the substitution method is prone to arbitrary choices for co-product substitutes, for example, can kernel meal be a substitute for soya meal or wheat? In attributional LCA, emissions can be allocated among the various products, for example, CPO, nuts or other downstream products such as palm kernel oil and palm kernel meal, while using physical (mass, energy content, nutrient content, etc.) or economic relationships. Obviously, all these choices will alter the results for a particular product (Wiloso et al., 2015). It is highly recommended to conduct a sensitivity analysis for the different options as well as an uncertainty analysis before discussing results. The epistemic uncertainty analysis is particularly crucial for LCI field emission models that are not well parameterised for

tropical perennial crops such as oil palm, and for cause–effect processes, notably those

related to soil functions, which are still not fully understood and modelled.

5 Oil palm LCA improvement tracks

5.1 The search for representative data sets

LCA studies of oil palm systems and their derived products are frequently restricted by

data gaps. Consequently, the principal challenge is to build a consensus-based modelling

framework, to gather regional- and management-specific inventory data and to define

inventory models in order to estimate emissions and temporary carbon storage effects.

Building a national LCI database for oil palm plantations and subsequent conversion

processes would be a valuable asset.

Independent to the system boundaries studied, the agricultural phase, in particular

fertiliser input, plays a key role in determining the final environmental profile. It is hence

paramount to adjust fertiliser input to enhance productivity while limiting loss to the

environment. To do so, there is an urgent requirement for adapted models (mechanistic

or operational models) that allow for more precise estimation of field emissions linked to

fertilisers. Indeed, the great majority of LCAs use IPCC emission factors to estimate nitrate

leaching and run-off as well as ammoniac or nitrous oxide emissions. These emission factors are poorly calibrated for tropical regions (Bouwman et al. 2002a,b; Stehfest and

Bouwman, 2006) and they do not take into account the specificities of perennial cropping

cycles such as palm plantations. A recent review emphasised that the combined initial

structure and long-term evolution of oil palm plantations induce specific spatio-temporal

patterns in nitrogen fluxes that are poorly quantified and thus need further research. This

review also highlighted that nitrogen losses through leaching and volatilisation may be

important and all nitrogen gaseous losses remain unknown (Pardon et al., 2016). More

field measurements are needed to establish more relevant emission factors.

Research projects are ongoing that will shed some light on ways to reduce uncertainty

in the LCA results. Development work on other approaches, such as agro-ecological

indicators, are complementary as they enable a better account of local conditions and

practices to build up the LCA inventories. New knowledge and model developments are

also expected to accurately account for the comprehensive role of organic fertilisers in soil

quality and potential field emissions.

5.2 The need for comprehensive impact assessments

There are 13–18 impact category indicators in the current standard LCA methods (ILCD,

ReCiPe; respectively). Nevertheless, a great proportion of published LCA studies on oil palm products solely focus on GHG and energy balances. Many LCA impact indicators need to be more widely explored across palm oil production systems such as the impacts of pesticides (e.g. paraquat or glyphosate) on terrestrial or freshwater ecotoxicity, or the impact of irrigation systems on water depletion (Nilsalab et al., 2016; Silalertruska et al., 2016). Given the important contribution of fertilisers to environmental impact during the agricultural phase, the eutrophication and acidification impacts related to nitrogen and phosphate inputs would also need to be further investigated. Several other environmental impact indicators (ecotoxicity, biodiversity, etc.) are still under development and consequently not ready for use.

The accounting of land use impacts on soil is critical for oil palm given i) the important challenge related to oil palm expansion and related LUCs and ii) the peculiarities of oil palm as a perennial compared with annual crops and due to the various and abundant recycled residues. Particular impacts related to co-variations in the associated physico-chemical and biological soil properties and soil functions are hardly addressed in LCIA due to limited knowledge. The impact of peat drainage on soil quality and causal relationship with increased risk of peat fires also need to be further investigated, and modelled within the LCA framework.

Finally, the limits of the linear globalised model may be overcome by developing regional characterisation factors that can be used to adapt the linear model to the sensitivity of the local environment. Such factors are particularly critical in the case of very local impacts that

are more sensitive to changes in the immediate environment – such as eutrophication – or

resources unequally distributed on the global scale, such as water in dryland areas. Such

regional factors have not yet been highly developed in regions where palm plantations

are established and in the context of LUC may affect the medium sensitivity during the

transition phase in particular.

6 Conclusion

LCA is a very useful tool for assessing the environmental impacts of oil palm products

as it helps to identify the hot spots across the whole commodity chain while avoiding

hidden trade-offs between different environmental impacts. Studies show that the oil palm

cultivation stage contributes to a major share of several impacts including climate change,

acidification and eutrophication, though the palm milling stage can also release significant

GHGs if wastewater is not properly managed. Palm mills also contribute significantly to

toxicity effects due to the particulate emissions from boilers.

The assessment of GHGs that contribute to climate change has been widely

carried out and a large contribution is from LUC and nitrogen fertiliser production

and application. For palm LCAs, delineation of the system boundaries is critical to provide consistency to studies, which can be particularly confounded by the challenge

of accurately defining and calculating the impacts from LUC and carbon stocks. This

is in part linked to a lack of consensus on the methodologies for the calculation and

also to the limited availability of robust and reliable inventory data on the history of

LUCs, influence of plantation management practices, nitrogen budget of oil palms and

residue treatment.

In the oil palm sector, the lack of representative data is accentuated by the great diversity

in cultivation practices observed in the field. Currently, specific data and consequently

knowledge on the influence of different management practices on the plantation and the

palm oil mills are limited. The nitrogen dynamics of oil palm are complicated due to the

long growing cycle, spatial heterogeneity and large internal fluxes and pools of nitrogen,

which lead to great uncertainty in the assessment of climate change, acidification and

eutrophication impacts. There is also a considerable lack of data on the various options of

residue management which can affect the assessment results.

Significant challenges also remain when selecting impact assessment methods for

characterising land use, biodiversity and including the effects of temporary carbon storage.

Land use causes various chemical, physical and biological changes to soil properties and

functions such as life support or nutrient cycling. There is currently no comprehensive

impact assessment of the various branches of the cause-effect chains implemented in

LCIA. In particular, impacts related to co-variations in the associated physico-chemical and

biological soil properties and functions are insufficiently addressed. Moreover, physical

and chemical changes of surface and soil have further effects on flora and fauna and hence

affect biodiversity. Comprehensive impact pathways to relate long-term trends and the

influence of practices on the temporary storage of soil carbon, improvement of soil quality

and protection from soil erosion are not currently part of the LCIA. To design the best

environmentally friendly scenarios of residues and global plantation management, correct

modelling of impact on the soil is crucial.

To address the challenges of conducting palm LCAs, a consensus-based modelling

framework is needed which can consistently define the inventory data needs for estimating

emissions from fertiliser application and temporary carbon storage. Regionalised land use

models need to be developed along with complementary agro-ecological indicators for

better characterisation of the effects of oil palm cultivation. Finally, the obtained results

have to be discussed with respect to the particular goal and scope of the study, including

model, allocation and other methodological choices as well as data quality assessment,

which when combined, define the validity domain of the results and hence the application

limitation of the analysis. Such limitations should be estimated by scenario analysis. It

is highly recommended to support the final interpretation of results by sensitivity and

uncertainty analyses.

7 Where to look for further information

Key organisations for LCA development:

SETAC: http://www.setac.org/

UNEP SETAC Life Cycle Initiative: http://www.lifecycleinitiative.org/

LCA networks in Southeast Asia:

Indonesian LCA Network (ILCAN): http://www.ilcan.or.id/

Thai LCA Agri Food Asia Network: http://www.lcaagrifoodasia.org

LCA networks in Europe:

European Platform: http://eplca.jrc.ec.europa.eu/

French Environmental Lifecycle and Sustainable Assessment: http://www.elsa-lca.

org/?lang=en

German LCA network: http://www.lcanet.de/en/

Dedicated journals and conferences:

International Journal of LCA: http://link.springer.com/journal/11367

Journal of Cleaner Production: https://www.journals.elsevier.com/journal-of-cleaner-

production

Indonesian Journal of LCA and Sustainability: http://ijolcas.ilcan.or.id/index.php/IJoLCAS

Environmental Toxicology and Chemistry:

http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1552-8618

Integrated Environmental Assessment and Management:

http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1551-3793

LCA-Food conferences: http://lcafood2016.org/

SETAC Europe LCA Case Study Symposium:
http://events.setac.eu/?contentid=179

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11 Chapter 11 Life cycle assessment (LCA) of palm oil in practice: the example of Malaysia

1 Introduction

Since the late 1990s there has been a widespread emergence of eco-labelling criteria

and the Environmental Management System, which have extended to the agriculture

products and processing sectors. Eco-labelling is slowly evolving to become a market

based voluntary mechanism in the greening of the agriculture products supply chain. Eco

label Type I is a voluntary third-party programme that awards a licence that authorizes the

use of environmental labels on a product indicating its better environmental performance.

Eco-label Type II is a self-declaration label on environmental performance, while Eco-label

Type III specifically requires a life cycle assessment (LCA) study to be conducted on the

product before certification. LCA is a tool for evaluating the environmental impact of a

product or process throughout its entire life cycle (SETAC, 1993). It was first developed

as a method for evaluating the impact of a product over its entire life cycle, the so-called

‘cradle-to-grave approach’, but it has since grown for use in evaluating the environmental

impact of business activities, and finally of all the economic activities of a nation as well.

Over the last decade there has been a rapid expansion in the demand for LCA studies

to chart the environmental performance of products. LCAs have thus become a common environmental management tool and an analytical method for assessing and optimizing

the environmental quality of a system over its whole life cycle (Stalmans et al., 1995).

The oil palm industry is continually expanding to meet the demand for its products.

However, as producing countries run out of land, the key to any future increase in

production must come from higher yields, whether by better planting materials or

by better agricultural practices or by both. This would avoid further clearing of forest

and peat swamps resulting in loss of biodiversity, erosion and greenhouse gas (GHG)

emissions. Sustainable palm oil production must maintain a long-term balance between

inputs and outputs across the system boundary during its life cycle. There is a need to

quantify the environmental impacts associated with the processes, products or activities

carried out along the oil palm supply chain. LCA is a decision support tool for mitigation

of ecological concerns in which the environmental impacts are quantified by auditing the

inputs and outputs to assess the environmental cost of producing palm oil. It is the most

holistic and comprehensive method known to assess the environmental burden of any

production.

The objective of this study was to chart the environmental performance of the production

of crude palm oil (CPO) and to suggest mitigation measures to overcome hot spots if any.

2 Life cycle assessment (LCA) methodology

The system boundary for the LCA of palm oil production was divided into three subsystems

(Fig. 1), namely the agricultural phase during which oil palm seedlings are grown in the

nursery and then transplanted to the plantation for the cultivation of oil palm fresh fruit

bunch (FFB) and extraction of CPO from FFB at the palm oil mill.

2.1 Nursery subsystem (production of palm seedlings)

The productivity of an oil palm plantation depends on many factors, the most important of

which is the quality of seedlings derived from cross-pollination of selected parent palms.

Besides the genetic characteristics of selected seeds, the production of high-quality oil

palm seedlings is also dependent on good nursery management and practices (Halimah

et al., 2010).

At nursery stage, the seedlings are grown in polybags and are given accurate treatment

during the first 10 to 12 months of their development. This ensures that well-developed NURSERY PLANTATION Seedling PALM OIL MILL FFB CPO PALM KERNEL PALM SHELL

Figure 1 System boundary for LCA of palm oil production.

seedlings with optimum vigour at the time of field planting can be quickly established in

the plantation (Corley and Tinker, 2003). Inventory data were collected from 21 oil palm

nurseries in Malaysia.

2.2 Plantation subsystem (production of FFB)

Oil palms from the nursery are transferred and planted in the oil palm plantation when they are approximately 12–13 months old. The palms are planted at a density of 136–48 palms per hectare on mineral soils. Before the palms are planted, the soil is ploughed, compacted and a leguminous cover crop is sown. Oil palm trees bear their FFB within two to three years and continue to do so for the next 20 to 25 years. Detached FFB are placed by the roadside and collected later by 5- to 10-tonne lorries before being transported to a nearby mill within 24 hours (Corley and Tinker, 2003).

Replanting of oil palms is carried out when palms are 25–30 years old because of the difficulty in harvesting tall palms. Old palms also give low FFB yield. The palms are felled, chipped and left in the plantation as a nutrient source for replants. The felled palms contain about 95 t of dry weight per hectare (Khalid et al., 2000, 2009) which would decompose within two years. Our inventory data were collected from over 281 plantations in Malaysia.

Two land-use change scenarios were chosen for these studies which were land-use change from logged-over forests and the continued land-use change from oil palm to oil palm. The reason for this was that most oil palm plantations that have been developed in peninsular Malaysia have continued land use while the more recently developed in Sabah and Sarawak are from logged-over forest.

2.3 Palm oil mill subsystem (production of CPO)

The FFB, delivered to the palm oil mill, are received at the FFB hoppers to be processed

into CPO which is pressed out of the mesocarp fibre. The nuts with the pressed

mesocarp fibres are separated at the fibre cyclone and then cracked to produce kernels

and shells. The kernels are shipped to kernel-crushing plants to be processed into palm

kernel oil while the shell and pressed mesocarp fibre are used as boiler fuel (Vijaya

et al., 2010).

The main solid waste from the milling process is empty fruit bunch (EFB), pressed

mesocarp fibre, shell and boiler ash while the liquid waste is palm oil mill effluent (POME).

The gaseous emissions are from the boiler stack and biogas from the effluent treatment

ponds (Vijaya et al., 2010). A contribution to soil fertility is carried out by composting EFB

on oil palm plantations while the boiler ash is used for land application. Biogas from the

anaerobic digestion from the POME is captured for use as an energy source. It can be

either burnt directly in the boiler or purified and run through a gas engine to produce

electricity for the grid (Vijaya et al., 2010).

The pressed mesocarp fibre and shells are burnt as fuel in the palm oil mill boiler while

the excess shells are sold to other biomass boilers. However, the credits from the use

of shells elsewhere are not included in this study as it is out of the system boundary.

Palm kernels and shells are the co-products of the milling process and are accounted for

by using a weight allocation of 61% CPO, 25% palm kernel and 14% palm shell (Vijaya

et al., 2010). The inventory data for this study was collected from 45 palm oil mills located

all over Malaysia. At the palm oil mills two scenarios were examined. One with biogas

emissions and the other with biogas capture.

3 Life cycle impact assessment (LCIA) case studies

The life cycle impact assessment (LCIA) was carried out using the SimaPro Software version

7.1 with the Eco-indicator 99 methodology.

LCIA was conducted for the system boundary of nursery plantation – palm oil mill with

allocation for three scenarios.

3.1 Scenario A

LCIA was conducted for one tonne of CPO produced at the palm oil mill for the system

boundary with land-use change from logged-over forest at the plantation and with biogas

emissions at the palm oil mill with allocation to co-products. The weighted results are

shown in Fig. 2.

The weighted results show that the impact categories with significant impacts are from

land use which shows the highest impact followed by fossil fuels respiratory inorganics and

climate change. The impact under the land-use impact category is due to the conversion

and occupation of the land by the oil palm plantation. The impact from the fossil fuels

category came from the production of the various
fertilizers as well as diesel usage for

transportation and harvesting which were used in the
nursery and plantation phases.

The parameters that contributed towards the impact
categories of climate change and

respiratory inorganics were from the application of N
fertilizer and energy use through

transportation, traction and production of raw materials
while the big effect on climate

change impact category comes from land-use change upstream
and POME at the palm

oil mill. Both these impact categories are related to air
emissions. The main air emission

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Analysing 1 tonne 'CPO (logged over forest with biogas) May 2010'; Method: Eco-indicator 99 (H) V2.03 / Europe EI 99 H/A / weighting

Figure 2 Weighting for LCIA of 1 tonne of CPO – land-use change 25 years logged-over forest, with

biogas emissions.

from the POME ponds during anaerobic digestion was the biogas which consisted of

methane, carbon dioxide and traces of hydrogen sulphide. The un-harvested biogas is

a greenhouse gas which harms the ozone layer and contributes to global warming. The impact from biogas falls under the climate change impact category. The impact under

respiratory inorganics and climate change from upstream activities was caused by the

application of nitrogen fertilizers in the plantation as well as in the nursery.

Under the Economic Transformation Programme (ETP) which was launched in 2011 by

the Malaysian government, palm oil was identified as one of the National Key Economic

Areas (NKEAs). Under this NKEA entry point project 5 (EPP5) envisages that all palm oil

mills in Malaysia will have a biogas capture facility in place by the year 2020 (Pemandu,

2011). In view of this the second scenario was to access the LCIA when biogas was captured

at an 85% capture efficiency.

3.2 Scenario B

LCIA was conducted for one tonne of CPO for the system boundary with land-use change

from logged-over forest at the plantation and with biogas capture at the palm oil mills with

allocation to co-products. The weighted results are shown in Fig. 3.

The weighted results show that when biogas is captured, the impact from climate change

impact category under POME is reduced significantly. The only remaining impacts are

again from the upstream in green under land-use impact category due to the occupation of

land; fossil fuel impact category due to the production of fertilizers and for climate change;

and respiratory inorganics impact category from the application of fertilizers and land-use

change. To date, about 20% of the palm oil mills in Malaysia have biogas capture facilities.

Another 35 % of the palm oil mills are in the various stages from planning to construction

to commissioning of their biogas plants. This shows a huge change in the practices of the

Malaysian oil palm industry making the industry more sustainable. A third scenario was

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0 Carcinogens Resp. organics Resp. inorganics Climate Radiation Ozone layer Ecotoxicity Acidification Land use Minerals Fossil fuels CPO (Logged-over Forest with Biogas Capture) May2010 FFB production (Logged-over Forest to OP) May 2010 Empty Fruit Bunch Palm Oil mill effluent (biogass harvested) 85(%) no recycling savings 28m3 Mesocarp fibre Boiler Ash2 Water for boiler & process at POM Reinforcing steel, at plant/RER U Fibre cement corrugated slab, at plant/CH U Steel low alloy ETH U Tractor, production/CH/I U Electricity Malaysia Electricity generated at POM Traction Truck 28t B250 change / Eutrophication

Analysing 1 tonne 'CPO (logged over forest with biogas capture) May2010'; Method: Eco-indicator 99 (H) V2.03 / Europe EI 99 H/A / weighting

Figure 3 Weighting for LCIA of 1 tonne of CPO – land-use change 25 years, logged over forest with

biogas capture.

conducted in order to examine the situation when the land transformation was from oil

palm to oil palm which is the case of most plantations in peninsular Malaysia which are

going into the second and third cycle of replanting.

3.3 Scenario C

LCIA was conducted for one tonne of CPO for the system boundary with continued land

use from oil palm to oil palm with biogas capture at the palm oil mills with allocation to

co-products. The weighted results are shown in Fig. 4.

When the land-use change scenario is from oil palm to oil palm which has a continued

land use, the impact under the land-use impact category is reduced significantly. This is

because with the continued land use there is no change in the land occupation. The climate

change impact category from FFB production in green is also reduced as there is no land

use change. When biogas is captured, the impact from POME in blue under the climate

change impact category has reduced and only the impact from the upstream for fertilizer

application is still remaining under this impact category.

4 Greenhouse gas (GHG) emissions

The GHG emissions for the production of one tonne of CPO were calculated, and are

shown in Fig. 5. This is the GHG right from the nursery to the plantation with continued

land-use change up to the palm oil mill with allocation to co-products.

The main parameter causing the contribution to the GHG emissions is the biogas from

the anaerobic treatment of the POME which totals to 546.85 kg CO_2 eq/tonne CPO in the

continued land-use change scenario. The biogas emission alone accounts for about 56%

of the total CO_2 emissions of 970.58 kg CO_2 eq/tonne CPO. When biogas is captured, the

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Analysing 1 tonne 'CPO (NO LUC wth Biogas Capture)May 2010'; Method: Eco-indicator 99 (H) V2.03 / Europe EI 99 H/A / weighting CPO (NO LUC wth Biogas Capture) May 2010 FFB production (Continued land use) May 2010 Empty Fruit Bunch Palm Oil mill effluent (biogas harvested) 85(%) no recycling savings 28m3 Mesocarp fibre Boiler Ash2 Water for boiler & process at POM Reinforcing steel, at plant/RER U Fibre cement corrugated slab, at plant/CH U Steel low alloy ETH U Tractor, production/CH/I U Electricity Malaysia Electricity generated at POM Traction Truck 28t B250 Carcinogens Resp. organics Resp. inorganics Climate change Radiation Ozone layer Ecotoxicity Acidification / Eutrophication Land use Minerals Fossil fuels

Figure 4 Weighting for LCIA of 1 tonne of CPO – continued land use, biogas capture.

total drops to 505.76 kg CO_2 eq/tonne CPO. This shows the urgency and need for the

palm oil mills to capture their biogas and use it as renewable energy.

5 Future trends and conclusion

To date, environmental management has been more for image purposes. However,

in recent developments, with a shift towards wanting a 'greener' earth, environmental

demands are becoming marketing tools. Consideration for the environment is becoming

a determining factor for the use of products. In view of the current shift towards higher

environmental demands from customers as well as the emergence of eco labels, the need

for the oil palm industry to also shift in parallel with the current trend is unavoidable.

The main hotspots along the system boundary are land use at the plantation and biogas

emissions at the palm oil mill. Land use in Malaysia is rather complicated as land issues

are governed by the state government of the respective states. Even though most of

the oil palm plantations in peninsular Malaysia have continued land-use change, new

developments in Sabah and Sarawak are cleared from logged-over forest. The oil palm

industry must somehow strive to strike a balance by increasing production and productivity

rather than land expansion. This is easier said than done. The oil palm industry is also moving towards biogas capture or methane avoidance by the year 2020 under the efforts

by the Malaysian government which shows a very positive step towards overcoming

an important environmental burden. LCA is a tool that helps not only to identify the

environmental burdens along the supply chain but also to improve the environmental 0 200 400 600 800 1000 1200 Biogas Emission Biogas Capture(85%)

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O Palm Oil Mill Nursery and Plantation (OP to OP)

Figure 5 The GHG emissions for 1 tonne of CPO (nursery-plantation continued land use from oil palm

to oil palm and palm oil mill with allocation).

performance of the product. This case can be seen in the Malaysian oil palm industry

moving towards methane capture or avoidance based on the findings of the national LCA

study conducted by MPOB. Under the Economic Transformation Programme (ETP) which

was launched by the Government of Malaysia in 2011, palm oil was identified as one of

the National Key Economic Area (NKEA). Under this NKEA entry point project 5 (EPP5)

envisages that all POMs in Malaysia will have a biogas capture facility in place by the year

2020 (Pemandu 2011).

6 Where to look for further information

More details of the NKEA EPP5 on biogas capture can be obtained in the ETP website

http://etp.pemandu.gov.my/Palm_Oil-@-Palm_Oil_-%E2%97%98-_Rubber_-_EPP_5-;_

Developing_Biogas_Facilities_at_Palm_Oil_Mills.aspx

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12 Chapter 12 Modelling environmental impacts of agriculture, focusing on oil palm

1 Introduction

Most people involved in the production, use and consumption of agricultural products,

including palm oil, are interested in reducing or eliminating adverse environmental

impacts of cultivation while maintaining or improving productivity. To do that we

need to know what the impacts are, and predict how they will respond to changes

in land use and management. Environmental impacts occur through movement and

transformations of energy and materials. In an ideal world, we might monitor all these

processes, but that is simply not feasible. We therefore need to estimate them, and this

involves models.

Models are simple abstractions of complex systems and always involve a trade-off

between complexity and comprehensibility. All of our understanding and knowledge of the

environment is in fact in the form of models, because we must simplify the system to make

sense of it. The better we understand systems, that is, the better our conceptual models,

the more likely we can quantify them and describe them with mathematical relationships.

A theoretically ideal model for a question might describe all the important processes

mechanistically across space and time, be initialised with easily measured parameters and be simple to process. However, that ideal is not realistic because of the complexity of the

environment.

What we have is a large and growing collection of models that are useful for many

purposes. Available models simulate some but not all processes and ignore, simplify

or assume others. They also overlap in diverse ways. Many can serve as useful tools for

tackling scientific and practical questions, if their scope and limitations are understood.

The optimal model for any particular purpose is one that includes sufficient complexity

to explain the processes of interest, but no more. The nature of models reflects the

purpose for which they were designed. There are various typical but overlapping purposes

related to environmental impact: developing a fuller understanding of environmental

processes, helping managers make decisions, producing indicators for reporting against

environmental certification criteria, informing policy to help officials plan and regulate

industry, and communication.

Here, we look at modelling of the ways in which cultivation of oil palm influences the

biophysical state of the environment within the field itself and in the wider environment,

in particular via exchanges with the atmosphere and hydrosphere (Fig. 1). Understanding

the environmental impacts of oil palm is essential because it is a globally important crop,

especially in the humid tropics, and is rapidly expanding

(Sayer et al., 2012). The area

of oil palm plantations grew by 680 000 ha/year worldwide over the 2005–2013 period

(FAOSTAT, Accessed 2016) and further expansion is expected (Corley, 2009). To put that

growth in context, it is slower than soybean and rice (2 311 000 and 1 306 000 ha/year over

the same period), but faster than rubber and cocoa (224 000 and 220 000 ha/year), which

are crops grown in similar areas.

The key issues for modelling environmental impacts of agriculture, including oil

palm cultivation, are choice of modelling approach, definition of the system and

key parameters (Section 2), providing useful outputs through integration of our

understanding (Sections 3 and 4) and accurate modelling of the causal processes

(Section 5). Finally, we summarise the information and make some suggestions about

future trends in research and where to look for further information (Sections 6 and 7).

We focus on process-based models that have been used in oil palm, but also touch on

conceptual and empirical models and relevant models that have not yet been applied

to oil palm but could be.

Figure 1 Cultivation of crops, including oil palm, impacts upon the environment through movement of

energy, materials and organisms (arrows) between the field and the atmosphere, aquatic ecosystems

and surrounding terrestrial ecosystems, and within the field itself.

2 Characteristics of models and the system

Environmental impacts of agriculture, and oil palm cultivation in particular, are diverse.

Therefore, when modelling, it is important to be clear about the question being asked.

Different questions must be tackled in different ways. Modellers have considered

different dimensions and scales of time and space, and used different conceptual and

numerical approaches, depending on their emphasis, the availability of data and the

understanding of the processes. Several authors have provided useful procedures for

selecting environmental models and evaluating their performance (Jakeman et al.,

2006; Makowski et al., 2009; Bennett et al., 2013; Kelly et al., 2013; Harmel et al.,

2014).

There are two main types of numerical model. On the one hand, there are statistical

or empirical models, which describe relationships between data sets, and range from

simple regressions to neural networks. They are useful for making predictions but because

they are a ‘black box’, not relying on mechanisms or causality, they are limited in their

predictive capacity outside of the conditions under which they were developed. On the

other hand, there are ‘physically based’, ‘deterministic’, ‘mechanistic’ or ‘process-based’

models, which are usually also ‘dynamic’, having a temporal dimension. They are based on understood causal relationships. The predictive capacity of models generally increases as

they become more complex and incorporate more parameters (Fig. 2). The two must go

together. There is no point in measuring many parameters if they cannot be incorporated

into a model, nor is there any point having a complex model if there are insufficient data

to run it.

For problems involving a high degree of uncertainty, models that incorporate probability

functions can be useful (Aguilera et al., 2011). For example, Bayesian networks, which are

based on probability of one event leading to another, have been used to model ecosystem

services (Landuyt et al., 2013), nutrient exports from agricultural areas (Nash et al., 2013;

Figure 2 Schematic diagram of the relationship between model complexity, data availability and

predictive performance (reproduced from R. Grayson and G. Blöschl, Spatial Patterns in Catchment

Hydrology, Cambridge University Press, 2001, with permission from Cambridge University Press).

Lucey et al., 2014) and habitat suitability (Hamilton et al., 2015). However, in this chapter

we focus on numerical rather than probability-based models.

No matter how sophisticated numerical process-based models are, or how well

they model a particular set of circumstances, they are never a perfect representation

of reality. Process-based models commonly incorporate relationships that were

determined empirically. There is also error involved in determining correct values for

parameters. Therefore, for any particular problem and situation, we might expect an

optimal model complexity (Fig. 3). Complex models are constructed by combining

simpler models, and it follows that model accuracy will be limited by the weakest

component.

Models can operate in one, two or three dimensions and at different temporal resolutions.

Those operating in two or three dimensions are often called ‘distributed’ or ‘lumped’.

Distributed models explicitly model lateral or vertical processes, whereas lumped models

assume processes are uniform within given areas. For both, the scale should match the

problem being tackled. As for time, some problems might be tackled adequately at coarse

timescales such as a year, but others need daily or finer resolution to provide a useful

representation of reality.

Impacts on the atmosphere are felt at a global scale because of the relatively well-mixed

nature of the atmosphere. Consequently, global climate models and earth system models

operate in two or three dimensions across the earth’s surface. However, they derive

inputs from, or link to, agricultural systems via one-dimensional models of the soil–plant–

atmosphere continuum operating with lateral resolution of fields to regions.

Impacts on aquatic ecosystems occur in the field, downstream of it and perhaps also upstream, due to effects on the movement of organisms. Thus, aquatic ecosystem

impact models may operate at various scales and dimensions, from one-dimensional

to three-dimensional. In general, the effects of agricultural land use tend to accumulate

downstream due to an increase in proportion of water that has passed through

agricultural fields. However, the impact of disturbance at points (e.g. road crossings and

mill outfalls) may diminish downstream and, once the estuary is reached, the effect of

the sea becomes important. The direct effect of shading is essentially one-dimensional,

Figure 3 As models become more complex, systematic error (i.e. error from the assumptions made)

tends to decrease and calibration error (resulting from limited knowledge about the necessary

parameters) tends to increase.

although distributed along stream reaches, whereas nutrient movements and effects

must be modelled in two or three dimensions due to downward leaching through the

soil, lateral movement through groundwater and discharge into surface water bodies.

Quality and ecology of the groundwater may also be important, especially when it is used

for drinking water.

Terrestrial impacts are felt in surrounding ecosystems and in the field itself (Fig. 1).

Impacts on the surrounding ecosystems tend to be proportional to size and distribution of agricultural fields, reaching negligible levels at distances from fields that are beyond the movement range of organisms and groundwater. Therefore, such models tend to be two- or three-dimensional. Models of in-field soil processes and quality tend to operate in the one-dimensional soil–plant–atmosphere continuum, but lateral variability and movement of materials and organisms may also be taken into account.

Models need parameters that adequately describe the characteristics of the environment, crop and management practices. The greater the availability of data and the more complex the model, the greater the predictive power (Fig. 2). To satisfactorily define parameters, modellers need to know and understand the key factors controlling the processes of interest. Or, on the other hand, models may help researchers find out which are the most important parameters. Models differ in the types of parameters they require, the ways in which the parameters are measured or estimated, and the ways in which they have been calibrated and evaluated (Mulligan and Wainwright, 2013a).

To define characteristics of the oil palm system, it is helpful to recognise that it has some characteristics in common with other cropping systems and others that are unique. Characteristics of oil palm systems are described in detail by Corley and Tinker (2016), but we briefly outline some key features here.

Key climatic characteristics of the system are related to the high temperature and water requirements of oil palm. Radiation tends to be high due to low latitude, although cloud cover can reduce it significantly. Day length varies little, but may affect flowering. Seasonal and daily temperature ranges are also limited, but are important for regulating the rate of processes (e.g. Wang et al. 2014), especially at higher altitudes or latitudes. Rainfall is usually greater than evapotranspiration for much of the year, leaving considerable surplus water available for surface run-off or deep drainage. High-intensity rainfall events mean timescales for modelling generally need to be short to adequately model water-related processes. Irrigation is practised in some places where long periods of water deficit impact on production. While appropriate historical climate data is an essential requirement for modelling, the availability and quality of such data is often limiting.

Key physical characteristics of the system are mostly determined by the climate and topography of tropical lowlands chosen for plantations (Paramananthan, 2011). Topography tends to be flat, often with shallow water table. However, steeper areas are also planted and topography is important for processes such as erosion. The maximum recommended slope is around 20–25°, although steeper slopes have been planted. Terracing is generally practised on slopes steeper than 6–10°.

Soils are typically deep, highly weathered and acidic, with low nutrient holding capacity

and high permeability. However, there is also considerable variation, with excessively

or poorly drained, shallow, stony, saline, sodic or acid sulphate conditions all existing

in plantations. These soil characteristics all affect environmental processes. Most soils

are ‘mineral’ soils with topsoil organic matter contents typically <10%. However, organic

soils or peats, which occur in waterlogged areas and have organic matter contents >65%,

are also important because of the extensive areas planted with oil palm in Malaysia and

Indonesia. Koh et al. (2011) demonstrated that 6% (or ≈880 000 ha) of tropical peatlands

in the region had been converted to oil palm plantations by the early 2000s. Appropriate

geomorphological and soil data are an essential requirement for modelling many

processes.

Infrastructure, especially drainage and road systems, is also an important feature of the

physical environment. Networks of earth and gravel roads are relatively dense in oil palm

systems, and have a large influence on the movement of water and wildlife, as do drains.

Road density and related erosion tends to increase with slope.

The oil palm crop itself has particular key features. It comprises palms at a density of

120–150 ha^{-1}, groundcover vegetation and areas kept bare for harvesting and access. The palms are planted as seedlings, grown to maturity (full canopy cover) by about five years of age and then continued to grow until they are cut down at about 25 years of age. Most oil palm is the ‘tenera’ type of Elaeis guineensis Jacq., a hybrid between ‘dura’ and ‘pisifera’ types. However, hybrids between E. guineensis and E. oleifera are increasingly planted in America (Corley and Tinker, 2016). Corporate plantations are generally managed in field blocks of 25–30 ha, surrounded by roads, whereas smallholder fields may be as small as 2 ha. Intercropping is common in smallholder fields during the immature phase but is not common in corporate plantations. The land use preceding oil palm is also important for many environmental processes. The previous crop may be oil palm, but due to the rapid expansion of the industry, most current oil palm was preceded by a different land use, typically forest, grassland, food crops or other commodity crops such as cocoa, rubber or coconuts.

Finally, models must consider key management practices. The most intensive management is undertaken during the establishment phase, which involves clearing and windrowing (sometimes burning) the existing vegetation, and forming of roads, drains and terraces. Considerable amounts of soil and surface organic matter can be eroded during this phase. The fields are then planted with palms and legume cover crop. The main materials applied are fertiliser (mostly urea or ammonium-based fertilisers and potassium chloride), the palm oil mill by-products–empty fruit bunches (especially around young palms and in fields close to the mill), liquid effluent and increasingly compost, and herbicides (to the harvest paths and weeded circles). Fruit bunches are removed in regular harvests, and old fronds are pruned regularly and placed in heaps between planting rows.

3 Integrated environmental impact modelling approaches

The main approach to quantifying all environmental impacts of the production of a particular agricultural product such as palm oil is life cycle assessment (LCA) (Fig. 4). LCA is, in a sense, an integrated model of environmental impacts, so we discuss it here. As for dynamic process-based models, 'earth system models' are in principle the most integrated. However, earth system models tend to focus on the atmosphere and do not yet incorporate many of the processes that are important in agricultural systems. Models that do so can be classified as 'agricultural (eco)system' models, 'catchment process' models or 'ecological' models. All these integrated approaches incorporate or couple simpler models, which we discuss further in subsequent sections. Ecological models tend to focus on the surrounding terrestrial ecosystems or the field itself so we also discuss

them later.

The challenge of integrating diverse data types, approaches and models increases

even more if social dimensions are included (Granell et al., 2013). Examples include

the SEAMLESS and Forest Land Oriented Resource Envisioning System (FLORES)

projects. The SEAMLESS modelling project, developed in Europe using the MODCOM

framework, is designed to facilitate development of policy (Brouwer and Ittersum, 2010;

Ewert et al., 2011). Agricultural systems are simulated using its Agricultural Production

and Externalities Simulator (APES) approach (Donatelli et al., 2010). The FLORES model

also analyses complex spatial, environmental and social processes (Vanclay et al., 2003).

FLORES was developed within the SIMILE graphical modelling environment (Muetzelfeldt

and Massheder, 2003) to assist in model development and transparency. Within FLORES,

land use decisions are made by ‘actors’ who can be individuals or groups of individuals

who collaborate as families, clans, associations and corporations. These actors can

make decisions to maximise benefits or minimise risks. Outputs are calculated from

models within a spatial context, allowing users to explore impacts at a landscape scale.

Socio-ecological systems have a high degree of uncertainty, so they lend themselves to

modelling approaches based on probability and expert judgement, such as Bayesian

networks (Ropero et al. 2016).

3.1 Life cycle assessment

LCA involves assessment of a suite of environmental impacts throughout the commodity

chain, from raw material production to end-of-life of the product or service, with respect to

a functional unit (e.g. 1 kg of palm oil). As LCA assesses environmental performance across

multiple impacts, such as climate change, acidification and ozone layer destruction, the

weightings can be documented and trade-offs assessed. LCA has become a worldwide

standard method (ISO 14040 series 2000–2006) for reporting on environmental impacts

Figure 4 Integrated biophysical modelling of environmental impacts of agriculture can be categorised

into different approaches: life cycle assessment on the one hand, or dynamic process-based modelling

of the earth system, agricultural systems or catchment processes on the other. Boxes represent typical

system boundaries and modelling focus, and lines represent the principal environmental impacts

modelled.

of production, and is the baseline modelling approach of various greenhouse gas (GHG)

inventory guidelines (IPCC, 2006; European Commission, 2009).

LCA of oil palm products enables assessment of palm cultivation together with other

parts of the production chain. It also facilitates comparisons between production of palm oil and alternatives (Schmidt, 2015). While palm oil generally performs worse than other

oil crops on climate change impact, due in particular to land use change from high carbon

stock systems, it performs better than rapeseed oil regarding eutrophication, acidification,

ozone depletion and photochemical ozone impacts (Schmidt, 2010).

About 70 full or partial LCAs of palm oil products have been published over the last

decade. Most of the published studies were on palm oil as biofuel, and focused on GHG

emissions (or climate change impact) and energy balance (or fossil resource depletion)

(Bessou et al., 2013; Manik and Halog, 2013). They mostly assessed the life cycle for

palm methyl ester or biodiesel, that is, including all processes from background input

production (e.g. fertiliser manufacture) up to the vehicle tank, assuming total combustion

or including engine efficiency, to calculate final energy and GHG indicators.

Palm oil LCAs have indicated that the agricultural phase is the main contributor to most

of the impact, except for human toxicity or respiratory impacts, to which boiler emissions

are the main contributor (Stichnothe and Schuchardt, 2011). Climate change impact is

strongly influenced by fertilisers, especially nitrogen fertilisers, and also by carbon stock

Figure 5 Decision tree for life cycle assessment of a perennial crop system. 'Field' means a unit of

plantation with a unique and homogenous planting date, genotype, climate and soil type. 'Crop cycle stages' generally encompass immature phase, most productive phase and declining production

phase. From Bessou et al. (2013).

changes in case of land use change or peat drainage (Bessou et al., 2014). Eutrophication

impact is driven by nitrogen- and phosphorus-compound emissions, although mill

emissions can also contribute. The main eutrophication factors at the agricultural stage are

nitrate leaching, and phosphorus and nitrate run-off. The acidification and photochemical

ozone impact categories are also influenced by fertilisers, especially due to their influence

on nitrogen compound emissions. The largest uncertainties relate to cultivation of peat

and emissions of N_2O (Schmidt, 2015).

Impacts originating outside the field are also influenced by in-field management

practices, in particular the use of fertiliser. Significant GHG emissions are generated in

the production of nitrogen fertiliser (10–30% of total emissions from fertilisers, compared

to 70–90% generated in the field), in palm oil mill effluent treatment ponds, especially

CH_4 (Wicke et al., 2008; Bessou et al., 2014). Emission factors for the manufacture and

transport of inputs are usually taken from databases such as ecoinvent (Nemecek and

Kägi, 2007, http://esu-services.ch/data/ecoinvent/).

LCA uses various process models to evaluate impacts, and these are discussed below.

Nitrogen management is critical for several impact categories. Perennial cropping systems

can be evaluated in different ways, depending on the objectives and the data available

(Fig. 5).

Several LCA impact indicators remain to be more widely explored in palm oil production

systems. Given the large contribution of fertilisers to environmental impact of the

agricultural phase, the eutrophication and acidification impacts related to nitrogen and

phosphate inputs need to be further investigated. Other indicators that are little studied

include the impacts of herbicides on terrestrial or freshwater ecotoxicity, and the impact of

irrigation systems on water depletion.

3.2 Earth system modelling

Earth system models generally focus on the atmosphere and climate, but are increasingly

including soil-plant-atmosphere and catchment processes (e.g. Krinner et al., 2005; Fatichi

et al., 2012a,b; Oleson et al., 2013; Shen et al., 2013). For example, the Community Earth

System Model (CESM) models climate together with land use, vegetation and catchment

processes in its Community Land Model (CLM) component (Hurrell et al., 2013; Oleson

et al., 2013). A palm growth module incorporating carbon and water cycling was recently

developed for the CESM and tested on oil palm (Fan et al., 2015).

Integrating process-based models to larger scales involves a range of challenges. Such integration is aided by software platforms that facilitate data exchange between models

while maintaining model transparency for developers and users. For example, The Invisible

Modelling Environment (TIME) (Rahman et al., 2003) uses the features of modern software

techniques (Rahman et al., 2004) to simplify the communications interface between model

components within its spatial modelling framework for issues such as catchment hydrology.

3.3 Agricultural system modelling

Dynamic agricultural system models provide a means for exploring environmental impacts

related to water, carbon and nutrient cycles and agrochemicals, especially where several

drivers of the system may interact in complex ways. A series of dynamic simulation models

are used extensively around the globe for various cropping systems. Examples include

Decision Support System for Agrotechnology Transfer (DSSAT-CSM) (Jones et al., 2003),

CropSyst (Stockle et al., 2003), Simulateur mulTIdisciplinaire pour les Cultures Standard

(STICS) (Brisson et al., 2003), APES (Donatelli et al., 2010) and Agricultural Production

Systems Simulator (APSIM) (Holzworth et al., 2014).

These agricultural system models have been developed over several decades to capture

an increasing number of environmental interactions. This development involved a shift of

focus from the crop to the soil resource base and the cropping system. The shift allowed

individual crops to come and go, finding the soil in one state and leaving it in another

(McCown et al., 1995). This move towards a stronger focus on soils was a major step from

plant models to environmental impact models and application to more complex systems,

including perennial crops.

New applications required the modelling of crop management decisions (Moore et al.,

2014). These capabilities also allowed the inclusion of livestock models, and simulations of

farms with multiple fields (Holzworth et al., 2014). This journey has seen a change in focus

such that model use was no longer aimed just at research, but also for management of

production systems and exploration of options for farming systems at various scales (van

Ittersum and Donatelli, 2003).

The APSIM model (Holzworth et al., 2014) is an example of a modern integrated

environmental model that has been applied to oil palm systems. APSIM is developed

and maintained within the APSIM community source framework, which provides a freely

available open source platform for collaborative development. The software design

allows models from different modelling teams and problem domains to be integrated

within a single modelling environment. Furthermore, the framework includes software and

processes, such as the APSIM Plant Modelling Framework (Brown et al., 2014), that assist

in the development of new models.

The APSIM-Oil Palm model (Huth et al., 2014) was developed to communicate with

previously developed and tested models for water, nitrogen and carbon cycling (Probert

et al., 1998), GHG emissions (Thorburn et al., 2010), surface organic matter dynamics

(Probert et al., 1998; Probert et al., 2005) and agricultural management (Moore et al., 2014),

in one dimension. The addition of an oil palm model within existing model capabilities

improved model reliability and facilitated the capturing of complex environmental issues.

For example, soil carbon stocks and nitrogen losses (leaching of nitrate and gaseous

emission of N_2O), along with fruit production, can be estimated in a dynamic manner,

taking into account soil type, climate and management (Fig. 6). This capacity allows trade

offs between production and environmental impacts to be assessed (Pardon et al., 2017).

APSIM-Oil Palm has been validated for growth and yield at several sites (Huth et al., 2014).

Another agricultural system model that has been applied to oil palm is WaNuLCAS

(Noordwijk et al., 2011), which used a different approach to the APSIM-Oil Palm model.

WaNuLCAS was formulated within the STELLA graphical modelling environment.

Development of the oil palm module benefitted from the group’s experience in modelling

agroforestry systems. WaNuLCAS focuses on interactions between crop species and can

incorporate lateral variability in the form of up to four zones.

Adding complexity to dynamic simulation models comes with costs associated with

increased data requirements and calibration error, and decreased ease of use and model

transparency (Soltani and Sinclair, 2015). Many of these concerns are now being addressed

using modern modelling and software engineering processes that ensure model

integrity during ongoing development (Holzworth et al., 2011), encourage collaboration

by simplifying model reuse (Holzworth et al., 2010) and assist model accessibility and

transparency through well-designed user interfaces and automated documentation

(Dietze et al., 2011; Brown et al., 2014).

3.4 Catchment process modelling

Catchment (or ‘drainage basin’ or ‘watershed’) process models are important tools for

examining environmental impacts related to movement water and solutes (e.g. nutrients

and pesticides) and erosion of soil. These processes directly impact on conditions of

the field, groundwater and downstream aquatic ecosystems. These models couple

Figure 6 Measured fresh fruit bunch (FFB) yield (points), modelled yield, soil C stock, N leaching and

N_2O emission (lines) of oil palm at three nitrogen fertiliser rates, over the course of a crop cycle in

Sangara, Papua New Guinea. Modelling was carried out using the agricultural system model APSIM

Oil Palm.

hydrological models with sediment and solute/contaminant models, and in some cases

biogeochemical and ecological models.

The hydrology of oil palm plantations differs to that of other vegetation types, and

changes through the crop cycle. Hydrological changes are particularly large during

establishment, due to clearing of vegetation, use of heavy machinery, compaction,

loosening and creation of bare areas during formation of terraces and roads. Changes are

also large, although less dramatic, during the immature phase, when palm canopies and

root systems are growing. The presence of roads and oil palm waste from factories and

human settlements in plantations also contribute to water quality degradation in these

areas (Comte et al., 2012).

Physically based catchment-scale models are ‘distributed’, dividing the catchment

into elements. This distribution is discussed below, in the discussion of the underlying

hydrological models. A variety of integrated catchment models have been developed

and used (Table 1), and the field is rapidly developing (Robson, 2014a; Paniconi and Putti,

2015). Most of the models do not consider redistribution of soil within the landscape,

although some do like LandSoil (Ciampalini et al., 2012).

An integrated surface water and groundwater model such as MIKE SHE/MIKE 11

simulates the major hydrological processes at different levels of spatial distribution and complexity within the catchment. Groundwater, surface water, recharge and

evapotranspiration are represented by MIKE SHE, whereas channel flow is represented

by the MIKE 11 component of the model. The model also predicts solute transport

in the unsaturated and saturated zones. This involves modelling advection and

dispersion of solutes in the unsaturated and saturated zone, sorption and desorption

processes, erosion and sediment transport (coupled with a sediment transport model),

geochemistry reactions for groundwater transport (Geochemistry module) and

agricultural applications such as crop yield and nitrogen consumption (MIKE SHE DAISY

module).

Complex process-based catchment models such as MIKE SHE require large

amounts of data, which is often not available, so simpler catchment models are often

used. For example, the SedNet/ANNEX model, developed for catchments of the

Great Barrier Reef in Australia, models flux of sediment, N, P and herbicides using

a modular empirically based approach (McKergow et al., 2005; Waters et al., 2014;

Wilkinson et al., 2014). Sediment sources are apportioned to hill slope erosion (using

the Revised Universal Soil Loss Equation, RUSLE), gully erosion and stream bank

erosion, and solutes are apportioned to point and diffuse dissolved sources. Budgets are calculated for subcatchments and stream links. SedNet/ANNEX is being used to

model the effects of changed agricultural management practices on pollutant loads

(Hateley et al., 2014).

So far, published literature on hydrological and solute/sediment modelling of oil palm

plantations are few and limited to hydrological impacts. Modelled oil palm run-off yields

have been compared with tropical rainforest run-off yields using the HEC-HMS model

(Yusop et al., 2007). The Soil and Water Assessment Tool model (SWAT) was used to model

run-off yield changes in oil palm at different stages of growth (Majid and Rusli, 2014) and

to compare run-off with other biofuel crops (Babel et al., 2011). Integrated hydrological

and sediment/solute models such as SWAT and MIKE/SHE provide opportunities to better

understand the hydrological and water quality impacts of oil palm plantations, and there is

potential to couple them with agricultural system models such as APSIM to model impacts

of different management practices.

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4 Modelling impacts of cultivation on components of

the environment

Integrated environmental impact models usually couple models focused on particular

components of the environment (Fig. 7). Concerns about climate change have driven

development of increasingly comprehensive and sophisticated models of atmospheric impacts, highly integrated in terms of the processes modelled. Modelling of impacts on aquatic ecosystems, surrounding terrestrial ecosystems and the field itself is not so developed, but our understanding of the processes is rapidly improving.

4.1 Modelling impacts on the atmosphere

Atmospheric impacts are felt via the net emission of the greenhouse gases CO_2, N_2O and CH_4; ozone; and haze-causing volatile organic compounds, smoke, dust and other particulates. Here, we do not consider ozone or haze, which originates mostly from burning during forest clearing, but focus on GHGs. Atmospheric impacts are modelled so as to better understand effects on climate. Conversion of land to agriculture may directly influence climate through decreased evapotranspiration and hence reduced rainfall. However, this effect is unlikely to be significant with oil palm because its transpiration rate is similar to intact forest (Henson, 1994), so the main concerns are related to GHG emissions.

To meet the requirements of the United Nations Framework Convention on Climate Change (UNFCCC) treaty, countries must report their annual GHG emissions. That accounting is based on the Intergovernmental Panel on Climate Change (IPCC) methods and thus involves various models. Most of the countries with an oil palm industry are classed

Figure 7 Modelling may simulate processes impacting upon a particular component of the environment

(ellipses). That involves different system boundaries and characteristics (rectangles) and different types

of exchanges (arrows and italic labels).

as developing economies and are given special status under the treaty as ‘non-annex’

parties. Nevertheless, palm oil producing countries such as Indonesia and Malaysia are

developing carbon accounting procedures (INCAS and MYCarbon, respectively).

Parallel to, and sometimes contributing to, the development of global accounting

systems, numerous process-based models have also been developed to simulate effects

of land use on the atmosphere. The global earth system models have been compared in

the Climate Modelling Intercomparison Project Phase 5 (CMIP5) and reviewed in the fifth

Assessment Report of the IPCC (Flato et al., 2013). In some cases they assess management

practices as well as land use, by incorporating various crop system, carbon and nitrogen

models, discussed in subsequent sections.

GHG emissions are usually modelled using the guidelines of the IPCC (IPCC, 2003,

2006, 2014). The IPCC approach offers several methodological approaches, which differ in

complexity. The ‘Tier 1’ methodology, the one most commonly employed in oil palm LCAs,

uses a coarse spatial scale for land use, specified emission factors and a specified timeframe for amortisation if land use changes, that is, an empirical linear model. 'Tier 2' involves locally

relevant emission factors, and 'Tier 3' methods involve the use of more sophisticated models

(discussed in Section 5, under carbon and nitrogen models), if data are available.

The two main considerations in GHG emission models are whether or not land use

change is incorporated and whether cultivation occurs on drained peat soils or mineral

soils. Net CO_2 and N_2O emission take place when there is a net decrease in organic

matter in the soil-plant system, which occurs most dramatically where oil palm replaces

vegetation with higher biomass and net primary production, such as forest, or when it

is established on peat soils. The amount of carbon in above-ground biomass is about

3–10 t ha^{-1} in annual crops and grasslands, 37–42 t ha^{-1} in oil palm (average over cycle)

and 50–300 t ha^{-1} in tropical forests (Lewis et al., 2013; Lucey et al., 2014; Khasanah et al.,

2015a). Establishment on peat entails drainage, which results in net mineralisation of the

peat and release of huge quantities of CO_2 . On the other hand, there is net sequestration

of CO_2 when oil palm replaces vegetation with lower net primary production, such as

grassland (Goodrick et al., 2015).

The effects of land use change on GHG emissions have been modelled in different ways.

Some studies that do not model it directly nevertheless provide information on the 'carbon debt' or 'payback time'. This carbon debt, initially developed in the context of bioenergy,

considers the time needed for a bioenergy value chain to compensate for the initial land use

change-related GHG emissions, given its GHG savings compared to the fossil equivalent

(Fargione et al., 2008; Gibbs et al., 2008). It ranges from 8 to 169 years for palm biodiesel,

with mean and median values of 54 and 43 years, respectively (Fargione et al., 2008; Wicke

et al., 2008; Pleanjai et al., 2009; Achten et al., 2010; de Souza et al., 2010; Harsono et al.,

2012). The type of previous land use can determine the final GHG balance.

The IPCC approach to modelling effects of land use change assumes that the net flux

of CO_2 to the atmosphere equals the difference between the original stock of carbon

in biomass and soil and the stock in the new land use. The first-order approximation

(Tiers 1 and 2) is to multiply the original stock, which depends on soil and climate type,

by 'emission factors' specific to the type of land use and land management. The method

operates on the annual time scale required for national reporting of GHG emissions, but

measurements or estimates might be done less frequently. There are additional guidelines

for calculating N_2O and CH_4 emissions.

GHG emissions from conversion of peatlands to plantations consist of both CO_2 and N_2O

emissions, due to the large amounts of organic carbon and nitrogen that are microbially mineralised when oxygen enters the drained peat. Changes in aeration may also affect

methanogenic processes. The IPCC provided guidelines for modelling emissions of GHGs

from converted peats and other wetlands in its 2013 supplement (IPCC, 2014). There

is a linear relationship between water table depth and carbon loss from drained peats,

although other factors are also important (Carlson et al., 2015).

After land use change, the second largest contributor to GHG emissions are N_2O

emissions. They are largely related to nitrogen inputs to the soil-plant system, especially

fertiliser. For emission of N_2O unrelated to land use change, the IPCC (2006) provides Tier 1

factors for 'direct emissions' from the field and 'indirect emissions', which occur elsewhere,

after the nitrogen has left the field. For direct emissions the factor of 1% is multiplied by

the amount of nitrogen applied in fertiliser or crop residues. The same emission factor is

applied irrespective of soil type or other factors. This emission factor was derived from a

statistical analysis based on several hundreds of field measurements across the world and

it hides large variability in practices and emissions.

However, tropical and perennial crops were poorly represented within the field

measurements used for the statistical analysis (Bouwman et al., 2002a,b; Stehfest and

Bouwman, 2006), so the factor does not take into account important characteristics of perennial cropping systems such as oil palm (Bessou et al., 2013; Pardon et al., 2016a).

For indirect N_2O emissions the factors are modified to account for nitrogen lost from the

field via volatilisation and leaching. The proportion of nitrogen volatilised is set at 10% for

synthetic fertiliser and 20% for organic fertiliser. The proportion of nitrogen leached is set

at 30% unless specific conditions of water stress or precise irrigation can be demonstrated.

The indirect N_2O emissions from these sources are then calculated as 0.75% of the leached

nitrogen and 1% of the volatilised nitrogen.

In PalmGHG, a GHG calculator designed especially for the oil palm system, GHG

emissions are calculated along the value chain according to the LCA approach, that is,

emissions from fertiliser production and transport, land use change and peat drainage,

field and mill fuel and electricity use, fertiliser application and palm oil mill effluent (Chase

et al., 2012; Bessou et al., 2014). Land use change and fertiliser application-related

emissions, as well as N_2O emissions from peat drainage, are calculated based on the IPCC

Tier 1 method. In contrast, CO_2 emission from peat drainage is based on an emission

factor related to the water table level (Hooijer et al., 2010), which allows more sensitivity

to drainage practices than the IPCC Tier 1 method.

Although we focus here on the effects of oil palm cultivation, it is worth briefly mentioning

other atmospheric impacts in the palm oil production chain.

The impact of palm oil mill effluent treatment on the overall GHG emissions has been investigated by several authors (Yacob et al., 2005; Vijaya et al., 2009; Basri et al., 2010). Methane emissions vary greatly depending on seasonal variations in fruit quality and technical features of mill operations and ponds. GHG assessments mostly rely on derived emission factors based on a few published studies (Yacob et al., 2005; Schmidt, 2007). Based on UNFCCC equations, methane emissions may also be derived from on-site measurements of the chemical oxygen demand reduction during treatment. Considerable emphasis has been placed on reducing these emissions by capturing the biogas at the mill (Choo et al., 2011; Harsono et al., 2014) or by using raw or partially treated effluent in the composting process (Singh et al., 2010; Stichnothe and Schuchardt, 2010).

The impact of fossil fuel use is generally not significant, being 0–5% and 0–2% of total emissions at the field and mill levels, respectively (Bessou et al., 2014). This low impact is due to a low level of mechanisation in the plantations and the use of mill by-products for generating heat and electricity. Most field fuel use is dedicated to fruit transport from plantations to the mill, and its relative contribution varies according to logistics and geography. The high ratio of energy output:input in oil palm systems is matched by very few other agricultural systems (Henson, 1994).

4.2 Modelling impacts on aquatic ecosystems

Impacts on aquatic ecosystems are challenging to model because they involve a complex of processes and events that occur in both nearby and remote ecosystems (Robson, 2014a; Davis et al., 2017). They are influenced by conditions and activities upstream, which are moderated by normal stream discharge and flood events. They are also influenced by connectivity to downstream ecosystems and the marine environment via the migrations of fish and invertebrates up- and downstream. These biological and physical connections between aquatic systems need to be considered before impacts from surrounding terrestrial environments can be modelled.

The riparian zone along the banks of watercourses directly influences the physical characteristics of streams. Natural riparian zones are generally heavily vegetated, due to reliable water supply, and they provide many key services to aquatic ecosystems (Fig. 8), so maintaining their biodiversity and biomass is critical to maintaining near-natural functioning of streams in oil palm landscapes (Singh et al., 2015). Riparian vegetation modifies the flow of water from the land to produce a complex of abiotic and biotic outcomes (Gurnell et al., 2012; Zhang et al., 2012). Sediment and nutrient transport and their delivery to streams are modified (Cooper et al., 1987; Zhang et al., 2003), and plant root systems help bind stream banks and reduce erosion (Kui et al., 2014). The shade provided by

overhanging vegetation acts as a major moderator of stream temperature (Moore et al.,

2005; Kristensen et al., 2013) and influences the pattern of light and temperature in the

water column, which in turn increases in-stream habitat diversity (Naiman et al., 1993) by

producing a mosaic of water conditions.

Riparian vegetation also provides vital sources of food and habitat for in-stream fauna

via detritus, fruit and insects that fall into streams (Gregory et al., 1991) and through

Figure 8 Summary of the services provided by riparian zones to aquatic ecosystems.

the feeding migrations of aquatic fauna into riparian areas during overbank flooding

(Welcomme, 1988; De Graaf, 2003). This provision of food helps support high faunal

diversity (Gregory et al., 1991). Fallen trees from the riparian zone are vital contributors to

in-stream structure (Acuña et al., 2013), substantially enhancing the health and diversity of

stream ecosystems (Boyer, 2003). Fallen timber provides structural complexity in streams

(Caddy, 2008) and furnishes vital habitat for structure-dependent species (Sheaves, 1996;

Valente-Neto et al., 2015), and traps and retains detritus in high-flow streams (Wantzen

and Junk, 2000).

While intact and sufficient riparian buffer zones are critical to isolating aquatic systems

from many of the impacts of oil palm, their value is circumvented where they are too

damaged or narrow to be effective (Singh et al., 2015), or where drains flow directly to

streams from plantation mill effluent outfall systems. Similarly, their value is reduced where

drainage works lead to the loss of swamps, peatlands and ephemeral wetlands (Anderson,

2008; Comte et al., 2012).

While there have been relatively few investigations of physical processes specific to the

oil palm–aquatic ecosystem link, individual physical processes have been quantified in

particular locations. For instance, Carlson et al. (2014, 2015) showed that some streams

draining oil palm plantations have elevated temperatures and increased total suspended

solids concentrations. Such quantitative data are amenable to modelling, at least on a

parameter-by-parameter basis. However, such results are likely to be very site- and

situation-specific (Chew and Goh, 2015), limiting the value of any models constructed.

Most quantitative models of physical processes that are relevant to the oil palm–aquatic

ecosystem situation have been developed in other systems or other parts of the world.

Where oil palm-specific studies have been conducted, the majority have been at the local

scale (Comte et al., 2012), with a few studies conducted at a watershed scale (but see

Yusop et al., 2008 for an example of a small-scale watershed study). Relevant studies

generally focus on the volume and quality of water moving into surface water bodies and

the physico-chemical nature of those water bodies (e.g. Comte et al., 2012).

Modelling becomes more complex with movement away from simple parameter-by

parameter models to more realistic modes that include the diverse interactions among

physical processes, and between physical and biological factors (Robson, 2014a,b;

Janssen et al., 2015). Examples of these interactions include the simple effect of riparian

vegetation shading on water temperature (Moore et al., 2005; Kristensen et al., 2013),

and the impact of converting riparian zones from natural forest to oil palm on surface

hydrology, which in turn changes the type and amount of sediment, woody debris and

terrestrial-derived food (insects, fruit, leaves) and nutrients entering aquatic food webs

(Bruijnzeel, 2004; Comte et al., 2012). This complexity is exacerbated by substantial and

unquantified spatio-temporal variation (Comte et al., 2012; Chew and Goh, 2015).

Biological understanding of the effect of oil palm on aquatic ecosystems is in its infancy.

There have been studies of impacts on aquatic insects in Malaysian rainforest streams

(Mercer et al., 2014) and fish in Papua New Guinea (Nelson et al., 2010b), but little or

no generalisation across oil palm areas. Therefore, ecological models of the relationship

between oil palm cultivation and aquatic environments are qualitative and mostly based on studies from other parts of the world. Although tropical systems are unique in many

respects (Gupta, 2011), most of the broader ecological understanding of streams and their

riparian zones probably still applies (Boulton et al., 2008). Holistic models are needed that

take into account characteristics of the environment, characteristics of the oil palm, the

human dimension and management practices.

There are aquatic ecosystem impacts of palm oil production other than those resulting

from cultivation practices. They include direct impacts, such as degraded water quality at

mill outfalls and eutrophication in streams resulting from excess nutrient inputs, and less

direct effects such as road crossings and gravel extraction for road building, which can

greatly increase turbidity in streams.

These impacts reduce the habitat quality of streams for key parameters such as turbidity

(Henley et al., 2000) and dissolved oxygen (Wannamaker and Rice, 2000). Other indirect

impacts stem from the food and space requirements of local human populations, which

are increased by oil palm developments. These impacts are manifested in harvesting of

edible aquatic organisms and clearing of riparian zones for cropping.

To effectively model the impacts of oil palm cultivation on aquatic ecosystems it is critical

that more extensive, more spatially representative and more holistic data are amassed.

Developing empirical models without substantive underpinning data is dangerous because

there is no way to understand either sources of error or spatio-temporal variability (Harris

and Heathwaite, 2012) or identify tractable components of the causal thicket underpinning

outcomes (Levin and Stunz, 2005). In the data-poor meantime, probability-based models

show promise for modelling some impacts on aquatic ecosystems (Death et al., 2015).

4.3 Modelling impacts on surrounding terrestrial ecosystems

Oil palm plantations influence the ecology of nearby terrestrial ecosystems, mainly through

their effects on populations and movement of organisms (Fig. 1). The degree of effect is

related to the relative size and positions of plantations, natural areas and human activity

(Foster et al., 2011), which determine size, quality and connectivity of habitat. There is

much debate about how conservation and agricultural productivity can be optimised

within landscapes (Sayer et al., 2012). Modelling of the interactions suggests that fewer

more contiguous areas of oil palm and natural vegetation have a less detrimental effect on

biodiversity than finer-scale mosaics of agricultural land and natural habitat (Phalan et al.,

2011; Lee et al., 2014).

At a global level, several conceptual models have been proposed to understand the

nature of these types of interactions (Tscharntke et al., 2012). It is clear that effects differ

between types of organisms (Phalan et al., 2011; Newbold et al., 2014). Such modelling should also include the effects of increased human populations associated (directly or not) with oil palm developments, especially their hunting, fishing and clearing of surrounding forest for food crop cultivation.

Oil palm plantations can also affect nearby terrestrial ecosystems via their effect on movement of groundwater and gases. Lowering of the water table with drains in low-lying plantations can lower the water table in neighbouring ecosystems, but mitigation of the effects using dams is possible. The effects can be modelled using standard hydrology models (Jaenicke et al., 2010), but the high permeability of peat must be taken into account (Baird et al., 2017). Concern has also been raised that terrestrial ecosystems downwind of oil palm plantations might be adversely affected by ozone produced by the reaction of N_2O and volatile organic compounds produced in the plantations (Hewitt et al., 2009).

4.4 Modelling impacts on in-field environmental quality

In-field environmental quality can be described as the abundance, diversity and nature of organisms (above- and below-ground) and the physico-chemical condition of the soil. High quality can be defined as soil conditions and organisms that are conducive to abundant and diverse plant growth and have no negative impact on other components of the environment (Fig. 9). There are no models that integrate all the effects of agricultural management on in-field environmental quality, but there are many modelling approaches

for various processes.

As for all agricultural systems, oil palm plantations have less biodiversity than the natural

systems they have replaced. Species richness and biomass at all trophic levels is lower than

primary forest due to lower net primary productivity and plant diversity (Henson, 1994; Sayer

et al., 2012; Barnes et al., 2014). Empirical modelling of bird, beetle and ant populations

showed that the larger-bodied species of higher trophic levels are most reduced in oil

palm compared to forest, whereas the relatively few species that are more abundant in

plantations tend to be smaller and from lower trophic levels (Senior et al., 2013). However,

ant populations and species numbers are also much reduced (Fayle et al., 2010).

The abundance and diversity of organisms are determined by energy inputs and habitat.

For above-ground organisms, such as insects and arthropods, habitat diversity within the

plantation, especially epiphytes and groundcover, appears to be a significant driver of

diversity (Koh, 2008; Fayle et al., 2013). The amount and proximity of natural forest in

the surrounding landscape is important for more mobile organisms like butterflies, birds

and mammals (Koh, 2008; Jennings et al., 2015; Prescott et al., 2016). The ecology and

management of weeds, pests and diseases, which is much better studied, is discussed further in this book.

Abundance and diversity of soil organisms are determined by inputs of plant residues

and physico-chemical properties of the soil (Carron et al., 2015a,b, 2016; Wakelin et al.,

Figure 9 Key interactions (dark red arrows) between oil palm growers, cultivation practices, soil

properties and soil functions. Soil is the place where there is a maximum degree of interaction between

the lithosphere, hydrosphere, atmosphere and biosphere.

2016). Soil physico-chemical condition can be quantified by fairly stable properties such

as texture and mineralogy, and by more dynamic characteristics such as the organic matter

content, pH, structure and content of toxic contaminants. Soil organic matter (or carbon)

content, accumulation of pesticides and other toxic materials and erosion are discussed in

other sections, so here we focus on soil structure and pH. Measurements of soil condition

in oil palm plantations must take into account the large spatio-temporal variability inherent

in them, and methods are now available to do that efficiently (Nelson et al., 2015a).

Soil structure is enhanced by the faunal activity associated with high inputs of organic

matter and is degraded by erosion and compaction. Compaction processes have been

modelled but the models have limited applicability in complex heterogeneous systems

(Hamza and Anderson, 2005), and simple, well-known empirical relationships can be

applied to management. Compaction and sealing can be minimised by minimising the

number of passes by machinery; reducing pressure on soil either by decreasing axle load

and/or increasing the contact area of wheels with the soil; confining traffic to fixed tracks

(using uniform axle widths); and maximising plant growth, including groundcover, and

inputs of residues.

Soil pH tends to decline naturally in wet climates but the decline can be accelerated

by agricultural management practices. Oil palm is tolerant to low pH, and the associated

high availability of aluminium and low availability of calcium, magnesium and potassium.

Therefore, accelerated acidification is not necessarily noticed or of concern in oil palm

plantations. Nevertheless, it can be considered a detrimental environmental impact. The

main drivers of soil acidification in oil palm are nitrate leaching and the off-take of non

acidic cations in harvested fruit (Kee et al., 1995; Nelson et al., 2010a; Dubos et al., 2016).

Crop system models simulate these processes, so they are potentially useful for modelling

soil acidification (Nelson et al., 2015b).

5 Modelling causal processes

Environmental impact models are based on models of causal processes. Energy enters the

field as light, which is used to convert CO_2 and water to organic compounds, and eventually

dissipates as heat. Energy transfer processes are discussed in the sections on crop growth models and carbon models. Energy also enters the field in the form of potential energy

in water, which is mostly converted to kinetic energy (movement) of water. The water

cycle and the associated movement of solutes and soil particles (erosion) are discussed

in the section on hydrology models. Apart from carbon and water, a material of particular

environmental interest is nitrogen, which is discussed in the section on nitrogen models.

Finally, the input of pesticides has particular environmental interest.

Models of elements with less environmental impact than carbon or nitrogen are not

considered here, although a range of other elements may be environmentally significant.

For example, phosphorus is important in terms of resource depletion and eutrophication

(Robson, 2014b), but it tends not to be a major environmental problem in oil palm growing

areas, partly because tropical soils tend to have high phosphate retention capacity and

also because the amounts of phosphorus fertiliser applied are relatively small. Potassium

and chloride are important for oil palm because the quantities taken up are similar to

nitrogen. Potassium and chloride have little direct environmental impact, but modelling

their cycling in oil palm systems may become important in the future because of their large

effect on palm growth.

5.1 Crop growth models

Crop models are not directly focused on environmental impacts, but can be used as

a component of integrated models. Early development of OPSIM, an oil palm growth

model (van Kraalingen et al., 1989), provided a model of photosynthesis, growth of

organs and canopy development, and how these responded to climate and basic

management actions such as planting population. After a conspicuously long delay

compared to other agricultural domains, other models were developed to capture a

wider range of impacts.

Models such as OPRODSIM (Henson et al., 2007), ECOPALM (Combres et al., 2013) and

PALMSIM (Hoffmann et al., 2015) added the capacity to model the effect of water supply

on crop growth through the incorporation of relatively simple soil water balance models

(Table 2). Perhaps more importantly, these models brought a stronger physiological

basis to the modelling of oil palm development. The more recent models provided a

more detailed description of frond and inflorescence production, which, in the case of

ECOPALM, has allowed exploration of the impact of water supply and photoperiod on

fruit dynamics. PALMSIM (Hoffmann et al., 2014) is somewhat simpler in some aspects, but

this has allowed it to be used in spatial analyses of potential production across climatic

regions. CLM-Palm (Fan et al., 2015) is also quite simple but is designed to integrate, via

the CLM (Oleson et al., 2013), with the global climate-focused CESM (Hurrell et al., 2013).

A wider range of crop and soil processes can be simulated by the models APSIM-Oil Palm (Huth et al., 2014) and WaNuLCAS (Van Noordwijk et al., 2011). These more detailed models provide opportunities for studying environmental impacts such as GHG emissions, hydrology, erosion and nutrient leaching and understorey management, as discussed in this chapter.

However, crop growth models do not yet represent many characteristics of the oil palm system, such as the presence of shallow groundwater or other soil constraints, or pests and diseases.

5.2 Hydrology, erosion and solute/sediment transport models

Water is the driver of sediment and solute/contaminant transport. Modelling the hydrological cycle and processes (Fig. 10) is important for applications such as water use and management, and water pollution. Hydrological models range in their complexity

Table 2 Oil palm crop models and the processes captured within them

Model Model components Reference Growth and yield Water Soil C&N Understorey Management

OPSIM ● ● van Kraalingen et al. (1989)

OPRODSIM ● ● ● Henson et al. (2007)

WaNuLCAS ● ● ● ● ● van Noordwijk et al. (2011)

ECOPALM ● ● Combres et al. (2013)

PalmSIM ● ● ● Hoffman et al. (2014)

APSIM ● ● ● ● ● Huth et al. (2014)

CLM-Palm • • Fan et al. (2015)

from simple ‘black box’ models developed from empirical data to powerful process-based

computer models that are based on laws of mass, momentum and energy conservation

(e.g. Richards equation and Darcy’s equation). These models require huge data inputs but

can provide distributed predictions of hydrological processes on a continuous timescale.

The development of hydrological models incorporating the interaction between

surface water and groundwater provides opportunities to study water flows and

contaminant transport between various parts of the hydrological system. Surface and

subsurface flows can be modelled in one to three dimensions depending on the type

of model. The MIKE SHE model simulates unsaturated flow in one dimension (Richards

equation), surface flows in two dimensions (St. Vernant’s equation) and groundwater

flows in three dimensions (Boussinesq’s equation). In addition, many hydrological

models now include components to model erosion and solute transport at various levels

of complexity (Table 1). Good examples of these coupled hydrological models include

the SWAT and the MIKE models.

Erosion of soil is one of the most destructive environmental impacts of poor cultivation

practices (Corley and Tinker 2016). Soil erosion is generally low in oil palm plantations due to low slope gradients, permeable soils and permanent ground cover (Lal, 1990; Labrière

et al., 2015; Corley and Tinker, 2016). However, erosion can be large in times and places

when the soil is exposed, especially during establishment and on steep slopes.

Erosion models simulate the detachment, transport and deposition of sediment

in sheetflow, rills, gullies and within stream channels. The simplest empirical sediment

transport model is the Universal Soil Loss Equation and its more recent modification,

the Revised Universal Soil Loss Equation (Morgan and Nearing, 2011). Other commonly

used soil erosion and sediment transport models are process-based, mostly modelling

the erosion process in one or two dimensions where the erosion process and resultant

Figure 10 Fluxes of water into, out of and within the field. Water movement has direct impacts on

aquatic ecosystems, as well as carrying other materials with their own impacts. Rainfall embodies a

significant input of kinetic and potential energy to the system, driving processes such as erosion. Some

water molecules are split during photosynthesis and created during mineralisation of organic matter

but the amounts are insignificant compared to the fluxes shown.

sediment loads can be predicted either on an event or on a continuous basis. De Vente

et al. (2013, 2014) recently made a useful evaluation of regional scale erosion models.

Solute transport models predict the transport of solutes through advection and/

or dispersion, sorption/desorption and other geochemical reactions such as aqueous complexation, ion exchange, precipitation/dissolution and oxidation/reduction reactions in subsurface transport. Most of these models simulate solute transport processes in one or two dimensions, although three-dimensional modelling for the saturated zone is increasingly possible with improved computational power. The HYDRUS model simulates water, heat and solute movement in one to three dimensions in variably saturated media and can be linked to the groundwater model MODFLOW. Other examples of solute transport models include MT3DMS (3D multi-species transport model), SUTRA and HST3D (Maliva and Missimer, 2012).

5.3 Carbon models

The carbon cycle is fundamentally important for productivity, sustainability and environmental impacts of agricultural systems. Those modelling the cycle are concerned mostly with simulating the amounts of carbon in the atmosphere (as CO_2 and CH_4), plant biomass and soil (as organic matter), and the fluxes between those three pools. We considered modelling of atmosphere-plant exchanges above ('Atmospheric impact models' and 'Crop growth models'). Therefore, in this section we focus on the cycling of carbon through soil, the largest pool of the three.

Carbon cycling through soil depends on dynamic and incompletely understood

interactions between organisms (all Kingdoms), substrates, availability and movement

of water and oxygen, temperature, supply of other elements, especially nitrogen, and

surface and solution chemistry (mineralogy and pH in particular). Carbon enters the soil

mostly as plant-derived organic matter, which then decomposes (Fig. 11). Decomposition

involves eventual loss of most or all of the carbon as CO_2, but along the way biomass and

organic compounds are formed, especially by microorganisms.

Some organic materials decompose slower than others due to chemical recalcitrance,

interactions with inorganic materials or physical inaccessibility to decomposing organisms

and enzymes. Overall, if there are no fresh inputs, soil carbon becomes less biologically

available over time, although organic matter stabilised by interactions with the mineral

phase may originate from initially labile plant components (Haddix et al., 2016). Significant

amounts of carbon may also arrive and leave via soil erosion and deposition at some

locations and times. Losses of carbon by leaching are generally insignificant compared to

the other fluxes.

Large changes in soil organic carbon stocks occur during and following land use change,

and these have been modelled using an empirical conversion factor approach. The IPCC

default values for soil organic carbon loss following change from forest to cropland are

0.69 (31% soil organic carbon loss) for the dry tropics and 0.58 (42% soil organic carbon loss) for the wet tropics (IPCC, 2003). The meta-analysis of Don et al. (2011) indicated about 30% loss following conversion of primary forest to perennial cropland, but more recent studies have suggested up to half may be lost after conversion (Bruun et al., 2013; Straaten et al., 2015). Much of the loss happens very quickly. However, within the oil palm crop, soil organic carbon stocks have shown no consistent decline, or even an increase over time (Henson, 1994; Haron et al., 1998; Law et al., 2009; Smith et al., 2012; Frazão et al., 2013; Goodrick et al., 2015; Khasanah et al., 2015a). Bahr et al. (2014) showed a pattern of decrease immediately after conversion, increase during the perennial cropping phase and then a decrease towards the end of the phase. Modelling with APSIM-Oil Palm shows a similar pattern (Fig. 6) and suggests it is due to inputs to the soil being high initially (from the preceding oil palm crop in the case of the modelling) and then reaching a steady state or declining depending on nitrogen supply.

Process-based models of change in soil carbon during land use change should focus on the key processes, which are redistribution due to erosion and a change in inputs due to the change in vegetation. This is usually achieved by combining erosion models with carbon cycling models (Lacoste et al., 2015). We discussed erosion models above, and now we discuss carbon cycling models.

There are three main approaches to modelling carbon cycling within a particular land

use (Smith, 2006). The first two are substrate-based, treating substrates either as several

discrete pools or as one continually changing pool. The third is ecologically or food web

based.

Substrate-based models that categorise soil organic carbon into several discrete pools

are the most used and developed of soil carbon models. In these models, carbon is

lost from each pool according to first-order kinetics, and each pool has a different rate

coefficient (or ‘constant’). Pools comprise plant residue inputs (one or several pools),

microbial biomass (one or several pools) and dead organic matter (several pools). The

dead organic matter pools have the lowest rate coefficients and some models have an

inert pool that does not decompose at all. Carbon lost from each pool is routed into

another pool (usually biomass pool or a pool with lower slower rate constant) or lost as

CO_2 , with the proportions specified by ‘carbon use efficiency’ factors.

Microbial carbon use efficiency factors are a fundamental component of carbon

models but are simply treated in most models. Geyer et al. (2016) have recently

defined the concepts involved in a way that will be useful for future advances in carbon modelling.

Figure 11 Fluxes of carbon into and out of the field, and transformations of carbon compounds.

Carbon represents the main flow of energy through the system. Energy from radiation is converted

to chemical bonds during photosynthesis, and used to drive all the biological processes in the

system. Net primary production (NPP) is the net amount of organic matter produced in the system, or

photosynthesis minus plant respiration.

The most well-known and used multi-pool models are CENTURY (Parton, 1996) and

its daily time-step version DAYCENT (Grosso et al., 2001), and Roth-C (Coleman and

Jenkinson, 2014). Other examples include APSIM (Probert et al., 1998), Biome-BGC

(Thornton and Rosenbloom, 2005), Candy (Franko, 1996), CN-SIM (Petersen et al., 2005),

DAISY (Mueller et al., 1996), DNDC (Li et al., 1994; Li, 2007), MIMICS (Wieder et al., 2014),

NCSOIL (Molina et al., 1997) and ORCHIDEE (Krinner et al., 2005). Some of these models

model nitrogen as well as carbon. Their structure and assumptions have been reviewed by

Molina and Smith (1998) and Smith (2006).

Multi-pool models can successfully simulate soil organic carbon contents (Smith et al.,

1997), but there are limitations to applying them. One problem is how to initialise the

model and another is how to measure or validate pool sizes, rate decay coefficients and

efficiency factors. Those things have been done by measuring the quantity of carbon in physically separated fractions and then either a) using the measured fractions as values

for the pools and calculating rate coefficients or efficiency factors by fitting the model

(Skjemstad et al., 2004), or b) using existing coefficients and splitting the measured pools

to match the model pools (Zimmermann et al., 2007). However, the parameters derived in

those ways for those situations are not necessarily applicable in other situations. Petersen

et al. (2005) showed that a seven-pool model could satisfactorily simulate soil organic

carbon contents for several sites using the same parameters, but the sites had similar

climate, soil properties and management. Alternatively, chemically characterised pools

have shown promise for modelling (Corbeels et al., 2005a,b). Application of multi-pool

models within earth system models has resulted in widely varying fits with observed

values, so there is considerable scope for improvement (Todd-Brown et al., 2013; Wang

et al., 2014; Luo et al., 2016).

The second substrate-based approach to modelling soil carbon cycling is to treat each

addition of plant residues as a cohort or single pool that changes with time, rather than

assigning all soil carbon to several discrete pools (Bosatta and Ågren, 1995; Yang and

Janssen, 2000; Manzoni et al., 2012). In these models the decomposition rate coefficient of

each cohort decreases continually with time. This approach is attractive compared to multi pool models because it reflects the continuously variable nature of substrates and because

it requires less parameters. Mono-pool models can be used to simulate soil organic carbon

dynamics with a similar degree of accuracy to multi-pool models (Manzoni et al., 2012).

However, single- and multi-pool approaches both suffer from the difficulty of measuring

pools that correspond with the conceptual pools, determining parameters (decay coefficients

in particular) that can be transferred from one situation to another, and initialisation.

Food web-based models have been reviewed by Smith (2006) and Luo et al. (2016). They

simulate the decomposing activities of soil organisms in various ways, usually focusing

on microbial biomass or components of it, or production and activity of enzymes. For

example, Kaiser et al. (2015) showed that soil organic matter accumulation is influenced

by interactions between microorganisms that produce catabolic enzymes and those that

do not. Food web-based models are able to simulate some aspects of carbon cycling

that substrate-based approaches cannot, such as the priming effect and responses to

wet-drying cycles. However, they require much more information than substrate-based

models. Furthermore, they may not provide much better descriptions of reality because

decomposition tends to be limited by substrate supply and physico-chemical conditions,

and microbial populations adapt accordingly.

All models modify decomposition rate or decomposer activity according to environmental

variables. The most important variables are temperature and the availability of water and

oxygen. Their effects are modelled using empirically derived factors, such as an Arrhenius

function for temperature and an optimal response function for water content (Luo et al.,

2016). The function for water content commonly uses a parameter such as water-filled

pore space, which to some extent integrates effects of water film thickness and oxygen

supply on microbial activity. Responses to pH, availability of other nutrients, litter quality,

litter layer thickness and clay content may also be modelled. Mineralogy, structure and

structural stability, particularly pore size distribution, are not included in most models,

even though they are known to affect stabilisation of organic matter.

Finally, we need to mention depth and management. The most commonly used

models initially focused on a topsoil layer, assumed to be uniform. Only recently has the

distribution of processes with depth been incorporated (Jenkinson and Coleman, 2008).

Carbon inputs and environmental parameters change with depth, and carbon is moved

vertically by fauna. In a similar vein, addition or loss of soil through erosion and deposition,

a process that occurs in three dimensions, influences soil depth and the distribution of

carbon with depth. Management factors may be included in some carbon models, or their

effect on carbon cycling may be accounted for in agricultural system models.

Of the soil carbon modelling approaches, the only one that has been adapted to oil palm

systems is the multi-pool substrate-based approach. It is used to model carbon and nitrogen

cycling in litter and soil in the agricultural system models APSIM and WaNuLCAS (Probert

et al., 1998; Noordwijk et al., 2011). APSIM uses a simplified approach, wherein all soil carbon

in the deepest soil layer is assumed to be inert, and the size of the inert pool is assumed to

be the same in all layers. It has successfully simulated long-term soil organic carbon contents

in other crops (O'Leary et al., 2016). When carbon models are incorporated into crop system

models they must realistically simulate not only soil organic carbon contents, but also the

mineralisation and immobilisation of nitrogen and its supply to the plant.

The ability of carbon models to simulate soil organic carbon contents in oil palm

plantations has not yet been tested. This is mostly because there are no long-term data

sets of soil carbon content under oil palm. Such model testing would be very useful,

given the peculiarities of oil palm systems. For example, none of the current carbon and

nitrogen models mechanistically model the spatio-temporal variability in cycling processes

in oil palm plantations, which may or may not be important. Temporal variability in carbon and nitrogen cycling processes is mostly related to the large input of organic matter at the end of the cycle and presence of legume cover crop at the start of the cycle. Spatial variability is largely due to placement of pruned fronds into concentrated stacks, root distribution, weeding and placement of mill by-products (Haron et al., 1998; Nelson et al., 2014; Carron et al., 2016; Goodrick et al., 2016).

5.4 Nitrogen models

The nitrogen cycle is fundamentally important for production and environment, but is complex and challenging to model. The main potential and observed environmental impacts are pollution of ground and surface waters and emission of GHGs, especially N_2O (Choo et al., 2011; Comte et al., 2012). For instance, during the cultivation period, 48.7% of the GHGs emitted to produce 1 t of palm oil fruit are due to nitrogen fertilisation (Choo et al., 2011). The main inputs of nitrogen to the field are manufactured fertilisers, palm oil mill by-products and biological fixation by legume cover crops (Fig. 12).

The largest losses of nitrogen from the field are due to leaching of mineral nitrogen (nitrate in particular) and volatilisation of NH_3, but the magnitude of these and other losses is highly uncertain (Pardon et al., 2016a). In their review, Pardon et al. (2016a) also emphasised that internal nitrogen fluxes in oil palm are large and important compared to other agricultural systems. As measurement of nitrogen losses is difficult and expensive,

modelling is useful to help identify management practices that could reduce losses.

The most commonly used process-based models of nitrogen cycling are the same models

used for carbon cycling, for example, CENTURY (Parton, 1996), DAYCENT (Grosso et al.,

2001), DNDC (Li et al., 1994; Li, 2007) and DAISY (Mueller et al., 1996). They generally

model mineralisation and immobilisation of nitrogen based on the C:N ratio of the pools,

in the one-dimensional soil–plant–atmosphere continuum, at the scale of the soil profile

or the field. Modelling nitrogen cycling is generally more complex than modelling carbon

cycling, and several dissolved and gaseous nitrogen compounds are important for plant

growth and the environment. In addition to the comprehensive nitrogen cycling models,

some models focus on specific fluxes, such as the emission of N_2O (Henault et al., 2005).

The concepts and challenges for modelling N_2O emissions have been discussed by

Farquharson and Baldock (2008) and Butterbach-Bahl et al. (2013).

When the aim is to identify practices to mitigate environmental impacts, process-based

nitrogen models suffer the same limitations as all complex models; they require precise

soil and climate input data to function, they tend be not very sensitive to management

practices and they are generally calibrated for temperate climate and annual crops and not easily adaptable to other conditions. In the case of nitrogen loss modelling, few models

are available for tropical crops, and even fewer for perennial tropical crops such as oil palm

(Cannavo et al., 2008; Pardon et al., 2016a,b).

In this context, simpler empirical agri-environmental indicators, such as the INDIGO®

method (Bockstaller et al., 2008), may be useful for environmental impact modelling.

Indicators combine quantitative and qualitative data based on expert knowledge and are

hence suitable in situations where data is limited (Girardin et al., 1999). Their structure

is adaptable to new cropping systems, allowing for the accounting of context-specific

practices. For instance, Thiollet (2003) developed an indicator of nitrogen losses for

vineyards, which might be adapted for oil palm systems.

Figure 12 Fluxes of nitrogen into and out of the field, and transformations of nitrogen compounds.

Nitrogen-containing compounds are important for many environmental impacts.

In a recent study, Pardon et al. (2016b) compared estimates of nitrogen losses from

oil palm plantations made by 11 models and 29 sub-models. Three of the 11 models

were process-based cropping system models [WaNuLCAS (Noordwijk et al., 2011);

SNOOP (Barros, 2012); APSIM (Huth et al., 2014)], but only APSIM-Oil Palm was validated

for production. Two models used a nitrogen budget approach at the scale of the field

(Banabas, 2007; Schmidt, 2007). The others were simpler static models that calculate

nitrogen losses using empirical relationships (Mosier et al., 1998; Roy et al., 2005; IPCC,

2006; Nemecek and Kägi, 2007; Brockmann et al., 2014; Meier et al., 2014).

The models were compared using the same scenario, a plantation in the Riau region of

Sumatra, on a typical Ultisol, over a 25-year growth cycle, using standard management

practices. Estimates of total nitrogen losses differed substantially between models,

ranging from 21 to 139 kg N ha^{-1} yr^{-1} (Fig. 13). Leaching was the most important pathway,

accounting for about 80% of the losses. On average, 31% of the losses occurred during the

first three years, which represents 12% of the cycle duration. Losses of nitrogen through

leaching and run-off seemed to be overestimated by some models and underestimated

by others, with no clear relationship between the complexity or comprehensiveness of

models and the magnitude of the losses predicted. All models seemed to underestimate

NH_3 volatilisation compared to measured values. Modelled N_2O emissions were similar

to field measurements, although the minimum modelled emissions were higher than the

minimum losses measured in the field. The most influential variables across the three

pathways were related to leaching losses, that is, soil clay content, rooting depth, and

nitrogen uptake by the palms. A recent sensitivity analysis using APSIM-Oil Palm identified nitrogen fertiliser rate, drainage and fraction of legume in groundcover vegetation as the factors having most influence on nitrogen losses (Pardon et al., 2017).

Several challenges for modelling nitrogen losses were identified by Pardon et al. (2016b). First, estimation of any one flux depends on accurate estimation of all other fluxes, because they are interdependent. For example, the amount of nitrogen fixed biologically has a large influence on losses, but there is surprisingly little data and only very simple models. Legumes can regulate nitrogen fixation rates depending on the mineral nitrogen content of the soil (Giller and Fairhurst, 2003). Hence, it could be useful to model legume fixation with a rate of nitrogen fixation changing according to the soil mineral N content, such as in the EPIC crop model for soybean (Bouniols et al., 1991). Similarly, the amount of nitrogen released in the soil by residue decomposition is significant, and the way it is modelled has a large influence on losses. Indeed, residue decomposition can be accompanied by temporary immobilisation of nitrogen in the litter and soil organic matter, and the magnitude and timing of losses depend on whether or not the nitrogen immobilisation is considered.

Another challenge is to find parameters that accurately reflect the most influential factors, such as soil water retention and conductivity. The availability of appropriate climate data is also an important limitation.

5.5 Pesticide and contaminant fate models

The use of pesticides is limited in oil palm plantations, but their fate must be considered

(Henson, 1994). Herbicides are used to keep the weeded circle and harvest path clear

and to control woody weeds. Usually the compounds used rapidly degrade or become

inactivated on contact with soil. Insecticides are occasionally used to control outbreaks

of pests, in conjunction with biological control methods. The most preferred method of

application for most insect pests is trunk injection, so opportunities for movement into

soil and water are limited. The site of most intense insecticide use, and also fungicides

and herbicides, is in nurseries. Rodenticides may also be used in plantations, although

alternatives such as encouragement of barn owls through deployment of nesting boxes,

is common practice.

To ensure the non-target impact of the pesticides is minimised, several questions must

be answered. These include: which pesticide to use, when, where and how? Will these

pesticides move offsite (Fig. 14) and if so, what potential impact they may have on the

ecosystem and human health?

What best management practices can be adopted/adapted to minimise such impacts?

Models and other decision support tools, for example risk indicators, can help answer such questions and assist decision makers (Kookana et al., 2007).

A plethora of models with various degrees of complexity and comprehensiveness have

been developed to assess the fate and behaviour of pesticides in the environment. Many

have been designed for a specific purpose or with a focus on certain transport pathways

(e.g. surface water or groundwater transport, and macropore flow). Therefore, while

choosing the model it is important to match the specific question or purpose the user has

in mind with the strength of the model.

Pesticide fate models may be classified, on the basis of their intended use and complexity,

into categories such as screening, research and management models (e.g. Addiscott and

Wagenet, 1985). Screening models are used to compare likely pesticide behaviour under

different conditions, or to categorise them into classes differing in potential mobility or

toxicity. These are often simple (e.g. analytical solutions) with low data requirement. Risk

indicators used in Europe and elsewhere (Reus et al., 2002; Kookana et al., 2007) are

this type of model. Research models are designed to quantitatively estimate pesticide

transport and transformations. They tend to be comprehensive in terms of fate processes

and commensurately hungry for input data. Management models are designed to assess

Figure 13 Estimates of N losses from an oil palm field in Sumatra by 11 models. (a) Distribution of the

annual average losses between three loss pathways. The hatched bars represent estimates in which

separate pathways were not distinguished. (b) Distribution of the annual average losses between

the immature and the mature phases (Reproduced from Pardon et al. 2016b, Biogeosciences 13,

5433–5452).

the effect of management practices on pesticide behaviour in field conditions (Bockstaller

et al., 2008). The input data requirement of such models is generally somewhere between

the research and screening models. A description of some of the models from these

categories and their potential uses are described in Table 3.

The fate and behaviour of pesticides in tropical conditions can differ substantially from

that in temperate conditions. Currently the database on pesticide behaviour in tropical

regions is not well developed and most models rely on pesticide fate data from temperate

regions, which may not accurately reflect pesticide behaviour in the tropics. For example,

pesticides degrade many times faster in tropical than temperate conditions (Laabs et al.,

2000; Kookana et al., 2010). The nature of tropical soils also needs to be considered.

Highly weathered tropical soils, rich in iron and aluminium (hydr)oxides, carry variable

charge and may have significant anion exchange capacity at ambient pH (Uehara and

Gillman, 1981). Some ionisable pesticides have been found to be substantially sorbed on

such soils (Regitano et al., 2000). Soil physical properties are also important. Some tropical soils tend to have substantial macroporosity (biopores), so pesticides may bypass the soil matrix in percolating water. Such preferential flow can result in significant leaching, despite high degradation rates (Laabs et al., 2000). Even if only a very small fraction of applied pesticide (e.g. 0.1%) reaches groundwater, it may breach stringent groundwater standards such as the one used in Europe (0.1 μg/L for any pesticide).

It is therefore important that as much as possible the local data on pesticide fate are used in the models. For degradation, correction factors for persistence based on temperature may need to be applied. For pesticide sorption, techniques such as mid- or near-infrared spectroscopy, together with chemometrics, may allow a rapid and cost-effective estimate of pesticide sorption coefficients (K_d) in a large number of soils (Forouzangohar et al., 2008; Kookana et al., 2014). Ismail and Ooi (2012) found, for a variety of Malaysian soils, adsorption of metsulfuron-methyl was related to soil organic matter and clay content, which are readily estimated.

Some models have been applied and/or tested in tropical conditions (Table 3), but mostly in annual cropping systems. For example, Bannwarth et al. (2014) used a SWAT hydrological model (Table 3) coupled with ANSLEM to simulate the fate of three

Figure 14 Fluxes and transformations of contaminants and pesticides in the field.

Table 3 Some examples of different types of mo dels developed for predicted fate and impact of pesticides from nonpoint sources

Model name	Class	Processes covered	Intended application	Comments
BAM (Jury et al. 1987)	Screening	Transport, sorption, degradation, volatilisation	To compare behaviour under specific conditions	Useful in grouping pesticides in behavioural classes
PIRI (Kookana et al. 2005)	Screening	Risk indicator integrating mobility, toxicity, application rate and method, topography, soil		

andenvironmentalconditionsTogr
ouppesticidesmobilityandtoxici
tytonontargetorganismsUsefulfo
ridentifyingrelativeriskofdiff
erentpesticidesPRoMPT(Whelanet
al.2007)ScreeningLeachingtogro
undwaterbasedonasimplewaterbal
ancemodelToidentifyareaspronet
opesticideleachingAppliedinoil
palminKenyabyUnileverPEARL(Lei
straetal.2000)Research/regulat
oryInputs,transport,sorption,d
egradation,volatilisation,leac
hing,uptake,transformationToas
sessgroundwatercontaminationat
regionalandlocalscaleUsedforre
gulatorypurposesinEuropeLEACHM
(WagenetandHutson1989)Research
Transport,sorption,transformat
ion,degradation,volatilisation
,plantuptake,managementToasses
sgroundwatercontaminationunder
croppingsystemsDoesnotcoversur
facerunoff,foliarwashoff,erosi
onandpreferentialflowMACRO(Lar
sboandJarvis2003)ResearchSpeci
allydesignedtoincorporatethepr
eferentialflowpathsforpesticid
eleachingToassessleachinginsoi
lswithmacroporesSWAT(Arnoldeta
l.2011)Research/managementSurf
aceandsubsurfacehydrologicalpr
ocesses.Fateandtransportofpest
icidesismodelledbasedonGLEAMSm
odel(Leonardetal.1987)Topredic
tconcentrationsinriversatdaily
timestepPerformedwellintropica
lnorthernThailand(Bannwartheta
l.2014)PRZM(Suárezetal.2005)Re
gulatory/managementSurfaceruno
ff,foliarwashoff,erosionlosses
andplantuptake.Notvolatilisati
onToassesseffectsofmanagementp
racticesPESTFADE(Clementeetal.
,1991)ManagementTransportviaru
noff,erosionandleaching(unsatu
ratedhomogenoussoil).Includesn
utrientsToassesseffectsofmanag
ementpracticesontransportatfie
ld,farmandwatershedscaleEvalua

t e d i n t r o p i c s , i n T h a i l a n d (S h r e s t h a a n d D a t t a , 2 0 1 5) R Z W Q M (A h u j a e t a l . 2 0 0 0) M a n a g e m e n t T r a n s p o r t v i a r u n o f f , e r o s i o n a n d l e a c h i n g (u n s a t u r a t e d h o m o g e n o u s s o i l) . I n c l u d e s n u t r i e n t s T o a s s e s s e f f e c t s o f m a n a g e m e n t p r a c t i c e s o n t r a n s p o r t a t fi e l d s c a l e E v a l u a t e d i n t r o p i c s , i n T h a i l a n d (S h r e s t h a a n d D a t t a , 2 0 1 5) I P h y (B o c k s t a l l e r e t a l . 2 0 0 8) M a n a g e m e n t L e a c h i n g , r u n o f f , e r o s i o n , d r i f t , v o l a t i l i s a t i o n T o a s s e s s e f f e c t s o f m a n a g e m e n t p r a c t i c e s o n t r a n s p o r t a t fi e l d s c a l e B e i n g e v a l u a t e d f o r g l y p h o s a t e i n o i l p a l m (M a r i c h a l e t a l . 2 0 1 6)

pesticides in a mountainous catchment of northern Thailand. The predicted daily pesticide

concentrations in the river water over two seasons (2008 and 2010) matched the observed

concentrations reasonably well, despite the complexity involved at the catchment scale.

In terms of sensitivity of different parameters, the percolation parameter was identified as

a key parameter.

Reliability of data on pesticide application rate and timing in the catchment is important

in such simulations. For pesticide leaching through a soil profile, Shrestha and Datta

(2015) evaluated the performance of two models (RZWQM and PESTFADE) for fate and

transport of metribuzin herbicide under field conditions in Thailand. While they were

generally satisfied with both models, they observed that RZWQM performed better in

simulating water content of the soil profile, whereas PESTFADE was better at simulating

the herbicide residue. Pesticide transport models are generally not well developed for plantation systems in tropical regions.

Risk indicators are being increasingly used in decision making by pesticide users, natural resource managers and regulators (Kookana et al. 2007). Some of the advantages of risk indicators over comprehensive models are their simplicity, ease of use and usability when input data are scarce. Risk indicators are helpful in assisting (i) growers to choose pesticides that are likely to be more environmentally acceptable, thereby also facilitating adoption of and compliance with integrated pest management or environmental management systems; (ii) growers and regulators to compare risk management options, identify potential hot spots, evaluate management practices and develop appropriate monitoring programmes; (iii) researchers to prioritise pesticides for greater understanding of their environmental fate and toxicology; and (iv) regulators and policy makers to analyse risk trends and develop appropriate policy interventions.

Risk indicators are often classified into two broad types (Reus et al., 2002; Feola et al., 2011). The first type uses simple algorithms such as a scoring table developed based on expert judgement, while the second type employ an exposure-to-toxicity ratio (ETR), that is, comparing the predicted exposure concentration to the toxicity parameter for organisms (e.g. LC_{50}). In the context of potential utility of risk indicators in emerging economies, Feola et al. (2011) used a case study based on small agricultural holdings in

Colombia to assess the suitability of a set of indicators drawn from the ETR group (POCER,

EPRIP and PIRI) and the non-ETR group (EIQ and PestScreen). They concluded that user

friendly ETR indicators were better suited than non-ETR indicators for reliably estimating

environmental risk.

Several risk indicators have been used in tropical tree crops, including oil palm. One

recommended risk indicator, PIRI (Kookana et al., 2005) (Table 3), has been promoted

over the last decade for use in several tropical countries of South America, Asia and Africa

by the joint division of FAO and IAEA on Food and Environment. For a comparative risk

assessment of pesticides in papaya plantations, Hernández-Hernández et al. (2007) used

SYNOPS risk indicator (an ETR-type risk indicator) and ranked 15 pesticides in terms

of their chronological biological risk index. The authors recommended SYNOPS_2 for

potential use in other tropical fruit plantations. The INDIGO® risk indicator for pesticides,

I-Phy (Bockstaller et al., 2008), is being adapted for oil palm plantations and evaluated for

glyphosate (Caliman et al., 2006; Marichal et al., 2016).

In addition to pesticides, trace metals and metalloids such as cadmium, mercury

and lead can contaminate soil and water due to inputs as trace contaminants of fertiliser. Although heavy metal contamination has not been detected in oil palm planted soils (Sulaiman et al., 2016), it is a possible threat depending on the source of fertilisers and other amendments applied. The behaviour of trace metals in soils can be modelled to some extent using geochemical models, but soil- and situation specific parameters are needed (Michel et al., 2007; Jacques et al., 2008; Selim and Zhang, 2013).

6 Conclusions and research directions

There are a variety of approaches and tools available for numerically modelling the environmental impacts of agriculture, including oil palm cultivation. They range from models of a single process or impact to models integrating many processes and impacts. In terms of operation, they range from simple empirical relationships to complex process-based dynamic models, operating at different scales and in different dimensions. For any particular purpose and situation, different models may be useful, but the unknowns and uncertainties must be kept in mind. Agricultural system modelling approaches such as APSIM are useful because they enable comparison of the effects of management changes or environmental factors on productivity and several environmental impacts. Such comparison allows managers to assess possible trade-offs between the two.

Environmental modelling is a rapidly developing field and there is still much to do to

make models more accurate and useful for growers, researchers and regulators. Models

developed for agricultural systems other than oil palm may be applicable, but peculiarities

of the oil palm system need to be taken into account. As for other crops, the most

important factors are the climatic, topographic and soil conditions, the nature of the prior

and surrounding ecosystems, and the ways in which crop establishment, water, pests,

nutrition and harvesting are managed. There is great need for more data on these factors

to drive and accompany development of better models.

The type, structure and use of environmental models are changing rapidly in response

to pressing needs. Focusing modelling on specific, practical problems of interest can

guide optimal selection of measurements, advance our understanding of processes, and

improve the integration of science into management and policy decisions. Current and

likely future research falls into five main themes.

Representing complexity

As our understanding of biological, chemical and physical processes improves, the

attendant complexity must somehow be represented in models. There are many ways

this is being or could be tackled, including development of more mechanistic process

based models, integration of existing models, assimilation of data into models, or

'model data fusion' (Keenan et al., 2011; Dietze et al., 2013), hybridisation of statistical

and probability-based models with process-based models (Aguilera et al., 2011)

and alternative ways of modelling complex self-organising systems, such as cellular

automata (Favis-Mortlock, 2013). 'Traditional (and still open) challenges in developing

reliable and efficient models are associated with heterogeneity and variability in

parameters and state variables; non-linearities and scale effects in process dynamics;

and complex or poorly known boundary conditions and initial system states' (Paniconi

and Putti, 2015).

Representing the oil palm system

Many models are not well suited to the nature of oil palm systems but could be applied

to them, given some evaluation using data from the field, or modifications to the models.

Enhancing usability

Much can be done to incorporate sufficient complexity into models but make them

operationally simple, accessible, up-to-date and relevant for managers and the broader

community.

Evaluation of models

Evaluation of models, including sensitivity and uncertainty analysis, is becoming

increasingly important. There is great scope for evaluation of existing models in oil palm systems and for development of better evaluation techniques.

Data from monitoring and experiments

There is a pressing and growing need for data to inform and evaluate environmental impact

models. Essential input data on climate and soil are available globally as estimates from

remote sensing and ground observations. However, data scarcity in many oil palm growing

regions means their accuracy is often untested and may be poor. There is also much

scope for exploiting data from new satellite- and ground-based sensors and other sources

such as palm oil mills. Long-term monitoring plots, especially those with experimental

treatments, have been valuable for calibrating and validating models and would be very

useful for oil palm. Finally, urgently needed data on many key processes could also be

obtained by shorter-term experiments.

7 Where to look for further information

The main scientific journals focusing on the topic of this chapter are Environmental

Modelling & Software and Ecological Modelling. Relevant conferences include those of

the International Environmental Modelling & Software Society' (http://www.iemss.org/

the topic in this chapter follow:

• The oil palm system, including modelling and environmental aspects: Corley and Tinker (2016).

• Environmental modelling: Granell et al. (2013), Wainwright and Mulligan (2013).

• Evaluation of environmental models: Jakeman et al. (2006), Bennett et al. (2013), Kelly et al. (2013).

• Life cycle assessment: ISO 14040 series 2000-2006 and the International Reference Life Cycle Data System Handbook http://eplca.jrc.ec.europa.eu/?page_id=86

• Earth system modelling: Heavens et al. (2013).

• Agricultural system (oil palm) modelling: Huth et al. (2014).

• Catchment process modelling: Mulligan and Wainwright (2013b), Paniconi and Putti (2015), Fatichi et al. (2016).

• Atmospheric impact modelling: IPCC (2003, 2006, 2014).

• Aquatic ecosystem modelling: Robson (2014a).

• Terrestrial biodiversity impacts: Foster et al. (2011), Phalan et al. (2011), Lee et al. (2014).

• Soil quality and erosion: Lal and Stewart (2013), Labrière et al. (2015).

• Erosion modelling: Morgan and Nearing (2011).

• Carbon and nitrogen cycle modelling: Molina and Smith (1998), Smith (2006), Cabrera et al. (2008), Campbell and Paustian (2015).

• Nitrogen environmental impact modelling: Cannavo et al. (2008), Pardon et al. (2016b).

• Nitrous oxide emission modelling: Chen et al. (2008), Butterbach-Bahl et al. (2013).

• Pesticide risk modelling: Kookana et al. (2007).

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14 Chapter 14 Balancing oil palm cultivation with forest and biodiversity conservation

1 Introduction

The past decade has seen a significant increase in environmental degradation and loss of

ecosystem services in most parts of the world (Bradshaw et al., 2009; Butler and Laurance,

2009; Craft et al., 2009; De Jong et al., 2015; Dobson et al., 2006; FAO, 2009; Ghazali

et al., 2016; Greenpeace, 2007; Goodman and Mulik, 2015; Hoeinghaus et al., 2009;

Kettunen and ten Brink, 2006; Koh and Wilcove, 2008; Malcolm et al., 2006; Petrenko et al.,

2016; Sodhi et al., 2004; UNEP, 2007; UNESCAPS, 2007). In Southeast Asia, the main driver

of deforestation is agriculture, specifically for palm oil production (Hansen et al., 2013;

Miettinen et al., 2011; Stibig et al., 2014), although pulp and logging in legal commercial

concessions in Indonesia is reportedly higher (Abood et al., 2015). The rapid agricultural

development resulted in habitat loss and fragmentation and, consequently, in the loss of

biodiversity (Canale et al., 2012; Gibson et al., 2013). Indeed, rivers, lakes and peat forests

suffered enormous siltation, pollution loading and dehydration. The draining of extensive

peat forests of Sumatra and Borneo lead to the occurrence of the most damaging event

when more than 45 000 km 2 of forest burnt by wildfires in 1997 (Heil et al., 2001) and

resulted in forest degradation and deforestation cost of US$1.62–2.7 billion (Tacconi, 2003). The associated cost of the smoke pollution was estimated at US$799 million

(Tacconi, 2003), which caused an estimated 20 million people in Indonesia alone to suffer

from respiratory illnesses (Brauer, 1997; Emmanuel and Lim, 1998; Heil and Goldhammer,

2001; WHO, 1998). The recent 2013–2015 wildfires have caused extreme carbon emission

(Gaveau et al., 2014; Huijnen et al., 2016) and serious health hazards (Koplitz et al., 2016).

The Roundtable of Sustainable Palm Oil (RSPO) was formed in 2004 to put in place

mechanisms aimed at promoting effective environmental-friendly practices within the

sector. RSPO introduced its principles and criteria (RSPO P&C) in 2007 (RSPO, 2007)

that presented a set of due diligence requirements for RSPO members. Whereas RSPO

membership is voluntary, it is mandatory for each member to commit to the RSPO P&C;

however, many seemed unaware of the real on-the-ground ramifications of committing

to these. For the RSPO P&C to have any meaningful positive conservation impact, it

needs to be (1) mainstreamed within each member company and (2) operationalized and

integrated into a respective company's standard operational procedures (SOP). In practice,

this means that the conservation agenda, as stipulated in the RSPO Vision and guided by

the RSPO P&C, must be made familiar to all employees in a company, in order to ensure

that environmental concerns are as important as traditional agricultural activities such as

pruning, harvesting and fertilizing. Embracing the RSPO concept of producing ‘sustainable’

palm oil means that agricultural, environmental and social aspects are suddenly equally

important (Fig. 1). Missing these three main pillars of sustainable production will lead to

failing an RSPO certification audit. In many cases, growers misinterpret the ‘sustainability’

demands as affording an equal financial investment in each component, with the argument

that social and environmental concerns do not constitute its core business. Indeed, many

companies fail to understand that these components must become part of the core business,

if they aspire to become environmental-friendly producers and pass RSPO’s ‘sustainable

certification’ audit. It is not akin to each pillar requiring an equal amount of investment and/

or operational budget (Fig. 2). The required investment into each pillar depends entirely

on the extent of each challenge in the relevant production area. In most cases, the planted

production areas dwarf the conservation areas and, consequently, the agricultural activities Sustainable Palm Oil Agriculture Community Environment

Figure 1 The three main pillars of ‘sustainable palm oil production’: agriculture, community and

environment.

will need a higher operational budget than conservation activities. The outcome of the

RSPO concept is that the palm oil sector plays an active role in conserving biodiversity as part of safeguarding important ecosystem processes and human welfare (Dobson et al., 2006; Duffy, 2009; European Communities, 2008; Ewel, 2009; Gamfelt et al., 2008).

In 2008, Malaysia-based United Plantations Bhd (UP) became the first RSPO-certified ‘sustainable’ palm oil producer. Many environmental NGOs perceived the certification as premature and untimely (Greenpeace, 2008a,b) and called for a temporary halt to certifying more. In addition, critical publications and reports focused on issues and recommendations that were often technical in nature (Bradshaw et al., 2009; Butler and Laurance, 2009; Koh et al., 2009; Laurence et al., 2010), rather than providing much needed useful operational support to the industry (Traeholt and Schriver, 2011). This, combined with a slow transformation progress within the industry has resulted in the delivery of positive conservation impact on the ground remain miniscule (Ruysschaert and Salles, 2014). The most serious evidence of the limited on-the-ground effect of RSPO certification was the recurrence of devastating forest fires in 2015, where World Bank reported more than 26 000 km^2 burnt, resulting in an estimate cost of more than US$16 billion to Indonesia alone. Petrenko et al. (2016) reported that 20% of all wildfires were caused by palm oil related development, and Marlier et al. (2015) stated that Indonesian fire emissions arose primarily from within logging, paper pulp and oil palm concessions. While 88% of the total emissions in Sumatra in 2006 was caused by pulp and paper concessions, 67% of

all emissions in Kalimantan in the same year was caused by palm oil concessions (Marlier

et al. 2015). With this in mind, sceptics across the world questioned the real value of the

RSPO 'sustainability' certificate, if such devastating events could happen again after the

1997 disaster. Recent studies, however, suggest that RSPO has had a positive effect in

reducing wildfires in members' concessions in the period 2012–2015, although only when

the fire likelihood is relatively low (Cattau et al., 2016). Palm oil Society Environment

Figure 2 The three main pillars of 'sustainable palm oil production' do not necessarily require the

same amount of financial input.

Most consumers, however, are unaware of RSPO being a voluntary organization and that

a major part of the industry still operates outside the RSPO regulation, with only 17% of

total production being certified as 'sustainable' (RSPO, 2016). It is not clear to many either

that RSPO has had a profound positive effect in terms of member companies undertaking

proper due diligence, that is, the RSPO P&C has resulted in a positive preventative effect.

In 2015, more than 144 000 ha of high conservation value habitat have been spared

(RSPO, 2015). The real issue is that preventative measures only make up half of the

challenge vis-à-vis compliance set aside is not enough. The other half constitutes actively managing conservation areas, including active population management of endangered

species. While the RSPO sustainability certificate ensures that a certified company has

taken the necessary precautionary steps to avoid indiscriminate development detrimental

to local societies and environment, it does not make a company ‘sustainable’ per se. The

key is for a company to be able to measure environmental impacts from its plantation

operations and document that biodiversity and ecological processes remain intact in the

post-development phase (Tallis et al., 2009; Tierny et al., 2009). This also includes the

application of biological pest management to reduce dependency of toxic chemicals

and prevent these from accumulating in the food chain. If key ecological parameters

show downward trends, the operations evidently have negative environmental impacts

and, hence, are not ‘sustainable’. The question remains, is it possible to document the

operational impact on the environment?

The present case study presents the results generated through six years of collaboration

between Copenhagen Zoo (Zoo) and UP, building environmental and biodiversity capacity

in UP, in the aim of measuring the ecological impacts of palm oil operation and make

biodiversity concern an integrated part of daily operational procedures.

2 Research methods

This case study took place in United Plantations Bhd subsidiary PT Suria Sawit Sejati estates

in Central Kalimantan, Indonesia. Of a total landbank of 15 560 ha, approx. 6000 ha have

been set aside as conservation land (UP annual report, 2015). Part of that land bank is

made of high conservation value (HCV) forest and riparian zones and tracts of wetland

areas in need of rehabilitation.

The basic idea of producing environmentally ‘sustainable’ palm oil is meaningless

without tools to measure any form of ecological footprints of plantation operations.

Consequently, we considered the meaning of ‘sustainable production’ in an environmental

context and defined it as follows: Sustainable palm oil production is applying agricultural practices that do not significantly undermine biodiversity values and/or degrade ecological processes in the area of operation and elsewhere.

3 Measuring operational impacts on biodiversity

To be able to assess the environmental impact of plantation operations, it is necessary

to measure various ecological parameters before and after such plantation operations

have begun. To measure biodiversity ‘values’ before commencing plantation operations,

we undertook substantial biodiversity surveys throughout the estate landscape and

subsequently monitor the same ecological parameters at various time intervals. We used

a range of standard biodiversity surveying methods, such as:

Camera trapping: Camera traps were used to record, primarily, medium-large mammals and other elusive species. For consistency, 60 cameras were set for 30 consecutive days in various study sites; however, after the basic surveys cameras remained active 24 hr/day across a range of monitoring sites. Mammals were identified from Payne and Francis (2007), Francis (2001) and Phillipps and Phillipps (2016) and birds from Myers (2009) and Robson (2005).

Ground traps: Terrestrial small mammals were recorded by deploying 60 small mammal traps, baited with coconut and banana. Trapping cycles lasted for nine consecutive days to increase the probability of trapping saturation (Anan et al., 1998; Lundahl and Olsson, 2000; Wilson et al., 1996). Species were identified from Payne and Francis (2007), Francis (2001) and Phillipps and Phillipps (2016).

Mist netting and harp traps: Three mist nets and three harp traps were set for nine consecutive days on various types of habitats, for example, understory tall dipterocarp forests, peat forest, mangrove, forest edges and grassland. These were used primarily to evaluate the understory bird and bat communities. Captured mammal species were identified using Payne and Francis (2007), Francis (2001) and Phillipps and Phillipps (2016), and birds were identified from Myers (2009) and Robson (2005).

Fish nets and traps: Local made box traps made of bamboo were placed in rivers and streams, and active fishing using scoop nets were carried out in streams, pools and rivers.

Fish were collected and identified while still alive, following Inger and Inger (2002) and

Atack (2006), and voucher specimens were stored for further identification.

Amphibians and reptiles: Amphibians and reptiles were collected opportunistically

during daytime. Amphibians were also collected after darkness using torchlight to identify

eye shine and prepared following Heyer et al. (1994), Inger (1966), Inger and Stuebing

(1997) and Das (2010).

Biodiversity monitoring: Spatial Monitoring and Reporting Tool (SMART) was setup as the

primary platform that integrates all observations, patrolling results and effort with the main

GIS database. This allowed the team to detect relative density changes in endangered and

vulnerable species, make seasonal predictions and identify specific areas in need of attention.

Tree censuses: Tree censuses were conducted in all study sites. Species were identified

from Engel and Phummai (2008) and LaFrankie Jr. (2010).

Rehabilitation processes: Habitat rehabilitation and restoration were designed to

reinstall native plant species. In order to ensure habitat similarity and appropriate species

composition, seeds were collected from adjacent similar forests and propagated in a

purpose-made tree nursery. Out planting was designed to maximize the growth rate for

faster natural recovery (Farikhah and Traeholt, 2014). Rehabilitation protocols followed the recommendations of Schumann and Joosten (2008) and Nuyim (2005). In the aim of

measuring the effect on biodiversity of rehabilitation, mist netting for understory birds are

undertaken regularly for five consecutive days.

4 Measuring operational impacts on abiotic factors

Land clearing for agriculture, infrastructure and urbanization causes extreme type of

habitat change. Apart from a physical removal of living species with subsequent loss of

biodiversity, many abiotic conditions are altered and the impact thereof is often detected

in waterways. Soil erosion, loss of top soil, fertilizer and pesticide washout, changes in

microclimate and organic waste efflux are some of the serious negative results of land

clearing. To measure the degree and impact of erosion, fertilizer/pesticide washout and

organic contamination of catchment areas and downstream river systems, we setup a

water monitoring system with strategic sample points, (1) inflow to UP's estates, (2) a few

downstream sampling points and (3) at the point where rivers exit the estates. All water

samples are tested for the following parameters:

Biological oxygen demand (BOD) is the amount of dissolved oxygen (DO) needed

by aerobic organisms to break down organic material present in a given water sample

at a certain temperature over a specific period. We measured the BOD as expressed in

milligrams of oxygen consumed per litre of water sample during five days of incubation at

20°C. This is used to assess the degree of organic pollution of streams/rivers in the estates

and is monitored weekly (Fig. 3).

Nitrate (NO_3), Phosphate (PO_4) and total dissolved solids (TDS). Nitrate and phosphate

constitute two of the most important fertilizer components, along with potassium (K)

and a number of macro- and micronutrients (e.g. Ca, Mg, S, Mn, MO). Poor application

of fertilizer combined with heavy rains can cause undesired run-off of these important

chemical compounds that, in turn, will contaminate the waterways and cause excessive

plant and algae growth, and decrease yield of palms. To capture a relative level of run-off

of other chemical elements, we also measured TDS, primarily at water sources supplying

households, to gauge the effect of water filtering systems.

Figure 3 Water quality monitoring in Lada Estate, 2015. From various sampling stations it is possible

to assess which streams/rivers are not performing to a certain threshold value. Non-performing

waterways will initiate an immediate response from the management, to identify a source of possible

contamination. If it emerges from within the estates, remediation actions will be taken.

Total suspended solids (TSS). TSS can include a wide variety of material, such as silt,

decaying plant and animal matter, industrial wastes and sewage. High concentrations

of suspended solids can cause many problems for stream health and aquatic life. In a plantation, this is primarily manifested as organic contamination (e.g. empty fruit bunches

(EFB), palm fronds and overflowing septic tanks).

pH is measured across all waterways to assess possible deviations from the baseline.

Such data are particularly important to collect in peat swamp areas, where many species

of plants and aquatic life are specialized to survive in very acidic conditions. If a peat

swamp turns increasingly basic, this is an indication that the ecological processes are

being undermined by activities outside the peat dome itself.

5 Biological pest management

Some of the most common pests in a palm oil estate belong to the animal kingdom.

Rats (e.g. Rattus argentiventer, Rattus tiomanicus), rhinoceros beetles (e.g. Oryctes

rhinoceros) and Lepidoptera larvae can inflict serious loss of fruits (rats), kill young palms

(beetles) and defoliate palms (Lepidoptera). The rhinoceros beetles are controlled by

installing pheromone traps, and beneficial plants (e.g. Turnera subulata and Antigonon

leptopus) are planted to attract predatory and parasitic wasps from in the Spheciformes

and Vespoidea families that predate or deposit their own larvae on Lepidoptera larvae

(Wäckers, 2004; Winkler et al., 2009). Rats can cause more than 5% economic loss in the

absence of proper control (Khoo, 1984) and have traditionally been controlled with rat

poison, until biological control in the form of barn owls, Tyto alba, were introduced in the 1980s (Duckett, 1984). To what degree these birds are effective is still questionable,

and they need careful management (Duckett, 1991; Duckett and Karuppuah, 1989;

Martin, 2009). The barn owl is not considered ‘native’ but a vagrant to the southern

part of Central Kalimantan, and it would contravene biological sense if these were

introduced. Instead, already-present predators in the estate landscape were assessed

for their effect as rat predators, namely the leopard cat, Prionailurus bengalensis, and

black cobra, Naja sumatrana. Both are common in the plantation landscape and feed

primarily on rats.

A total of 11 leopard cats and 2 black cobras were captured and fitted with radio collars.

Dispersal range, territory, mate monopolization, food and foraging were studied along

with population dynamics.

6 Results and discussion

6.1 Biodiversity

The biodiversity surveys produced 278 terrestrial vertebrate species (55 mammals, 158

birds, 35 reptiles and 30 amphibians), 79 fish species and 107 tree species (Fig. 4). Five

mammals and one bird species are listed as endangered on the IUCN Red List (Table 1),

with a total of 25 listed as vulnerable. All the endangered species, except for orangutan

(Pongo pygmaeus) and the proboscis monkey (Nasalis larvatus), are very rarely recorded.

A total of 79 fish species were recorded of which many are endemic to Borneo.

The significant number of vertebrate species reflects the importance of maintaining HCV

areas. Future surveys are likely to uncover more species, in particular reptiles, amphibian

and fish species. The study site consists of a complex hydrological landscape affected

by both seasonal changes (flooding/drought) and tidal interchanges. There remains little

information about the area’s aquatic fauna, exemplified by the fact that a majority of the

recorded fish species have not yet been evaluated for the IUCN Red List.

Two tree species, Shorea belangeran and Dipterocarpus elongatus, are listed as critically

endangered and six species, Agathis borneensis, Anisoptera laevis, Anisoptera marginata,

Shorea ovali, Shorea parvifolia and Shorea cf acuminate, are listed as endangered on the

IUCN Red List (Table 2). Further six species are listed as vulnerable (e.g. Ulin, Eusideroxylon 0 T r e e s F i s h A m p h i b i a n s R e p t i l e s M a m m a l s B i r d s 20 40 60 80 100 120 140 160 180 N u m b e r o f s p e c i e s

Figure 4 Baseline biodiversity of various taxon recorded in UP/PTSSS plantation landscape.

Table 1 Endangered vertebrates recorded in UP/PTSSS plantations, Central Kalimantan

Common name	Latin name	IUCN Red List status
Flat-headed cat	Prionailurus planiceps	Endangered
Pangolin	Manis javanicus	Endangered
Bornean gibbon	Hylobates muelleri	Endangered

Orangutan Pongo pygmaeus Endangered

Proboscis monkey Nasalis larvatus Endangered

Storm's stork Ciconia stormi Endangered

zwageri). Most species turned out to be relatively easy to propagate, although certain

species with hard-shelled seeds (e.g. Ulin, Eusideroxylon zwageri) required some excision

to promote sprouting in 1–2 months (control seeds sprouted only after 9–13 months).

Survival rate of seedlings planted in semi-shaded habitat, that is, with oil palm stands

intact or reduced by 50% were higher than survival rates in clear-cut areas (Farikhah and

Traeholt, 2014) (Fig. 5). Areas planted with oil palms but in need of restoration, therefore,

underwent gradual replacement of oil palms with trees, rather than removing all oil palms

before commencing rehabilitation planting. Rehabilitation of non-peat habitat progressed

well, and various species of trees planted in 2012 have reached a height of 5–8 m

(Fig. 6). Due to the ongoing canopy formation, low undergrowth consisting of grasses

(e.g. Imperata cylindrica) and ferns (e.g. Dicranopteris linearis) is progressively suppressed

Table 2 Endangered tree species recorded in UP/PTSSS plantations, Central Kalimantan

Common name Latin name IUCN Red List status

Belangiran Shorea belangeran Critically endangered

Keruing tempudau Dipterocarpus elongatus Critically endangered

Ketimpun Anisoptera laevis Endangered

Ketimpun Anisoptera marginata Endangered

Borneo kauri Agathis borneensis Endangered

Meranti Shorea cf acuminata Endangered

Meranti luang Shorea ovalis Endangered

Light-red meranti Shorea parvifolia Endangered 50.00 55.00 60.00 65.00 70.00 75.00 80.00 85.00 90.00 95.00 Plot A Plot B Plot C S u r v i v a l r a t e

Figure 5 The survival rate of seedlings from five tree species (Gluta renghas, Calophyllum castaneum,

Cratoxylum arborescens, Shorea balangeran and Mesua sp) in a rehabilitation test plot. A = 100%

palm stand, B = 50% palm stand and C = cleared (From Farikhah and Traeholt, 2014).

due to, primarily, photosynthesis competition and changes to the soil surface microclimate

(e.g. Germer, 2003). Subsequently, the number of bird species recorded is increasing and

significantly higher than in an oil palm plantation (Fig. 7).

Peatland rehabilitation has been less successful. While the collection and propagation

of seedlings in nurseries was successful, the mortality rate of outplanted seedlings reached

95%. This may have been aggravated by the El Niño episode, which occurred during

Figure 6 Mohd Silmi, manager of the UP/BioD division, standing next to trees planted at the end of

2011. Note the absence of Dicranopteris linearis and the relatively short growth of lalang Imperata

cylindrical. 5 13 28 0 5 10 15 20 25 30 Estate Rehabilitation area HCV area N u m b e r o f s p e c i e s

Figure 7 The number of bird species in three different types of habitat. The results reflect species

count from three adjacent areas four years after planting the first seedlings in the rehabilitation area.

the 2014-2015 season, which caused extreme wet conditions in 2012-2014, resulting in

extended flood periods that drowned most seedlings. The following outplanting process

succeeded a little better, suffering extended drought periods, combined with occasional

fires, which decimated 95% of the seedlings. At present, the biodiversity team experiments

with planting seedlings on 50-80 cm earth mounds, thereby reducing the risk of mortality

due to flooding.

6.2 Water quality

Water quality fluctuated seasonally, according to the location, types of vegetation and size

of the waterways. Generally, the concentration values measured for NO_3, PO_4 and BOD

fell within the legal limits throughout the entire study period. The TSS dropped sharply

in all areas once planting commenced, except for a few streams that were still affected

by outside infrastructure development and large abandoned agricultural sites. On a few

occasions, severe organic contamination was detected and the source could be identified

as EFB. Due to their high content in urea, phosphate and potash, EFBs are recycled and

brought back to the field as an organic fertilizer after being milled for oil. In two recorded

cases, a truck carrying EFBs to the fields had tilted into a drain and offloaded its cargo

of EFBs. In three cases, EFB deposition had been undertaken poorly, with several EFBs

ending up in streams, and, in one case, heavy rains washed out effluents from piles of

EFBs, before these had been dispersed in the field. Similarly, palm oil mill effluent (POME)

is recycled as a liquid organic fertilizer. After passing through decomposition processes

in purpose made ponds (a large portion of POME is fed into a biogas plant) POME is

pumped into the fields. To avoid serious risk of organic contamination, POME is deposited

into ‘cascading flatbeds’ consisting of an elaborate system of 4–6 m 3 holes. This system is

designed to prevent washouts; however, during heavy rains many of the ‘flat beds’ can fill

up and overflow and cause run-off into adjacent waterways. During the rainy season, this

is the most common cause of organic contamination. Weather monitoring and prediction,

combined with effective management has reduced the number of overflows to a minimum

by (1) building mini bunds around the flat beds, (2) digging more flat beds and (3) reducing

volume in high-risk areas.

6.3 Pest management

Within three months, the two radio-tracked black cobras were killed and eaten by king

cobras (Ophiophagus hannah). Therefore, it was not possible to quantify the effect of

black cobras as rat predators, despite observing several cobras hunting and killing rats.

The preliminary results from radio-tracking leopard cats conclude that the average number

of rats killed and eaten by a cat is 2 rats/day, or approx. 730 rats/year/cat. While leopard

cat population density depends on the habitat, the population density in some areas

was estimated to be approx. 1 cat per 10 hectares (1000 individuals per 100km 2). This is

significantly higher than the 12–16 individuals per 100km 2 recorded by Mohamed et al.

(2013) in disturbed forests habitats and 89 individuals per 100 km 2 in Pulang Tekong,

Singapore (Chua et al., 2016). Chua et al. (2016) observed that the predation on murids

were far higher in monocrop plantations than in diverse forest habitats. Based on its

energy needs, Duckett and Karuppuah (1989) suggested a pair of barn owls could kill

1300 rats in a year, or 650 rats/year/owl. Considering the optimal number of barn owls

per area unit is approx. 8 ha/owl, there are potentially more leopard cats in an oil palm

plantation with suitable habitat. In the study site, suitable habitat was created by leaving

palm fronds stacks to overgrow with natural vegetation. This vegetation does not compete

with palms for nutrients or photosynthesis and it provides ideal cover for leopard cats,

even during harvesting rounds. In the study site, no chemical rat baiting has been required

since the project commenced in 2012, which suggests that the leopard cats and other

natural predators are keeping the rat population at a level where potential crop damage is

negligible. Whereas these generalist rat predators thrive in an oil palm landscape, better

biological pest management results may be developed by maintaining pockets of forests

refuges within the plantation landscape to increase the mammalian diversity foraging for

rats and other rodents in the plantations (Sasidhran et al., 2016; Yue et al., 2015).

7 Future trends and conclusion

The formation of an internal Biodiversity Division gathering a wide variety of experts

from limnology to forestry and GIS has proven fundamental for UP in the aim of reaching

‘sustainable’ production of palm oil. The division is responsible for protecting and

managing UP’s conservation areas, as well as essential in a management process designed

to ensure ‘sustainable’ palm oil production. This means that all sampling results are used

in an adaptive management system, that is, results are processed by the Biodiversity

Division and, if deemed necessary, corrective and/or preventative actions will be initiated.

The present study also demonstrates that measuring the operational impact of palm oil

production on the environment is possible, provided the right internal capacity is in place

at the estate level, rather than a ‘sustainability officer’ in a far-away urban headquarter.

Indeed, it is well within the obligations of many growers to develop internal capacity

to conserve and manage its natural resources, including biodiversity and ecological

processes.

Biological pest management forms a key part of sustainable palm oil production.

The more natural pest predation that takes place, the less need there is for highly toxic

chemicals for controlling pest outbreaks. The decision to use leopard cats as rat controllers

instead of importing barn owls is a direct result of having a knowledgeable, dedicated and

effective biodiversity team in place. It resulted in saving thousands of barn owls and nest

boxes and, from an environmental perspective, more importantly, less rat poison has been

deployed if compared to previous methods.

There remains significant future challenges in biodiversity management. Due to the

ongoing agricultural and urban development, more natural habitat is being replaced with

monoculture cropland or fast-wood plantations and habitats are increasingly fragmented.

This effectively isolates many species found in plantation conservation areas, thereby

inhibiting the flow of genetic diversity. As a result, plantation companies with isolated

tracts of HCV forests harbouring small populations of endangered species risk losing a

major part of its biodiversity due to stochastic variables (e.g. inbreeding, catastrophes and

diseases). Whereas previous studies have documented that small HCV areas in plantation

landscapes are important for biodiversity (Phalan et al., 2009), preventing the loss of isolated populations constitutes one of the biggest future management challenges for

the industry.

Removing individuals of an endangered species does not constitute a meaningful

management intervention, because it usually does not solve a conservation problem but

merely transfers it to another location. Habitat protection, enrichment and extension are

required; however, with the ongoing habitat loss and fragmentation, the management of

particularly large mammals and birds require dedicated meta-population management

(Byers et al., 2013; Steinmetz et al., 2009). This is a tried-and-tested process amongst zoos,

livestock producers and safari game reserves worldwide; however, it requires a central

management authority that is committed to and capable of coordinating such efforts. For

example, if a plantation company harbours a small population of 8–10 of endangered

orangutans in an isolated plot of HCV forest, the population is considered genetically non

viable, because there is a high risk that inbreeding depression will occur already in the first

generation. In addition, it can significantly undermine endangered species conservation, if

such a ‘population’ is captured and sent to already bulging poorly financed rehabilitation

centres. Such isolated populations need to be managed as an ecological closed population

that requires regular genetic supplementation and exchange in the form of external unrelated individuals. Such intensive species management is unlikely to happen, unless a responsible

company invests in the necessary in-house capacity with a responsibility to engage.

The lack of progress in integrating ecosystem services with plantation activities has

often lead to the general perception that the palm oil industry lacks the commitment

to incorporate environmental divisions. Traeholt and Schriver (2011) suggested that

limited conceptual understanding of the RSPO P&C combined with inadequate guidance

explained the slow progress in driving the industry towards sustainable production.

However, the future market requirements and present environmental emergencies will

impose far greater obligations for RSPO member companies, which want to be certified

as ‘sustainable palm oil producers’. It is imperative that the necessary investments are

made to ensure environmental and biodiversity concerns forms part and parcel of SOP.

This study documents a range of biodiversity conservation and environmental management

activities that could never have taken place without the necessary internal capacity put in

place by the plantation company itself. It also demonstrates that the process of measuring,

monitoring and managing biotic and abiotic parameters as part of an adaptive management

process is needed to document ecological sustainability in palm oil production.

8 Where to look for further information

Information about palm oil and sustainability, Global markets and statistics can be found

on the following websites:

Food and Agricultural Organization of the United Nations: www.fao.org/

Roundtable for Sustainable Palm Oil: www.rspo.org

Indonesia sustainable palm oil: http://ispo-org.or.id/index.php?lang=ina

Malaysian Palm Oil Board: http://www.mpob.gov.my/

Malaysian Palm Oil Council: http://www.mpoc.org.my/

United Plantations Bhd: http://unitedplantations.com/

More information about climate change, biodiversity conservation, environmental issues

at strategic and policy level, ecological sustainability, agricultural and social impact of

palm oil and other agricultural products can be found on the following sites:

Convention on Biological Diversity: https://www.cbd.int/

NASA: https://climate.nasa.gov/

International Union for Conservation of Nature: https://www.iucn.org/

United Nations Development Programme: http://www.undp.org/

Center for International Forestry Research: http://www.cifor.org/

Copenhagen Zoo: www.zoo.dk

European Association for Zoos and Aquaria: www.eaza.net

American Association for Zoos and Aquariums: www.aza.org

World Resources Institute: http://www.wri.org/

Alliance for Leading Environmental Researchers & Thinkers

(ALERT): http://alert

conservation.org/

Union of Concerned Scientists: http://www.ucsusa.org/

HCV Resource Network: https://www.hcvnetwork.org/

Forest Peoples Programme: http://www.forestpeoples.org/

Sawit Watch: http://sawitwatch.or.id/

International Work Group for Indigenous Affairs: http://www.iwgia.org/

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15 Chapter 15 Waste management and recycling in oil palm cultivation

1 Introduction

The abundance of wastes from the palm oil industry, coupled with the huge environmental

impact of palm oil production, has made sustainable management of plantations and

mills an urgent necessity. The palm oil industry generates huge quantities of waste, which

must be fully utilized in order to avoid enormous disposal problems. The situation is

compounded by the fact that tens of millions of oil palms are cut and/or burnt each year

to make way for new plantations.

The palm oil industry, besides producing crude palm oil (CPO) and palm kernel oil,

produces palm kernel shell (PKS), press fibre, empty fruit bunches (EFBs), palm oil mill

effluent (POME), palm trunk (during replanting) and palm fronds (during pruning). These

solid by-products can be converted to value-added products in order to generate

additional profit for the flourishing palm oil industry in Southeast Asia and other parts of

the world, in addition to saving the environment from greenhouse gas (GHG) emissions

and ecological degradation.

2 Palm oil mills and their wastes: overview

2.1 Palm oil mills

The palm oil fruits grow in branches and when mature and harvested, are referred to as

fresh fruit bunches (FFBs). Palm trees typically begin flowering and producing fruit after

3–4 years, and profitable yields are obtained by the owner well enough after 6–8 years.

Oil palm plantations generally remain profitable for 25 years, after which they need to

be replanted. Peak palm oil yields occur anywhere between 10 and 18 years of age, and

gradually decline thereafter (Shiel, 2009). After harvesting, the FFBs are transported to the

oil mills.

The capacities of the palm oil mills are measured in input tons per hour of FFB, and

more than 60% of the oil mills in Southeast Asia have capacities exceeding 30 tons per

hour. In the palm oil mill, the FFBs are sterilized (treated with heat under pressures of up

to 3.6 bar) after which the oil fruits can be removed from the branches. The EFBs are left

as residues, and the fruits are pressed in oil mills. The palm oil fruits are then pressed, and

the kernel is separated from the press cake (mesocarp fibres). The palm kernels are then

crushed, and the kernels then transported and pressed in separate mills.

EFBs, fibres and kernel shells are the main waste products from the palm oil industry that

may be utilized as fuel for energy production due to their high-energy value, as shown in

Table 1, and many of the palm oil mills today use their fibres and a part of the shells for

energy purposes. Due to steam sterilization, the EFBs have, without separate treatment, a

moisture content of 60–70% (Zafar, 2015).

In a typical palm oil plantation, almost 70% of the FFBs are turned into wastes in the

form of EFBs, fibres and shells, as well as liquid effluent. Fibres and shells are traditionally

used as fuels to generate power and steam. Effluents are sometimes converted into biogas

that can be used in gas-fired engines.

Like sugar mills, palm oil mills have traditionally been designed to cover their own

energy needs by utilizing low-pressure boilers and backpressure turbogenerators. Thus,

palm oil factories have the potential of generating large amounts of electricity, for internal

consumption and public grid, using their own wastes.

2.2 Wastes from the palm oil industry

Oil palm is a perennial tree crop, which is cultivated extensively under the humid tropics.

For efficient productivity, the average planting of a palm tree spans over a period of about

25 years. Because of the conversion of solar radiation to carbohydrates by photosynthesis,

the chemical energy content of the harvested palm fruit and biomass exceeds the energy

input through the farming system. Thus, oil palm can act as a net source of useful energy.

For example, palm oil plantations in Malaysia are planted with a density of 148 palms

per hectare. One stand of oil palm tree occupies 0.0068 hectare (ha) of land. Each palm

yields about 150 kg of FFBs per year. Therefore, the average total production of FFBs per

palm tree for 23 productive years is 3.45 tons (Hill, 2013).

The pruning of fronds is carried out at each round of harvesting in order to allow cutting of ripe fruit bunches. The dry weight of fronds from annual pruning is more than 10 tons/ha (von Uexkull and Fairhurst, 1991). For 23 years of productive period for a palm tree that bears fruit, the total dry weight of frond per palm from pruning is 1.8 tons. On the other hand, total biomass that fell during the replanting after 25 years is about 0.71 ton of trunk and fronds per palm. With an estimated calorific value of 10 GJ/ton, the total biomass energy available per palm tree, excluding the FFB, amounts to 25.1 GJ (Yusoff, 2006).

Table 1 Fuel characteristics of FFB residues

	Moisture (%)	Ash (%)	Chloride (%)	LHV (MJ/kg)	HHV (MJ/kg)
Empty fruit bunch	58.6	2.25	0.38	7.2	8.7
Fibres	38.5	3.45	–	11.4	12.3
Shells	10.9	2.10	–	18.2	18.5

The main residues obtained after processing of FFBs include:

- EFBs
- POME
- Mesocarp fibre
- PKS
- Palm kernel cake

Ng et al. (2013) observed that the processing of 1000 kg of FFBs approximately leads to:

- Production of CPO – 200 kg
- Generation of EFBs – 230 kg
- Generation of POME – 600–700 kg
- Generation of PKS and mesocarp fibres – 190 kg
- Utilization of 20–35 kWe per ton FFB
- Utilization of 730 kg steam per ton FFB

Until recently, most of the wastes from palm oil mills were either burnt in the open or thrown away in waste ponds, despite the fact that palm oil wastes are rich in energy content (as shown in Table 2). The palm oil industry contributes significantly to global climate change by emitting carbon dioxide and methane even if substantial efforts are

being made for recycling both plantation and mill wastes. Like sugar and rice mills, palm oil

mills have traditionally been designed to cover their own energy needs (process heat and

electricity) by utilizing low-pressure boilers and backpressure turbogenerators. Efficient

energy conversion technologies that can utilize all palm oil residues, including EFBs, are

currently available. Thus, palm oil factories have the potential of generating large amounts

of electricity for captive consumption as well as export of surplus power to the public grid.

In conclusion, each ton of FFB gives residue equivalent to 4.2 MJ of heat. The milling

process for a ton of FFB requires 20–25 kWh electricity and steam of 0.73 ton (2.5 bar),

for which a total primary energy of 2.2 MJ is required. Thus, surplus energy from the

mill is 2 MJ for each ton of FFB being processed (Prasertsan and Sajjakulnukit, 2006).

Interestingly, the demand for palm shell has increased considerably in countries such as

Malaysia, Indonesia and Thailand, resulting in a price close to that of coal. Nowadays,

cement industries are using PKS to replace coal mainly because of the benefits of carbon Table 2 Energy value of different palm oil wastes Biomass residue Energy value Palm oil mill effluent (POME) 434.3 MJ per m 3 Empty fruit bunches (EFBs) 4.6 MJ/kg Pressed mesocarp fibre 9.6 MJ/kg Palm kernel shell (PKS) 17.4 MJ/kg

credits (Kanadasan and Razak, 2015). In fact, the demand of PKS for commercial power generation and industrial heating is steadily increasing in Asia-Pacific countries such as

Japan and South Korea.

3 Residues after processing: kernel shells, mesocarp fibres and effluent

3.1 Palm kernel shells

PKS are the shell fractions left after the nut has been removed after being crushed in the

palm kernel oil mill. Kernel shells are a fibrous material and can easily be handled in bulk

directly from the product line to the end use. Large and small shell fractions are mixed

with dust-like fractions and small fibres. Moisture content in kernel shells is low compared

to other biomass residues with different sources suggesting values between 11 and 13%.

PKS contain residues of palm oil, which accounts for its slightly higher heating value

than average lignocellulosic biomass. Compared to other residues from the industry, it is a

good-quality biomass fuel with uniform size distribution, easy handling, easy crushing and

limited biological activity due to low moisture content.

PKS generated by the mills are traditionally used as solid fuels for steam boilers. The steam

generated is used to run turbines for electricity production. These two solid fuels alone are

able to generate more than enough energy to meet the energy demands of a palm oil mill.

Most palm oil mills in Malaysia and Indonesia are self-sufficient in terms of energy generation

as they make use of kernel shells and mesocarp fibres in cogeneration units (Zafar, 2015).

The problems associated with the burning of these solid fuels are the emissions of dark

smoke, and the carry-over of partially carbonized fibrous particulates due to incomplete

combustion of the fuels can be tackled by commercially proven technologies in the form

of high-pressure boilers.

Dual-fired boilers capable of burning either diesel oil or natural gas are the most suitable

ones for burning palm oil waste since they could also facilitate the use of POME-derived

biogas as a supplementary fuel. However, there is a great scope for the introduction of

high-efficiency combined heat and power (CHP) systems in the palm oil industry, which will

result in substantial supply of excess power to the public grid.

3.2 Palm oil fibres

Palm oil fibre is produced from EFB, which is considered as waste after the extraction of

oil palm fruits. To become the useable fibre, the EFBs go through a process that involves

shredding, separation, refining and drying.

Palm oil fibres are non-hazardous, clean, non-carcinogenic and free from pesticides and

soft parenchyma cells. Palm fibres are versatile and stable and can be processed into

various dimensional grades to suit specific applications such as erosion control, mattress

cushion production, soil stabilization, horticulture and landscaping, ceramic and brick

manufacturing, paper production, acoustics control, livestock care, compost, fertilizer

and animal feed (Abdullah and Sulaiman, 2013). Palm fibres can also be used as fillers

in thermoplastics and thermoset composites that have wide applications in furniture and

automobile components.

Oil palm fibres and shells can be dried using pyrolysis and be used as fuel for boiler.

The ash formed after burning can be utilized as an absorbent for removing pollutant

gases such as nitrogen oxide and sulphur oxide. Ash thus formed contains high amounts

of calcium, silica, potassium and alumina which can all be utilized to synthesize active

compounds to absorb the pollutant gases into absorbent.

Carbon molecular sieve (CMS) is a material containing tiny pores of a precise and

uniform size, which is used as an adsorbent for gases and liquids, and used for separating

nitrogen from other gases contained in it. CMS is produced from oil palm wastes from

lignocellulosic materials. Basically, there are three steps involved in preparing CMS from

oil palm wastes – carbonization of the wastes, activation of the chars produced and pore

modification of the activated carbons to obtain CMS.

3.3 Palm oil mill effluent (POME)

Palm oil processing also gives rise to huge quantities of highly polluting wastewater,

known as POME, which is often treated in clarification ponds where catabolization occurs,

resulting in the leaching of contaminants that pollute the groundwater and soil, and in

the release of methane gas into the atmosphere. Methane slippage from conventional

treatment systems for POME can account for up to 70% of the total GHG emissions in

CPO production.

POME contains high concentrations of protein, nitrogenous compounds, carbohydrate,

lipids and minerals that could be converted into useful material using microbial process,

called anaerobic digestion, to produce biogas and fertilizer. Anaerobic digestion of POME

results in energy-rich biogas which consists of 60–70% methane, 30–40% CO_2 and trace

amounts of hydrogen sulphide. At many palm oil mills, this process is already in place

to meet water quality standards for industrial effluent. The gas is flared off or used in

generators to produce electricity.

In a conventional palm oil mill, 600–700 kg of POME is generated for every ton of

processed FFB. As per conservative estimates, more than 100 million m^3 of POME are

generated each year in Malaysia and Indonesia. Anaerobic digestion is widely adopted

in the industry as a primary treatment for POME. Palm oil mills in Malaysia, Indonesia and

Thailand use open lagoon systems for anaerobic and aerobic treatments of POME before

discharge to a recipient due to their low costs and operational simplicity (Langerak, 2015).

A conventional open lagoon system consists of four types of ponds: a fat pit, cooling pond, anaerobic pond and aerobic pond. The fat pit recovers any remaining CPO in the

POME and is generally recovered by the mill operator. The cooling pond decreases the

temperature of POME, creating optimal conditions for the decomposition of organic

material in the anaerobic and aerobic ponds. After treatment in these four ponds, the

effluent is safe to be discharged to waterways or to be applied on land as a fertilizer.

Although the open lagoon system is economical, it is land- and time-intensive, and releases

large volumes of methane to the atmosphere primarily from the organic decomposition

that occurs in the anaerobic pond.

Technologies for the effective treatment and handling of POME have been applied in

several palm oil mills in Malaysia and Indonesia. The present systems typically involve

the anaerobic decomposition of the organic components of POME and are sufficient

to meet the required final effluent biochemical oxygen demand limits imposed by the

respective governments. As to the biogas produced during POME treatment, there

are no government regulations yet requiring palm oil mills to prevent its release to the

atmosphere. However, with advancements in anaerobic digestion technologies, it is now

possible to generate biogas in a profitable and sustainable manner, as shown in Fig. 1.

4 Residues after processing: empty fruit bunches (EFBs)

In a typical palm oil mill, EFBs are abundantly available as fibrous material of purely

biological origin. EFB contains neither chemical nor mineral additives, and depending on

proper handling operations at the mill, it is free from foreign elements such as gravel, nails,

wood residues, waste and so on. However, it is saturated with water due to the biological

growth combined with steam sterilization at the mill. Since the moisture content in EFB

is around 67%, pre-processing is necessary before EFB can be considered as a good fuel

(Carlos et al., 2015).

In contrast to shells and fibres, EFBs are usually burnt causing air pollution or returned

to the plantations as mulch. EFBs can be conveniently collected and are available for

exploitation in all palm oil mills around the world. Since shells and fibres are easy-to

handle, high-quality fuels compared to EFB, it will be advantageous to utilize EFB for

on-site energy demand while making shells and fibres available for off-site utilization which

may bring more revenues as compared to burning on-site.

Pyrolysis technology can be used to convert palm oil waste, especially EFB, into

biochar which can be further utilized for the improvement of soil, thus minimizing the

waste management problem arising from palm oil plantation and mills. The yield and

characteristics of biochar from EFBs are dependent on various factors such as operating Gas Engine CPO Plant Wastewater Treatment Plant Dewatering Unit Covered Anaerobic Lagoons Drying Yard FFB CPO Shell, Fiber, EFB BIOGAS Power Heat Wastewater Cake Biofertilizer Irrigation Water for Plantation Digestate Sludge Hot Exhaust Gases POME

Figure 1 Schematic of biogas production from palm oil mill effluent.

parameter, heating rate, holding time, as well as the type of reactor. The EFB biochar in

soil applications has the potential as a carbon sequestration due to its capability of storing

carbon for long periods, thus preventing it from being released to the atmosphere and

mitigating GHGs (Ariffin et al., 2014). In fact, oil palm biochar with high yield and higher

heating value under low energy requirement is required for improved waste management

and utilization in the palm oil industry (Juferi et al., 2015).

4.1 Processing and utilization of EFB

Unprocessed EFB is available as very wet whole EFBs each weighing several kilograms,

while processed EFB is a fibrous material with a fibre length of 10–20 cm and a reduced

moisture content of 30–50%. Additional processing steps can reduce fibre length to

around 5 cm and the material can also be processed into bales, pellets or pulverized form

after being dried (Thuy et al., 2016).

There is a large potential for transforming EFB into renewable energy feedstock that

could meet the existing energy demand of palm oil mills or other industries. Pre-treatment

steps such as shredding/chipping and dewatering (screw pressing or drying) are necessary in order to improve the fuel property of EFB. Pre-processing of EFB will greatly improve

its handling properties and reduce the transportation cost to the end user, that is, power

plant. Under such scenario, kernel shells and mesocarp fibres which are currently utilized

for providing heat for mills can be relieved for other uses off-site with higher economic

returns for palm oil millers.

The fuel could be either prepared by the mills before being sold to the power plants,

or handled by the end users based on their own requirements. Besides, centralized EFB

collection and pre-processing system could be considered as a component in the EFB

supply chain. It is evident that the mapping of available EFB resources would be useful for

EFB resource supply chain improvement. This is particularly important as there are many

different competitive usages. With proper mapping, assessment of better logistics and

EFB resource planning can lead to better cost-effectiveness for both supplier and user of

the EFB.

A covered yard is necessary to supply a constant amount of this biomass resource to

the energy conversion sector. Storage time should, however, be short, for example, five

days, as the product, even with 45% moisture, is vulnerable to natural decay through fungi

or bacterial processes. This gives handling and health problems due to fungi spores, but

it also contributes through a loss of dry matter through biological degradation (Zafar,

2015). Transportation of EFB is recommended in open trucks with high sides which can be

capable of carrying an acceptable tonnage of this low-density biomass waste.

For EFB utilization in power stations, the supply chain is characterized by size reduction,

drying and pressing into bales. This may result in significantly higher processing costs, but

transport costs are reduced. For use in co-firing in power plants, this would be the best

solution, as equipment for fuel handling in the power plant could operate with very high

reliability having eliminated all problems associated with the handling of a moist, fibrous

fuel in bulk.

4.2 Important issues in combustion of EFB

A comparison between EFB and wheat straw suggests that the two fuels have similar

combustion characteristics. This implies that the risk of slagging and fouling, common in

straw combustion systems, would also be present in EFB systems. These problems can

be resolved by using lower temperature in the combustion zone (Nyakumaa et al., 2013).

Additional solutions to EFB combustion include the following: • Fuel handling facilities should include shredder and screw press to pre-treat the EFB into suitable size and moisture. The conveying systems ought to be specially designed. • Controlled combustion will be useful to minimize the generation of nitrogen oxides and to promote better degradation of carbon in EFB. • Co-combustion or use of additives could be the option for EFB combustion. • Higher thermal efficiencies can be achieved by selecting higher boiler pressure and lower condenser pressure thermodynamic.

4.3 EFB-based pyrolysis plant in Malaysia

In cooperation with the Malaysian-based Genting Sanyen Bhd, BTG Biomass

Technology Group BV has completed the first pyrolysis plant based on rotating cone

pyrolysis technology in which EFBs are converted into pyrolysis oil. Usually, the wet

EFBs (moisture content approximately 65 wt%) are combusted on-site, yielding only

ash which can be recycled to the oil palm plantations. The palm mill produces about

six tons per hour of this wet EFB, and as a new alternative to combustion, the EFB can

be converted into fast pyrolysis oil. Prior to feeding it into the pyrolysis plant, the EFB

is comminuted and dried to a moisture content of about 5–10%. In this way, all the wet

EFBs from the palm are converted into approximately 1.2 ton per hour of pyrolysis oil

(Venderbosch et al., 2007).

4.4 Composting of EFB

In recent years, composting of EFB is gaining traction across Southeast Asia due to the

numerous benefits associated with the use of EFB as an organic fertilizer for oil palm

plantations. Composting of EFB reduces its volume which makes it easier to be transported

and spread on the fields. In addition, it helps in protecting the soil and crops by reducing

the spread of weeds, parasites and pathogens, a common problem associated with the

use of manure as a fertilizer (Siddiquee et al., 2017). EFB can also be co-composted along

with POME, thereby further reducing costs and minimizing waste disposal issues at mills

(Krishnan et al., 2017).

Composting of EFB not only offers oil palm plantations a cost-effective and

environmentally friendly solution to dispose wastes, but also provides additional

revenue stream, thus helping the mills in maintaining a competitive edge over their

rivals.

5 Cogeneration technologies

The characteristic feature of energy systems installed in palm oil mills is the stress on cost

effectiveness, rather than efficiency, due to plentiful availability of on-site biomass resources.

Most of the existing combustion systems in palm oils utilize low-efficiency low-pressure

boilers. The average conversion efficiencies of steam and electricity generation processes

are 35% and 3%, respectively, while the average overall cogeneration efficiency is 38%.

Commercially proven technologies are available in the international market for efficient

production of power and heat from all kinds of palm oil wastes – PKS, EFB and POME.

The state-of-the-art modern technologies utilize efficient high-pressure boilers. Some

of these boilers are capable of dual-fuel burning, utilizing either liquid (e.g. diesel oil)

or gas (e.g. natural gas) fuel as the supplementary energy source. Dual-fired boilers can be used in palm oil waste-fired boilers to facilitate the use of POME-derived biogas as

supplementary fuel.

Local manufacturing capacity of efficient high-pressure steam generators in palm oil

production is presently low. Most of the equipment for a palm oil waste-based power

generation and cogeneration (also known as CHP) has to be imported, making the capital

cost of a conventional biomass power plant or CHP facility high (typically around US$

1500/kW). Moreover, with the market potentials of palm oil waste-based power projects

and a suitable government policy on power pricing, the local boiler industry could possibly

take up the manufacturing of high-pressure palm oil biomass boilers, when the market and

demand for efficient biomass power technology takes off in major palm oil-producing

countries.

6 Conclusion

Since the palm oil mills have abundant waste resources, their energy systems have

traditionally been designed to be of low cost instead of being efficient. Most of

the existing biomass combustion systems in the region utilize low-efficiency low

pressure boilers where the overall cogeneration efficiency is less than 40%. An

additional source of energy in palm oil mills is the biogas produced in the anaerobic

decomposition (for wastewater treatment purposes) of POME. However, at that time, POME-derived biogas (mostly methane, CH_4) was not being recovered and used but allowed to dissipate into the atmosphere. Retrofitting existing palm oil mills with new cogeneration equipment and biogas systems capturing the methane released from the wastewater ponds are promising commercial opportunity as well as sustainable waste management options.

The current palm oil production system, around the world, is generally seen as unsustainable because of detrimental effects on biodiversity such as loss of virgin forests and GHG emissions associated with current waste disposal methods. The use of by-products for energy recovery and value-added products offers fresh perspectives for designing a sustainable palm oil production chain that is essential for the development of a bio-based economy. The recognition that utilizing by-products for added value is beneficial to the sustainability of palm oil production is essential for certifying the sustainability of the palm oil biomass energy and products.

7 Where to look for further information

Wastes from the palm oil industry can be converted into heat, power and a wide range of bio-based products. Research activities may range from conventional applications such as compost, mulching mats and etc. to latest applications like biomass pellets and biofuels.

Future research in palm oil waste management may be directed towards commercializing

the following:

1 Biomass fuel for power generation

2 Use of palm oil waste in concrete production

3 Use of palm oil waste in production of biochar and activated carbon

4 Use of palm oil waste in production of polymer and metal matrix composite.

Organizations involved:

1 Malaysian Palm Oil Board (MPOB), Malaysia http://www.mpob.gov.my/

2 Oil Palm Biomass Center (OPBC), Malaysia

3 Indonesian Oil Palm Research Institute (IOPRI), Indonesia http://www.iopri.org/

4 Roundtable on Sustainable Oil Palm (RSPO) http://www.rspo.org/

5 ASEAN Centre for Energy http://www.aseanenergy.org/

6 Oil Palm Research Institute, Ghana

7 ICAR - Indian Institute of Oil Palm Research, India http://dopr.gov.in/

8 Food and Agriculture Organization, FAO http://www.fao.org/

9 Japan International Research Center for Agricultural Sciences https://www.jircas.go.jp/en

10 IEA Bioenergy http://www.ieabioenergy.com/

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17 Chapter 17 Closing yield gaps for small- and medium-scale oil palm producers: improving cultivation practices

1 Introduction

The structure of the Colombian oil palm sector has changed during the past decade. The proportion of small- and medium-scale growers has increased both in terms of area planted and in number of growers. However, a yield gap has been found among producers, which depends upon their size. Large scale producers tend to reach higher yields in comparison to small- and medium-scale producers. On average, the annual yield gap between the aforementioned groups, when the oil palm crop has reached maturity, has been estimated in 6.6 ton FFB per hectare 1 . Among the reasons that could help explaining this yield gap are the lack of adoption of technologies that could overcome various limiting factors that hamper the proper development of oil palm cultivation.

The Colombian oil palm sector is organized in clusters made up of one main node and several peripheral nodes. The main node produces fresh fruit bunches (FFB) in large scale and it has a mill where palm oil is extracted. Peripheral nodes also produce FFB that are sold to the main node. Such peripheral nodes are made of small- and medium-sized FFB producers who are located near the main node. Fedepalma (The Colombian Federation of Oil Palm Growers) suggested to the main nodes that they should change their view about small- and medium-scale growers; they should consider them not only as raw material providers, but

1. According to the Colombian Federation of Oil Palm Growers Federation, a large producer owns a plantation larger than 500 ha, a

medium-scale grower owns a plantation between 50 ha and less than 500 ha and a small-scale producer is defined as a grower whose

plantation is smaller than 50 ha.

also as strategic partners. Therefore, the main node should be in charge of organizing

technical assistance for fruit providers and also, it should be in charge of facilitating the

access of FFB providers to credit, inputs and services (such as machinery). In Colombian

rural areas, this is important because of the lack of access to formal credit for smallholders

and the absence of governmental institutions in charge of technology transfer. The FFB

suppliers honour their debts to the main node at the moment they receive the payments

from the fruit they sell (periodically). The fruit suppliers' plantations using best agronomic

practices will be less prone to attacks by pests and diseases, which improves not only their

own sanitary conditions, but also those of the nearby main node plantations, as pests and

diseases will not be transferred from one plantation to another. This is therefore a win

win strategy, given the fact that fruit suppliers, having better conditions, will have higher

yields and their income will increase, while at the mill, the use of the installed capacity will

increase, which in turn, implies a decrease in the fixed costs of the oil extraction process.

Based on the framework described above, the Colombian Oil Palm Research Center

(Cenipalma) implemented a strategy known as ‘Narrowing the yield gap’. The goal was to

enhance technology adoption by small- and medium-scale growers and consequently to

improve their actual yields. This strategy required technical and financial support from the

main nodes and it was developed from a novel approach for technology transfer, which

was named ‘producer to producer’.

Briefly, the ‘producer-to-producer’ strategy begins with the identification of producers

who are leaders and are willing to implement the best practices suggested by extension

officers (from the main node and Cenipalma). Such leaders must be willing to share

with their peers the results obtained by implementing the best practices in their own

plantation. Afterwards, technical staff from the main node (and Cenipalma) are in charge

of determining the limiting factors that hamper the actual generation of potential yields.

Based on this diagnostics, a set of low-cost best practices is proposed for implementation

by the identified leader. Once results from best practices are evident, the leading

producer is in charge of sharing his experience during field days that will take place in

their plantations.

This chapter presents results from the first four years of research undertaken in the

Colombian Northern Zone where water deficit is predominant and is worsening with climate change. The practices implemented in plantations owned by producers identified as leaders were as follows: application of organic matter and wide furrow irrigation. The latter was implemented at plantations with access to irrigation. Results indicate that after four years of continuous implementation, the annual yield increased on average by 6 ton FFB/ha and the production costs of a ton of FFB decreased by 6%, on average as well. Production costs are expressed in terms of US$ per ton of FFB (i.e. US$/ton FFB). The maximum increase in annual yield was found to reach 13.5 ton FFB/ha with a consequent decrease in unit costs of 16%. These numbers indicate that small- and medium-sized producers can be part of an economic activity that is not only sustainable, but also profitable and inclusive.

In the introductory paragraphs of this chapter, we present literature reviews on three topics that are crucial for developing this work. We refer to yield gap, organic matter application to oil palm stands and irrigation on oil palm.

1.1 Yield gap in oil palm production

The yield gap is defined as the difference between potential yield and actual yield. The potential yield is obtained when the crop is grown in ideal conditions of climate, soil and management. Meanwhile, the actual yield is obtained by a grower who needs to handle the limiting factors that affect his/her own plantation (Sadras et al., 2015). Yield

gap analyses contribute to determining the best practices to implement with the aim of

narrowing the yield gap measured in oil palm cultivation.

In practice, determining the potential yield is a very difficult task because there are

many interactions among variables such as variety, soil characteristics, soil nutritional

content, rainfall, temperature, solar radiation and management practices, among others.

Determining the potential yield for a perennial crop brings additional complexities such

as considering long-term yield (Affholder et al., 2013). The following information presents

a synthesis of the methods that are commonly used to determine the yield potential of

a given crop. Please note that it is possible to use more than one method (Lobell et al.,

2009).

Crop simulation models: in order to develop these types of models large amounts of

data (over long periods of time) are required, which is a time-consuming and expensive

process. The main limitation of these models is that they tend to be site specific (Tittonell

et al., 2008; Fisher, 2015). Based on the gathered data, scientists develop mathematical

models, which are intended to predict the yield response to changes in environmental

conditions and crop management (Ittersum et al., 2013).

Yields measured in experimental stations: in research stations, the crop management conditions are ideal, in the sense that any limiting factor is adequately controlled. Such limiting factors include water deficit, lack of nutrients, inappropriate nutrient balance, and pests and diseases, among others. Keeping these ideal conditions along the lifespan of a perennial crop is very costly, so this may be the most expensive way of determining the potential yield. Nonetheless, scientists can generate growth curves that are possibly the closest to potential yield curves (Beddow et al., 2014; Ittersum et al., 2013; Affholder et al., 2013; Sadras et al., 2015).

Highest yields obtained by farmers: this method is based on yield reports provided by growers. Researchers interested in establishing potential yield need to study the appropriate yield records. Commonly, the yield data are organized by regions or by places where environmental conditions are similar (Licker et al., 2010). This is the least expensive manner to determine the yield gap. However, because the yield gap is calculated based on information reported by growers, the main drawback of this method is the reliability of the gathered information (Ittersum et al., 2013).

The yield gap tends to affect the net income of a grower [2], because when the actual yield is less than the potential one, resources are not being used efficiently (Beddow et al., 2014). Once the relationship between yield gap and net income is taken into account, it is evident that the yield gap affects the profit maximization goal of the grower. Academics

have established that the lag between actual yield and potential yield is 40% on average

at a global level. For instance, small-scale growers from Indonesia tend to produce 10–15

ton FFB/ha, while large-scale producers reach 25 ton/ha (Woittiez et al., 2015).

2. The net income is understood as the result of subtracting the unit production cost from the gross income (per unit).

1.2 Applying organic matter to oil palm stands

Most of the studies on the use of by-products from the oil palm agro-industry, such as empty

fruit bunches (EFB), pruned fronds and palm oil mill effluent (POME) at oil palm stands have

focused on soil preservation, and on determining the nutrient content of the different types of

residues. Several authors have reported the benefits of this practice in oil palm crops:

- The organic matter contributes to keeping moisture in soils and it also provides nutrients to oil palms, and helps to neutralize the soil exchangeable aluminium (Corley and Tinker, 2003; Pulver, 2014).

- The organic matter helps to increase fertilization efficiency, as it stimulates the development of adsorbent roots (Ruiz Alvarez and Molina, 2014).

- The organic matter improves soil structure, thus allowing water to penetrate into the soil (permeability) (Caliman et al., 2001).

1.2.1 Organic matter and soil conservation

With respect to soil preservation, one must refer to the work by Comte et al. (2013),

who present results from a long-term research project undertaken in Indonesia that was aimed at evaluating the response of low fertility tropical soils to application of mineral and

organic fertilizers. Comte et al. (2013) recommended that in order to preserve low fertility

tropical soils, organic matter should be applied as fertilizer. Moradi et al. (2014) came to

the conclusion that nutrients are released faster, and in larger amounts, at the initial stages

of the decomposition process of the organic matter.

Another interesting result is presented by Moradi et al. (2012). They evaluated soil

conservation methods for a three-year period, in some plantations in Malaysia. The soil

preservation methods considered were application of EFB, application of compressed EFB

mat and application of pruned oil palm fronds. Their results showed that the application

of EFB provides the highest amount of dry matter and the highest concentration of

nutrients, when compared to the application of other mulching materials (Moradi et al.,

2012).

1.2.2 Nutrient content of organic matter

The literature on nutrient contents from the different types of by-products of the oil palm

agro-industry may be grouped as follows:

Leaves: studies on organic fertilization have arrived at the conclusion that from a highly

productive oil palm plantation, one may obtain about 10 ton/ha of dry matter from the

pruned fronds. A ton of fronds contain 12.5 kg N, 0.5–1 kg P, 0.71–1.5 kg Mg, 15 kg K and

6.38 kg Ca (Comte et al., 2012; Moradi et al., 2014).

Empty fruit bunches: according to Taillez (1998), the application of EFB may reduce the

need of chemical fertilizers by 50% in young oil palm stands and 5% in mature oil palm

stands. Results published by academics on nutrient content from EFB relate that dispensing

one ton/ha of FFB, is equivalent to applying: 2.7–8.7 kg N, 0.31–0.51 kg P, 8.1–18.9 kg K,

0.5–1.22 kg Mg and 0.5–2.04 kg Ca (Comte et al., 2013; Moradi et al., 2014).

Compressed EFB mat: one ton of compressed EFB mat contains 6 kg N, 0.3 kg P,

11.26 kg K, 1.72 kg Ca and 0.5 kg Mg (Moradi et al., 2014). Note, in the process of

obtaining the EFB mat there is a loss of nutrients. However, this loss is compensated by

the lower transportation costs for the EFB mat.

Palm oil mill effluent: dispensing one ton of POME is equivalent to applying 1 Kg N, 0.3

Kg P, 0.3 kg K and 1.3 kg Mg (Comte et al., 2013).

1.2.3 Composting

Yuliansyah et al. (2009) have analysed alternatives to deal with solid waste produced in

oil palm plantations and palm oil mills. They mention that, in the past, it was common

to incinerate EFB and the resulting ash was used as fertilizer. However, this procedure

had its main drawbacks in the large amount of energy required, and in the emissions

from the incineration process. As an alternative, the direct application of EFB as mulch was suggested. This had a positive effect on yields with increases ranging from 8 to 34%

(Loong et al., 1987; Singh et al., 1989; Yussof, 2006; Beltrán et al., 2015).

As indicated above, EFB direct application imposes high transportation costs and high

costs of distribution in the field, and in addition there are traces of palm oil residues in

EFB (Schuchardt et al., 2002). In order to overcome these limitations, efforts were made to

compost EFB combined with POME. The time taken by the process of composting varies

between 2 and 12 weeks, depending upon the presence of nitrogen, which accelerates

the decomposition process, and the POME is used as a source of nitrogen (Schuchardt

et al., 2002; Silalahi and Foster, 2006). During the process of composting, compounds

containing carbon and nitrogen are transformed into more stable organic matter (Singh et

al., 2010). Furthermore, using POME for composting brought the extra benefit of dealing

with CPO milling residues.

With respect to the content of nutrients in compost, it was found that the application of

15 tons of compost (EFB+POME) supplied the same amount of mineral fertilizers (N, P and

Mg) that are commonly applied in Sumatran plantations, with the exception of potassium

(Tohiruddin and Foster, 2013). Comte et al. (2012) found that when EFB and POME are

composted, the resulting compost contributes to maintaining soil fertility and decreasing the required investment in mineral fertilizers.

1.3 Irrigation

Water management at an oil palm plantation must deal with the stress to oil palm trees caused by water deficit and water excess; both stresses are detrimental to yields. In this chapter, we focused our attention on water deficit literature because this is the condition found in the plantations where this research was undertaken. There are no absolute figures quantifying the yield responses to drought, but according to academics that have studied this topic, it is safe to say that there is a yield loss of about 10% for every 100 mm increase in the potential soil water deficit (Carr, 2011).

In order to avoid water deficit stress, it is necessary to irrigate oil palm trees. This has proven to be effective in increasing yields because watering increases the number of bunches (female inflorescences) and reduces losses caused by abortions (Carr, 2011). For instance, experiments undertaken in Southern Thailand showed that yields increased between 14 and 23% for oil palms under irrigation, when compared to oil palm trees that were not irrigated. They also found that there is a positive yield response to irrigation, if there are enough nutriments available for oil palms (Palat et al., 2008). The experiments undertaken in Southern Thailand were aimed at determining the best method to irrigate oil palms. The irrigation systems considered were dripper irrigation, sprinklers, microsprayers and furrow irrigation. The most cost-effective results were obtained by drip irrigation (Palat et al., 2008).

In Colombia, Alvarez et al. (2007) conducted an experiment in which they implemented

two strategies oriented towards improving the water use efficiency of a flood irrigation

system. The first strategy consisted of using wide furrow irrigation in order to cut the

amount of water required. The second strategy consisted of covering the water conduction

channels with geomembrane, in order to avoid the water loss by infiltration. Their results

indicated that water use efficiency improved from 5.8 to 20%. The authors concluded that

it would be necessary to carry out major improvements in water conduction. The latter is

due to the fact that the implemented system of water conduction channels, had ignored

relevant aspects of the topography of the plantation (Alvarez et al., 2007).

Among recommendations to avoid drought impact on yields one may highlight:

• Selected planting sites where there are deep water retentive soils (Carr, 2011).

• Subsoiling before planting, as it allows roots to grow and to distribute all over the field (Carr, 2011).

• Mulching with organic materials, since it helps to conserve water (Carr, 2011; Comte et al., 2012).

• Implementation of the most efficient irrigation system, in terms of water use (Palat et al., 2008).

This chapter is organized into four sections. In the first one, we present a brief

contextualization of the Colombian oil palm agro-industry.

In the second section, we present

the institutional arrangement that is being promoted by the Colombian Federation of Oil

Palm Growers (Fedepalma). Additionally, we describe the technology transfer strategy

implemented by Cenipalma, which is oriented towards increasing the actual yields from

Colombian small- and medium-scale producers. In the third section, we present the results

in terms of yield, of four years of implementation of practices under the producer-to

producer technology transfer system. These results correspond to plantations of small-

and medium-scale producers in the Colombian Northern Zone where the main limiting

factor is the water scarcity. The practices implemented were oriented towards water deficit

mitigation and towards increasing the efficiency of the irrigation system (where available).

Finally, in the fourth section, we present some concluding remarks.

2 Analysing yield gaps

2.1 Structural change in the Colombian oil palm agro-industry

During 2000–10, many investors entered the Colombian oil palm sector by means of a public

policy, known as Productive Alliances. In order to illustrate the structural change, one must

refer to the figures on total area planted, according to the plantation size. In 1998, large

scale plantations accounted for 52% of the total area planted with oil palm in Colombia

(288.500 ha), while the remaining 138.457 ha were owned by small- and medium-scale oil

palm growers. In 2011 large-scale growers accounted for 30% of the total area planted

with oil palm (404.101 ha), while medium- and small-sized plantations reached 282.871

ha. In summary, there was a decrease in the participation of large scale plantations in the

total area planted with oil palm trees in Colombia, mainly due to bud rot outbreaks, while

the area owned by medium- and small-scale growers doubled its size (Girón and Mahecha,

2015). Unfortunately, most newcomers lack, or have, very limited access to financial

and technological resources that allow them to implement technologies that help them

overcome limiting factors to the proper development of their crops. The latter has caused

poor adoption of available technologies, with subsequent low yield (Fontanilla et al., 2015).

2.2 Yield gap among oil palm growers in Colombia

The Colombian large-scale companies usually own a mill for the extraction of palm oil.

The mill is fed with oil palm fruit from their own fields and from fields owned by small- and

medium-scale growers located in its area of influence. It should be remembered that the

large-scale growers who own a mill are referred to as main nodes. Their relationship with

small- and medium-scale growers is governed by the biology of the oil palm because

once the oil palm fruit is cut, its oxidation process has to be stopped. This is carried out

at the mill by means of sterilization (high pressure at high temperatures). If sterilization

is delayed, the quality of the oil obtained at the mill will decrease. In Colombia, price

penalization is imposed by oil buyers when oil quality is decreased by the presence of free

fatty acids ocurring in more than 3% of the total volume of oil.

Figure 1 depicts the yield gap measured in 19 main nodes and their fruit suppliers

(i.e. crops from medium- and small-scale growers). An average yield gap of 6.6 tons of FFB

per hectare is measured. These data correspond to 34% of the total area planted with oil

palm in Colombia and represent all areas where oil palm is planted in the aforementioned

country (Fedepalma, 2015). These data do not allow the interpretation of what part of

the yield gap is due to lack of productivity and what part is due to the age of plantations

(Fedepalma, 2015). However, it is possible to foresee the existence of a trend that links

the obtained yield to the scale of the grower (Beltrán et al., 2015). Finally, it must be

Figure 1 Yields at plantations of large-scale oil palm growers (main nodes) vs yields at plantations of

medium- and small-scale oil palm growers, at their areas of influence.

highlighted that yields in main nodes are far from reaching oil palm potential yield;

however, they serve as a goal for small- and medium-sized growers.

2.3 The impact of climate change

Climate change is evidenced in Colombia through extreme weather conditions that

oscillate between intense rains causing floods and long drought periods (Jarvis and

Escobar Carbonari, 2014). Palm oil yields are affected by both water deficit and water

excess (Cornaire et al., 1994). In the case of the Colombian Northern Zone, the main

obstacle faced by oil palm cultivation is water deficit (Pulver, 2014).

Figure 2 illustrates records of monthly rainfall during the 2010–15 period. The records were

provided by Sevilla (Magdalena) weather station, which is the area where this research was

undertaken. The horizontal line at 150 mm of precipitation in Fig. 2 indicates the monthly

water requirements of the oil palm. It is evident that over the period of study, the number

of months for which the oil palm water requirement is met has decreased gradually. In fact,

during 8 months of 2010, the rainfall was enough to cover the water requirement of the crop

whereas in 2015, the water requirement was only covered during one month of the year.

In summary, the low yields recorded for oil palm in Colombia are the result of several

factors. A public policy was put in place which provided incentive to small- and medium

sized growers in order to enter the oil palm business, but then this policy left planters

alone once they had entered. As a consequence, they lacked both financial resources and

access to technologies to adequately face the obstacles of oil palm cultivation (Bardhan and Udry, 1999). In this chapter, we present the results of four years of research (2010–14) and extension, which was aimed at helping medium- and small-scale growers increase their yields.

Figure 2 Monthly precipitation during the period 2010–15. Records from the weather station at the Municipality of Sevilla, Magdalena (Colombia).

3 Strategies to improve yields

3.1 Institutional arrangements

In the 1980s, after major Latin American countries had failed to pay their debt, agencies such as the World Bank and the International Monetary Fund requested that Latin American nations adopted orthodox fiscal and monetary policies (Bulmer-Thomas, 2003). Among other consequences, the national budgets for agricultural research and development (R&D) in Latin America were reduced. As a consequence, R&D has been progressively undertaken by the private sector (Franko, 2007). This trend favoured sectors that were already organized and profitable, such as agro-industries. However, this trend left behind the small farming communities and the result was a lack of success of inclusive rural development (Sili et al., 2008).

Fedepalma, as the organization representing the interests of the Colombian oil palm growers, has been promoting a strategy that allows medium- and small-sized growers to have an access to inputs and services through the company buying their fruits:

the main node. This means that the main node should go further than only providing

technical assistance to their fruit providers. It should also help them to overcome their

main obstacle, precisely, their limited access to formal credit. For instance, the main

node may lend resources to their fruit providers for buying fertilizers or pesticides.

Additionally, the main node will provide services that require economies of scale such

as implementing the use of machinery (for instance, drainage or irrigation systems).

Small- and medium-sized growers pay their debts to the main node with the fruit they

sell. This mechanism is formalized by means of contracts between the main nodes and

their fruit suppliers.

As mentioned before, this is a win-win strategy for both the fruit suppliers and the main

nodes. The fruit suppliers' plantations which use the best agricultural practices are less

likely to be attacked by pests and diseases, increasing their productivity and therefore

the fruit suppliers' income. In addition to the fruit suppliers improving their own sanitary

conditions they will also improve those of the nearby main node plantations, as they will

not be transferring pests and diseases to these plantations (Beltrán et al., 2015). Given the

fact that these fruit suppliers will have higher yields the mill figures for use of the installed

capacity will improve. Nowadays, the Colombian indicator on mill capacity use averages

60%. This low percentage indicates that there is plenty of room to reduce fixed costs by

increasing mill use. Under this strategy set by Fedepalma, the main nodes become the

target of the technology transfer research programme and extension service of Cenipalma

(Colombian Oil Palm Research Center). Using this approach a win-win strategy is created

for both the fruit suppliers and the main nodes, because everyone in the chain gains by

the improved conditions, which lead to increased yields, and so greater mill usage, and

increased income for everybody.

3.2 Cenipalma's technology transfer strategy

Cenipalma was in charge of coordinating the research and extension strategy aimed at

increasing the yields obtained by medium- and small-sized oil palm growers in Colombia.

The participation from main nodes that were capable of switching from the traditional

view of fruit suppliers to strategic allies was a determinant factor in the success of this

initiative.

A technology transfer strategy known as 'producer to producer' was implemented

(Pulver and Jennings, 2010). This strategy may be divided into four stages, which will be

described in this section:

1 Selection of leader producers

2 Determination of the main limiting factors to attaining potential yields

3 Implementation of demonstrative plots at plantations of leader producers

4 Field trips to demonstrative plots

Selection of leader producers: this stage was carried out based on information collected

by the main nodes regarding their fruit suppliers. The focus was on yield records, use

of available technology and leadership ability. The selected producers, as well as being

willing to implement the suggested practices, had to be respected by their peers, and

they also needed to be good at communicating their experiences and results. Once such

producers were identified, they were asked to participate in the study on a voluntary basis.

Determination of the main limiting factors to attaining potential yields: a methodology

proposed by Cenipalma was used that groups oil palm productive activities (Franco et al.,

2012), from the establishment stage (crop planning, soil preparation, selection of planting

material, etc.) to crop management (nutrition, pest management, harvesting, weed

control, among others). Each set of activities was evaluated in the field by technical staff

(from Cenipalma and the main node) and a score was given. The result is a diagnostic of

the use of available crop management technologies. Additionally, these results are used

to prioritize the low-cost practices to be implemented at the demonstration plot level.

Implementation of demonstrative plots in plantations of leader producers: leader producers participated in implementing the best practices at the demonstrative plots in

their own fields. In case there were several factors limiting oil palm development, the

most critical ones were tackled first. This is important because it is not wise to overwhelm

growers by implementing too many practices at once. The follow-up process to the

practices implemented and their results was set on a monthly basis and it was carried out

by technical assistants and extension officers. At each visit, technical staff were asked to

point out and highlight the improvements observed in the field so they could help leader

producers understand their achievements. In addition, this helped leader producers

to internalize and share their experiences with peers. Finally, the main advantage from

establishing demonstrative plots was the fact that neighbouring producers could witness

on a daily basis the improvements at the demonstrative plot of the leader producer. This

strategy fostered the technology adoption process.

Field trips to demonstrative plots: it was recommended that transfer technology events

took place after results in the field were evidenced. Neighbouring producers were invited

to these field trips and the message on practices implemented and the results obtained

was transmitted by the leader producer. Technical staff from Cenipalma and the main node

were there in a supporting role and helped in the logistics of the field trip, but the leading voice was that of the leader producer. As well as bringing neighbours to the events, field trips were organized for medium- and small-scale growers from distant regions so that they could have a chance to witness the results from implementing low-cost practices.

4 Results of Cenipalma's strategy

4.1 Identification of yield-limiting factors

The oil palm plantations studied in this research were cultivated under dry and warm climates on floodplains and terraces (sub-recent and ancient). With respect to floodplains, the main groups of soils were namely Haplusterts (30%), Fluvaquents (15%), Endoaquepts (10%), Endoaquerts (30%), Haplustepts (10%) and Ustifluvents (5%). In terraces, the most representative groups of soils were Haplustepts (50%), Ustifluvents (20%) and the remaining 30% are soils such as Plintustults, Natrustalfs, Haplustolls and Haplusterts (Instituto Geográfico Agustín Codazzi, 2009).

The physical properties of the soils from the area of study were found to have good drainage and effective depth, which implies that these soils were suitable for the development of oil palm plantations. From a soil physics perspective, the main limiting factors to oil palm cultivation are compaction and the presence of sandy textures with low moisture-holding capacity. With respect to the chemical characteristics of the soils, calcium and magnesium are abundant and available. However, the availability of potassium tends

to be compromised by imbalance of bases. In addition, the high content of calcium may

limit the availability of iron and manganese (Paramananthan, 2003).

The measurement of the level of technology was conducted in the plantations of

fourteen small- and medium-scale producers, following the methodology of Franco et al.

(2012). It was established that the score for technology adoption was on average 36 points

out of a possible total of 100 points. The scores ranged from 25 to 47 points. These results

reflect a very low level of technology adoption from medium- and small-scale growers in

the Colombian Northern Zone. The most limiting factors that were found at plantations

owned by fruit suppliers in this zone were water deficit, inefficiency of flood irrigation

systems and lack of nutrients in the soil.

The yield attained by growers depended upon their access to water. Thus, growers with

access to irrigation obtained an average annual FFB yield of 24 ton/ha, despite their delay

in implementing proper crop management practices and the deficiency of the irrigation

system. Meanwhile, growers that had no access to irrigation obtained, on average, annual

FFB yields of 15 ton/ha, as a result of low adoption of technology and their exposure to

water deficit. Based on the results just mentioned, the technical staff from the project

decided to implement several practices in each demonstration plot. These practices

consisted of reaching a nutritional balance and the application of organic matter (mulch)

around palm circles. Additionally, for those plots that had access to flood irrigation, a wide

furrow irrigation system was implemented, which increased the overall efficiency of the

irrigation system.

In addition, from a sample of the oil palm fruit produced, the cost of production per ton

FFB was estimated for producers, using the method proposed by Mosquera et al. (2014).

The estimation of production costs was of crucial importance in order to determine whether

the extra resources required to implement the practices mentioned above represented

a profitable investment. The costs' estimation results from the baseline showed that

producers who had no access to irrigation had a production cost of US$49.06/t FFB while

those who had access to irrigation had a production cost of US$53.75/t FFB. The difference

is explained by the costs of installing the irrigation system, its maintenance costs and the

payments for the use of water (Fontanilla et al., 2015). However, the net income per hectare

was 50% higher in irrigated plots due to higher yield. In fact, it was estimated that the

annual net income per hectare without irrigation was US$500 per hectare, while the annual

net income in plots with irrigation was US$750 per hectare (Fontanilla et al., 2015).

4.2 Implemented practices

4.2.1 Applying organic matter around oil palm circles

The mulch was placed around the circles of oil palm trees, forming a ring-shaped cushion

of organic matter. Two types of mulch were used in this study: EFB and oil palm leaves.

The first were brought from the mill, where EFB constitute a by-product. The leaves came

from harvest and pruning (Fig. 3).

4.2.2 Costs of applying organic matter

The cost of applying EFB and leaves were considered separately. Regarding the application

of EFB, the amount placed around the oil palm circles was 400 kg per palm, every three

years. A worker may be able to apply EFB to 20–50 oil palm circles in a working day. It

Figure 3 Organic matter around oil palm circles. Above: Empty fruit bunches. Below: Leaves that were

cut at pruning. Photo: Yasmin Penagos. Extensionist at Cenipalma.

was determined that it is easier to apply EFB during the dry season. With respect to EFB

transportation costs from the mill to plantations oscillated between US$3.13 and US$6.25

per ton (Table 1).

With respect to the application of leaves while pruning, it was decided to increase the

payment per pruned palm by US$0.03, in order to compensate workers for the extra

effort of placing the leaves around oil palm circles (Fig. 3). Regarding the application of

leaves while harvesting, it was found that placing leaves around the oil palm circle did not mean an extra effort for the worker, but just a modification in where to allocate the leaves.

Therefore, it was not necessary for this to incur additional costs. In short, implementing

these practices (i.e. to place EFB and leaves, around oil palm circles), increased the annual

crop management costs by US$108.55 per hectare (Table 1).

Given that organic matter helps in increasing the number of adsorbent roots and keeping

moisture in the soil, fertilization efficiency consequently increases. In other words, the amount

of chemical fertilizer that is lost by lixiviation and volatilization decreases. Additionally, the

potassium content from EFB (approximately 1.2% wet basis) was considered, and given that

organic matter decomposes rapidly under the tropical conditions and nutrient liberation

occurs over a short period of time (Khalid et al., 1999), we assumed that the potassium

content of EFB was enough to cover the oil palm requirement for this nutrient for one year.

However, the potassium applications in the field were not cut.

Table 2 presents two scenarios of increase in the fertilization efficiency (15% and 30%).

Our starting point is the cost of the fertilizers prescribed at the demonstrative plots, which

averaged US$469.22 per hectare. Beginning from there, we estimated an increase in

fertilization efficiency of 15%, which means the oil palms will actually absorb 15% extra

from the applied nutrients. The result for this scenario indicates that the grower will not waste 24% of the total value spent on fertilizers (Table 2). Furthermore, if the increase in fertilization efficiency is 30% the grower will not waste 37% of the total value spent on fertilizers (Table 2).

These estimations imply that dispensing organic matter, specifically EFB and cut leaves, around the circles of oil palms is cost efficient. In other words, incurred costs are overcome

Table 1 Costs related to applying organic matter around oil palm circles

Organic matter	Description	Quantity
Empty fruit bunch	Amount of EFB applied (kg/palm)	400
	Labour (US$/ton of EFB applied)	0.47–1.25
	EFB transportation costs (US$/ton)	3.13–6.25
	Average EFB application costs (US$/ha)*	299.41
Leaves	Prunes per year	2
	Extra costs of placing the leaves around the circle (US$/palm)	0.03
	Annual total extra costs of placing leaves around oil palm circles (US$/ha)	8.94
Organic matter application annual costs (US$/ha)		108.55

*The EFB application is done every three years.

by their economic benefits. This is a very strong argument that motivated producers to adopt these practices (Fontanilla et al., 2015).

4.2.3 Wide furrow irrigation

As we referred to previously, there is low rainfall in the region where the study took place.

These conditions impose the need for watering oil palms. In the region, the most commonly used system is flood irrigation. However, in most plantations, these systems were not designed based on soil studies and topographical characterization. In consequence, the

irrigation systems implemented in the region tend to display very low values of water use

efficiency. A study was carried out at a plantation in the region and it was determined that

the water use efficiency value was 5.8%. It resulted from a conveyance efficiency of 35.6%

and 16.1% of application efficiency. In short, for every 100 litres of water that left the water

source, just 5.8 litres actually reached the oil palm roots (Alvarez et al., 2007).

Table 2 Economic benefit from increasing fertilization efficiency and value of the potassium content

in EFB

Estimated value of increasing the fertilization efficiency

Fertilization efficiency increase 15% 30%

Value of the total fertilizer prescription per hectare (US$/ha per year) 469.22

Value of the fertilization efficiency increase (US$/ha per year) 70.38 140.77

Value of the potassium content in EFB

Fertilization efficiency increase 15% 30%

Value of the potassium content (US$/ha per year) 39.88 32.85

Total economic benefit (US$/ha per year) 110.27 173.61

Figure 4 Wide furrow irrigation. Photo: Gabriel Enriquez. Extensionist at Cenipalma.

The wide furrow irrigation consists of building two walls that help to guide and control

the water path. A width of 1.5 m is recommended in sandy soils and 2.5 m in clayey soils.

This system allows for more adequate irrigation and also allows for directing water to

where it is needed (Fig. 4). As mentioned above, this practice was implemented in those

plantations where small- and medium-scale producers had access to irrigation and used

flood irrigation.

4.2.4 Costs of wide furrow irrigation

Implementing wide furrows required two passages of a disc furrower and installing

tubes with lids that allowed switching the flow of water from one furrow to the next. The

wide furrow implementation had a cost of US$49.21 per hectare. Additionally, the costs

related to the maintenance of the irrigation system had to be taken into account. It was

determined that in the region where the study took place, the furrows had to be repaired

using the disc furrower every two years and, the tubes that allowed the water to pass from

one furrow to the next, also had to be replaced with the same frequency. All in all, the

annual maintenance costs of the system reached US$8.23 per hectare (Table 3).

From gathered information through the project, we studied the impact of switching

from flood irrigation to wide furrow irrigation, in terms of water consumption and labour

requirement. A potential evapotranspiration of 1800 mm/year was assumed. Our results

indicate that water consumption decreased by 42% and that the area served by an

irrigation operator increased by 62% per working day. Since the water runs along the

Table 3 Wide furrow irrigation system. Implementation and maintenance costs

Item	Implementation	Maintenance (Every two years)
Cost of a disc furrower pass (US$/ha)	22.04	11.02
Cost of the tubes for directing the flow of water (US$/ha)	27.16	5.43
Total costs	49.21	16.45

Table 4 Economic benefit from the wide furrow irrigation system

Item Irrigation system	Inundation	Wide furrow
Frequency (episodes of watering per year)	10	10
Labour costs of watering per episode (US$/ha)	9.94	3.75
Water consumption per episode of watering (m^3/ha)	1462	736
Price of water (US$/$m^3$)	0.01	0.01
Irrigation district yearly fee (US$/ha)	35.21	35.21
Total irrigation costs per year (US$/ha)	234.58	118.71
Water savings per year (m^3/ha)	7258	
Yearly savings on irrigation costs (US$/ha)	107.2	

furrows, the irrigation process is less time-consuming and uses less water, compared to the flood irrigation system that was used before. The irrigation system used previously demanded an operator to unblock the tubes that allowed the water to enter the field. Additionally, the operator was in charge of ensuring that the whole area was irrigated. Summarizing, the savings in annual costs were US$107.2 per hectare, meaning that this technology is also cost efficient (Table 4).

4.2.5 Effect of implemented practices on yields (tons of FFB per hectare)

After four years of implementation of the practices discussed above, the annual FFB

yield increased, on average, by 6 ton/ha. This happened, on average, on irrigated plots

(from 24 to 30 ton/ha) and on plots without irrigation (from 14 to 20 ton/ha). However,

the maximum increase in annual yield observed was of 16 ton/ha in plots with irrigation

(reaching 40 ton/ha at the end of the fourth year), and 11 ton/ha in plots without irrigation

(reaching 25 ton/ha at the end of the fourth year (Table 5).

In order to assess the economic viability of the implementation of the practices, a

variation of the discrete simulation model proposed by Mosquera et al. (2015) was

used. This economic model considers cost variations and gross income variations over

the long term. We simulated two scenarios of practice implementation (with and without

irrigation), and two scenarios of yield increase (average and maximum) for when practices

were implemented. In total, we studied six scenarios: three scenarios for plots that have

no access to irrigation: (1) without practices, (2) with practices and average increase in

yields, and (3) with practices and maximum increase in yields (Fig. 5); and the same three

scenarios for plots with irrigation (Fig. 6). The unit area of the model is one hectare and

the time unit is one year. The lifecycle length for an oil palm plantation was set as 25 years.

From the estimated cash flows, we estimated, for each scenario, the income per hectare, the cost per ton of FFB and the internal rate of return (IRR).

The cash flow from year zero is negative because it represents the financial resources invested in establishing the oil palm plantation. Year one and two are also represented by negative cash flows, because in those periods, growers must invest resources in crop maintenance, but do not receive payments from selling oil palm fruits. At some point, between years three and four, the net cash flows become positive, indicating that gross income from selling fruit is higher than production costs (Fig. 5 and 6). Figures 5 and 6 show the ups and downs of net income curves. This is due to the investment in dispensing organic matter around oil palm circles and to the maintenance costs of the wide furrow irrigation system.

Table 5 Yields at plantations of medium- and small-sized growers, according to adoption of best practices and access to irrigation system

Scenario	Without irrigation	With irrigation
Before implementing the best practices (baseline)	14	24
With adoption of best practices (average yield increase)	20	30
With adoption of best practices (maximum yield increase observed)	25	40

*Tons of oil palm fruit (FFB) per hectare per year.

Finally, it can be concluded that the unit cost decreases according to the extent in

which yields increase (Table 6). Another very important result is that the internal rate of

return (IRR) is positive for all scenarios, meaning that the investment on implementing the

practices discussed in this document is viable from an economic standpoint (Table 6).

Figure 5 Annual net income attained by small- and medium-scale oil palm growers, according to

adoption of best practices and yield. Scenarios without irrigation.

Figure 6 Annual net income attained by small- and medium-scale oil palm growers, according to

adoption of best practices and yield. Scenarios with irrigation.

5 Future trends and conclusion

The results of the present research work show that it is possible for small- and medium

scale producers to adapt to climate change with low-cost technologies. Specifically, in the

region under study, the limiting condition is water deficit, which is worsening with time as

shown by the rainfall records. Water deficit was tackled by applying organic matter around

oil palm circles (EFB and leaves) and by installing a more efficient irrigation system.

The impact assessment of these technologies showed that they complied with the

objective of increasing productivity and were profitable. As a result, they helped to

increase the net income, and thus the welfare of small- and medium-sized growers. All

these features indicate that such practices are sustainable.

One of the pillars of success of the work undertaken by Cenipalma and the main

nodes was the ‘producer-to-producer’ strategy implemented for technology transfer: This

strategy encouraged leader producers to familiarize themselves with the implementation

of best practices and it also assigned them with the role of extensionists. In addition, the

neighbouring growers to the leader producer, and those who attended the field trips,

witnessed the results at plantations owned by their peers. Having seen the results, it was

more likely that they would decide to adopt the best practices.

Another pillar of success for the research undertaken was the participation of technical

staff from the main nodes and the willingness of the main nodes to facilitate the access

of their strategic partners (i.e. FFB suppliers) to inputs and services required for the

implementation of best practices. Those producers that benefited from accessing inputs

and services have been paying their debts to the main node, with the money that they

receive from selling their fruit. The joint work between the links in the chain allowed

medium- and small-sized producers to overcome their most limiting productive obstacles

(i.e. credit, access to technology and access to inputs). This fosters integration along the

value chain between large-, medium- and small-scale producers.

Table 6 Profitability indicators for medium- and small-scale growers who participated in this project

Access to

irrigation Scenario Yield 1 * Unit cost 2 Annual net income 3 * IRR 4

Without

irrigation Before implementing the best practices (baseline) 14 49.06 500.00 11 With adoption of best practices (average yield increase) 20 45.63 781.25 11 With adoption of best practices (maximum yield increase observed) 25 41.56 1093.75 15

With irrigation Before implementing the best practices (baseline) 24 53.75 750.00 12 With adoption of best practices (average yield increase) 30 51.56 1000.00 12 With adoption of best practices (maximum yield increase observed) 40 45.00 1593.75 18

1 Tons per hectare per year; 2 US$ per ton of oil palm fruit; 3 US$ per hectare per year; 4 Internal rate of return expressed

in percentage. *Measured in adult palms.

It should be noted that the joint work between the main nodes and their fruit

suppliers is a win-win strategy. On the one hand, the fruit providers improve their

yields, their net income and their welfare. On the other hand, the main node improves

its indicators of installed capacity use, because of the increase in the amount of fruit

processed at their mills.

The oil palm agro-industry is facing market constraints derived from the successful

campaign by associations of vegetable fat producers from temperate countries. These

associations promoted the idea that palm oil is an unhealthy fat source. This idea is hard to change, even with the recent findings showing that the process of hydrogenating soya

oil causes the formation of trans fatty acids that are related to cardiovascular-associated

diseases. Naturally, these findings have not caused as many waves as may have been

expected, but big corporations from temperate countries are including oil palm stearin

into their preparations. Nowadays, the arguments against oil palm have switched from

health reasons to sustainability concerns. In fact, oil palm cropping is seen as a threat to the

environment. There are many voices in high-income countries saying that in order to establish

oil palm plantations, tropical countries are devastating tropical forests and destroying

biodiversity hot spots. Another negative aspect that further adds to the poor reputation of

the oil palm agro-industry worldwide is that it poorly remunerates its workers. Unfortunately,

there are many examples that serve to justify these statements. Finally, the initial capital

outlay for oil palm cropping is seen as a barrier for smallholders to enter into the business,

and the consequence is that the oil palm agro-industry is not considered to allow inclusive

development. The present work in Colombia and the successful Malaysian experience

indicate that this is not actually the case, and that when proper access to technology and

resources are in place oil palm is a crop that may contribute to rural development.

The market constraints described above have fostered the initiative of certifying oil palm with a sustainability label: roundtable for sustainability of oil palm – RSPO. It allows the trader

to show that the palm oil (or fractions/products made out of it) has been properly obtained.

This means, environmentally friendly practices and fair trade practices have been used.

From the cropping standpoint, research should be aimed at

• The development of nutrient recycling practices. These should be at the core of research since they will lessen the use of mineral fertilizers in oil palm plantations. Additionally, these practices will allow smallholders to have access to low-cost fertilizing inputs.

• Water management. In a climate-changing scenario, the water management practices in oil palm plantations under water deficit should be oriented towards improving the water use efficiency, and to exploring alternatives to flood irrigation methods for smallholders.

• Pest management. In order to reduce the application of pesticides in oil palm plantations, there is a need to carry out research on pest management based, as much as possible, on biological control, and to provide resistance to pests via improved genetic materials.

• Mill practices. At the mill, there is need for research on waste disposal, and on avoiding toxic discharges into water sources. We suggest that composting with combinations of EFB and POME should be favoured.

• Labour compensation. Regarding labour, it is necessary to enforce fair labour practices, and from the research standpoint we suggest carrying out research on worker's fair compensation. For instance, in Colombia the oil palm agro-industry is well known for providing higher payments to their workers when compared to other agro-industries, and for providing social security (retirement fund and health services). The latter are quite rare in rural Colombia.

• Organizational strategies. Finally, research on organizational strategies that allow smallholders to access technology and resources is required. Researchers in the field of social sciences are needed to help the agro-industry in designing policies oriented towards inclusion. The model developed by Fedepalma and described in this chapter provides just one successful example on how to target smallholders in order to be part of an inclusive rural development strategy.

Appendix 1 Determination of the level of technology adoption by growers Crop management activity Maximum score

Crop Establishment

(Max. 20 points) Soil characterization studies 2 Topographic studies 2 Design of irrigation and drainage channels 6 Design of agronomical management units 3 Soil preparation 4 Establishment of legume covers 3

Crop maintenance

(Max. 10 points) Oil palm circles cleanness 3 Intercropping lanes cleanness 1 Pruning 2 Proper allocation of pruned leaves 2 Irrigation and drainage channels maintenance 2

Crop nutrition

(Max. 30 points) Foliar sampling for fertilizer prescription 4 Soil sampling for fertilizer prescription 5 Future production estimation (counting) 5 Fertilization efficiency 6 Fertilization fractioning 4 Opportune application of fertilizers 4 Measurement of vegetative growth 2

Pest control

(Max. 25 points) Pest scouting and record keeping 10 Opportune pest control 10 Leaf quality 2.5 Leaf area 2.5

Harvest and yields

(Max. 15 points) Harvest cycle and ripeness criteria 3 Collection of loose fruits 3 Quality of fruits that have been harvested 3 Yields 6

Source: Franco et al. (2012).

6 Where to look for further information

For further information on this topic, readers may refer to the webpage of the Common

Fund for Commodities where reports on this research project are kept (CFC-FLIPA Project.

Ecuador/Colombia). Additionally, at the CID-Palmero from Fedepalma (at Fedepalma's webpage) there are a few written communications that present the details of the rural development initiative named after 'Closing productivity gaps' (in Spanish: 'Cerrando brechas de productividad').

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18 Chapter 18 Artisanal mills and local production of palm oil by smallholders

1 Introduction

Elaeis guineensis, the most commonly grown oil palm in the world, is native to the Gulf of

Guinea. Before colonisation of the African continent, the African people were traditionally

red palm oil producers and consumers. The existence of wild palm groves, regionally

called ‘natural’ palm groves, substantiates the origin of such traditional production and

consumption (Hartley, 1988). During the colonial period, European colons traded with

African custom authorities to export artisanal red palm oil to Europe mainly for industrial

uses (Rouzière, 1995). For centuries Africa remained as the main producer of traditionally

processed red palm oil. Slaves exported the knowledge about production, culinary

traditions and seeds to Brazil (Bahia region) and to some West Indies islands. During

the twentieth century, the development of massive processing units occurred until the

present-stage industrial mills and refinery with high processing capacities (i.e. 40 t/h).

Owing to the introduction of industrial mills and refineries, the oil palm development took a

world scale from the 1960s, particularly in Southeast Asia, and also in Latin America. Nowadays,

two types of consumers constitute the world consumption of palm oil on the basis of food uses: • Artisanal and industrial red palm oil consumers, who are still mainly African people and the descendants of the African slaves; they know and appreciate the taste of red oil palm and its culinary properties, especially its use in the preparation of traditional African and Bahianese meals, although they are also consuming refined oil (Cheyns and Rafflegeau, 2005); • Refined palm oil consumers are the people in the rest of the world who consume only refined, deodorised and bleached palm oil (after elimination of carotenes, vitamins and taste), because they are not used to the taste of the red palm oil in their culinary recipes.

From this brief historical context, we conclude that Africa is the continent of production

and consumption of artisanal red palm oil. This chapter will focus on the artisanal red palm

oil production in Africa, where more than 80% of the oil palm production area is controlled

by smallholders, including family farms (Rafflegeau et al., 2015). Referring to the history of

oil palm development in Africa, the first section will describe the emergence of red palm

oil from pre-colonial times up to the recent actual supply chain of artisanal red palm oil,

from production to markets.

The existing diversity between smallholders, from family farms to agricultural enterprises,

has previously been explained. The different types of smallholders previously described

induce a huge range of planting conditions, of technical management of smallholdings,

during both immature and mature phases, and of replanting conditions. There are different

reasons for smallholders to process by themselves their oil palm fresh fruit bunches (FFB),

and a diversity of processing conditions. The second section will show which types of

smallholders have embarked on the artisanal processing of red palm oil and will discuss

why smallholders decide to do it according to the local context of oil palm development.

The third section will describe the artisanal processes and tools associated with artisanal

extraction units which are presently at work in Africa.

Due to smallholders’ diversity, the processing diversity between smallholders induces a

quality diversity of artisanal red palm oil. As a matter of fact, artisanal red palm oil is not

a standardised product for the exporting market, but rather a heterogeneous artisanal

product sold on the local market. The fourth section will present the quality, properties

and uses of artisanal red palm oil. The range found in the proportions of the main chemical

components will govern the heterogeneity of quality, which will be assessed in terms of its

benefits and risks for human health.

2 Emergence of artisanal extraction of red palm oil in Africa

2.1 Production and consumption zones in Africa

Comparing three African oil crops, namely oil palm, cotton and peanuts, Jannot (2013)

established a map showing where colonial agricultural services advised to grow each

crop in the 1950s; thus before the independence of African nations, and after this period

international institutions started funding the huge national development projects (see

Fig. 1). However, the oil palm agricultural area was actually wider than the green line on

the map, which just shows the recommended zone, but not the zone classified by colonial agronomists as ‘marginal’ , where family farms were producing artisanal red palm oil.

Important projects for oil palm development were located in the recommended zones, rather

than in the so-called marginal zones, where the oil palm production is less due to climatic

conditions. In the 1950s, the zone of artisanal red palm oil production by family farms was wider

than what the green line on the map represents, and it is still the case. As local traders are selling

artisanal red palm oil to south Sahelian population, its consumption zone is even wider.

2.2 Impact of oil palm development history

Ndjogui et al. (2014) described in detail the history of oil palm development in Cameroon,

starting from the pre-colonial period. This historical review is not specific to Cameroon as

it describes what happened in the palm-oil-producing countries located near the African

equatorial zone already described by other authors (Hartley, 1988; Corley and Tinker,

2003). Regarding what we call now ‘smallholdings’ and ‘smallholders’, the interest of

Ndjogui’s review (2014) lies on the description of two parallel transitions due to oil palm

development: an agricultural one and a technological one. These two transitions have

impacted artisanal red palm oil production.

An agricultural transition

For ages, African men were climbing the palm trees to harvest ripe FFB in ‘wild groves’

(the community-owned groves of palms described by the European colons) and in agroforestry food crop systems (privately owned plots producing mixed food crops in

rotation with fallows). In the ‘marginal’ zones where there was no planned action for oil

palm development, African rural farmers were still harvesting local ‘wild’ palm in those

agroforestry food systems and wild groves. In ‘recommended’ zones, farmers benefited

from oil palm development actions after independence. Most of the smallholders first

adopted harvesting tools, thus halting the very dangerous harvesting practice of climbing

the palm trees for collecting bunches. They secondly adopted the use of selected planting

materials because of its much higher red oil yield, even with a bit lower kernel oil yield.

Following agricultural recommendations, they created monospecific oil palm plantation

with palms planted in line with a spacing design such as 9 by 9 m in triangle, thus

corresponding to 143 palms/ha (see Fig. 2).

Figure 1 The green line on the map represents the agronomists’ recommended zones for oil palm

in the 1950s for colonial settlers. Post-independence, oil palm development projects were localised

in these recommended zones. Traditional production zones of red palm oil by family farms are wider

(from Jannot, 2013).

Nowadays, palm groves exhibit two different situations: • oil palm tree areas of high density (from 200 oil palm trees/ha), with trees being sowed or planted with no spacing design, no maintenance and are only harvested; • area dedicated to food crop production, where few tens of trees (less than 50/ha in order to preserve sunshine for food crops) are saved while clearing fallows with slashand-burn practices; these are agroforestry systems where the main products are food crops including oil palm bunches.

In both situations, local unselected planting materials (Dura type) or open-pollinated

progenies collected in selected plantations (natural pollination between Tenera types

giving progenies of 25% Dura type + 50% Tenera type + 25% Pisifera type) are used by

family farms. Open-pollinated progenies of unselected materials still produce more oil,

even with the 25% sterile Pisifera-type palm trees (Cochard et al., 2001). Figure 2 shows

the impact of the type of planting materials on expected oil yields.

A technological transition

For ages, in the oil palm growing area, African people used two traditional methods of oil

extraction:

i treading with feet and washing with water in order to extract the floating red oil from the pulp, and

ii heating of the kernel nuts in a saucepan in order to extract kernel oil.

After independence in the 1960s, the huge national development projects funded by

international institutions provided access to industrial extraction for smallholders benefiting

from the project with plantation credit and technical support. After the funding banks had

become bankrupt, the smallholders located inside industrial mill supply areas decided to

create their own oil palm plantations in order to benefit from existing industrial mills to

Figure 2 Oil palm development induced an agricultural transition. The type of planting materials used

impacts the oil extraction rate for both artisanal and industrial extraction processes (from Cochard,

2001; Rafflegeau, 2008; Ndjogui, 2014).

process their FFB without having to invest in an extracting tool. In French-speaking African

countries, oil palm development was based on the extraction of oil by high-capacity

industrial mills which belonged to state-owned development companies. These mills were

built to process FFB production from industrial plantations managed by the development

company and also from smallholdings developed inside the mill supply area. In English

speaking African countries, oil palm development was based on both industrial mills in

large palm oil production area and small-scale processing units for smaller production

area (Rouzière, 1995). Artisanal red palm oil production was thus supported by post

independence projects mainly in Nigeria and Ghana and, to a lesser extent, in Sierra

Leone and Liberia. Those projects involved national research institutes such as Nigerian

Institute for Oil Palm Research (Poku, 2002; Rouzière, 1995).

From the late 1980s, NGOs mostly took over the post-independence projects to

promote the artisanal extraction of red palm oil using small-scale mills replicated from

English-speaking countries. NGOs – such as APICA and SOWEDA in Cameroon and CFTS in Benin – worked in French- and English-speaking countries, within the recommended zone but also in the marginal zones where many people were involved in traditional oil extraction (Poku, 2002; Rouzière, 1995). Firstly, those NGOs trained blacksmiths to locally produce artisanal extraction tools and secondly they trained smallholders' group to establish and use the small-scale mills. Artisanal extraction immediately boomed because blacksmiths and smallholders copied each other's innovations. On the one hand, turning from traditional extraction of red oil palm into artisanal extraction using a small scale mill does not affect the quality of the oil and significantly saves time, allowing the same quantity of cooked oil palm fruit to be processed (Fournier et al., 2001). On the other hand, traditional extraction by treading with water facilitated the collection of kernel nuts. As households generally used artisanal red palm oil for food preparation and kernel oil for traditional medicinal purposes, the artisanal extraction process too was adopted, paralleling agricultural innovations. Traditional and artisanal extraction processes coexist, but the artisanal process emerged where and when development occurred.

Figure 3 shows the present mosaic of technological situations for palm oil extraction according to the location – either recommended or marginal – and to the presence – or absence – of oil palm development plans. Trends are thus described: since the Types of extraction Oil palm agronomic suitability Oil palm development action Industrial Artisanal Traditional Recommended zone With Frequent Frequent Uncommon Without Possible Common Uncommon Marginal zone With Never Frequent Disappearing Without Never Possible Frequent Oil extraction rate with selected planting material 21-26% 15-18% 15-18%

Figure 3 Oil palm development induced a technological transition as traditional extraction has slowly

been disappearing from the 1980s with the boom of artisanal extraction. Artisanal extraction allows

some sizeable saving of time to process the same quantity of cooked oil palm fruit.

1980s, traditional extraction has slowly been disappearing with the boom of artisanal

extraction.

These two parallel transitions – agronomical and technological – occurred where oil

palm development plans were undertaken. Oil palm production can still be traditional

elsewhere, if technical innovations were not introduced and implemented. The result

is that, nowadays, in a given African country, all types of agricultural and technological

situations coexist. Within such a diversity of technical situations, the most important factors

for artisanal palm oil production are i) the type of planting materials (see Fig. 2) and ii) the

type of extraction method, tools and process, as described in Section 3.

2.3 The present supply chain for artisanal red palm oil

Like in other palm oil producing countries in Asia and Latin America, agro-industries

are extracting crude palm oil (CPO) and palm kernel oil from their own industrial

FFB and from FFB bought from smallholders. Many African smallholders and palm

oil producers without plantation are producing artisanal red palm oil through both

artisanal and traditional processes, and figures of such an informal production remain

uncovered by international statistics (see Fig. 4). Nevertheless, it represents a huge

part of national production in Nigeria. Indeed, Nigeria has not really increased its

palm oil production in the last 50 years, dropping from the position of world's leading

producer down to fifth rank now – trailing Indonesia, Malaysia, Thailand and Colombia.

While it is clear that wild groves cannot satisfy the world's booming demand, artisanal

red oil production does meet local demand and foot habits (Cheyns and Rafflegeau,

2005).

Palm groves produce exclusively artisanal red palm oil, but their actual acreage is totally

off record and they cannot be considered as plantations because of their specific densities

Figure 4 Smallholders are producing artisanal red palm oil by artisanal and traditional extraction, but

there is no available production statistics because it is sold on informal market from Lacan et al. (2015).

and structures. They are mainly located out of official palm development zones and thus

out of the supply areas of industrial mills.

Figure 4 shows first that artisanal red palm oil is exclusively produced from FFB harvested in smallholdings (except in case of theft from industrial plantations) by local actors: both smallholders and palm oil producers without plantation. Figure 4 also shows that inside a given mill supply area, smallholders can decide to sell their FFB either to the industrial mill or to an artisanal red palm oil producer who does not own any oil palm plantation. They also have the opportunity to process FFB through their own artisanal processing unit or their neighbours' one, the milling cost being traded against a part of the extracted oil (20% in general). In the next section we will describe the reasons governing smallholders' choice for one or the other of these options.

As artisanal red palm oil being sold on the informal market, there is no opportunity to collect production data from custom services or industrial mills similar to those collected for industrial red palm oil and refined palm oil. Because of this informal market, Jannot (2013) explains the difficulties to obtain accurate data of production and uses in Africa which cover both industrial and artisanal red palm oils. When palm oil data from Africa are presented, we must remember that they are only roughly estimated, both for areas (acreage of unselected plantations and palms out of plantation areas are not taken into account) and for production (artisanal palm oil is only roughly estimated or even not taken into account at all).

Artisanal red palm oil can be used for both alimentation and soap production (artisanal

and industrial). Industrial refineries do prefer to buy industrial red palm oil rather than

the artisanal one in order to reduce the risk of high free fatty acid (FFA) content linked to

process conditions and poor preservation.

3 Who is producing artisanal red palm oil and why

We show in Fig. 4 that artisanal red palm oil is produced either by smallholders extracting oil

from FFB harvested in their own smallholdings or by oil producers buying smallholders' FFB.

3.1 Diversity of actors producing artisanal red palm oil

Marzin et al. (2015) have characterised the diversity of farm types between entrepreneurial

agriculture and family agriculture. Applying their typology to oil palm agricultural actors

proved useful in order to show the diversity of farming situations hidden behind the

general 'smallholders' name. This typology is built using labour as the main factor, with

capital, management, home consumption, legal status and land status being considered

as secondary factors. Family farms have no permanent labour, while managerial enterprises

employ exclusively paid staff. Family business farms have at least one permanent labour.

They could be a 'mature' family farm with enough oil palm area to employ one permanent

labour, or an oil palm farm created by a small investor (retail trader, salaried employee,

retired person, etc.) involving his family labour force (see Fig. 5).

Only agro-industries are able to invest millions of dollars necessary for setting up an industrial oil mill with high extraction performance and a high level of compliance with environmental requirements, especially regarding the treatments of effluents. Besides, the Caltech model of small-scale hand mill, which costs a few hundred dollars in Cameroon, is within the reach of family business farms and even of family farms. Outside of industrial mill supply area, when a family business farm invests in some processing equipment which cannot be used at full capacity, it initiates momentum for local development by opening the facility to neighbours. This service will be paid by trading a portion of the produced oil. This is often the case in Africa: a small farmer buys a small-scale mill which he uses only a few days every fortnight. Either inside or outside a mill supply area, clear land tenure situations then allow the synergistic coexistence of family and entrepreneurial forms of production based on market needs for smallholders and on supply needs for all types of mills. From one ton of FFB produced by selected palms, a small-scale mill usually produces 150–180 kg of artisanal red palm oil, whereas an industrial oil palm mill produces about 250 kg of CPO and palm kernel oil. Despite its low oil extraction efficiency, the small scale process is considered as economically viable and socially sustainable outside the mill supply basin (Plédran et al., 2016).

Oil producers without oil palm plantations show the same diversity as found for

smallholders' farms, with the same characteristics about the factors chosen to build

the typology presented in Fig. 5, except for land tenure because such stakeholders do

not really need agricultural land. Comparing the levels of investment channelled into

extraction units really helps in representing the differences existing among the types of

producers' exploitation. Some managerial enterprises of producers can invest to create

a semi-industrial extraction unit, in between artisanal extraction units and industrial mills

(see Fig. 6 and 7).

Where there is land conflict between state-owned development company and land

owners, or between a private agro-industry and people from the neighbouring villages, some

oil producers generally steal FFB from inside the industrial plantations at night. Sometimes,

theft of FFB can be at the origin of the conflict. Conflicts can also flare up because of FFB

stealing, land conflict or jealousy, outside of a mill supply area between a managerial oil

palm farm and producers whose farms are adjacent to these managerial farms.

Figure 5 The name 'smallholder' hides a huge diversity of farm types, from family farms with no

permanent labour to managerial enterprises with only salaried employees. In contrast, it is easy to

imagine what an oil palm agro-industry is with its huge capital invested by multinational capitalist firms and its technical organisation of tasks by salaried labour from Marzin et al. (2015).

3.2 Reasons for artisanal extraction by smallholders

The way FFB is processed by smallholders or producers depends on market opportunities

for smallholders and on labour available for processing operations. Smallholders have a

maximum of four market opportunities for FFB:

1 to sell FFB to the industrial mill or to artisanal producers: this opportunity requires neither investment in processing tools nor labour for processing;

2 to process FFB using their own artisanal extraction unit: this opportunity requires some investment in processing tools and labour for processing;

Figure 6 (S. Rafflegeau): Examples of investment in the mini-mill, a semi-industrial extraction unit by

managerial enterprises of producers: Global view of a container extraction unit processing stemmed

fruit in Côte d'Ivoire.

Figure 7 (S. Rafflegeau): Examples of investment in the mini-mill, a semi-industrial extraction unit, by

managerial enterprises of producers: view of a self-made steam FFB cooker in Cameroon.

3 to process FFB using the neighbour's artisanal extraction unit: this opportunity does not require any investment in processing tools, but a proportion of the produced oil must be given to the owner of the extraction unit (20% in general) and for the payment of labour time for processing;

4 to process FFB by traditional extraction: this opportunity requires almost no investment in processing tools, but much more labour for processing than through the artisanal process.

Figure 8 presents a decision chart of the reasons for smallholders and producers to choose between artisanal and traditional processes for the production of artisanal red

palm oil.

Outside of industrial mill supply area, the first reason for smallholders to produce

artisanal red palm oil is that there is neither industrial mill nor an oil producer for buying

FFB. As a consequence, ripe FFB which is not harvested in due time will get rotten on

the palm trees. That is the reason why during the peak season of production, extension

services do recommend to harvest bunches every 10 days. Ripe FFB which are already

harvested will rot much faster than the ones left on the palm tree.

Figure 8 The decision chart shows how smallholders and producers select an extraction process

in order to produce artisanal red palm oil. Selling FFB requires no labour for processing, and

the traditional process requires the most labour.

Inside an industrial mill supply area, there are three reasons which bring smallholders to

invest in an artisanal extraction equipment: • if the industrial mill is structurally saturated during high production period, collecting from smallholders is temporarily stopped and smallholders lose their FFB; • if the industrial mill experiences regular breakdowns due to lack of maintenance, smallholders regularly lose FFB; • if the collecting is consistent during the high production period but voluntarily interrupted during the low production period. This can be due to long travel to farms for a too low quantity of FFB, or high risk for the trucks transporting FFB to get stuck in the mud during heavy rains.

Smallholders located inside an industrial mill supply area can also choose to invest in some processing equipment without any risk of losing FFB, in the following cases: • if they want to self-process the lost fruit once a fortnight in between two harvests in order to get cash to pay harvesters (day labour) while the mill pay them on a monthly basis; • if they get more profit from selling the artisanal red palm oil they have processed than from selling FFB to a mill, especially during the low production period when price of artisanal red palm oil is high in the local market, and when labour is not too busy in the food crops plots; • if there is a disagreement between the industrial mill and the smallholder, like for reimbursing plantation credit.

Artisanal oil extraction is presently booming in Africa, due to investments made by all types of

smallholders and producers presented in this section, for all the reasons cited in this section.

4 Major operations and equipment for artisanal processing

Palm oil extraction from FFB is usually done according to the following process (Jacquemard

1995; Nchanji et al., 2013): after harvesting, FFB are transported to the extraction site

where bunches are stored. The risk of FFB being stolen increases if FFB stay in the field.

The major operations are to stem the fruit, sift and cook them. Subsequently, the cooked

fruits are crushed and the palm oil can be extracted by • washing the mass with water: the lipid top phase obtained is clarified to give artisanal red palm oil; • pressing the mass: the liquid obtained is clarified to give artisanal red palm oil.

For each operation of the process, we present the corresponding equipment.

4.1 Harvesting FFB

Even if it is not a technological one, this artisanal operation can directly impact oil quality.

Harvesting with knife (Fig. 9) can cause cuts on the fruit which promotes the activation of the lipolysis reactions which are responsible for the increase of FFAs content in oil. It is

therefore important to handle FFB carefully to limit these reactions (Ngando et al., 2011).

When FFB are falling down from the top of a 10-m high old palm tree, some fruits may be

damaged.

4.2 Storage

FFB are generally stored for several days (from two to more than ten days) in order to

facilitate the destemming of fruit from the bunch. In other cases, bunches are stripped

and the spikelets are then stored for a shorter time than bunches. This step induces a

fermentation process leading to an increase in FFA content in the fruit due to lipase

activity, thus affecting the quality of the oil (Ngando et al., 2011; Owolarafe et al.,

2008).

4.3 Threshing (removal of fruit from bunches)

Fruit are removed from bunches and those which remain attached are removed using

various objects such as machete, axe, stick and so on (Fig. 10).

Various NGOs have tried to disseminate the use of mechanical threshers but smallholders

and producers are not investing in such equipment so they are rarely found.

4.4 Steam sterilising or cooking fruit in boilers

The simplest way of cooking the stemmed fruit is in boiling water in steel barrels (Fig. 11).

Managerial smallholders or producers may have invested in the mini-version of industrial

mills with the capacity to generate steam to sterilise FFB (Fig. 7). The dried oil cake or

dried fibres and kernel, if the kernel oil is not extracted, are often used as cooking fuel.

Kernel nuts can be burned as fuel in dried oil cakes, or given to cattle or hand-collected

to make traditional kernel oil.

Figure 9 (S. Rafflegeau): Harvesting palm fruit with a specific tool.

In most artisanal mills, firewood (with poor energy efficiency) is used, thus causing

some environmental impact on surrounding forests (Rouzière, 1995). In some small-scale

Ghanaian mills, they even burn old tyres for fuel causing further environmental and food

security problems. Industrial mills, however, are self-sufficient in energy, by burning the

fibres and nutshells and even produce extra electricity for villages surrounding those

mills.

The cooking time very often depends on the amount of fruit and the intensity of the

fire. Cooking softens fruit, thus facilitating the crushing process and it also inactivates

mesocarp lipase (Babatundé et al., 2003).

4.5 Crushing and mixing

Home-made wood mortar and pestle are the cheapest tools for crushing cooked fruit

(Fig. 12), although crushing can also be done mechanically (Fig. 13).

Figure 10 (D. Nanda): Removal of fruit from FFB after few days of storage.

Figure 11 (D. Nanda): Cooking stemmed fruit using firewood.

4.6 Oil extraction

Oil extracting tools are more often bought, adapted or created by smallholders and

producers, whereas other innovative equipment such as clarifiers or mechanical threshers

have poor success (Rouzière, 1995; Jannot, 2000). For this reason, there are much more

tools for oil extraction than for other processing operations.

Extraction by washing with water

The simplest traditional oil extraction process, which does not require any tool or

equipment, was historically the first way to extract oil from the mass of crushed cooked

fruits. This method consists in washing it with water and foot treading. This practice still

persists in marginal zones despite the harshness and low remuneration of labour (Fournier

et al., 2001). A recent adaptation of the traditional extraction consists in building a concrete

basin (see Fig. 14) rather than to dig a basin in the ground.

Oil extraction by washing with water can also be done using a motorised water extractor

(Fig. 15). It consists of a metal cage inside which there is a rod, around which opposite

blades are arranged, connected to a motor. During the oil extraction process water is

added. The fruits are mixed and then water is poured into the extractor, which brings

Figure 12 (S. Rafflegeau): Hand crushing.

Figure 13 (S. Rafflegeau): Mechanical crushing and mixing.

out the crude oil to the exhaust of the extractor. This equipment is the highest water

consuming one (Rouzière, 1995).

Extraction by pressing

In marginal zones, smallholders and producers are adapting their existing cassava press

(see Fig. 16) or are using a stick and wood structure to press the mass inside a polyethylene

bag, such as a rice bag (see Fig. 17). The oil palm cake remains really oily even after

two following extraction cycles (pressing, mixing, pressing), showing poor efficiency in oil

extraction of such home-made equipment.

There are two major types of oil extraction equipment made by local blacksmiths for

smallholders (Jannot, 2000): • Discontinuous press, with three steps per extraction cycle: filling, pressing and emptying (Fig. 18 and 19). They can be either manual or using hydraulic force to press (Fig. 20) with a manual or motorised pump. They were the first artisanal presses to be disseminated in Nigeria and Ghana. Manual discontinuous press similar to the small Ivorian model shown in Fig. 19 is considered as a valuable tool: it is cheap and provides good performance in terms of labour and oil extraction rate.

Figure 14 (D. Nanda): Traditional extraction by foot treading and washing with water inside a concrete

basin.

Figure 15 (D. Nanda): Workers emptying a motorised water extractor.

Figure 16 (S. Rafflegeau): Adaptation of a traditional cassava press for palm oil extraction.

Figure 17 (S. Rafflegeau): The cooked fruits are manually mashed in the traditional mortar, and then

are put in a bag and oil is extracted by pressure using a stick.

Figure 18 (S. Rafflegeau): Pressing with manual and robust discontinuous press imported from Nigeria

to Southwest Cameroon for a few hundreds of dollars. • Continuous equipment: the press is filled from one side, while it is emptied by itself. This is the case of the Caltech-type screw press which also has the advantage of combining two functions into the same equipment: i) crushing the fruit by opposite blades at the beginning of the screw and ii) pressing. They can be either manual (Fig. 21) or motorised (Fig. 22). Today, such artisanal presses are the most appreciated tools because they need less labour, and they can rapidly process fruits (for the motorised ones). Screw presses, due to the turbulence and kneading action exerted on the fruit mass in the press cage, can effectively break open the oil-rich cells and thus release more oil. These presses act as an additional digester and are very efficient for oil extraction. Motorised Caltech-type screw presses are becoming the most popular press in Africa for artisanal palm oil extraction.

The efficiency in oil extraction of the various designs of fruit presses ranges from 60%

to 70% for discontinuous presses, 80–87% for hydraulic discontinuous presses and

Figure 19 (S. Rafflegeau): Pressing with manual discontinuous press, a smaller model appreciated by

women producers in Côte d'Ivoire because of its cheap price (few tens of dollars) and facility of handling.

Figure 20 (D. Nanda): Hydraulic discontinuous press: the cooked fruits are mashed with a digester.

The mass is placed in a heavy metal cage and a metal plunger is used to press the materials. The

pressure should be increased gradually to allow time for the oil to escape. The plunger can be moved

manually or by a motor. If the depth of mass is too great, oil will be trapped in the centre of the mass.

75–80% for the continuous Caltech-type screw presses (Poku, 2002). In another study, the

press efficiencies ranged from 67% to 88%, with the lowest for discontinuous manual mills

and the highest for Caltech-type screw press (Rouzière, 1995).

4.7 Clarification

This is the last major step in the production of artisanal red palm oil. The CPO is cooked

with water. At the end of cooking, the palm oil (supernatant) is skimmed (Fig. 23). This

operation is either manual or mechanised depending on the production site. The oil

collected is then poured into containers.

Figure 21 (S. Rafflegeau): Manual continuous screw press (Caltech type). This vertical model is sold for

a few hundreds of dollars in Cameroon.

Figure 22 (D. Nanda): Continuous motorised screw press (Caltech type). This model has a mechanical

speed reducer between the engine and the press. Motorised models are sold from about one

thousand dollars for the cheapest to a few thousands for the best ones.

4.8 Oil drying

Drying the oil consists in heating the oil similar to the clarifying process, but without

any water in order to evaporate the humidity that may cause oil alteration by oxidation.

Generally, the oil drying operation is not often done after extracting oil by Caltech-type

screw presses. However, oil drying is a common operation if extraction has been done with a motorised water extractor (Rouzière, 1995) or traditionally because of too high humidity content.

5 Artisanal extraction units

Artisanal extraction units are combinations of extraction equipment and many authors present the diversity of possibilities in grey literature rather than in scientific papers (Rouzière, 1995; Jannot, 2000; Poku, 2002). For a given extraction unit, the less performing equipment will behave as the bottleneck which will define the potential theoretical extraction capacity, assessed in tons of FFB processed by hour. If the succession of operations in the extraction unit is well organised with the right amount of dedicated labour force, its real extraction capacity equals its theoretical capacity. Traditional extraction units have no proper capacity because each operation is handmade. As most of artisanal extraction units are processing fruits but not FFB, the threshing operation is not taken into account, while it can easily become a bottleneck during the high production period because it requires a lot of labour force. Comparing the press capacity will then give a magnitude of what can be the capacity of the whole extraction unit. In order to rank the various types of artisanal extraction units available, we modified the typology presented by Rouzière (1995) in order to include the traditional extraction process by treading and washing with water (Table 1).

Traditional types of units correspond to marginal zones of palm oil production and

also to women producers and young smallholders who are newly established. Micro-mills

are the most common situations, as they can offer the best value for a quick investment

return. Motorised continuous screw presses are the best systems in terms of oil extraction

rate and labour need. Mini-mills are ‘businessmen extraction units’ showing the lowest

labour need and the best extraction rates, but with the longest lag for investment return

(Rouzière, 1995).

Figure 23 (D. Nanda): Skimming clarified red palm oil before filling containers. T a b l e 1 T y p o l o g y o f
e x t r a c t i o n u n i t s T y p e o f e x t r a c t i o
n u n i t T h r e s h i n g O i l e x t r a c t i o n t o o
l M a i n c h a r a c t e r i s t i c s O i l e x t r a c t
i o n r a t e I n v e s t m e n t L a b o u r n e e d 1 A T
r a d i t i o n a l b y w a s h i n g M a n u a l F o o t t
r e a d i n g , w a s h i n g w i t h w a t e r H a n d p r
o c e s s w i t h o u t e x t r a c t i o n t o o l M e d i
u m N o n e H i g h e s t 1 B T r a d i t i o n a l b y p r
e s s i n g M a n u a l P r e s s i n g m a s s i n a b a g
w i t h a m a n i o c p r e s s H a n d p r o c e s s w i t
h a h o m e m a d e t o o l L o w e s t N o n e V e r y h i
g h 2 A M i c r o m i l l s m a n u a l f r o m 2 0 0 k g t
o 5 0 0 k g F F B / h M a n u a l M a n u a l p r e s s c o
n t i n u o u s o r d i s c o n t i n u o u s H a n d p r o
c e s s w i t h a m a n u a l p r e s s m a d e b y a b l a
c k s m i t h M e d i u m (d i s c o n t i n u o u s) h i
g h (c o n t i n u o u s) T e n s o r h u n d r e d s o f
$ V e r y h i g h (d i s c o n t i n u o u s) h i g h (c
o n t i n u o u s) 2 B M i c r o m i l l s m o t o r i s e
d b y w a s h i n g M a n u a l M o t o r i s e d w a t e r
e x t r a c t o r H a n d p r o c e s s w i t h a n e x t r
a c t o r m a d e b y a b l a c k s m i t h M e d i u m T e
n s o r h u n d r e d s o f $ H i g h 2 C M i c r o m i l l
s m o t o r i s e d f r o m 5 0 0 k g t o 1 t F F B / h M a
n u a l o r m e c h a n i c H y d r a u l i c c o n t i n u
o u s p r e s s w i t h m o t o r i s e d p u m p o r c o n
t i n u o u s s c r e w p r e s s H a l f m o t o r i s e d
u n i t l o c a l l y m a d e H i g h T h o u s a n d s o f

$ Medium 3 Minimills mainly around 1 or 2 t FFB/h Mechanic Continuous screw press Small scale reproduction of industrial units extraction, often imported in container Highest Tens of thousands of $ Lowest

None of the artisanal extraction units is equipped for the treatment of mill effluents,

even with the simplest lagoon for decantation. They quickly cause water pollution in the

water courses and rivers surrounding the units and in the worst cases some contaminate

the water table. Extraction by washing the mass is probably the process which produces

a lot of effluents. Sometimes the quality of the water for processing itself becomes a

problem because of the pollution of the rivers by effluents.

6 Artisanal red palm oil composition, quality and uses

6.1 Red palm oil composition and human health

Red palm oil is a lipid extract from the mesocarp of the fruits from oil palm tree

(E. guineensis). Throughout the world, 90% of red palm oil is used for edible purposes,

while the remaining 10% is used for soap and oleochemical manufacturing (Edem, 2002).

Acyl glycerol composition

Palm oil, like all other vegetable oils, consists mainly of acyl esters of glycerol (94–98%) and

a minority of other compounds (O'Brien, 1998) (Table 2). TAGs are composed of: 7–10%

saturated TAG (mostly tripalmitates) and 6–12% completely unsaturated TAG (Karleskind

and Wolff, 1996).

The functional properties of palm oil and its components as ingredient in prepared

foods are directly related to the type of triacylglycerols present in these oils (Williams

and Hron, 1996). However, the types of triacylglycerols are determined by their fatty Table 2 Fatty acid ester composition of palm oil (Che Man et al., 1999) Triglycerides Content (%) OOO 3.90 OOL 1.22 PLO 10.02 POO 21.39 OOS 2.78 MPL 3.03 PPL 9.37 PPO 27.39 POS 5.29 SOS 1.39 MMM 0.76 MMP 2.38 PPP 4.81 L: linoleic acid; M: myristic acid; O: oleic acid; P: palmitic acid; S: stearic acid.

acid composition and by the distribution of fatty acids in the individual triacylglycerol

molecules. The quantities of each type of triacylglycerols depend on the proportions of

the individual fatty acids, the fat or oil source and the processing history of a product

(Reske et al., 1997).

Fatty acid composition

The fatty acid composition of palm oil has been widely reported by many researchers

(Tan et al., 1981; Che Man et al., 1999) (see Table 3).

Palmitic and oleic acids are the most abundant fatty acids in palm oil. The proportions

of saturated, monounsatured and polyunsatured fatty acids are approximately 50%, 40%

and 10%, respectively.

Over-consumption of any vegetable oil could have detrimental effects on health. There

are two types of fatty acids in oils: the saturated ones and also the unsaturated ones that

contain the essential fatty acids. Palm oil is made of about 50% naturally saturated fatty acids (SFA) (palmitic acid), but that does not make it unfit for human consumption. In fact

since the 1990s, it has been considered by the food industry as a good alternative to

hydrogenated vegetable oil, which could contain trans-fatty acids, a known cancer risk.

Nestel et al. (1992) reported a more favourable LDL/HDL ratio with a diet rich in palmitic

acid than with a diet rich in trans-fatty acid.

Minor components

They are represented by vitamin E, carotenoids, partial glycerides, sterols and polar lipids. • Vitamin E (600–1000 ppm): fat-soluble vitamin is predominantly represented by tocotrienols (78–82%) and tocopherols (18–22%) (Tan and Oh, 1981). Tocopherols are structurally characterised by a saturated side chain on the Table 3 Fatty acid composition of palm oil Fatty acids (%) Results 1 Results 2 Saturated fatty acids Lauric acid C12:0 Trace 0–0.4 Myristic acid C14:0 1–2 0.5–2 Palmitic acid C16:0 43–46 40–48 Stearic acid C18:0 4–6 3.5–6.5 Arachidonic acid C20:0 – 0–1 Unsaturated fatty acids Oleic acid C18 :1Δ 9 37–41 36–44 Linoleic acid C18: 1Δ 9, 6 9–12 6.5–12 Linolenic acid C18: 1Δ 9, 6 , 3 Trace 0–0.5 Eicosenoic acid C20 :1Δ 9 – 0–0.2 Source : Karleskind, 1992 1 ; Firestone, 2006 2 . chroman nucleus (Munne-Bosch and Alegre, 2002), whereas the tocotrienols possess an unsaturated side chain of phytyl. Tocotrienols are mainly in the form of alpha (22%), gamma (46%) and delta (12%), and tocopherols in the alpha form. During the refined, bleached and deodorised (RBD) process, the vitamin E content of palm oil is partially lost. Palm stearin, palm olein and palm oil RBD retain approximately 76, 72 and 69%, respectively, of the vitamin E content of red palm oil (Sambanthamurthi et al., 2000).

Palm oil is particularly rich in tocotrienols, unlike other vegetable oils (soya, sunflower)

which contain only tocopherols. The α-tocotrienol is known for its protective effect of red

blood cells against haemolysis (Sambanthamurthi et al., 2000). Qureshi et al. (1991), on evaluating the cholesterol-lowering effect in humans of tocotrienol-rich palm oil fractions,

noted a significant reduction in total cholesterol and LDL in 20 hypercholesteremic

subjects. • Carotenoids, highly unsaturated tetraterpenes biosynthesised from 8 isoprene units (Sambanthamurthi et al., 2000), are responsible for the pronounced red colour of palm oil. They are subdivided into two classes: carotenes (700–800 ppm), which make up the majority of carotenoids (90%) and xanthophylls. Since plants are able to synthesise carotenoids de novo, the carotenoid composition of foods and plant origin is variable (Delia et al., 2008), so it is not strange for it to occur in various vegetable oils, for example, yellow maize oil, groundnut oil and soybean oil. However, the concentrations of carotenoids in these vegetable oils are very low, less than 100 ppm (Ong and Tee, 1992). Carotenes are present in the alpha, beta and gamma forms, the first two forms being the most abundant (Goh et al., 1985). They are removed during the refining and deodorisation of the crude oil to produce a light yellow palm oil preferred by consumers (Cottrell, 1991).

β-carotene is the precursor of vitamin A, which is essential for cell growth,

differentiation and vision. Because of its rich β-carotene, red palm oil is recommended

for the control of vitamin A deficiency (Seshadri, 1996; Gopalan et al., 1992), as it is

available year-round, is cheaper and is an accessible resource for most developing

countries. In addition, vitamin E, essential for the assimilation of vitamin A ‘in vivo’,

is present in palm oil (Ames, 1969). Murakoshi et al. (1992) showed the ability of

α-carotene and carotenes isolated from palm oil to inhibit skin and liver cancers in

mice. These authors concluded that carotenes naturally present in red palm oil possess

chemopreventive activities against cancer. The same effects cannot be attributed to

synthetic β-carotene.

Carotenoids and vitamin E found in red palm oil are particularly important from a

nutritional point of view because of their antioxidant and anti-carcinogenic properties. • Partial glycerides, generally present in very small quantities, except for oils produced from damaged fruits. Their content will also be high in oils extracted from fruits that were in a state of advanced maturity (Siew and Ng, 1997) or that were not treated immediately after harvest. • Phytosterols, tetracyclic compounds with 27, 28 and 29 carbon atoms, are present in very small amounts (0.03% of the constituents of palm oil) and have anti-inflammatory properties.

6.2 Artisanal red palm oil uses for human consumption

Home consumption

Palm oil is the most widely consumed edible vegetable oil in the world. In African countries

such as Côte d'Ivoire and Cameroon, red palm oil is highly valued and used in the

preparation of many traditional dishes (Cheyns et al., 2000; Cheyns and Rafflegeau, 2005).

The domestic consumption of red palm oil relies on the local demand for oil, the quality of

which is intimately linked to the terroir, the type of planting materials and local processes

(Cheyns et al., 2004). Artisanal palm oil is highly appreciated in the local market because

of its organoleptic properties (smell, taste and colour) which make this oil an irreplaceable

ingredient in several local culinary recipes. With its different characteristics from CPO,

artisanal red oil meets local demand for use in cooking specific dishes of the region.

African artisanal palm oil shows the highest values with the FFA level reaching

9% (Ohimain, et al., 2012) and even exceeding 15% (Osei-Amponsah et al., 2012).

According to the Codex Alimentarius standards, any oil containing more than 5% FFA

content is considered as improper for human consumption.

The problem of acidification in artisanal oil is more acute for smallholders and producers

who are used to storing FFB for long periods between harvesting and cooking. Indeed,

the problem extends from the whole industry down to the consumer in those African

countries where artisanal red palm oil is a major commodity oil. There is no guarantee

of quality for the artisanal red palm oil found on local markets nor when it is sold to

neighbouring countries. Assessing the artisanal red palm oil’s quality is also a problem for

housewives when they buy oil from the local market. For that reason, market retailers of

artisanal palm oil have usually tried to develop loyalty relationship with their customers.

Uses in the food industry

Due to its richness in SFA, palm oil remains the best ingredient used to replace partially

hydrogenated fat which may contain trans-fatty acids. Intake of high amounts of trans

fatty acids is positively correlated with increased risks of coronary heart disease (Hu et al.,

1997), inflammation (Mozaffarian et al., 2004) and cancer (Astorg, 2005). The natural solid

fat fraction of palm oil, palm stearin, became a suitable main ingredient in margarines, shortenings and vanaspati.

Low level of polyunsaturated fatty acids and high proportion of vitamin E make palm

oil and its products resistant to oxidation (Sambanthamurthi et al., 2000). This makes

palm oil a good alternative as frying oil. In addition, its solid and semi-solid state at room

temperature due to the presence of SFA is a property which is exploited in food products

such as margarines. The combined effect of carotenoids, SFA (about 50% of total fatty

acids), tocopherols and tocotrienols provides outstanding oxidation stability over time

compared to other vegetable oils (Arora et al., 2006). The choice of the frying oil should

be based on economic, nutritional and physico-chemical quality factors, so palm oil is

obviously an interesting vegetable oil for food industries.

7 Sustainable development issues for artisanal red palm oil production

Outside the mill supply areas, the artisanal processing of FFB through small-scale extraction

units can be considered as economically viable and socially sustainable, while offering job

opportunities in rural areas. However, using tyres as fuel for cooking the fruit and clarify

the oil has to be banished. It is of general interest to reduce the number of extraction units

in order to promote fewer but more performing units – such as the mini-mills described

in Table 1 – owned and managed by local businessmen creating managerial enterprises.

We recommend to support smallholders and producers for creating cooperatives or better

kind of inclusive business by Alliances, for example, the South American 'Alianzas', to really

build a win–win partnership between the managerial oil producer and the smallholders

who will become shareholders of the Alliance (Rafflegeau and Feintrenie, 2013). In such

partnerships, shareholders are taking part to decide the rules, such as fixing the price to

pay smallholders.

There are three reasons for supporting such a development of mini-mills outside the

supply area of industrial mills, rather than promoting the installation of micro-mills: • with a higher oil extraction rate, oil palm production can increase without changing anything else; • as mini-mills are processing FFB rather than stemmed fruit, the delay between harvest and process can be drastically reduced if compared with other technologies, thus having a direct impact on the quality of the artisanal red palm oil; new development with less extraction units of a higher capacity will allow to implement an efficient treatment of mill effluents, thus reducing the environmental impact on water quality in surrounding water courses and rivers; mini-mills are also energetically self-sufficient as they use heaters that are not burning firewood, reducing again the environmental pressure around the mills.

Inside the supply areas of industrial mills, if the mill is saturated during the high production

period, the situation becomes exactly the same as outside of mill supply area. If the mill is

not saturated during the high production period, it is then a pity to process FFBs through

artisanal extraction units, then losing one-third of the oil and polluting the rivers. As we

described the reasons for smallholders to process by themselves, industrial mills have to redesign their relationship with smallholders. Win–win partnerships between smallholders and agro-industries can lead to improvements in smallholders' yields, and to increases in the part of FFB originating from smallholdings supplied to industrial mills rather than to small-scale mills (Nkongho et al., 2015; Rafflegeau et al., 2010). Smallholders are not only interested in defining the price of FFB, but also in technical advice; extension services; and supply of certified selected planting materials and of fertiliser, micro-credit and so on.

The present situation of water pollution of the rivers in tropical Africa by a multitude of artisanal extraction units should lead researchers, governments, civil society and actors of development to urgently find adapted solutions for existing extraction units. Secondly, smallholders and producers must be informed and trained for the preservation of the quality of the waters surrounding their artisanal extraction units. This is a major issue hampering the sustainable development of artisanal red palm oil production.

African consumers are expecting more uniformity in quality among artisanal red palm oils which they buy in the local markets. They also need more information about the health properties of red palm oil, which is naturally rich in E vitamins and β-carotene. There is a need for halting the bizarre trend of African people consuming less red palm oil and more refined palm oil. The worst African trend consists in ‘bleaching’ artisanal red palm oil by

over-heating it at home, in order to change the colour of the oil before its incorporation

in non-traditional meals. In other parts of the world, the same health reasons led to the

promotion of red palm oil consumption rather than refined oil which is poorer in vitamins.

8 Where to look for further information

Biochemical information about palm oil composition and information concerning palm

oil consumption’s impact on health can easily be found in many scientific papers from

specialised journals on chemistry and nutrition. Information about extraction units,

artisanal palm oil production and economic analyses is mostly available as grey literature.

As the technological development of extraction equipment has already been undertaken,

technical information describing artisanal extraction units is available in expert assessment

reports which are unfortunately not always available online.

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