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Achieving sustainable cultivation of oil palm

Volume 1: Introduction, breeding and cultivation techniques

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

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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. Oil palm cultivation faces a range of challenges, such as its environmental impact (deforestation and biodiversity loss) as well threats from pests and diseases. There is an urgent need to make oil palm cultivation more efficient and environmentally 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

The chapters in Volume 1 review the latest developments in conventional and marker-assisted breeding, as well as transgenic approaches, as well as assessing ways of assessing and optimising yields through integrated approaches relying on precision agriculture aimed at fine tuning nutrient and soil management.

Part 1 Setting the scene

The first part of the volume begins by reviewing trends in production and key challenges facing the sector. Chapter 1 addresses the growth of the palm oil market , key actors and trends. For many years palm oil has proved to the most productive, highest yielding oil crop, with a yield 4 to 10 times higher than any other oil crop. This has driven palm oil to become the most consumed vegetable oil in the world. The chapter provides an overview of oil palm cultivation and palm oil production throughout the world, with a particular focus on Indonesia and Malaysia, and describes the growth of the palm oil industry and the nature of the global market. The chapter also addresses the diverse ecological and social impacts of palm oil and suggests future directions for sustainable palm oil production.

Chapter 2 moves from the commercial market to consider research trends in oil palm cultivation. Since its establishment as a commercial crop in Malaya in 1917, palm oil has become the most important vegetable oil traded in the world. Its standing in the world market is attributed to the oil's versatile applications, stable supply and affordability. With the estimated global world population reaching nine billion by 2050, the supply of palm oil must grow to help meet the demand for vegetable oils. The chapter summarises the trends in research which have been driven by key challenges faced by the industry. It covers the establishment of oil palm as an economic crop, the improvement of yield by selective breeding, the use of genomics to expedite research and a holistic approach to remodeling cultivation systems for eco-efficiency, with the goal of achieving cultivation of oil palm with minimal environmental impact.

Following on from the aspirations for oil palm cultivation outlined in Chapters 1 and 2, Chapter 3 addresses the issues of achieving sustainable oil palm cultivation on the ground via detailed case studies drawn from Indonesia, Colombia and Cameroon, which are compared and contrasted. The chapter discusses the conceptualization of sustainable pathways in oil palm production and the background to oil palm production in

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three contrasted producing countries which involve different groups of stakeholders with different production goals. The chapter outlines the challenges of sustainable production pathways and sustainability initiatives. Finally, it considers the actors, regulations and practices in the dynamics of sustainability that may make sustainable production possible in Asia, South America and Africa.

Building on Chapter 3, Chapter 4 deals with the role of governance and land tenure in regulating the oil palm boom. Oil palm expansion has delivered economic development in host countries, including indirect benefits for local infrastructure development and rural poverty reduction, as well as multiplier effects for the national economies. However, its development has often come at the cost of basic rights and to the detriment of biodiverse, carbon-rich tropical forests, with local communities sometimes evicted from their lands and precious ecosystems destroyed.

Chapter 4 identifies several structural constraints to better governance, and argues that these must be addressed in order to build more sustainable and inclusive oil palm supply chains and landscapes. The chapter lays out the conceptual framework of palm oil governance, identifying the key action arenas and actors. The chapter explores the institutional architecture and critical problems affecting the palm oil governance complex, while highlighting major gaps in the governance of the commodity chain.

Part 2 Plant physiology and breeding

The focus of the second part of the volume is on developments in understanding oil palm physiology, genetics and genetic diversity, as well as their application to improved breeding techniques. Chapter 5 examines advances in understanding oil palm reproductive development. As for many other crops, yield components of the oil palm rely partly on the optimal implementation of its reproductive development. As a result, studies focusing on the mechanisms underlying sex ratio determination, inflorescence development or fruit maturation have rapidly multiplied, significantly improving our understanding of these critical processes. The chapter describes the impact of sex ratio, inflorescence and flower development on oil palm yields and describes the processes of fruit development and shedding and their importance, as well as oil acidification. The chapter looks ahead to the likely future impact of climate change and developments in this area that may increase the sustainability of oil palm cultivation.

Chapter 6 develops Chapter 5's focus on oil palm breeding by examining the importance of genetic resources in the implementation of efficient strategies of genetic improvement. Oil palm planting materials have been generated from an extremely narrow genetic base, and it has been generally recognized that the narrowness of the genepool is a major obstacle towards increasing yields in many crops. The chapter discusses the work undertaken by the Malaysian Palm Oil Board to broaden this genetic base. It also examines ways of assessing genetic diversity in oil palm, through the analysis of fruit forms and types, morphological traits and genetic markers. The chapter also reviews methods for the conservation of oil palm collections and ways of utilizing germplasm in order to develop improved varieties which constitute the basis of sustainable plantations.

Chapter 7 follows on from Chapter 6's focus on oil palm genetics to consider advances in conventional oil palm breeding techniques. At the beginning of the twentieth century, oil palm was a semi-wild crop which had not been subjected to modern breeding

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techniques. The chapter discusses oil palm breeding objectives, breeding methods and data collection methods currently in use; it then reviews the impacts and progress of oil palm breeding programs. Finally, the chapter considers seed production and future trends in oil palm breeding.

Returning to the theme of genetics, the focus of Chapter 8 is on advances in marker-assisted breeding of oil palm. Oil palm, with its long breeding cycle and large land requirement for breeding trials, can be considered a suitable candidate crop for marker assisted selection (MAS). The chapter explores the applications of MAS in oil palm breeding, including pedigree testing and the prediction of monogenic and quantitative traits. The chapter shows that MAS enables accurate tagging of markers related to polygenic traits, a prerequisite for their integration into in oil palm breeding strategies, and suggests future lines or research.

Complementing the themes of the preceding chapter, Chapter 9 addresses advances in genetic modification of oil palm. Transgenic crop are generated through recombinant DNA methods to alter gene expression in order to create new varieties for breeders that may be either difficult or impossible to produce using conventional approaches. Over the past few decades, transgenic methods have been successfully applied to develop genetically modified (GM) varieties of the major oilseed crops. The chapter reviews research efforts for production of GM oil palm plants over the past 20 years. Although these efforts have yet to result in stable lines of commercially useful GM varieties of oil palm, there are good prospects that the greatly improved knowledge of genomics coupled with advanced technologies such as genome editing will be successful in the future, provided it meets public approval.

Part 3 Cultivation techniques

The final part of the book discusses developments in oil palm cultivation practices. Chapter 10 examines the modelling of crop growth in order to achieve higher oil yields. Since the development of the first semi-mechanistic oil palm model, OPSIM, the development of new models has increased in frequency, aiming to take into account aspects of oil palm physiology and the physical processes and causal relationships between the environment and the crop. The chapter describes the development of a new oil palm growth and yield model called PySawit. The chapter discusses the evaluation of PySawit's accuracy when its predictions were compared with several measured parameters of growth and yield in oil palm. The chapter includes a full explanation of the methodology of the model and discussion of its results, and explores the modeling of meteorology, photosynthesis, energy balance, soil water and crop growth

Continuing the theme of improved agricultural practices, Chapter 11 addresses efforts to improve soil and nutrient management in oil palm plantations. Soil health is increasingly regarded as a key factor in oil palm nutrition and productivity. The chapter presents the current state of knowledge about soil and nutrient management through several examples of efficient and productive oil palm cultivation. The chapter highlights the challenges which still need to be addressed in order to make the crop more sustainable in the long term while considering some new concepts in plant nutrition and soil fertility management. The chapter also considers the potential of new technologies such as sensors and drones. The chapter considers key issues relating to soil fertility, nutrient management, mineral nutrition and planting materials, and focuses particularly on issues affecting smallholders.

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Complementing Chapter 11's focus on soil management, Chapter 12 focusses on maintaining soil health in oil palm cultivation. Many existing oil palm plantations were established after clearing tropical rainforests. In tropical soils under forest, the topsoil is where the fertility lies due to its physico-chemical properties, developed through an accumulation of organic matter and intense biological activity. The properties of this topsoil change rapidly in the first four years after felling, but it has been reported that the topsoil then evolves towards a new, stable chemical state. A central challenge is therefore to ensure that this new stable state possesses the properties that enable high yields. The chapter considers the key issues and challenges in maintaining soil health. It then reviews the effects of management practices in oil palm plantation on soil biological activity, and considers the potential benefits of biomass recycling.

The volume's final chapter, Chapter 13, considers the increasingly important issue of palm oil's use as biomass for biofuel. The use of fossil fuels depletes the world's limited supply of coal, oil and gas, and releases stored CO_2 into the atmosphere. Biofuels, derived from biomass, are renewable and carbon neutral, because consumption merely releases CO_2 taken from the atmosphere by the growing biomass. However, increasing the use of biofuels could also increase the pressure on ecosystems which must support the production of additional biomass. The chapter assesses the sustainability of biofuels, discusses their production and economics, and considers levels of government support for production and related geopolitical issues.

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Part 1

Setting the scene

Chapter 1

The palm oil market: growth and trends

Stefano Savi, Roundtable on Sustainable Palm Oil, Malaysia

1 Introduction

For many years now, palm oil has proved to be the most productive, highest yielding oil crop. Its yield is 4–10 times higher compared to that of any other vegetable oil, a factor that has helped palm oil in becoming what is today the most consumed vegetable oil in the world (Alias et al., 2014, see Fig. 1). Palm oil is derived from the fruit of a specific species of palm tree, known as *Elaeis guineensis*. There are two types of oil that can be produced from the fruit of oil palm. The first type of oil is extracted from the flesh of the fruit and is used in a variety of applications, mostly in food, where its properties make it especially suited to be used as cooking oil, or in margarines, as substitutes of cocoa butter, and also as a replacement for milk fat. The second type of oil is derived from the palm fruit kernel. Derivatives of this palm kernel oil can be utilized in cosmetics and other speciality applications. Of the goods that are present on the shelves of the stores, over half of them contain palm oil as an ingredient.

The vegetable oil market is divided into three major segments: food, industrial non-food and biodiesel feed. A major share of the consumption market is taken by the applications of food; however, the biofuels segment is considered the fastest growing one due to its use as biodiesel feedstock. Recent data have shown that, in Europe, use of palm oil in the biofuel market has overtaken both food and cosmetics, and now represents the majority of the palm oil use in the region (RSPO, 2016). It is forecasted that biodiesel will reach the highest growth of approximately 8.8% from 2015 till 2022 (Grand View Research, 2016). With governments trying to limit reliance on conventional fossil fuels, it is expected

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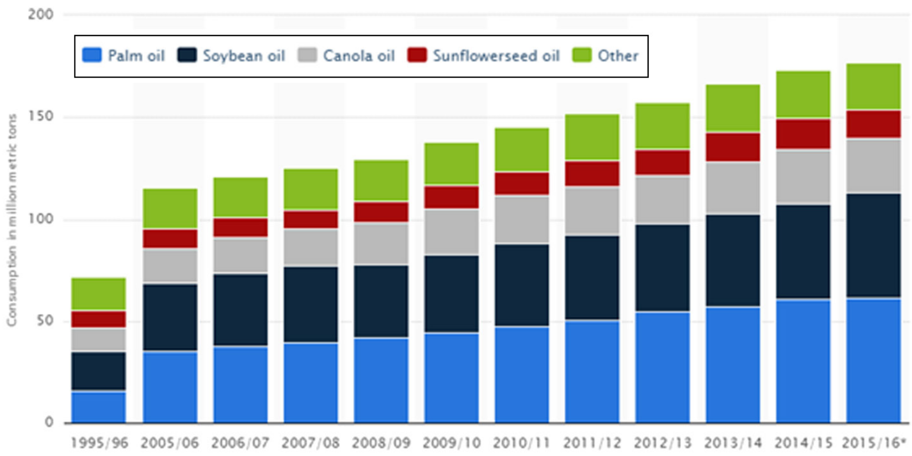

Figure 1 Consumption of vegetable oils worldwide from 1995/1996 to 2015/2016, by oil type (in million metric tons). Source: Statista.com.

that biodiesel fuel will witness a rapid growth in the forthcoming years, at least initially contributing to an increase in demand of first-generation biofuels, such as those derived from palm oil.

2 Oil palm cultivation and palm oil production

The expansion of palm oil plantations globally started in the early twentieth century, driven by the Industrial Revolution in Europe and expansion of overseas trade. Although oil palm is originally from West Africa, the first commercial-scale oil palm plantations were established by the British in South East Asia (initially in Malaysia) and saw great expansion in the 1960s when land settlement schemes for planting oil palm were introduced as a means to eradicate poverty for landless farmers and smallholders in the region. Today, Indonesia is the largest palm oil producer, followed by Malaysia and Thailand (USDA, 2016, see Table 1).

Table 1 Global palm oil production by country

(Values in metric tons)	
Indonesia	35,000,000
Malaysia	21,000,000
Others	4,945,000
Thailand	2,300,000
Colombia	1,280,000

Source: (Globalpalmoilproduction.com, 2016).

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3 Regional oil palm production trends

3.1 Oil palm in Indonesia

There has been a vigorous growth in the palm oil industry of Indonesia, where very few industries have experienced the same growth as that of palm oil. The growth is clearly visible, not only in the exports and production statistics but also in the estate areas converted to oil palm. The industry originated in Sumatra during the Dutch colonial period and around 70% of the plantations are situated there. The rest of the 30% can be located in the island of Kalimantan (Investments, 2016). Over the years, palm oil has proven to generate high yields and, due to increasing demand, both large corporations and medium and small farmers have shown interest in the industry and have switched from other crops (Castiblanco et al., 2013). This switch has lead Indonesia to become the largest producer and exporter of palm oil worldwide. India, Europe (via the Netherlands), Malaysia, China and Singapore are among the most important destinations where Indonesian palm oil is exported (Investments, 2016). The export and production statistics of palm oil in Indonesia are given in Table 2.

Today, the processing industry and plantation of oil palm in Indonesia are the most important industries of the country in terms of contribution to the national economy. Moreover, this industry provides numerous employment opportunities to millions of individuals in Indonesia.

The data extracted from the Indonesian Ministry of Agriculture show that the overall area covered by palm constitutes about eight million hectares (Investments, 2016). It is expected that by the end of 2020, this amount will increase to 13 million hectares (Investments, 2016).

Private organisations produce approximately half of the overall production of Indonesian palm oil, whereas the government-owned plantations play a relatively modest role. The remaining 35% of the production comes from smallholder farmers (Investments, 2016).

3.2 Oil palm in Malaysia

In 1870, the oil palm was introduced for the first time as an ornamental plant in Malaysia. The area of land planted with oil palm experienced a very rapid growth since the 1960s. In 1985, the area of land planted with oil palm reached about 1.5 million hectares, which later increased to 4.3 million hectares by 2007. By 2011, the amount of planted area reached 4.917 million hectares, and today, Malaysian oil palm is considered as one of the most useful and important commodity crops for this country.

Table 2 Export and production statistics of palm oil in Indonesia

	2008	2009	2010	2011	2012	2013	2014	2015	2016
Production (million tons)	19.2	19.4	21.8	23.5	26.5	30.0	31.5	32.5	32.0[1]
Export (million tons)	15.1	17.1	17.1	17.6	18.2	22.4	21.7	26.4	27.0[1]
Export (in USD billion)	15.6	10.0	16.4	20.2	21.6	20.6	21.1	18.6	18.6[1]

[1]Indicates forecast.
Sources: Indonesian Ministry of Agriculture & Indonesian Palm Oil Producers Association (Gapki).

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Table 3 Export and production statistics for palm oil in Malaysia

	2008	2009	2010	2011	2012	2013	2014	2015	2016
Production (million tons)	17.3	17.8	18.2	18.2	19.3	20.2	19.9	18.8	21.0[1]
Export (million tons)	16.0	16.6	17.2	17.6	18.5	17.3	17.4	17.5	18.0[1]

[1]Indicates forecast.
Source: Malaysia Palm Oil Board.

Until 2012, Malaysia was the leading producer of oil palm, but more recently, due to the unavailability of new cultivable land in Malaysia, Indonesia has overtaken Malaysia to become the top producer of palm oil (Table 3). While in 1999 the production of palm oil in Malaysia contributed to about 51% of global palm oil output, as of year 2011 this percentage has decreased to 38% (Palmoilworld.org, 2016).

Currently, a replanting programme has been launched by Malaysia, where old trees are replaced so that the excess of existing stock can be cleared out, in an effort to increase currently lowering prices for crude palm oil. Moreover, there are efforts made by the government to open up new markets for palm oil in countries such as Turkey, Turkmenistan, Iran and Kazakhstan (www.thesundaily.my/news/1545769).

3.3 Oil palm in the rest of the world

Following the crop's success and the increasingly limited availability of land in South East Asia, the oil palm industry has in more recent years expanded to other regions, particularly in Latin America and Africa. Particularly in West Africa, governments are seeing oil palm development as a potential source of tax and export revenue. A growing number of investors, including some of the world's largest plantation companies, are experiencing purchase of new concessions in Africa. This said, developments for oil palm in this region are still at the very early stage, and often, it is slowed down by high operational costs linked to the lack of appropriate infrastructure.

Yields are found to be much lower in Africa than those in South East Asia for various reasons, including climate and infrastructural limitations and a predominantly smallholder approach to production. In fact, in Africa, where oil palm is traditionally cultivated as a subsistence crop for food, smallholders account for between 70% and 90% of growers, depending on the country (sustainablepalmoil.org, 2016).

In Latin America, both production and consumption of palm oil are increasing. In that region, palm oil is grown in 12 countries, thus contributing nearly 6% of global production per annum. Colombia is the region's largest palm oil producer and is among the top five producers worldwide (sustainablepalmoil.org, 2016).

4 Palm oil industry and market

4.1 Growth in the palm oil industry

It is forecasted that the market for palm oil on a global level will exceed 80 million metric tons by 2020, a figure driven by a growing demand for both non-edible and edible

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applications (Grand View Research, 2016). With a growth rate of 3.2% per annum, it is considered as one of the fastest growing markets. Among the reasons for the growth in global market size of palm oil (and vegetable oils) is the ever-growing global demand for food, driven by fast development, especially in the Asian subcontinent, and the demand for biodiesel feedstock.

The recent changes in biofuel policies globally have in fact increased the supply requirements of the biodiesel industry and have diverted large volumes of raw materials, traditionally meant to enter the food supply chain, from the food sectors towards the biofuel industry. This has at times resulted in a shortage of food supply, with food prices hiking up resulting in a constraint on the vegetable oil market (Flammini, 2008).

4.2 Palm oil applications

The physical and chemical properties of palm oil allow for it to be utilised in a variety of applications, which have led to the expansion of its market on a global level. Palm oil has traditionally been used in Asia and Africa as cooking oil. Additionally, it is used as an ingredient in the manufacture of margarine, non-dairy creams and ice creams. It is used in products such as lubricants, grease and candles and in biodiesel production, replacing mineral oils both in the transport industry and for power generation. Its derivatives are used for the manufacturing of soaps and detergents, cosmetics, pharmaceuticals, water-treatment products and production of bactericides.

In 2015, global demand was dominated by crude palm oil followed by palm kernel oil and palm kernel meal (USDA, 2016). A rapid increase in edible oil, biodiesel, lubricants, surfactants and cosmetics use is expected to further increase demand in the future. There has also been a growth in the demand of animal feed (where palm kernel cakes are mostly utilised) in areas such as Asia Pacific and North America. The overall market of palm oil derivatives is also expected to continue growing in volumes as the demand for cosmetics increases globally (Grand View Research, 2016).

In recent years, the global market has been dominated by edible oil and followed by lubricants, surfactants and biodiesel, with the latter gaining enormous traction in Europe (RSPO, 2016). A global tendency to move away from *trans*-fats in food has benefited the palm oil market, resulting in palm oil taking over soybean as the most consumed vegetable oil in the years after 2004/2005 (USDA, 2016). With the increase in energy needs, consumer preference and regulations have shifted energy production towards the use of biofuels. As bio-based lubricants and surfactants are encouraged to be used by national governments and industry environmental regulations, expectations are that such trends will help in the growth and development of the industry (Grand View Research, 2016).

4.3 Global demand

The oil crops sector has been in the past years the fastest growing agricultural sector, with growth rates exceeding those of livestock products. One of the main reasons for this growth has been the increasing demand for vegetable oils in developing countries, where development and the population's higher access to disposable income have caused an increase in food consumption and a shift towards diets richer in oils and fats (FAO, 2003).

Consumption in each country tends to favour locally produced oils and fats. Although in temperate regions annual seed crops are the main sources of oil, in tropical countries coconut oil and palm oil, together with groundnut oil, are the most produced and

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consumed oils. The high yield and relatively lower costs of production of palm oil have resulted in the price of crude palm oil being considerably lower compared to those of other vegetable oils, making it the favoured choice of consumers particularly in regions such as South East Asia and West Africa. From 2015 to 2022, it is expected that crude palm oil will observe the highest growth in the sector at approximately 7.5% compound annual growth rate. Availability of key raw material due to increased planting, especially in South East Asia, together with growing disposable income levels in China, India and Indonesia are expected to drive the market. Asia Pacific remains in fact the largest palm oil consumer region, covering 65% of the overall market volume in 2014, with India remaining the largest importer. Besides, recent studies forecast an 8% growth in the South and Central American markets from 2015 to 2022 (Grand View Research, 2016).

4.4 Comparison with other vegetable oil markets

In the last decade, the production growth rates of major fats and oils have varied significantly. Among these vegetable oils, the fastest growth was in the palm kernel oil and palm oil with production rates reaching about 70% and 82%, respectively, while rapeseed increased by 70%, soybean oil increased by 43% and sunflower oil increased by 64%. Although in 2005 palm oil and palm kernel oil represented 25% of global oils and fats production (including animal fats), by 2015, their combined share grew to 33% (Oil World, 2016).

As a result of a move towards the replacement of *trans*-fatty acids with palmitic acid due to health concerns, palm oil took over soybean, and it became the most used vegetable oil in the mid-2000s. In 2015, production of soybean oil was 47 million tonnes, whereas production of palm oil was at around 61 million. The two vegetable oils together accounted for a total of approximately 50% of 202 million global productions of oils and fats in the year (USDA, 2016). This said, the oil palm (together with rapeseed and sunflower) is considered among those vegetable oil crops that are grown mainly for their oil content, and its production is based directly on the demand of oils and fats. Soybean oil, on the other end, is a by-product in the production of soybean meal, which remains the main driver of the crop's production growth. In 2014–15, around 78 million tonnes of fats and oils were exported on a global level. Among these, palm kernel oil and palm oil made up the biggest single export at approximately 47 million tonnes with a significant lead over that of soybean, which ranked second as the most exported oil, at 10 million tonnes. The production level of palm kernel and palm oil was also significantly higher than any of the other fats and oils at 71% (USDA, 2016).

5 Ecological impact of palm oil production

5.1 Economic and climatic factors

The economic conditions, the changing and different eating habits of consumers in developing countries and the rise in living standards and the growth in the demand of vegetable oils are a few of the factors that hint that palm oil is here to stay. However, there are several factors that inhibit the growth and expansion of the palm oil market such as changing climatic conditions, fluctuations in the price and adverse effects on the people and environment due to unsustainable oil palm cultivation, such as exploitation of local

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communities and labour, deforestation and loss of habitat of different endangered species (Obidzinski et al., 2012).

There have been significant movements in the price of palm oil, which played an important role in leading fats and oils imports and exports on the global platform. In 1998, the world market suffered a decrease in supply of palm oil due to the harmful effect on the crop caused by the 1997 drought due to El Niño, which was coupled with the Indonesian Government's imposed ban on the export of palm oil (which was later converted to an export tax). After the drought due to El Niño in 1997 and 1998, a downfall in the world's stock related to fats and oils was observed, where stocks reached a low of 12 million tons in September 1998. Changes in climatic conditions, such as the ones associated with the El Niño events, can have tremendous effects in the production of the oil palm. A recurrence of the El Niño phenomena in 2015 has led some to speculate that palm oil prices will rise as much as 17% in 2017 (Bloomberg, 2016).

In the beginning of 1999, a significant downfall in the prices of palm oil was observed because of the increased production of palm oil in Indonesia and Malaysia as the market recovered from the effects of the drought and uncontrolled bushfires, which blanketed the whole region with haze. Moreover, as the Indonesian Government reduced export taxes, the Indonesians producers returned to the export markets (Rea.co.uk., 2016). There is a need for the skilful prediction of such climatic changes so that precautions can be taken before their harmful effects come into observation, while the development of adaptation strategies may also help in building resilience against climate changes in the future (Slingo et al., 2005).

5.2 The issue of deforestation

One of the advantages of the oil palm plant is that it does not require a lot of effort to grow and produce oil. Oil palm is also a perennial crop, which about three years after planting starts yielding fruits, with a continual productive lifespan of 25–30 years. Moreover, the land required by oil palm can be relatively little, and it can grow in small places as it is land efficient and generates profits even at a small scale. Farmers who cultivate oil palm can have beneficial levels of income that are comparatively more than those of the farmers who cultivate other crops such as rice, rubber and cassava, even if on a small scale. Even though the production of palm oil can be a benefit for all stakeholders, including governments and local populations (Obidzinski et al., 2012), these benefits come at a cost. Consequences of the unsustainable production of palm oil have in fact been vastly documented in the past years, including deforestation (Mukherjee and Sovacool, 2014). It has been shown that tropical deforestation, as associated with unsustainable oil palm cultivation, results in warmer, drier conditions at the local scale, and that large-scale deforestation under the tropics could result in global warming equivalent to that caused by burning of fossil fuels since 1850, with more warming and considerably dryer weather in the tropics (Nature Climate Change, 2015). This is not only an issue for the environment but also an important risk factor for the security of supply and market of palm oil itself, considering the effects of droughts and El Niño in the past years.

5.3 Loss of habitat of endangered species

The oil palm is a tropical plant and as such can only be grown successfully in an area spanning from 10 degrees South to 10 degrees North of the equator. This is not only one of the areas with the highest levels of poverty in the world (World bank, 2009), but also

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where most of the world's remaining forests and biodiversity hot spots can be found. As tropical forests are being converted into oil palm plantations on a large scale, the habitat of animals and plants are being affected adversely. Due to increased deforestation, the animals are isolated in specific areas while majority of the land is being used for plantation purposes. Most of the habitats that are being converted for the production of oil palm are home to animals and species that are endangered (Castiblanco et al., 2015). Moreover, mainly due to a lack of proper governance in some of the countries where palm oil is cultivated, there have been cases of illegal expansion of palm oil plantations, both by large- and middle-sized companies and smallholders. There have been cases in which national parks have been negatively affected, an example being the Tesso Nilo National Park in the island of Sumatra, Indonesia, where 43% of its area has been cleared off and overrun with illegal plantation of oil palms (World Wildlife Fund, 2016).

5.4 Air pollution

In traditional land clearing practices, such as those used for the plantation of oil palm especially in South East Asia, burning is commonly used to clear out the vegetation and prepare the soil for planting. Due to the burning of the vegetation and, in some cases, of the peatlands where plantations are being developed, smoke is released resulting in huge amounts of emissions of carbon dioxide into the air, thus polluting the environment and as a consequence has contributed to climate change (World Wildlife Fund, 2016).

5.5 Water and soil pollution

Waste generated from palm oil mills has been highlighted as one of the major single sources of environmental pollution. It has been ascertained that for every metric ton of palm oil produced, 2.5 metric tons of palm oil mill effluent (POME) are generated in the process. In recent years, the industry has put a lot of effort in coming up with solutions in order to minimise and control both solid and liquid wastes generated by palm oil mills' operations. Direct release of this effluent causes freshwater pollution, which can negatively affect both biodiversity and local population activities such as fishing and farming. Direct release of chemicals used in plantations is also a major factor of concern. Although palm oil productions require fewer fertilisers than other crops, the uncontrolled discharge of these materials in the environment can affect underground water and pollute the surface (World Wildlife Fund, 2016).

5.6 Soil erosion

The impacts of oil palm plantation on the land not only involve soil quantity but also soil quality. When land is prepared and vegetation is removed in preparation of planting, soil erosion can start occurring, adversely affecting the soil quality due to the reduction of nutrients and organic matter levels contained in the soil and also by affecting soil properties such as infiltration rates (World Agriculture & Environment, 2004). Erosion occurs mainly during forest clearing and plantation establishment when the soil is left uncovered. Effects are most visible on steep slopes and are accentuated by planting trees in rows up and down hillsides instead of contours. Later in the oil palm cycle, soil erosion can have the additional burden of transporting fertilisers and pesticides, which adhere to the suspended solids, which can further contaminate waterways (NBPOL, 2011).

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5.7 Climate change

Tropical forests such as those covering large parts of Indonesia and Malaysia are considered to be the last remaining global 'carbon sinks'. Their conversion into oil palm plantations, especially when the biomass is cleared by burning, release high amounts of carbon dioxide in the environment, thus contributing to climate change. The practice of draining and converting tropical peatland forests is particularly damaging as these 'carbon sinks' store more carbon per unit area than any other ecosystem in the world. For example, in 1997, peatland fires in Indonesia may have been one of the main sources of global carbon emissions in the country. An estimated 0.81–2.57 gigatons of carbon were released into the atmosphere by the fires representing values in a range from 13% to 40% of the mean annual global carbon emissions from fossil fuels that year. The impact has such a scale that Indonesia is considered to be the third largest emitter of greenhouse gases on a global level (World Wildlife Fund, 2016).

6 Social impacts

Oil palm developments can also create social conflicts if local communities and workers are not appropriately taken into consideration when new developments are initiated and during ongoing operations. Issues can occur not only between the companies and the workers, or the companies and the local community, but also within neighbouring communities, especially in the case of customary land disputes, such as in those incurred by the Dayak communities in Borneo (Colchester, 2012). For example, in Indonesia, indigenous lands cover between 40 and 70 million hectares; however, only 1 million hectares are legally recognised by the government. The non-legal recognition of indigenous peoples' customary land rights can lead to issues in the assignment of land concessions if villagers are pushed out of their customary lands.

Agriculture is one of the three most dangerous sectors in terms of work-related fatalities, non-fatal accidents and occupational diseases. About 59% of all children aged 5–17 years involved in hazardous work are in agriculture (ILO, 2016). Oil palm cultivation is not immune to these issues, and the use of forced, child and trafficked labour has been reported in the industry (US Department of Labour & UNICEF 2012).

7 Conclusion and future trends

Negative impact of unsustainable oil palm cultivation is and will play a fundamental role in the growth and development of the industry itself. Palm oil, being the world's most consumed vegetable oil, has received a lot of attention from global environmental and social NGOs due to the magnitude of effect, frequency of occurrence and duration of its impacts. A number of cases have been highlighted of companies not operating according to civil society's expectations. This has not only harmed these companies' social license to operate but also have proven to define the perceived level of sustainability of the industry, based on its lowest common denominator. The issue of unsustainable production is in fact one that has already demonstrated to have been linked to the industry as a whole, despite the efforts from virtuous players, leading to movements by both the market and

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civil society to advocate towards a shift away from the use of palm oil. This is an issue that the industry must continue to tackle, not only by showing its sustainable credentials, but also by becoming more transparent in acknowledging these issues and allow for improved transparency and public scrutiny of its progress. Although some industry players are making strides in this direction, a lot more needs to be done by the industry in acknowledging the issues (both in terms of environmental and social negative impacts) and by all players including governments in catalysing a transformation leading to greater transparency (e.g. in resolving the issues surrounding the publication of concession boundaries, especially in Indonesia and Malaysia), shared responsibility and trust.

In view of the above, there are two major factors that will shape the trajectory of growth of the palm oil market in the near future, namely its substitutability (driven by the availability, affordability and acceptability of its substitutes) and its sustainability when compared to other oils.

The growth of palm oil has happened for good reasons. Its low land intensity, combined with the lowest input for energy, fertiliser and pesticides per tonne of production, has made it the most economically viable vegetable oil in the market. This said, recent favourable harvests of US soybean and Eastern European sunflower oil seeds have made such oils more competitive when compared to palm oil, while lacking the notorious negative perception (if not the environmental and social issues) of the first, and the production of which would not be constrained to tropical forest regions. Furthermore, recent efforts by several biotech companies have led to the development of new vegetable oils produced by algae or yeasts that have similar chemical and physical properties as those of palm oil (and palm kernel oil) (*The Guardian*, 2014). Several consumer goods companies are investing in research and development of these substitutes which, while failing to currently demonstrate viability at scale, certainly pose a risk for the outlook of the palm oil market in the future, and the connected value chain.

Although substitutes could become possible, negative impacts (such as those linked to unsustainable agriculture and oil palm cultivation specifically) are common to all human activities and are effected to a greater degree by operation practices, rather than by the nature of the activity itself. In view of this, a more common position has arisen in the past years among NGOs working on palm oil that focuses on the production of palm oil that is more sustainable, rather than promoting substitution. For this purpose, several of the industry players, together with social and environmental NGOs, and with the involvement of banks and investors, have worked towards developing and promoting methods of production that limit the negative impacts of oil palm cultivation. Of the several initiatives (both industry and government led) that have arisen in the last years, the Roundtable on Sustainable Palm Oil (RSPO), a global multi-stakeholder initiative on sustainable palm oil founded in the year 2004, is the longest standing and the most widely accepted by the market. The RSPO has now almost three thousand members, which include plantation companies, processors and traders, consumer goods manufacturers and retailers of palm oil products, financial institutions, environmental NGOs and social NGOs, from many countries that produce or use palm oil. Following the principles and criteria that are set by the RSPO, the expectation is that the organisation's voluntary members need to work in the process of producing and using palm oil that is sustainable, according to the RSPO standards. In the years from its creation, sales of sustainable palm oil have continued increasing at a pace higher than the global production of palm oil. As such, RSPO has grown to certifying about 20% of the global palm oil production in 2016. The RSPO also reported increase of sales of approximately 162% for January 2016 (RSPO, 2016).

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Sustainability standards are not only guiding the decision of producers on how to carry out developments and manage operations but also are more and more importantly guiding investors in deciding which sectors and companies present the lower investment and reputational risk, thus influencing the market. Financial institutions, both through their involvement in the RSPO and in other initiatives pushing for sustainable investment, such as the United Nations Principles for Responsible Investment (UN PRI), have made moves to stop investing in companies that are accused of environmental or social issues. Responsible finance principles have also been applied at government level. In 2013, the Norwegian Government Pension Fund announced that they would be pulling investments from 23 Asian palm oil companies due to the concerns related to deforestation and climate change. The United Kingdom (Defra, 2012) also decided to use only certified sustainable palm oil (CSPO) in 'Central Government Food and Catering Services' starting from October 2012. In the following years, industry groups in several European countries have joined forces to ensure a fully sustainable palm oil supply chain in Europe by 2020 by forming national initiatives for sustainable palm oil in the Netherlands, Germany, the United Kingdom, France, Belgium, Norway, Denmark, Sweden and Italy (RSPO, 2016). In response, the governments of six key European Union countries have recently declared their support towards the project by signing the Amsterdam Palm Oil Declaration. Although major progress in the uptake of CSPO has been made in Europe, India and China – the first and third largest importers of palm oil – are also making strides in the uptake of CSPO. In China, the three companies who are the major importers of palm oil now have plans towards 100% CSPO uptake (RSPO ACOP data, 2016). Other companies operating in China, such as Mars, have announced that they have already covered all their palm oil supplies with certified materials.

The influences of large corporations and governments who have committed to sustainable palm oil sourcing, together with the interrelation of the global markets for palm oil, are factors that continue to influence the move towards a future where sustainable palm oil will be the norm.

8 Where to look for further information

For further information on the author and related work, please visit www.rspo.org

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1 Chapter 1 The palm oil market: growth and trends

1 Introduction

For many years now, palm oil has proved to be the most productive, highest yielding oil

crop. Its yield is 4–10 times higher compared to that of any other vegetable oil, a factor

that has helped palm oil in becoming what is today the most consumed vegetable oil

in the world (Alias et al., 2014, see Fig. 1). Palm oil is derived from the fruit of a specific

species of palm tree, known as Elaeis guineensis. There are two types of oil that can be

produced from the fruit of oil palm. The first type of oil is extracted from the flesh of the

fruit and is used in a variety of applications, mostly in food, where its properties make it

especially suited to be used as cooking oil, or in margarines, as substitutes of cocoa butter,

and also as a replacement for milk fat. The second type of oil is derived from the palm fruit

kernel. Derivatives of this palm kernel oil can be utilized in cosmetics and other speciality

applications. Of the goods that are present on the shelves of the stores, over half of them

contain palm oil as an ingredient.

The vegetable oil market is divided into three major segments: food, industrial non-food

and biodiesel feed. A major share of the consumption market is taken by the applications

of food; however, the biofuels segment is considered the fastest growing one due to its use as biodiesel feedstock. Recent data have shown that, in Europe, use of palm oil

in the biofuel market has overtaken both food and cosmetics, and now represents the

majority of the palm oil use in the region (RSPO, 2016). It is forecasted that biodiesel will

reach the highest growth of approximately 8.8% from 2015 till 2022 (Grand View Research,

2016). With governments trying to limit reliance on conventional fossil fuels, it is expected

that biodiesel fuel will witness a rapid growth in the forthcoming years, at least initially

contributing to an increase in demand of first-generation biofuels, such as those derived

from palm oil.

2 Oil palm cultivation and palm oil production

The expansion of palm oil plantations globally started in the early twentieth century,

driven by the Industrial Revolution in Europe and expansion of overseas trade. Although

oil palm is originally from West Africa, the first commercial-scale oil palm plantations were

established by the British in South East Asia (initially in Malaysia) and saw great expansion

in the 1960s when land settlement schemes for planting oil palm were introduced as a

means to eradicate poverty for landless farmers and smallholders in the region. Today,

Indonesia is the largest palm oil producer, followed by Malaysia and Thailand (USDA,

2016, see Table 1). Table 1 Global palm oil production by country (Values in metric tons) Indonesia 35,000,000 Malaysia 21,000,000 Others 4,945,000 Thailand 2,300,000

Colombia 1,280,000 Source: (Globalpalmoilproduction.com, 2016).

Figure 1 Consumption of vegetable oils worldwide from 1995/1996 to 2015/2016, by oil type (in million

metric tons). Source: Statista.com.

3 Regional oil palm production trends

3.1 Oil palm in Indonesia

There has been a vigorous growth in the palm oil industry of Indonesia, where very few

industries have experienced the same growth as that of palm oil. The growth is clearly visible,

not only in the exports and production statistics but also in the estate areas converted to

oil palm. The industry originated in Sumatra during the Dutch colonial period and around

70% of the plantations are situated there. The rest of the 30% can be located in the island

of Kalimantan (Investments, 2016). Over the years, palm oil has proven to generate high

yields and, due to increasing demand, both large corporations and medium and small

farmers have shown interest in the industry and have switched from other crops (Castiblanco

et al., 2013). This switch has lead Indonesia to become the largest producer and exporter of

palm oil worldwide. India, Europe (via the Netherlands), Malaysia, China and Singapore are

among the most important destinations where Indonesian palm oil is exported (Investments,

2016). The export and production statistics of palm oil in Indonesia are given in Table 2.

Today, the processing industry and plantation of oil palm in Indonesia are the most important industries of the country in terms of contribution to the national economy.

Moreover, this industry provides numerous employment opportunities to millions of

individuals in Indonesia.

The data extracted from the Indonesian Ministry of Agriculture show that the overall

area covered by palm constitutes about eight million hectares (Investments, 2016). It

is expected that by the end of 2020, this amount will increase to 13 million hectares

(Investments, 2016).

Private organisations produce approximately half of the overall production of Indonesian

palm oil, whereas the government-owned plantations play a relatively modest role. The

remaining 35% of the production comes from smallholder farmers (Investments, 2016).

3.2 Oil palm in Malaysia

In 1870, the oil palm was introduced for the first time as an ornamental plant in Malaysia.

The area of land planted with oil palm experienced a very rapid growth since the 1960s. In

1985, the area of land planted with oil palm reached about 1.5 million hectares, which later

increased to 4.3 million hectares by 2007. By 2011, the amount of planted area reached

4.917 million hectares, and today, Malaysian oil palm is considered as one of the most

useful and important commodity crops for this country.

Table 2 Export and production statistics of palm oil in Indonesia 2008 2009 2010 2011 2012 2013 2014 2015 2016

Production

(million tons) 19.2 19.4 21.8 23.5 26.5 30.0 31.5 32.5 32.0[1]

Export

(million tons) 15.1 17.1 17.1 17.6 18.2 22.4 21.7 26.4 27.0[1]

Export

(in USD billion) 15.6 10.0 16.4 20.2 21.6 20.6 21.1 18.6 18.6[1]

1 Indicates forecast.

Sources: Indonesian Ministry of Agriculture & Indonesian Palm Oil Producers Association (Gapki).

Until 2012, Malaysia was the leading producer of oil palm, but more recently, due to

the unavailability of new cultivable land in Malaysia, Indonesia has overtaken Malaysia

to become the top producer of palm oil (Table 3). While in 1999 the production of palm

oil in Malaysia contributed to about 51% of global palm oil output, as of year 2011 this

percentage has decreased to 38% (Palmoilworld.org, 2016).

Currently, a replanting programme has been launched by Malaysia, where old trees are

replaced so that the excess of existing stock can be cleared out, in an effort to increase

currently lowering prices for crude palm oil. Moreover, there are efforts made by the

government to open up new markets for palm oil in countries such as Turkey, Turkmenistan,

Iran and Kazakhstan (www.thesundaily.my/news/1545769).

3.3 Oil palm in the rest of the world

Following the crop’s success and the increasingly limited availability of land in South East

Asia, the oil palm industry has in more recent years expanded to other regions, particularly

in Latin America and Africa. Particularly in West Africa, governments are seeing oil palm

development as a potential source of tax and export revenue. A growing number of

investors, including some of the world’s largest plantation companies, are experiencing

purchase of new concessions in Africa. This said, developments for oil palm in this region

are still at the very early stage, and often, it is slowed down by high operational costs

linked to the lack of appropriate infrastructure.

Yields are found to be much lower in Africa than those in South East Asia for various

reasons, including climate and infrastructural limitations and a predominantly smallholder

approach to production. In fact, in Africa, where oil palm is traditionally cultivated as a

subsistence crop for food, smallholders account for between 70% and 90% of growers,

depending on the country (sustainablepalmoil.org, 2016).

In Latin America, both production and consumption of palm oil are increasing. In that

region, palm oil is grown in 12 countries, thus contributing nearly 6% of global production

per annum. Colombia is the region’s largest palm oil producer and is among the top five

producers worldwide (sustainablepalmoil.org, 2016).

4 Palm oil industry and market

4.1 Growth in the palm oil industry

It is forecasted that the market for palm oil on a global level will exceed 80 million metric tons by 2020, a figure driven by a growing demand for both non-edible and edible

Table 3 Export and production statistics for palm oil in Malaysia

	2008	2009	2010	2011	2012	2013	2014	2015	2016
Production (million tons)	17.3	17.8	18.2	18.2	19.3	20.2	19.9	18.8	21.0[1]
Export (million tons)	16.0	16.6	17.2	17.6	18.5	17.3	17.4	17.5	18.0[1]

[1]Indicates forecast.

Source: Malaysia Palm Oil Board.

applications (Grand View Research, 2016). With a growth rate of 3.2% per annum, it is considered as one of the fastest growing markets. Among the reasons for the growth in global market size of palm oil (and vegetable oils) is the ever-growing global demand for food, driven by fast development, especially in the Asian subcontinent, and the demand for biodiesel feedstock.

The recent changes in biofuel policies globally have in fact increased the supply requirements of the biodiesel industry and have diverted large volumes of raw materials, traditionally meant to enter the food supply chain, from the food sectors towards the biofuel industry. This has at times resulted in a shortage of food supply, with food prices hiking up resulting in a constraint on the vegetable oil market (Flammini, 2008).

4.2 Palm oil applications

The physical and chemical properties of palm oil allow for it to be utilised in a variety of

applications, which have led to the expansion of its market on a global level. Palm oil

has traditionally been used in Asia and Africa as cooking oil. Additionally, it is used as an

ingredient in the manufacture of margarine, non-dairy creams and ice creams. It is used

in products such as lubricants, grease and candles and in biodiesel production, replacing

mineral oils both in the transport industry and for power generation. Its derivatives are

used for the manufacturing of soaps and detergents, cosmetics, pharmaceuticals, water

treatment products and production of bactericides.

In 2015, global demand was dominated by crude palm oil followed by palm kernel oil

and palm kernel meal (USDA, 2016). A rapid increase in edible oil, biodiesel, lubricants,

surfactants and cosmetics use is expected to further increase demand in the future. There

has also been a growth in the demand of animal feed (where palm kernel cakes are mostly

utilised) in areas such as Asia Pacific and North America. The overall market of palm oil

derivatives is also expected to continue growing in volumes as the demand for cosmetics

increases globally (Grand View Research, 2016).

In recent years, the global market has been dominated by edible oil and followed by

lubricants, surfactants and biodiesel, with the latter gaining enormous traction in Europe

(RSPO, 2016). A global tendency to move away from trans-fats in food has benefited

the palm oil market, resulting in palm oil taking over soybean as the most consumed

vegetable oil in the years after 2004/2005 (USDA, 2016). With the increase in energy

needs, consumer preference and regulations have shifted energy production towards the

use of biofuels. As bio-based lubricants and surfactants are encouraged to be used by

national governments and industry environmental regulations, expectations are that such

trends will help in the growth and development of the industry (Grand View Research,

2016).

4.3 Global demand

The oil crops sector has been in the past years the fastest growing agricultural sector,

with growth rates exceeding those of livestock products. One of the main reasons for this

growth has been the increasing demand for vegetable oils in developing countries, where

development and the population's higher access to disposable income have caused an

increase in food consumption and a shift towards diets richer in oils and fats (FAO, 2003).

Consumption in each country tends to favour locally produced oils and fats. Although

in temperate regions annual seed crops are the main sources of oil, in tropical countries

coconut oil and palm oil, together with groundnut oil, are the most produced and consumed oils. The high yield and relatively lower costs of production of palm oil have

resulted in the price of crude palm oil being considerably lower compared to those of

other vegetable oils, making it the favoured choice of consumers particularly in regions

such as South East Asia and West Africa. From 2015 to 2022, it is expected that crude

palm oil will observe the highest growth in the sector at approximately 7.5% compound

annual growth rate. Availability of key raw material due to increased planting, especially

in South East Asia, together with growing disposable income levels in China, India and

Indonesia are expected to drive the market. Asia Pacific remains in fact the largest palm oil

consumer region, covering 65% of the overall market volume in 2014, with India remaining

the largest importer. Besides, recent studies forecast an 8% growth in the South and

Central American markets from 2015 to 2022 (Grand View Research, 2016).

4.4 Comparison with other vegetable oil markets

In the last decade, the production growth rates of major fats and oils have varied significantly.

Among these vegetable oils, the fastest growth was in the palm kernel oil and palm oil with

production rates reaching about 70% and 82%, respectively, while rapeseed increased by

70%, soybean oil increased by 43% and sunflower oil increased by 64%. Although in 2005

palm oil and palm kernel oil represented 25% of global oils and fats production (including animal fats), by 2015, their combined share grew to 33% (Oil World, 2016).

As a result of a move towards the replacement of trans-fatty acids with palmitic acid

due to health concerns, palm oil took over soybean, and it became the most used

vegetable oil in the mid-2000s. In 2015, production of soybean oil was 47 million

tonnes, whereas production of palm oil was at around 61 million. The two vegetable

oils together accounted for a total of approximately 50% of 202 million global

productions of oils and fats in the year (USDA, 2016). This said, the oil palm (together

with rapeseed and sunflower) is considered among those vegetable oil crops that are

grown mainly for their oil content, and its production is based directly on the demand

of oils and fats. Soybean oil, on the other end, is a by-product in the production of

soybean meal, which remains the main driver of the crop's production growth. In

2014–15, around 78 million tonnes of fats and oils were exported on a global level.

Among these, palm kernel oil and palm oil made up the biggest single export at

approximately 47 million tonnes with a significant lead over that of soybean, which

ranked second as the most exported oil, at 10 million tonnes. The production level of

palm kernel and palm oil was also significantly higher than any of the other fats and

oils at 71% (USDA, 2016).

5 Ecological impact of palm oil production

5.1 Economic and climatic factors

The economic conditions, the changing and different eating habits of consumers in developing countries and the rise in living standards and the growth in the demand of vegetable oils are a few of the factors that hint that palm oil is here to stay. However, there are several factors that inhibit the growth and expansion of the palm oil market such as changing climatic conditions, fluctuations in the price and adverse effects on the people and environment due to unsustainable oil palm cultivation, such as exploitation of local communities and labour, deforestation and loss of habitat of different endangered species (Obidzinski et al., 2012).

There have been significant movements in the price of palm oil, which played an important role in leading fats and oils imports and exports on the global platform. In 1998, the world market suffered a decrease in supply of palm oil due to the harmful effect on the crop caused by the 1997 drought due to El Niño, which was coupled with the Indonesian Government's imposed ban on the export of palm oil (which was later converted to an export tax). After the drought due to El Niño in 1997 and 1998, a downfall in the world's stock related to fats and oils was observed, where stocks reached a low of 12 million tons in September 1998. Changes in climatic conditions, such as the ones associated

with the El Niño events, can have tremendous effects in the production of the oil palm.

A recurrence of the El Niño phenomena in 2015 has led some to speculate that palm oil

prices will rise as much as 17% in 2017 (Bloomberg, 2016).

In the beginning of 1999, a significant downfall in the prices of palm oil was observed

because of the increased production of palm oil in Indonesia and Malaysia as the market

recovered from the effects of the drought and uncontrolled bushfires, which blanketed the

whole region with haze. Moreover, as the Indonesian Government reduced export taxes,

the Indonesians producers returned to the export markets (Rea.co.uk., 2016). There is a

need for the skilful prediction of such climatic changes so that precautions can be taken

before their harmful effects come into observation, while the development of adaptation

strategies may also help in building resilience against climate changes in the future (Slingo

et al., 2005).

5.2 The issue of deforestation

One of the advantages of the oil palm plant is that it does not require a lot of effort to grow

and produce oil. Oil palm is also a perennial crop, which about three years after planting

starts yielding fruits, with a continual productive lifespan of 25-30 years. Moreover, the

land required by oil palm can be relatively little, and it can grow in small places as it is land efficient and generates profits even at a small scale. Farmers who cultivate oil

palm can have beneficial levels of income that are comparatively more than those of the

farmers who cultivate other crops such as rice, rubber and cassava, even if on a small scale.

Even though the production of palm oil can be a benefit for all stakeholders, including

governments and local populations (Obidzinski et al., 2012), these benefits come at a

cost. Consequences of the unsustainable production of palm oil have in fact been vastly

documented in the past years, including deforestation (Mukherjee and Sovacool, 2014).

It has been shown that tropical deforestation, as associated with unsustainable oil palm

cultivation, results in warmer, drier conditions at the local scale, and that large-scale

deforestation under the tropics could result in global warming equivalent to that caused

by burning of fossil fuels since 1850, with more warming and considerably dryer weather

in the tropics (Nature Climate Change, 2015). This is not only an issue for the environment

but also an important risk factor for the security of supply and market of palm oil itself,

considering the effects of droughts and El Niño in the past years.

5.3 Loss of habitat of endangered species

The oil palm is a tropical plant and as such can only be grown successfully in an area

spanning from 10 degrees South to 10 degrees North of the equator. This is not only one of the areas with the highest levels of poverty in the world (World bank, 2009), but also

where most of the world's remaining forests and biodiversity hot spots can be found. As

tropical forests are being converted into oil palm plantations on a large scale, the habitat

of animals and plants are being affected adversely. Due to increased deforestation, the

animals are isolated in specific areas while majority of the land is being used for plantation

purposes. Most of the habitats that are being converted for the production of oil palm are

home to animals and species that are endangered (Castiblanco et al., 2015). Moreover,

mainly due to a lack of proper governance in some of the countries where palm oil is

cultivated, there have been cases of illegal expansion of palm oil plantations, both by

large- and middle-sized companies and smallholders. There have been cases in which

national parks have been negatively affected, an example being the Tesso Nilo National

Park in the island of Sumatra, Indonesia, where 43% of its area has been cleared off and

overrun with illegal plantation of oil palms (World Wildlife Fund, 2016).

5.4 Air pollution

In traditional land clearing practices, such as those used for the plantation of oil palm

especially in South East Asia, burning is commonly used to clear out the vegetation and

prepare the soil for planting. Due to the burning of the vegetation and, in some cases, of the peatlands where plantations are being developed, smoke is released resulting in huge

amounts of emissions of carbon dioxide into the air, thus polluting the environment and as

a consequence has contributed to climate change (World Wildlife Fund, 2016).

5.5 Water and soil pollution

Waste generated from palm oil mills has been highlighted as one of the major single

sources of environmental pollution. It has been ascertained that for every metric ton of

palm oil produced, 2.5 metric tons of palm oil mill effluent (POME) are generated in the

process. In recent years, the industry has put a lot of effort in coming up with solutions in

order to minimise and control both solid and liquid wastes generated by palm oil mills'

operations. Direct release of this effluent causes freshwater pollution, which can negatively

affect both biodiversity and local population activities such as fishing and farming. Direct

release of chemicals used in plantations is also a major factor of concern. Although palm

oil productions require fewer fertilisers than other crops, the uncontrolled discharge of

these materials in the environment can affect underground water and pollute the surface

(World Wildlife Fund, 2016).

5.6 Soil erosion

The impacts of oil palm plantation on the land not only involve soil quantity but also soil

quality. When land is prepared and vegetation is removed in preparation of planting, soil erosion can start occurring, adversely affecting the soil quality due to the reduction

of nutrients and organic matter levels contained in the soil and also by affecting soil

properties such as infiltration rates (World Agriculture & Environment, 2004). Erosion

occurs mainly during forest clearing and plantation establishment when the soil is left

uncovered. Effects are most visible on steep slopes and are accentuated by planting trees

in rows up and down hillsides instead of contours. Later in the oil palm cycle, soil erosion

can have the additional burden of transporting fertilisers and pesticides, which adhere to

the suspended solids, which can further contaminate waterways (NBPOL, 2011).

5.7 Climate change

Tropical forests such as those covering large parts of Indonesia and Malaysia are considered

to be the last remaining global ‘carbon sinks’. Their conversion into oil palm plantations,

especially when the biomass is cleared by burning, release high amounts of carbon

dioxide in the environment, thus contributing to climate change. The practice of draining

and converting tropical peatland forests is particularly damaging as these ‘carbon sinks’

store more carbon per unit area than any other ecosystem in the world. For example, in

1997, peatland fires in Indonesia may have been one of the main sources of global carbon

emissions in the country. An estimated 0.81–2.57 gigatons of carbon were released into the atmosphere by the fires representing values in a range from 13% to 40% of the mean

annual global carbon emissions from fossil fuels that year. The impact has such a scale that

Indonesia is considered to be the third largest emitter of greenhouse gases on a global

level (World Wildlife Fund, 2016).

6 Social impacts

Oil palm developments can also create social conflicts if local communities and workers are

not appropriately taken into consideration when new developments are initiated and during

ongoing operations. Issues can occur not only between the companies and the workers,

or the companies and the local community, but also within neighbouring communities,

especially in the case of customary land disputes, such as in those incurred by the Dayak

communities in Borneo (Colchester, 2012). For example, in Indonesia, indigenous lands

cover between 40 and 70 million hectares; however, only 1 million hectares are legally

recognised by the government. The non-legal recognition of indigenous peoples'

customary land rights can lead to issues in the assignment of land concessions if villagers

are pushed out of their customary lands.

Agriculture is one of the three most dangerous sectors in terms of work-related fatalities,

non-fatal accidents and occupational diseases. About 59% of all children aged 5–17 years

involved in hazardous work are in agriculture (ILO, 2016).

Oil palm cultivation is not immune

to these issues, and the use of forced, child and trafficked labour has been reported in the

industry (US Department of Labour & UNICEF 2012).

7 Conclusion and future trends

Negative impact of unsustainable oil palm cultivation is and will play a fundamental role

in the growth and development of the industry itself. Palm oil, being the world's most

consumed vegetable oil, has received a lot of attention from global environmental and

social NGOs due to the magnitude of effect, frequency of occurrence and duration of its

impacts. A number of cases have been highlighted of companies not operating according

to civil society's expectations. This has not only harmed these companies' social license to

operate but also have proven to define the perceived level of sustainability of the industry,

based on its lowest common denominator. The issue of unsustainable production is in

fact one that has already demonstrated to have been linked to the industry as a whole,

despite the efforts from virtuous players, leading to movements by both the market and

civil society to advocate towards a shift away from the use of palm oil. This is an issue that

the industry must continue to tackle, not only by showing its sustainable credentials, but

also by becoming more transparent in acknowledging these issues and allow for improved

transparency and public scrutiny of its progress. Although some industry players are making strides in this direction, a lot more needs to be done by the industry in acknowledging

the issues (both in terms of environmental and social negative impacts) and by all players

including governments in catalysing a transformation leading to greater transparency (e.g.

in resolving the issues surrounding the publication of concession boundaries, especially in

Indonesia and Malaysia), shared responsibility and trust.

In view of the above, there are two major factors that will shape the trajectory of

growth of the palm oil market in the near future, namely its substitutability (driven by

the availability, affordability and acceptability of its substitutes) and its sustainability when

compared to other oils.

The growth of palm oil has happened for good reasons. Its low land intensity, combined

with the lowest input for energy, fertiliser and pesticides per tonne of production, has made

it the most economically viable vegetable oil in the market. This said, recent favourable

harvests of US soybean and Eastern European sunflower oil seeds have made such oils

more competitive when compared to palm oil, while lacking the notorious negative

perception (if not the environmental and social issues) of the first, and the production of

which would not be constrained to tropical forest regions. Furthermore, recent efforts by

several biotech companies have led to the development of new vegetable oils produced by algae or yeasts that have similar chemical and physical properties as those of palm

oil (and palm kernel oil) (The Guardian, 2014). Several consumer goods companies are

investing in research and development of these substitutes which, while failing to currently

demonstrate viability at scale, certainly pose a risk for the outlook of the palm oil market

in the future, and the connected value chain.

Although substitutes could become possible, negative impacts (such as those linked to

unsustainable agriculture and oil palm cultivation specifically) are common to all human

activities and are effected to a greater degree by operation practices, rather than by the

nature of the activity itself. In view of this, a more common position has arisen in the past

years among NGOs working on palm oil that focuses on the production of palm oil that

is more sustainable, rather than promoting substitution. For this purpose, several of the

industry players, together with social and environmental NGOs, and with the involvement

of banks and investors, have worked towards developing and promoting methods of

production that limit the negative impacts of oil palm cultivation. Of the several initiatives

(both industry and government led) that have arisen in the last years, the Roundtable on

Sustainable Palm Oil (RSPO), a global multi-stakeholder initiative on sustainable palm oil

founded in the year 2004, is the longest standing and the most widely accepted by the market. The RSPO has now almost three thousand members, which include plantation

companies, processors and traders, consumer goods manufacturers and retailers of palm

oil products, financial institutions, environmental NGOs and social NGOs, from many

countries that produce or use palm oil. Following the principles and criteria that are set

by the RSPO, the expectation is that the organisation's voluntary members need to work

in the process of producing and using palm oil that is sustainable, according to the RSPO

standards. In the years from its creation, sales of sustainable palm oil have continued

increasing at a pace higher than the global production of palm oil. As such, RSPO has

grown to certifying about 20% of the global palm oil production in 2016. The RSPO also

reported increase of sales of approximately 162% for January 2016 (RSPO, 2016).

Sustainability standards are not only guiding the decision of producers on how to

carry out developments and manage operations but also are more and more importantly

guiding investors in deciding which sectors and companies present the lower investment

and reputational risk, thus influencing the market. Financial institutions, both through their

involvement in the RSPO and in other initiatives pushing for sustainable investment, such

as the United Nations Principles for Responsible Investment (UN PRI), have made moves to

stop investing in companies that are accused of environmental or social issues. Responsible finance principles have also been applied at government level. In 2013, the Norwegian

Government Pension Fund announced that they would be pulling investments from 23 Asian

palm oil companies due to the concerns related to deforestation and climate change. The

United Kingdom (Defra, 2012) also decided to use only certified sustainable palm oil (CSPO)

in ‘Central Government Food and Catering Services’ starting from October 2012. In the

following years, industry groups in several European countries have joined forces to ensure

a fully sustainable palm oil supply chain in Europe by 2020 by forming national initiatives for

sustainable palm oil in the Netherlands, Germany, the United Kingdom, France, Belgium,

Norway, Denmark, Sweden and Italy (RSPO, 2016). In response, the governments of six

key European Union countries have recently declared their support towards the project by

signing the Amsterdam Palm Oil Declaration. Although major progress in the uptake of

CSPO has been made in Europe, India and China – the first and third largest importers of

palm oil – are also making strides in the uptake of CSPO. In China, the three companies

who are the major importers of palm oil now have plans towards 100% CSPO uptake (RSPO

ACOP data, 2016). Other companies operating in China, such as Mars, have announced that

they have already covered all their palm oil supplies with certified materials.

The influences of large corporations and governments who have committed to

sustainable palm oil sourcing, together with the interrelation of the global markets for

palm oil, are factors that continue to influence the move towards a future where sustainable

palm oil will be the norm.

8 Where to look for further information

For further information on the author and related work, please visit www.rspo.org

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2 Chapter 2 Research trends in oil palm cultivation

1 Introduction

The role of agriculture in ensuring continued economic development is crucial. Although

the agricultural sector was neglected for a short period when Malaysia, for example,

focused on industrialisation in the 1980s and 1990s, it was promoted as the third engine

of growth (Wong, 2007) in the Ninth Malaysia Plan which covered the 2006–2010 period.

In this respect, the oil palm industry played a key role because oil palm is currently the

most important commodity crop in Malaysia. Malaysia also has world-renowned expertise

in the management and research and development (R&D) of tree crop agriculture, first in

the rubber industry and then the oil palm industry and plantation forestry as well.

Besides its role as an important source of revenue to Malaysia, the oil palm industry

provides a source of income for smallholders and plantation workers, and in so doing

helps rural development and improves livelihoods for current and future generations of

rural Malaysians. Despite its vital role in the economy, oil palm has been described as a

forest risk commodity because of allegations that significant areas of tropical forest have

been destroyed to clear land for commercial planting of oil palm.

Trends in oil palm cultivation evolved in response to changing landscapes associated with development (Malaysia is a developing country hoping to reach the status of a developed

nation in 2020), urbanisation, sensitivity to the issues of environmental protection, social equity

and economic progress; and increased agricultural activity resulting from increasing demand

for food to feed the growing world population. Thus, at the initial phase of establishing oil

palm as a commodity crop, the focus was on selection of suitable oil palm cultivars, followed by

the improvement of oil palm yield using selective breeding of the Malaysian Palm Oil Board's

(MPOB) large germplasm collection from Africa. At the same time, experience gained

from cultivation of oil palm was further refined using best management systems based on

good agricultural practices (GAP), where soil fertility and enhancement of soil nutrients to

maximise the land yield and therefore oil palm yield were main concerns. Control of pests

and diseases was also important in setting the trend for oil palm cultivation.

The next phase of new cultivation patterns was led by advances in biotechnology

where the unravelling of the oil palm genome presented opportunities for the mining for

genes associated with yield, resistance to environmental stress, height, and chemical and

physical properties of the palm oil.

At the same time, with the increasing impact of climate change on global weather

patterns, growing attention on the sustainability of the oil palm industry resulted in issues on conservation and protection of the environment becoming key drivers which impact not

only the palm oil trade but also the way oil palm is cultivated. This is because all agricultural

activities involve the consumption of natural resources and land use change, both of which

influence greenhouse gas (GHG) emissions that trigger climate change. In short, the trend

in research on oil palm cultivation has been propelled firstly by the need to establish oil

palm, native to Africa, as an agricultural crop in Malaysia; secondly, the requirement to

ensure its success as a commercial crop by implementing GAP and nurturing breeds with

good yields; thirdly, by the successful discovery of the oil palm genome when genes can

now be mined for designer oil palms; and last but not least, by pressure on the oil palm Establishment of oil palm as an economic crop Identification and establishment of suitable cultivar for commercialisation, use of GAP to increase productivity Improvement of yield based on selective breeding of breeds in germplasm collection followed by propagation of high yielding clones derived from tissue culture Successful sequencing of the oil palm genome for subsequent mining of useful genes for height reduction, oil yield and particular oil composition and resilience to climate change Cultivation practices with minimal impact on the environment and biodiversity PHASE A d d r e s s i n g C l i m a t e C h a n g e Y i e l d I m p r o v e m e n t M o l e c u l a r B r e e d i n g C r o p E s t a b l i s h m e n t Y i e l d I m p r o v e m e n t S e l e c t i v e B r e e d i n g

Figure 1 Phases denoting trends in R&D for oil palm cultivation.

industry to demonstrate commitment to sustainability while addressing issues pertaining

to conservation and protection of the environment and biodiversity.

In essence, the trend is really reflective of the demand to address key issues and

challenges which oil palm faced at particular phases of the industry since its establishment

as a commercial crop in 1917.

The chronological and main phases of R&D in oil palm cultivation trend are depicted in

Fig. 1.

It was observed that the trend in R&D on cultivation of oil palm was defined by challenges

and opportunities presented at the time.

2 Establishment of oil palm as an economic crop

Oil palm is from the genus Elaeis with two taxonomically well-defined species, the African

oil palm Elaeis guineensis and the American oil palm E. oleifera. As the yield of the

American palm is significantly lower compared to the African oil palm, E. guineensis is the

species which is commercially exploited. This native palm from Africa has three common

varieties, that is, pisifera, dura, and tenera. The latter is a result of hybridisation between

the pisifera and the dura and commercial oil palm plantations are dominated by tenera

palms because of their higher content of reddish-orange palm oil in the mesocarp oil.

As both male and female flowers are produced by the oil palm, it is therefore a

monoecious crop. In nature, cross-pollination of the palm is performed by insects or wind.

In order to increase yield of fruit bunches in commercial plantations, assisted or manual pollination was carried out until the 1970s. This practice changed dramatically in 1981

when pollinating weevils, Elaeidobius kemerunicus, were released to replace laborious

hand pollination. The introduction of pollinating weevils not only reduced the workforce

needed for manual pollination but also increased the fruit set and thereby oil yields per

surface unit. This remarkable change in oil yield is attributed to Leslie Davison (http://www.

merdekaaward.my/Recipients/By-Category/Outstanding-Contribution-to-the-people-of

Malaysia/Datuk-Leslie-Davidson.aspx), who noticed the extremely efficient pollination

rate of palms in Africa and hypothesised through keen observation that an insect and not

wind was the pollinating agent for the oil palm. He lobbied for investigation to confirm

his hypothesis and subsequently research by scientists from the Commonwealth Institute

of Biological Control led by Dr. Rahman Syed confirmed that oil palm is indeed insect

pollinated and the most effective pollinator is the African weevil Elaeidobius kamerunicus.

In addition to the amazing success of the pollinating weevil in increasing yield,

replacement of manual pollination greatly benefited smallholders who do not have the

resources to carry out hand pollination.

3 Yield improvement

A wide gap still exists between actual yield per hectare and the theoretical potential

yield of oil palm. The current yield stands at about 20 tonnes fresh fruit bunch (FFB) per hectare per year, although some plantations can easily get 30 tonnes while 40-46 tonnes are achievable with well-managed practices. Closing this yield gap will boost production significantly without any impact on surrounding protected area.

Oil palm is a perennial crop with a productive lifespan of 20 years or more. The hybridisation of the pisifera and dura (D x P) resulted in the tenera (T), the oil palm type with the better value in terms of oil yield. Fruit set starts as early as 25 months or less after field planting with peak yields seen in palms after four years. The quality of seedlings planted will determine the yield and health of oil palms in plantations and therefore good nursery practices are critical factors to consider in oil palm cultivation. Good planting materials can only be obtained from certified selected seeds and it follows that the selection of seeds and the implementation of good nursery practices are key factors in the assurance of high-yielding palms.

3.1 Good agricultural practices

To ensure the availability of good planting materials for more than five million hectares of oil palm planted area in Malaysia (Malaysian Oil Palm Statistics, 2015), in the 1980s the Palm Oil Research Institute of Malaysia (now the MPOB) established a certification scheme, the Oil Palm Nursery Competency Certification. This scheme was later incorporated into the MPOB Code of Good Nursery Practice for Oil Palm Nurseries (Choo et al., 2015).

3.2 Selective breeding

In 1941, Beirnaert and Vandederweyen found that the monogenic inheritance of the oil

palm shell of dura, tenera and pisifera was in the ratio of 1:2:1. This was an important

discovery as the tenera (D x P) hybrid has a thicker mesocarp compared to dura and

pisifera and is therefore the preferred commercial planting material. Since the pisifera

is partially fertile, it is used for breeding by crossing the male pisifera with the dura to

generate the tenera hybrid. Knowledge of the single-gene inheritance of shell thickness in

oil palm has led to oil palm breeding for tenera planting material.

As the success of breeding programmes depends largely on the availability of genetic

variety for improvement, PORIM/MPOB made several prospecting trips to Africa and South

America to collect additional oil palm germplasm (Rajanaidu and Rao, 1988; Rajanaidu, 1994).

The oil palm breeding programme (Rajanaidu et al., 2000) was initiated with the objectives of: • increasing oil palm yield, for example, from current 4 t/ha/yr to 9 t/ha/yr; • selecting palms with low vegetative growth, for example, short palms; • enhancing of oil quality and composition, for example, high vitamin E content, high carotene content and high oleic acid content; • increasing resistance to diseases, for example, Ganoderma tolerant; • characterising physiological traits such as bunch index (BI), total dry matter (TDM) and bunch dry matter (BDM); • exploiting genotype and environmental interaction.

Conventionally, BI (BDM/TDM ratio) has been used to screen for physiologically efficient

progenies for high FFB yield. However, the harvesting index (HI) also needs to be taken into account because this would indicate economic yield as the HI is a ratio of economic yield to biological yield.

The breeding programme in MPOB has successfully produced planting materials with slow height increment (PS1), high iodine value (PS2), high kernel content (PS3), high carotene content (PS4), higher oil content thin-shell teneras (PS5) and large fruit duras (PS6), high BI (PS7) and high vitamin E content (PS8), long stalk palms for easier harvesting (PS10), high carotene E. guineensis (PS11), high oleic palm (PS12) and low lipase palm for lower free fatty acid and high-quality palm oil (PS13).

3.3 Tissue culture for high-yielding clones

The vegetative propagation of oil palm, because of its botanical characteristics, can only be done through tissue culture. The first tissue culture attempt was initiated in the 1960s with the successful production of plantlets in the 1970s (Jones, 1974; Rabéchault and Martin, 1976). MPOB (then PORIM) followed up on this with research on refining in vitro propagation. However, this achievement was later challenged because of the need to overcome the incidences of abnormal clones with mantled fruits and other vegetation aberrations (Corley et al., 1986).

Despite the issue of abnormal clones, research in tissue culture to enhance clonal efficiency went ahead with the focus on improving the tissue culture protocol to meet the demand for ramets. Progress made to improve culture media, protocols for cloning and

field trials, and efficient bioreactor systems for multiplication of oil palm cultures are some

of the solutions to supply ramets to the industry.

Besides the concern on abnormality, another issue is the low embryogenesis rate. To

address the latter, gene expression (Ong-Abdullah and Ooi, 2007) and gene mapping (Ting

et al., 2013) studies, focusing on the development of biomarkers for tissue culture amenity

and abnormality, were successful in identifying putative markers for embryogenesis.

The abnormality issue was a problem but improvements in tissue culture processes and

stringent culling in many oil palm tissue culture laboratories resulted in more manageable

levels of fruit mantling. Jaligot et al. (2014) were able to shed some new insights into the

epigenetic origin of the problem; then research work by Ong-Abdullah et al. (2016) later

identified the actual cause of mantling, which was due to epigenetic change in the Karma

transposon in the intron of the homeotic gene DEFICIENS.

4 Oil palm genomics and genetic engineering

4.1 Oil palm genomics

The genome is the genetic material in a chromosome, and unravelling the oil palm genome

was one of the major achievements of R&D for the improvement of oil palm cultivation. In

2004, MPOB initiated a small genome sequencing project on the oil palm genome to look at hypomethylated and gene-rich regions which encode for the genes and their regulatory

regions. Since then, two private companies including MPOB (Singh et al., 2013a) have

sequenced the oil palm genome.

MPOB is also the host and developer of a database available at the Genomsawit portal

(https://genomsawit.mpob.gov.my) to manage and share oil palm DNA sequences and

other relevant information on oil palm genomic resources. The sharing of data is vital in

expediting research particularly for molecular breeding or marker-assisted breeding of

the oil palm. Molecular markers are becoming crucial in breeding programmes. These

markers could help in reducing long and tedious phenotypic selection in the conventional

breeding programme and greatly accelerating the production of improved cultivars.

Simple sequence repeat (SSR) markers are the preferred molecular markers for mapping,

genetic analyses and market-assisted plant improvement programmes. Various workers

(Singh et al., 2008; Low et al., 2008, 2014; Seng et al., 2011) have described the mining

of SSR from available oil palm sequences. SSR markers have also been effectively used to

analyse oil palm germplasm (Singh et al., 2008; Zulkifli et al., 2012; Bakoume et al, 2015)

and mapping populations (Billotte et al., 2005, 2010; Singh et al., 2009; Ting et al., 2013,

2014; Montoya et al., 2014; Jeennor et al., 2014).

The availability of the oil palm gene sequence also allows for the mining of markers for

important agronomic traits such as fruit colour (Singh et al., 2014), presence or absence of shell

and oil quality. Indeed the successful identification of a single gene, called Shell, can help to

increase the oil palm's yield by 30% (Singh et al., 2013b). In the past, selective breeding was

the technique to ensure planting of elite tenera palms. However, this technique is not fail-save

and about 10% of plantings can still be contaminated with the low-yielding dura because of

uncontrolled wind and insect pollination. Confirming whether a palm will be of the desired

shell type, that is, tenera, will need at least three years when the palm starts to bear fruits, at

which time it would be uneconomical to uproot the palm for replanting. The identification of

the shell gene enabled the developing of a molecular method on seedlings so that cultivation

of tenera palms are ensured, thereby raising the yield of oil palm plantations.

As to the issue of abnormal clones from tissue culture, the gene responsible for mantled

or shrivelled oil barren fruits was identified by MPOB and its collaborator, the United

States-based biotechnology company Orion Genomics in 2015 (Ong Abdullah et al.,

2015). The latter has been licensed by MPOB to develop a diagnostic test based on a

simple leaf-based assay to identify clones with the mantle gene, thereby circumventing

the planting of mantled palms (Ong-Abdullah et al., 2016).

Several oil palm breeding programmes around the world now include objectives to use

genomic data to develop disease-resistant palms and produce value-added products. The

annotated sequence of the oil palm genome is also a resource for biomarker discovery

and also for the development of diagnostic tools subsequent to identification of genes

responsible for both desirable and undesirable agronomical traits.

4.2 Genetic engineering

Gene manipulation through genetic engineering has gained attention because of some

limitations of conventional breeding. It allows for specific genes of interest to be introduced

directly into a genome and radically reduces the time needed for selective breeding to

obtain the desired traits. With this technique, the fatty acid composition of palm oil could

be modified to produce either a highly saturated or unsaturated oil or a lycopene instead

of carotene-rich palm oil (Parveez et al., 2011).

Research in genetic engineering of the oil palm covers work on the following: • gene and enzyme isolation in the oil palm fatty acid and carotenoid biosynthetic pathways; • isolation of promoters for effective targeting of transgenes into specific tissue and to ensure optimal timing of the transgenic expression; • construction of various transformation vectors carrying combinations of genes; • promoters and other genetic materials for transforming oil palm; and • development of transgenic oil palm and production of value-added transgenic oil palm.

There are concerns about the putative effects of transgenic crops on the environment

and human health. Potential approaches to address such apprehension include the elimination of marker genes using plasmids (Komari et al., 1996), replacement of antibiotic marker genes with more 'friendly' genes (Joesbo et al., 1998) and self-containment of the transgene through chloroplast transformation (Daniell et al., 1998). Research is also required to tackle the probability of integrating a plasmid or DNA vector, besides the gene of interest, into the oil palm genome. More recently, research on plant transformation approaches to obviate the concerns on genetically modified plant products saw the emergence of gene editing technologies such as the CRISPR/CAS system (Belhaj et al., 2013; Alpeter et al., 2016).

5 Cultivation with minimal environmental impact

The world population is now reaching 7.3 billion, with the global middle class making up 1.7 billion, and it is expected to go up to 9.5–9.7 billion by 2050. Vegetable oil demand is expected to go up to 125–150 million tonnes in the next five years. The drivers for vegetable oil demand will come from population growth and the booming middle class.

Palm oil will play a key role in meeting this demand because of its stable supply, availability, affordability and its versatile functionality in both food and non-food applications.

Research in oil palm cultivation had previously been more centred on increasing productivity through selection of quality planting materials obtained from selective breeding or tissue culture work. Though genomics will also be key to both quality and designer palms with high productivity and desired oil composition, this is still work in progress because the science is new and ethical, religious and philosophical concerns still revolve around palms engineered by man.

The defining issue at the moment is climate change due to global warming which in turn is triggered by the increasing level of GHG emissions produced by increasing anthropogenic activities. Deforestation and forest degradation are estimated to account for around 12% of global GHG anthropogenic carbon dioxide (CO_2) emissions (van der Werf et al., 2009), while the remaining 88% are through other anthropogenic activities such as transportation and production of industrial goods and the combustion of fossil fuel. These figures clearly indicate that reducing fossil fuel emissions remains the key element for stabilising atmospheric CO_2 concentrations and consequently global warming which lead to climate change.

5.1 Increasing yield to minimise land use change

The key here is the goal of increasing productivity without expansion onto new land, that is, no land use change. Under this scenario, if the yield of FFB per hectare could be increased from 20 to 25 t/ha, any additional amount of palm oil can be produced from the increased FFB without requiring an additional hectare of new land. This is why yield improvement through the tissue culture and genomic routes are top R&D priorities,

together with best management practices.

5.2 Integrated pest management for control of pests and diseases

Two important factors governing the measured yield gap between potential yield of

hypothetical oil palm genotypes and the actual yield of palms in plantation are attacks

by pests and palms infected by diseases. A major disease which threatens the oil palm

in Malaysia is the basal stem rot (BSR) caused by Ganoderma spp. fungi (Idris, 2011a).

Since BSR is lethal and infected palms stop producing and eventually die, studies were

carried out to understand its biology and epidemiology with the aim of (a) establishing a

rapid and accurate diagnosis of the disease and (b) discovering solutions for its detection

and implementing management strategies for controlling the Ganoderma. Proper land

preparation at replanting is also a way to control the spread of BSR. Other solutions to

BSR are the breeding of oil palm progenies which are resistant to Ganoderma and the use

of biological control such as fungi, mycorrhiza and bacteria. Studies have also shown that

the manipulation of fertiliser nutrients can reduce BSR incidences significantly. Although

the ultimate objective is to find a cure for BSR infected palms, these interim solutions are

important measures to curb the spread of the disease.

Other important diseases of the palms include vascular wilt disease which is also

known as Fusarium wilt, bud rot, red ring disease, sudden wilt and leaf spot disease

(Idris, 2011b).

Cultivation of oil palm in plantations often stretches over a large geographical zone

is a monoculture, and many view this method as the worst possible way to grow crops.

Monocultures are usually more susceptible to outbreaks of diseases and pest infestations

than crops harbouring genetic polymorphism (Mundt, 2002). Thus, one of the greatest

risks of monoculture is the danger of the entire crop being wiped out by a single pest or

disease. This risk is exacerbated by the normal practice of planting vast areas with palms

from a reduced number of distinct genotypes. Indeed, high genetic diversity could be a

safeguard against the spread of pest and disease in monoculture crops (King and Lively,

2012). As oil palm is a perennial crop, diverse crop rotation, that is, polyculture, is not a

solution because oil palm takes at least three years to start fruiting and establishment of

oil palm plantations is costly and laborious. Thus, further work could be done to weigh the

advantages and problems associated with the cultivation of palms from various different

genetic backgrounds.

The Malaysian palm oil industry is always on the alert with continuing research for ready

preventions/solutions against new pests and diseases. Steps are taken to circumvent

disasters such as the bud rot scourge which wiped out some 50 000 ha of oil palm estates

in South America. Stakeholders at the global level in oil palm R&D must remain very

vigilant on emerging diseases and new pathogens and also follow through with ready

action plans.

With the growing concerns on the use of agrochemicals to control pest infestation,

alternative methods with less negative impact on the environment are important areas of

research in oil palm cultivation. Biological control such as the use of microbial pesticides

has great potential in avoiding the adverse impacts associated with the use of synthetic

agrochemical insecticides. The bacterium Bacillus thuringiensis (BT) has proven to be a

highly successful microbial insecticide (Rosas-Garcia, 2009). BT is mainly a soil-dwelling

bacterium and was first discovered by the Japanese biologist Shigetane Ishiwata in 1901.

Research has shown that BT is effective for the control of the bagworm (Metisa plana),

an oil palm defoliator (Siti Ramlah et al., 2011). Other types of biological control agents

include contact fungi and ingested viruses. The other common pest infestation in oil palm

plantations is that by the rhinoceros beetle (Oryctes rhinoceros) and its larvae. The powder

formulations of the fungus Metarhizium anisopliae and the Oryctes virus have proven to

be effective in reducing the population of the larvae and the adult beetles, respectively

(Ramle et al., 2005, 2008).

5.3 Soil and nutrient management to increase land yield

Available arable land and soils containing sufficient nutrients form the foundation of the

cultivation of high-yielding palms. R&D actions are needed to ensure and enhance soil

fertility so that the palm can produce yields which are near to its theoretical yield potential

(Carron et al., 2015a,b, 2016). The nutrients in soil only support plant growth while the

type and characteristics of the soil will determine the palm’s ability to absorb water and

nutrients. If the palm is to produce a yield near to its genetic potential, the soil must

provide a suitable medium for its growth. Fertilisers can be added to make up for soil

nutrient deficiency but these can be lost through leaching and runoffs, especially in tropical

countries with characteristic heavy rainfall. The issue of fertiliser eutrophication of surface

water and contamination of groundwater must be considered. Consequently, any use of

either chemical or organic fertilisers exceeding the optimum amount required is not only

a direct economic loss but also increases the risk of pollution and environmental burden.

The microbiome is also an important factor in determining the health of soils. Within

the soil, organisms function within an ecological food web where nutrients are cycled

through the soil biomass. This soil food web is the basis of healthy, living soil. Vital soil organisms involved in the soil food web include bacteria, fungi, protozoa, nematodes,

arthropods and earthworms. Besides reducing the use of pesticides and fertilisers, the soil

microbiome improves palm growth and health. A detailed study of the entire genome of

soil biota through metagenomics approach is expected to provide important information

on complex soil microbial communities for innovation of novel agricultural applications

(Mocali and Bendetti, 2010).

Hence, in the matter of maintaining soil health, the holistic management approach is

proposed as the basis for further research in oil palm cultivation. The relationship among

the soil, oil palm and water must be managed as a ‘whole’ entity so that the cultivation of

oil palm can continue indefinitely where land (soil) and water sustainability is created for

future generations of oil palm growers.

5.4 Sustainability-centred cultivation

With the increasing demand on the earth’s natural resources to feed and house the growing

world population, oil palm cultivation will have to yield more oil using less land in order to

protect and conserve human population, natural resources, biodiversity and the environment.

High-yielding palms curb land expansion but great care and governance are also needed

to ensure that cultivation does not have a negative impact on the natural environment and

its biodiversity.

The issue of oil palm cultivation on peat soils is a long-standing debate between the oil palm industry and environmental/conservation groups. Peatlands are important carbon sinks because they capture approximately one-third of the world's soil carbon and 10% of global freshwater sources reside in them. Oil palm grows best on mineral soils but because of the scarcity of arable land, about 8% of Malaysian oil palms are planted on peatlands.

As peatlands must be drained before conversion to oil palm estates, oxidation and loss of organic carbon as CO_2 occur. However, in many instances oil palm is planted only after the peat forest is logged/degraded for timber harvesting. If these areas had not been planted with oil palm, it would have been left degraded, thereby incurring heavy GHG emissions anyway. Thus, the burden of GHG emissions should not be entirely borne by oil palm alone.

Despite the fact that the cultivation of oil palm on peat is both difficult and costly, much research over the years (Gurmit et al., 1988; Mutert et al., 1999; Hasnol et al., 2010, 2011; Haniff et al., 2011) have proven that with the correct land preparation, drainage and water management, optimal planting practices and fertiliser regimes, planting on peat can be carried out with minimal carbon losses and production costs.

While there is consensus among the planters that pristine peat and high biodiversity peat areas should be preserved as natural carbon sinks, opinions vary on the extent to

which secondary peat forests and degraded peatlands are to be excluded from agricultural

development in a developing country. Certain quarters have even advocated that peatlands

should be no-go areas for cultivation of oil palm. One noteworthy point which has been

overlooked in the eagerness for this moratorium on peatland development is the non

differentiation of tropical and temperate peat. On the contrary, tropical lowland peats have a

distinctly different morphology compared to temperate and boreal peats (Veloo et al., 2014).

Most publications on tropical peat refer to generic peat without any further characterisation.

Paramananthan and Wahid (2015), based on the mapping of over 700 000 ha of organic

soils, suggested that tropical peats, especially in the surface tier (0–50 cm), are mostly

sapric with low GHG emissions. In addition, hardwood is often present, again implying

low GHG emissions.

Tropical peat soils are quite different from temperate peats not only because of the

formation under different climate conditions but also because temperate peats are mainly

derived from low growing plants while tropical peats are from forest species. Paramanthan

and Wahid (2015) reported that the organic materials making up the peat vertical profile

range from highly decomposed sapric material at the surface to a partly decomposed hemic material and to an undecomposed fibric material.

Thus, it is believed that a proper quantification of peat emissions should take note of their inherent differences not only in peat from different climatic regions but also within the same region because of the variations in peat vertical profile (sapric, hemic and fibric). This will require development of system models for different peat ecosystems including characterisation of peat according to an appropriate peat classification system for tropical peat, carbon exchange between peat ecosystems and the atmosphere at different spatial (different regions, countries, etc.) and temporal scales (different seasons, e.g. wet and dry season in the tropics). The unified peat classification (UPCS), as worked out by Paramanathan and Wahid (2015), will be useful for identifying the site characteristics of a peat area (Paramanathan, 1998, 2010a,b; Paramananthan and Wahid, 2008) and whether these could be both economically viable and environmentally acceptable for cultivation of oil palm (Paramanantan, 2014).

Answering to the question on whether development can be done on peat because of the issue of GHG emissions from drainage of peatlands, confirmation can only be obtained from investigation after the measurement of emissions from different peat types as grouped under the UPCS. This work is currently in progress.

6 Conclusion

Clones from tissue culture are the second wave of improvement following high-yielding

materials derived from selective breeding. The unravelling of the oil palm genome heralds

exciting advances through mining of traits to produce designer palms with high yield; disease,

pest and drought resistance; quality; desired fatty acid; and phytochemical composition and

which are short for easier harvesting. Such science-based innovations address the pressing

needs for the cultivation of oil palm to produce more oil using less inputs and arable land,

and with minimal adverse social, environmental and economic impacts.

However, a precautionary approach must be taken in the production of genetically

modified palms because of the uncertainty on the effects of genetically modified organisms

on human health and the environment and the variable acceptance of such technologies

in different societies, especially in the developed world. The complete sequencing,

assembling and annotation of the oil palm genome could also be invaluable in reducing

the carbon emissions associated with the cultivation of oil palm.

Post-genomic research could provide information to drive the development of designer

palms with sustainable high yields, disease resistance and ease of harvesting FFB.

Additionally, new techniques for genetic crop improvement including advances in the use of

genome editing could address some of the concerns associated with genetically modified

crops as the process is claimed to mimic that in nature albeit at an accelerated rate.

With growing attention on the effectiveness of the best cultivation methods, it is no

longer just about producing more with less, that is, eco-efficiency. Neither is it about

conservation alone because sustainability is now the key word driving research in oil

palm cultivation. Be that as it may, science-based approaches will remain the key in

ensuring improvement of yield as well as good cultivation practices that protect both the

environment and people. In this context, the best approach for research is to integrate a

systems or holistic approach to address the three elements of sustainability, namely social

equity, environmental protection and economic progress.

7 Where to look for further information

Further information on development of the oil palm in Malaysia can be obtained from:

- Ministry of Plantation Industries and Commodities (MPIC), Malaysia, www.kppk.gov.my
- Malaysian Palm Oil Board (MPOB), www.mpob.gpv.my

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3 Chapter 3 Sustainability pathways in oil palm cultivation: a comparison of Indonesia, Colombia and Cameroon

1 Introduction

Oil palm (Elaeis guineensis) is a versatile crop with increasing multiple uses, especially for food and energy (Alonso-Frajedas et al. 2016). Palm oil has a number of comparative advantages over other vegetable oils. The oil palm has the highest oil yield, which could reach as high as ten times of the yield of soybean, rapeseed and canola oils. It also has the lowest land requirement to produce one ton of oil, and the lowest production cost per hectare (Corley and Tinker 2015). While covering 6% of the total global agricultural land, palm oil production contributes to one-third of global vegetable oil production. Oil palm also has a long lifespan, as it can provide continuous harvest in about 25–30 years.

Oil palm can grow on many types of soil, provided the general physical characteristics are not extreme and the climate is suitable. The ideal latitude for its growth is between 15 o N and 15 o S (Corley and Tinker 2015). An adequate combination of rainfall and sunshine is important for the growth of oil palm. A minimum of 2,000 mm per year of annual rainfall that is evenly distributed, minimum temperature of 20˚C and maximum between 28 and 34˚C, and at least 1800 hours of sunshine per year are needed to allow the crop to reach its potential (Ngando-Ebongue et al. 2012, Corley and Tinker 2015).

Palm oil, the processed oil from oil palm, has a variety of derivative products. The demand for palm oil has been increasing since the last three decades. It has surpassed soybean as the most consumed and traded oilseeds globally (Ngando-Ebongue et al. 2012, FAO 2014). China, India and the European Union are the largest importing countries for palm oil.

Despite being very versatile, oil palm is currently one of the most debated crops. For the key producing countries, oil palm has become an important contributor to the economy.

Cultivation of oil palm absorbs a vast amount of labour for large-scale estates, as well as millions of smallholders who cultivate and process oil palm. Oil palm also has a vast amount of derivative industries that serve many sectors.

Together with the economic benefits that have been provided through the development and expansion of oil palm, there are a number of significant associated environmental and social costs. A number of studies have highlighted deforestation and biodiversity loss as the main environmental costs (Linder and Palkovich 2016). Koh and Wilcove (2008a, 2008b) show that about half of oil palm expansion in Malaysia and Indonesia has gone through prior deforestation. Subsequent studies on the sources of deforestation from 2000s also confirm the contribution of oil palm as one of the key drivers of deforestation (Abood et al. 2014).

Fayle et al. (2010) found that the total number of ant species in oil palm plantations was significantly lower than under forest cover. Conversion to oil palm dramatically reduces

species richness, with significantly fewer primary-forest species than found on logged

forests, notably for birds, leaf-litter ants, beetles, aerial hymenopterans, flies and true bugs

(Edwards et al. 2014b). Earlier studies in Indonesia also found similar results: oil palm

plantations support much fewer species than do forests and often also fewer than other

tree crops (Fitzherbert et al. 2008).

In terms of social costs, dispossession of smallholders' land by corporations and violent

groups has become an important social impact (e.g. Budidarsono et al. 2013, Linder and

Palkovitz 2016). Most of the countries with dominant role of corporations in driving the

oil palm production are characterized by poor social impacts (IFC 2013, Buitron 2001).

Specifically in Colombia, the social cost of oil palm has involved cases of dispossession of

land by violent groups (Garcia-Ulloa et al. 2012, Maher 2015).

A number of governance initiatives have been launched in order to minimize the

negative ecological and social impacts as well as to enhance positive impacts of oil palm

cultivation. Initiatives from public agencies, private multi-stakeholder process as well as

corporate self-regulation to develop standards, best management practices, certification

and corporate commitments have emerged with the aim of achieving sustainable and equitable oil palm development. Each country experiences different pathways in moving towards sustainable production of oil palm.

The present chapter aims at identifying the pathways towards sustainable oil palm production in three countries: Indonesia, Colombia and Cameroon. Indonesia and Colombia are the leading oil palm countries in Southeast Asia and Latin America, respectively. While Cameroon is not the leading palm oil producer in Africa, its stage of development is similar to the one of other countries in the region. The three countries reflect different levels of complexities of interactions among actors, different governance challenges, as well as different routes and achievements towards sustainable oil palm production.

2 Conceptualizing sustainable pathways

Increasing palm oil production in a sustainable way is a huge challenge for governments, private-sector actors and smallholders. On the production side, actors from both government and private sectors set the production ambitions or targets for palm oil. On the consumer side, there are demands that oil palm is produced in a sustainable manner, that is, not destructive to the environment as well as respectful to the rights of the communities. Though considerations on sustainability are important, the way in which these considerations are translated into specific policies and are combined with production ambitions and targets varies across places (Wittmayer et al. 2014). This leads

to a variety of pathways to sustainable palm oil production.

We conceptualize sustainable pathways as trajectories that connect technical,

environmental and governance practices that reinforce each other, and consisting of actors

at different levels that regulate, manage, implement and monitor these practices towards

sustainable production (Hospes et al. 2017; Leach et al. 2010). This conceptualization has

three components: sustainable production as the aspiration, as a variety of practices that

support each other, and governed by actors at different levels with different roles.

Sustainable production can be seen as a desired situation, a vision or an ambition.

Generally, this includes not being destructive to the environment as well as respect

for social conditions. It is important to note that sustainable production itself is both a

context-specific and contested concept. Both different contexts and different frames of

problems and solutions for sustainable production explain different steps, and ideas on

steps, towards sustainable production.

Sustainable pathways involve the combination of technical, environmental, regulatory

and governance practices that reinforce each other in contributing towards sustainable

production. An example in the oil palm context is the combination of best management

practices using the best available planting material and agronomic techniques to realize

optimal yields, and regulatory practices that set limits to expansion of palm oil production

into forest areas and peat land. Regulatory practices can consist of public regulation and

regulation by multi-stakeholder initiatives but also corporate self-regulation. An example

within the field of governance and regulation is the combination of integrated land-use

planning at national and regional level, and procedural requirements on mutual consultation

and agreement between companies and communities at local level.

Sustainable pathways involve different actors with different roles (Hospes et al. 2017;

Leach et al. 2010). The government is generally seen as a key regulator agency. However,

different bodies and levels of government may execute their regulatory role in different

ways, for instance, through the development of a national standard for sustainable palm

oil, organizing forest moratoria, licensing palm oil production or monitoring the private

sector. Next to complying with government regulations, private-sector actors may also set

their own regulations, manage resources and make decisions on land use. Smallholders

can be seen as private-sector actors from the entrepreneurship point of view, but also as

those who need empowerment as they have much more limited resources to produce in

sustainable manners.

There is no single pathway towards sustainable oil palm production (Hospes et al. 2017; Leach et al. 2010; Lindahl et al. 2015). Pathways are historically contingent and context specific. The historical development of the palm oil sector, changes of the political regime, and political frames of the issue together define the scope for sustainable pathways in a country. Different forms and combinations of regulation exist in different countries, as the involvement of different actors in the palm oil sector in, for instance, Indonesia is not necessarily the same as the one in Columbia and Cameroon. In Indonesia, public, private and corporate self-regulation exists. In Colombia, private regulation dominates. Meanwhile, perhaps sustainability has not yet become an important policy agenda in Cameroon.

3 Oil palm production in Indonesia, Colombia and Cameroon

3.1 Indonesia

From four plants brought to Bogor Botanical Garden in 1848, oil palm has gone through a long history to become one of the most economically important crops in Indonesia. Commercial oil palm during the Dutch colonial period began in 1911, where a Belgian company opened plantations in Pulau Raja (Asahan) and Sungai Lipoet (Aceh). The oil palm sector then grew faster through the development of the first palm oil factory in 1919, and by 1937 Indonesia took over Nigeria as the largest palm oil exporter. However, the oil palm sector fell dramatically during World War II, and the trend continued until the late

1960s (PASPI 2014).

During the New Order period that started when Suharto seized power in 1967, the

development of the oil palm sector was facilitated by the enactment of Law 1/1967 on

foreign investment. The Government of Indonesia, with the assistance of international

donors, developed a variety of programmes to boost the development of the oil

palm sector. The introduction of programmes for smallholders dramatically increased

the participation of smallholders. Another turning point came in late 1990s, when the

economic Indonesian crisis opened doors for a significant increase of palm oil exports.

By 2006, Indonesia regained the position as the world’s leading exporter of palm oil,

surpassing Malaysia. Indonesia is not only the largest exporter but also one of the largest

consumers of palm oil in the world. The government has also declared cooking oil, that

is mainly palm based, as one of the so-called ‘nine essential products’. This is yet another

reason why the government has supported the increase of palm oil production.

One of the key drivers that has facilitated the expansion of oil palm in Indonesia has been

supportive government policies. The Government of Indonesia has formulated policies to

promote private-sector investment as well as the involvement of smallholders into the palm oil business through a number of schemes since the 1970s. Indonesia became famous

with the introduction of a number of schemes, such as nucleus-plasma and cooperative

scheme. Throughout history, the Government of Indonesia has used different financial

schemes to achieve economic growth by developing palm oil (Pramudya et al. in press). A

number of additional policy measures supported investments in the palm-oil-processing

industries. More recently, the national energy policy has provided room for palm oil-based

biodiesel to flourish with the biodiesel mandates. These policies are designed to reach a

mid-term target of achieving 40 million tons of CPO production by 2020.

Indonesia has also formulated policies to support the development of advanced palm

oil-processing industries. The Government of Indonesia supports biodiesel development

through the establishment of biodiesel mandatory targets. Indonesia has been moving

up and down with the blending targets, and is aiming to reach 20% of biodiesel by 2016

and 30% by 2020 (Ministry of Energy and Mineral Resources 2016). However, the biofuel

mandate that has been in place since 2006 has been hampered by the fact that at the

same time the country also heavily subsidized the fossil fuels (Dermawan et al. 2012). The

lower the oil price, the higher the amount of subsidies to be allocated for biodiesel.

Currently, the Indonesian palm oil sector is dominated by large-scale private actors.

Some 11.5 million hectares in Indonesia are planted palm oil areas, which is about 5% of the country’s land area. More than half of this amount, that is 5.9 million hectares, are owned by large-scale private companies. State-owned enterprises, which dominated the sector during 1960s–1970s (see Pramudya et al. in press), currently control 0.8 million hectares. In addition, there are 1601 palm-oil-processing mills throughout Indonesia.

The remaining 4.7 million hectares are controlled by smallholders. Smallholders account for 40% of the total planted area. Indonesia is the country with the largest number of smallholders in the world (Central Statistical Agency of Indonesia 2015).

In Indonesia, palm oil yield varies across different business models (smallholders versus private companies), or even within the same business model, for example between independent smallholders and smallholders under partnership with companies (called plasma smallholders). Independent smallholders carry out oil palm cultivation by themselves, often using planting material of unreliable origin. Meanwhile, smallholders under plasma scheme have their cultivation controlled by the nucleus companies. Such smallholders can obtain higher fresh fruit bunches yield by 15% when compared to independent smallholders (IFC 2013). The best estates can reach yield levels of six tons of palm oil per hectare and beyond.

3.2 Colombia

Oil palm was brought to Colombia in 1932 (Potter 2015). It is called the African oil palm

as there is another oil palm species Elaeis oleifera that naturally grows in the Amazonian

region. Currently, oil palm development is concentrated in 16 states in four production

zones: 1) the Western Zone, at the south of western Colombia on the Pacific coast; 2) the

Northern Zone, in the northeastern part of the country, near the Atlantic coast; 3) the Central

Zone, an inter-Andean valley of the Magdalena river system; and 4) the Eastern Zone, at the

foothills of the eastern chain of Andes range (Gomez et al. 2011).

In the beginning, there were a small number of companies and local growers that

tried to plant oil palm, mainly to supply domestic markets. Expansion took place

rapidly since early 2000s as the government provided incentives to increase palm oil

production for exports and to meet biodiesel blending targets of 5% by 2008 (Pacheco

2012). Currently, Colombia cultivates the largest oil palm area in South America. The

development of oil palm in Colombia is driven by large-scale actors (although in terms

of scale they are still far below those in Indonesia and Malaysia). Currently, about 33%

of planted areas are between 200 and 1000 hectares, and another 35% are over 1000

hectares (Potter 2015). The National Federation of Oil Palm Growers, or Fedepalma, was formed in 1962 with the aim of organizing the growers and ensuring the progress of oil

palm development. Smallholders formed ‘Strategic and Productive Alliances’, where an

association of smallholders forms a contract with the source of funding, usually large

scale plantations (Potter 2015). In 2008, 55 mills were operating in Colombia, about half

of which were relatively small (less than 15 tons fresh fruit bunches per hour). Thirteen

mills had the capacity of more than 25 tons per hour, of which only two mills had a

capacity of more than 60 tons per hour (Pacheco 2012).

Being the largest producer in South America, Colombia has reached over 1.1 million

tons of palm oil in 2015 (Index Mundi 2016). However, the oil palm production in the

country has to deal with a number of limiting factors, such as topographic, climatic

(seasonal dry periods), and less suitable soil conditions, as well as the presence of pests

and diseases (Henson 2011, Pacheco 2012, Torres et al. 2016). Waves of cool temperature

and the bud rot disease have also hampered the oil palm production in the country in the

last few years, with some significant social impacts (Potter 2015). Still, in 2015 the country

recorded a national average yield of 3.2 tons of CPO per hectare, which is comparable to

the performance of the Southeast Asia (Index Mundi).

The Colombian government has a target of establishing a total three million hectares of oil palm by 2020. In addition, the government also aims to reach a 20% biodiesel

blending by the same year. A number of policies to reach the targets have been issued,

for example, a policy on tax holidays, implementation of free tax zones, tax reduction from

investments in productive assets and credits for establishing and maintaining plantations

(Pacheco 2012). Despite these policies, some have argued that the target is overly

ambitious. Reaching three million hectares means increasing the current planted area by

approximately six times in five years (Garcia-Ulloa et al. 2012, Castiblanco et al. 2013,

Pinto et al. 2014).

3.3 Cameroon

Cameroon has been traditionally using a variety of products from oil palm: the red oil from

the mesocarp, the oil contained in the kernel, and the sap that ferments to generate palm

wine (Nkongho et al. 2015). Local populations harvested oil palm for subsistence and

trade. Oil palms were harvested in the wild groves and were introduced on farmland as

a mixed crop with other food and cash crops. After the arrival of the German and British

colonial powers, large-scale oil palm sector began to emerge.

Five of Cameroon’s ten regions are suitable for oil palm cultivation: the Southwest,

Littoral, South, Centre and East regions. These regions are deemed suitable for oil palm

cultivation as they meet biophysical requirements in terms of temperature, sunshine, precipitation, soil type and altitude (Hoyle and Levang 2012). These regions have become attractive for investments in the oil palm sector.

In 2015, Cameroon had 130 000 hectares of oil palm producing 270 000 tons of palm oil (Index Mundi 2016). Although about three quarters of oil palm areas are under the smallholders, they have very low yield, with the average of 0.8 ton oil per hectare. This is lower than the yield of agro industries, which could reach 2.3 tons per hectare (Hoyle and Levang 2012, Nkongho et al. 2014). Cameroon has a target of reaching 450 000 tons of palm oil production by 2020 (Holye and Levang 2012).

Cameroon is a net importer of palm oil. The country has become an interesting place for oil palm investment to serve domestic markets, regional markets and demand from Europe. The availability of cheap land, political support from the government and the governmental plans to develop agricultural sector are also factors that make investing in Cameroon more interesting (Hoyle and Levang 2012).

Similar to the independent smallholders in Indonesia, the agronomic performance of smallholders in Cameroon is also poor. A study by Nkongho et al. (2014) found that only 35% of smallholders use certified planting material, while the rest use either uncertified Tenera or Dura planting material (Nkongho et al. 2014). Fertilizer application follows a similar trend, with only 1.1% of smallholders applying fertilizer timely and 68% of smallholders not using fertilizers at all. The yields are quite low: smallholders produce only seven tons of fresh fruit bunches per hectare.

This section has highlighted that each of the three selected countries has set targets for oil palm production. Each of the targets often implies a significant amount of expansion. Such expansion means either opening new land from forests or changing existing land use to give way to oil palm. The next two sections discuss sustainability issues that are emerging in each of the three countries and how actors are responding to these issues.

4 Sustainable pathways: challenges and initiatives

4.1 Sustainability challenges

With the economic benefits provided through the development and expansion of oil palm, there are a number of significant associated environmental and social costs. Some of the environmental impacts of the oil palm expansion are deforestation, biodiversity loss, carbon stock losses and greenhouse gas emissions (Linder and Palkovitz 2016). Koh and Wilcove (2008a,b) show that about half of oil palm expansion in Indonesia has gone through prior deforestation. Subsequent studies on the sources of deforestation from the 2000s also confirm the contribution of oil palm to deforestation (Margono et al. 2012).

However, there are disagreements on how much oil palm has contributed to deforestation.

For example, the study by Gunarso et al. (2013) shows that undisturbed forests are only about 5% of the land converted to oil palm, which is much smaller than concluded by other studies (Miettinen et al. 2011, Margono et al. 2012, Busch et al. 2015, Vijay et al. 2016). In Colombia about half of the oil palm plantations established in 2002–2008 were previously classified as pastures, and less than 15% of the oil palm replaced natural vegetation (forests, savannah).

With regard to biodiversity, Fayle et al. (2010) concluded that total ant species in Sabah, Malaysia, decreased from 309 to 110 due to the conversion of forests to oil palm plantations.

In general, conversion of habitat has decreased the number and richness of species, with significantly fewer primary-forest species than found on logged forests, notably for birds, leaf-litter ants, beetles, aerial hymenopterans, flies and true bugs (Edwards et al. 2014b). Other studies in Indonesia found similar results: oil palm plantations support much fewer species than do forests and often also fewer than other tree crops (Fitzherbert et al. 2008, Kurz et al. 2016).

The associated greenhouse gas emissions from the expansion of oil palm, especially those that come through forest clearing using fires, are also significant. Establishment of oil palm reduces soil organic carbon (van Straaten et al. 2015). Van Straaten et al. (2015) also found that the higher the initial soil organic carbon, the higher the losses. Carbon losses from forest peat conversion to oil palm could reach 405 tonnes in one planting cycle

(25 years) (Murdiyarso et al. 2009, Schrier-Uijl et al. 2013). The greenhouse gas emissions

depend on the previous land use. In Colombia, the differential production of greenhouse

gas depends on whether the land use that precedes oil palm is forest or pasture. In the

case of pasture, the greenhouse gas intensity is lower (Castanheira et al. 2014).

In terms of social impact, dispossession of smallholders' land by corporations or (para)

military forces is one of the key social impacts (e.g. Budidarsono et al. 2013, Maher 2015).

Most of the countries with a dominant role of corporations in driving the oil palm production

are characterized by poor social impacts of oil palm (Obidzinski et al. 2012, IFC 2013,

Li 2015). Examples are lack of smallholder involvement in large-scale oil palm projects and

poor working conditions of farmer-labourers (Hoyle and Levang 2012). In Colombia, the

social cost of oil palm involves dispossession of land by (para)military groups (Garcia-Ulloa

et al. 2012, Maher 2015). Oil palm companies are also found to show lack of respect to

traditional rights (Obidzinski et al. 2012).

4.2 Taking steps towards sustainability: certification and beyond

A number of initiatives have emerged to deal with the sustainability issues in the palm

oil sector. In 2001, the World Wildlife Fund (WWF) and a number of European food manufacturers explored the idea of establishing a Roundtable for Sustainable Palm Oil

(RSPO), which was eventually established in 2004. Through multi-stakeholder consultation,

RSPO developed principles and criteria for sustainable palm oil. The vision of the RSPO is

to transform markets and to make sustainable palm oil the norm. Specific objectives of the

RSPO are to promote the production, procurement, finance and use of sustainable palm

oil products; to develop, implement, verify, assure and periodically review credible global

standards for the entire supply chain of sustainable palm oil; to monitor and evaluate

the economic, environmental and social impacts of the uptake of sustainable palm oil

in the market; and to engage and commit all stakeholders throughout the supply chain,

including governments and consumers. Membership of the RSPO is voluntary for palm oil

companies as well as for the estates that wish to have their operations certified.

The RSPO has agreed on eight principles: commitment to transparency, compliance with

applicable laws and regulations, commitment to long-term economic and financial viability,

use of appropriate best practices by growers and millers, environmental responsibility

and conservation of natural resources and biodiversity, responsible consideration of

employees and of individuals and communities affected by growers and mills, responsible

development of new plantings, and commitment to continuous improvement in key areas

of activity (RSPO 2013). For each of these principles specific criteria and indicators have

been formulated against which a palm oil operation is evaluated. The principles and

criteria are generic. Countries have to develop their own national interpretation in order

to ensure that the principles and criteria are relevant under national contexts. Colombia

and Indonesia have their own national interpretations of the RSPO principles and criteria.

Both the governments of Indonesia and Malaysia have also established official principles

and criteria for sustainable palm oil. Indonesia launched a national sustainability standard

in 2011 that was updated in 2015: the Indonesian Sustainable Palm Oil (ISPO) standard.

The Government of Indonesia emphasized that the plantation sector in Indonesia

has to be developed in accordance with a number of principles, such as sovereignty,

sustainability, efficiency, fairness and environmental integrity. ISPO is aimed to ensure that

oil palm planters and processing companies apply the principles and criteria correctly and

consistently to produce sustainable palm oil (Ministry of Agriculture Regulation 11 of 2015).

Since the ISPO is established as a regulation by ministerial decree, it is mandatory for

processing companies and large-scale plantations. Plasma and independent smallholders

as well as eligible oil palm companies that produce palm oil to serve the renewable energy are exempted.

Similar to RSPO, ISPO also consists of a number of principles, criteria and indicators.

The principles and criteria are differentiated for different types of plantations: plantations

that are integrated with the processing facilities, plantations that are not integrated with

processing facilities, processing facilities that are not integrated with plantations, and

plantations for biodiesel. Though not mandatory for plasma and independent smallholders,

the ISPO does specify the principles and criteria for these smallholders. These principles

include business legality, plantation management, protection to use primary forests

and peatland, environmental management and monitoring, responsibilities to the

workers, social responsibilities and community economic empowerment, and continuous

improvements (Ministry of Agriculture Regulation 11 of 2015).

The Malaysian Sustainable Palm Oil (MSPO) standard was launched in 2013. It was

officially implemented in January 2015. Unlike ISPO, MSPO is voluntary. The government

has the ambition to get all actors certified by 2020. Given this ambition, several observers

expect that the MSPO may turn into a mandatory standard in the future. MSPO is

applicable to independent smallholders, oil palm plantations and organized smallholders

and palm oil mills. MSPO has eight principles related to management commitment and responsibility; transparency; compliance to legal requirements; social responsibility,

health, safety and employment conditions; environment, natural resources, biodiversity

and ecosystem services; best practices; and development of new planting. 1

The third kind of initiatives towards producing sustainable palm oil comes from

corporate self-regulation. The most recent one of this kind is the pledge of six giant palm

oil companies to zero-deforestation in Indonesia under the Indonesian Palm Oil Pledge

(IPOP) initiative. 2 These six companies are Golden Agri Resources, Wilmar International

Limited, Cargill, Asian Agri, Musim Mas and Astra Agro Lestari, with support from the

Indonesian Chamber of Commerce. IPOP has a vision to advance Indonesia's sustainable

palm oil business practices by collaborating with the government and all stakeholders

to attain a sustainable palm oil sector. The giant palm oil companies have to work in a

collaborative way to develop sustainable palm oil production that delivers stakeholder

value, is deforestation free and respects human and community rights.

Indonesia is a perfect example of how the three regulations – RSPO, ISPO and self

regulation – are coexisting. By May 2016, there were approximately 115 members of

the RSPO in Indonesia. Thirty-five companies have a number of their estates and mills

certified, covering 1.6 million hectares that produce 6.6 million tonnes of certified sustainable palm oil (CSPO) from approximately 24 million tonnes of fresh fruit bunches.

By the same period, there were 148 estates or mills that were certified under ISPO. The

Government of Indonesia originally targeted to certify all actors by 2014, but the level

of compliance to date remains low. It was reported that by 2014, approximately 200

out of the 881 companies that are eligible to pursue ISPO certification, had registered.

However, only 67 were certified. 3 Next to seeking compliance with ISPO, six giant palm oil

companies in Indonesia established IPOP. Although the size of their plantations and the

capacity of their mills are not known publicly, it is estimated that these companies control

at least 90% of the CPO intake in Indonesia (AgroIndonesia 2015).

In Colombia and Cameroon, the discussion on sustainability has centred on RSPO

compliance, although Colombia is more advanced than Cameroon in terms of engagement

with RSPO. A national interpretation of the RSPO principles and criteria exists for Colombia

and it is under revision to align with the 2013 version of RSPO principles and criteria.

There are 28 RSPO members in Colombia, where five of them produce 107 000 tons of

CSPO from 39 500 hectares of total certified areas. Fedepalma has a desire to implement

the principles and criteria of RSPO and move its members gradually into certification

(Potter 2015). With Colombia’s CPO export at approximately

30% of the production,

and European countries being the main export destination, it could be expected that

Colombia will move towards being fully compliant with RSPO certification.

As of 2016, there are no RSPO members in Cameroon, although some efforts are

geared towards moving to RSPO (RSPO n.d., TFA2020 2015). Both Colombia and

Cameroon have laws or regulation on the practices of oil palm plantations and processing

units, although they might not be structured in the same way as the RSPO or ISPO.

1. Hospes, O. (2014) explains that the ISPO and RSPO standards are look-alikes but differ on critical points. These differences are also

listed by Efeca (2016) in its comparative study of RSPO, ISPO and MSPO.

2. It is important to note that the members of IPOP have ended IPOP as a group by end of June 2016. However, each individual

company will continue to implement zero-deforestation commitment individually.

3. Wibowo, A. D. 2014. Baru 7% Perusahaan Sawit Miliki Sertifikat ISPO. http://ekonomi.metrotvnews.com/read/2014/10/05/300849/

baru-7-perusahaan-sawit-miliki-sertifikat-ispo.

For example, WWF and Greenpeace reported that one large company in Cameroon

did not follow the requirement (in the form of presidential decree) to establish the oil

palm concession in terms of avoiding forest clearing. Allegedly, the same company

also violated the court order to suspend the operation after complaints by local people (Greenpeace 2013).

5 The dynamics of sustainability: actors, regulations and practices

Decision-making processes in the oil palm sector take place in different policy arenas at different levels. Three policy arenas can be distinguished. First is land-use planning at national, regional and local level. The specific issue is whether or not to allocate land for oil palm, and if so, in what areas. Second is the issuance of permits, that is, decision making on whether a company or smallholder can be given a licence to cultivate palm oil in the areas designated for palm oil cultivation. Third is planning of palm oil production at the estate level, which takes place after the permit has been issued by the government and obtained by the permit holder (Paoli et al. 2015).

Decision-making processes in the oil palm sector are complex because of three issues. The first issue is that the different arenas involve a diversity of public authorities with different, often overlapping, mandates on palm oil issues. In Indonesia, the Ministry of Agriculture has issued the ISPO standard but is not mandated to take decisions on land-use planning, which is a delicate and longstanding issue in Indonesia (Brockhaus et al. 2012, Bettinger 2015, McCarthy and Robinson 2016, Setiawan et al. 2016). Spatial planning is not clear or contested. Different ministries use different maps to define and

designate areas for agriculture, mining and forestry. As a result, (unclear) spatial planning

is generally seen as one of the most important problems in the palm oil sector in Indonesia

(Gaveau et al. 2016). Decentralization processes have not made things easier or more

transparent. Decentralization has led not only to more regulations (at provincial and district

level) but also to lack of clarity on how decisions on land allocation, issuance of permits

for oil palm concession and operational practices are made in Indonesia. This lack of clear

rules of the game has enabled local authorities to abuse their public power and to enrich

themselves personally. Similarly, Colombia is faced with competing authorities, competing

land uses and politicization of palm oil production. One of the drivers that facilitated the

expansion of oil palm in Colombia was the political support given during the president

Uribe administration with the notion that the country could reach three million hectares of

oil palm. As a result of this political support and compared to other commodities, oil palm

got extraordinary support through the Rural Capital Incentive programme (Potter 2015).

The second issue is that different public and private regulatory systems are used or

referred to in the different policy arenas. These systems may complement, but also

compete with, each other. RSPO and ISPO generally serve the same purpose. Also, they have a number of similar principles and criteria. However, beyond their respective voluntary/mandatory status, there are major differences between RSPO and ISPO in many key areas, such as the treatment on areas called high conservation value and the implementation of free and prior informed consent (Efeca 2016, Hospes 2014, Ministry of Agriculture and RSPO Secretariat 2016). This is not (yet) the case in Colombia and Cameroon, as these countries do not have any mandatory national public sustainability standards, although these countries have legislations that regulate how oil palm must be cultivated and processed.

The complexity has become even more intense with the pledge of six giant palm oil groups to establish IPOP to pledge for ‘zero deforestation, no peat land and no exploitation’ practices in the oil palm production. These companies have their estates and mills both RSPO and ISPO certified. Although IPOP is currently only directed at palm oil production in Indonesia, the pledge could have implications for other countries. Depending on how each member company defines and translates the commitment, each of these companies may move their expansion plans to other countries. Without improving their practices, environmental and social problems of palm oil production in Indonesia and Malaysia could be ‘transported’ to Africa (Linder 2013, Wich et al. 2014, Linder and Palkovitz 2016).

Since IPOP has been disbanded as a group and each member carries out its own zero deforestation commitment individually, it remains to be seen how each company defines, translates, implements and monitors its commitment to zero-deforestation.

Interestingly, the Government of Indonesia and Malaysia established the Council of Palm Oil Producing Countries (CPOPC) in 2015. The objective of the Council is ‘to promote, develop and strengthen cooperation in the oil palm cultivation and industry among the Member Countries as well as to ensure long term benefits of such palm oil endeavours to the economic development and well-being of the people of the Member Countries’ (President of the Republic of Indonesia 2016, p.2). The Council invites other producer countries to participate as members of CPOPC. Whereas the CPOPC is an intergovernmental initiative, the council could play a role in harmonizing or orchestrating RSPO, ISPO and MSPO standards to generate a unique and recognized standard for the sustainable production of palm oil. Of course, there is also the risk of more confusion and controversy. The council could turn into a political tool or arena to challenge private initiatives, like the RSPO and IPOP.

The third issue is about the translation of different regulatory systems into technical, land use and governance practices. While each practice may well be within the scope of a specific regulatory system, it may conflict with other regulatory system. The conflicts may

be more severe under the conditions of unclear land use and tenure. Land-use planning and

how it is enforced has been a contentious issue in each of the countries (Hoyle and Levang

2012, Njoh 2012, Garcia and Slunge 2015, McCarthy and Robinson 2016). For example,

in Indonesia, the Plantation Law 39 of 2014 still requires that all land under concession is

planted, including those with high conservation values. Meeting production and biodiesel

targets may require additional forests to make room for oil palm. Large-scale companies

may be able to implement best management practices as a means for intensification

to increase the yield, although under unclear land tenure they may also expand their

plantations outside their concessions (Gaveau et al. 2016). However, implementing best

management practices might still be a dream for independent smallholders, as most of

them are trapped into a vicious circle of low inputs, low production and low income.

To increase income, smallholders often consider clearing of new land for oil palm as the

only option. This only aggravates the struggle and problems of smallholders to meet the

requirements of both public and private regulations. Even worse, the largest companies

that committed themselves as a group and then individually to zero-deforestation will not

accept their products if and when these smallholders establish their plantations through deforestation.

6 Conclusions: creating sustainable pathways

The variety of sustainability initiatives of public and private actors shows that all actors in

the palm oil industry acknowledge environmental and social impacts of palm oil expansion

and the need to minimize these. However, there is no agreement on what actor or regulatory

system should be leading in addressing these impacts. Given the many different actors

and increasing number of regulatory systems in the palm oil sector, we consider organizing

deliberation and collaborative interaction between different actors as critical for defining

and achieving context-specific sustainable pathways for palm oil production.

Taking lessons from Indonesia where all regulatory systems are coexisting, it is possible

to see how pathways towards sustainability may emerge and to distinguish different steps.

The first step is to agree on a common vision and to discuss this vision with a view to

identify shared principles, acknowledging that the definition of sustainability is not rigid

and is open to multiple interpretations. When there is a common vision, the second step

is to specifically define the pathways or the actor-practice connections that reinforce the

technical, land use and governance practices. This framework allows for context-specific

combinations. The third step could be to improve one standard by learning from other standards, using the principle of continuous improvement (that is common for both RSPO and ISPO). The fourth step could be to acknowledge diversity of authorities and regulatory systems and at the same time seek mutual recognition. Mutual recognition is a principle and mechanism to cope with plural legal order (Berman 2009).

The establishment of the RSPO, the rise of national standards for palm oil in Indonesia and Malaysia, and, more recently, the emergence of private self-regulation and commitment to zero-deforestation show that sustainable palm oil has been tabled by all policymakers and stakeholders in the field of palm oil. The challenge is now to define mutual responsibility and shared sovereignty, such as to prepare a concerted effort and to create context specific sustainable pathways for palm oil production in Indonesia, Columbia, Cameroon and all other oil-palm-producing countries of the world.

7 Where to look for further information

Wageningen University, the Netherlands, has embarked on various interdisciplinary, multi-level and multi-PhD research programmes on global value chains and sustainable food and agriculture. These include the INREF-funded SUSPENSE programme on the identification of sustainable pathways for the production, processing and governance of palm oil, and the NWO-funded programme on the Next Generation of Global Value Chains.

Both programmes are focused on sustainable palm oil. The research consortia of these programmes are led by Katrien Termeer and Otto Hospes of the Public Administration and

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4 Chapter 4 The palm oil governance complex: progress, problems and gaps

1 Introduction

Oil palm is one of the most controversial global commodity crops, which has undergone one of the highest rates of expansion in comparison with other crops in the tropical world. It is a controversial crop since the conditions under which it expands as well as their social and environmental impacts are ambiguous. On one hand, oil palm expansion has delivered important economic development in host countries, including indirect benefits for local infrastructure development and rural poverty reduction, and multiplier effects for the national economies. On the other hand, its development has often come at the expense of basic human and customary rights and of biodiverse, carbon-rich tropical forests, as local communities have been evicted from their lands and precious primary forest and peatland ecosystems have been destroyed (Sayer et al. 2012; Pacheco et al. 2017; Sheil et al. 2009).

While the crop originated in West Africa, much of its industrial expansion under large scale monocrop plantation systems has occurred in Southeast Asia, notably in Malaysia and Indonesia (Rival and Levang 2014). Governments in palm-oil-producing countries have seen its rural development potential and therefore supported its expansion through different incentive and tenure policies that attracted private investments in

the plantations development. However, the growing environmental impacts associated

with oil palm expansion, along with the increasing concerns of consumer markets in

developed economies, have led to the emergence of institutional architectures and

arrangements for supporting the adoption of more sustainable socio-environmental

practices (Hospes 2014). In addition, following consumer pressures, some major

companies have adopted 'No deforestation, no peat and no exploitation' commitments

among traders and producers (Climate Focus 2015). Those concerns, along with growing

pressure from civil society groups in oil-palm-producing countries, are also prompting

the adoption of policies with the potential to guide a more sustainable expansion of the

palm oil sector (Daemeter Consulting 2015).

The palm oil value chain has increased in complexity over time; while the main palm

oil-producing countries are Malaysia and Indonesia, they fill markets all around the

globe and their products have multiple uses ranging from cooking oil to ingredients in

industrial products (e.g. processed foods, detergents and cosmetics), as well as biodiesel

(Lai et al. 2012). The palm oil global value chain comprises a wide range of stakeholders,

from producers of all sizes to processors, traders, consumer goods manufacturers

(CGMs) and retailers. Despite being dominated by a handful of companies at the refining

and international trading stages, production involves a wide range of suppliers from

companies to smallholders and manufacturing involves a wide range of CGMs in a

market that is diversifying. The main markets consist of developed economies, mainly

the European Union, and emerging markets, particularly China and India. This global

complexity makes the palm oil value chain harder to govern for social and environmental

outcomes.

The palm oil sector faces some critical performance issues. The first is persistent conflicts

over land and benefit flows linked to industrial plantation expansion. For example, in

Indonesia, several unresolved land disputes persist since local customary rights have

often been neglected in plantations development, either associated with companies or

immigrants (Colchester and Chao 2013). The second is the large yield gap obtained by

independent smallholders with regard to those of smallholders in partnership schemes

with companies, which can be even higher than those obtained by well-managed large

scale plantations (Molenaar et al. 2013). The third is the detrimental environmental

impacts since palm oil tends to place pressure on forests and agroforestry lands,

resulting in biodiversity loss and water pollution (Sheil et al. 2009), and relatively large

carbon emissions, particularly when it expands in peatlands

(Khasanah et al. 2012). The governance of palm oil production is to a large extent aimed at tackling these three issues, which are embedded in wider institutional contexts in the landscapes where oil palm is expanding. Thereby, the governance of palm oil intersects with key challenges associated with enhancing the governance of landscapes.

The palm oil governance conundrum expresses how multiple agents' interests can be met while addressing short-term economic goals under long-term environmental objectives. The main questions that this chapter wants to address are: Why is that in spite of evolving governance architectures and arrangements still no major changes are observed in the performance of the palm oil sector? What governance factors prevent progress in achieving a faster and widespread transition towards a more sustainable palm oil production in the tropics?

Answering these questions requires an in-depth understanding of the palm oil governance complex. This chapter aims to unpack it under three different dimensions. The first comprises the constituent parts of the governance systems (i.e. action arenas, actors, architectures and arrangements), and their interactions. The second dimension embraces the various governance problems encountered in the palm oil sector, which require a resolution in order to transition towards more sustainable development scenarios. These problems are related to allocation and access to resources favouring some social groups over others,

power distribution across actors in decision-making that allows some rules to be imposed

in detriment to others, upward and downward accountability and institutional checks

and-balances, and transparency in monitoring compliance and verifying progress towards

achievement of targets and commitments to the wider society. The third dimension relates

to the major gaps associated with the process of governing the palm oil sector, aimed at

addressing some of the main social and environmental performance issues. This chapter

provides a thorough analysis of these three dimensions (i.e. constituent parts, governance

problems and gaps) shaping the governance complex when applied to oil palm development

in the tropics.

2 Conceptual framework: the palm oil governance complex

The palm oil governance complex is constituted by the multiple interactions that different

stakeholders establish along the production, processing and trade in the value chains,

and the interactions unfolding in the landscapes where those value chains are embedded.

The complex reflects how different institutional architectures and arrangements, linked

to mandatory state regulations and voluntary private standards, work in conjunction

to regulate, provide incentives and improve the economic performance of the palm oil sector, while addressing the main social and environmental impacts and trade-offs

emerging from their rapid development, which affect its overall performance. More

complex transnational policy regimes are emerging for governing natural resources

(Overdevest and Zeitlin 2012).

We propose here a framework comprising three dimensions that help to understand

the performance of the palm oil governance complex and to identify corrective measures

for potential public and private policy action (Fig. 1). The first dimension has to do with

the constituent parts that characterize the palm oil governance complex per se. These are

1) action arenas, which configure the space where roles and responsibilities are exerted;

2) actors and agency, which contribute to reshaping the rules and regulations that apply

in the social, political and economic systems; 3) the evolving institutional architectures,

in both the public and private domains; and 4) the agreements and arrangements

established by social actors. The second dimension looks at the major governance

problems that have an influence on shaping the performance of the palm oil governance

complex. The main problems relate to the allocation and access to resources, issues of

unequal power distribution among actors, weak accountability and institutional checks

and-balance systems, and opaque transparency in decision-making and reporting of both progress and failures in the accomplishment of targets. The third dimension relates to the

gaps observed when assessing the functioning of the governance complex, in the light of

the different problems faced by the institutional system for governing both supply chains

and landscapes. We argue that both the problems and gaps have to be evaluated while

considering how they contribute in addressing the socio-environmental performance and

trade-offs of the sector as a whole. Table 1 provides more detail on the specific elements

or features identified in each of these dimensions.

The first dimension in our framework has to do with the constituent parts characterizing

the governance of the palm oil complex. These parts constitute the material configurations

and networks shaping the performance of the palm oil sector (e.g. differentiated yields

among producers, unequal benefit sharing, land conflicts and detrimental environmental

Figure 1 A framework to assess the performance of the palm oil governance complex.

Table 1 The main dimensions configuring the palm oil governance complex

Governance system	Problems	Gaps
Action arenas involving global supply chains and local territorialities	Allocation of resources and benefits associated with access to diverse economic and institutional rents	Capacity gaps in linking effectively supply chain and landscape management institutional initiatives

Multiplicity of actors

involving public,

private and civil society

organizations Power distribution across different actors with effect on decision-making and imposition of rules Cooperation gaps across different government levels and within private organizational structures

Evolving architectures

involving public

administrative systems

and voluntary standards Upward and downward accountability mechanisms and the associated existing checks-and-balances Compliance of voluntary self-regulations and pledges, and enforcement of public mandatory regulations

Multi-level agreements

and arrangements

involving competition and

collaboration Transparency in the monitoring and verification of compliance of public and private commitments Credibility and legitimacy gaps of public regulations and private standards

impacts), under which they evolve and are deployed in the different actions and initiatives

for addressing the challenges of palm oil development in both the supply chains and

landscapes hosting oil palm plantations expansion. Below is a description of these

constituent parts.

• Action arenas refer to the social space where individuals and actors exchange goods and services and establish social interactions to solve problems or dominate one another, among other things (Ostrom et al. 1994). Two action arenas are involved in palm oil development: first, the global palm oil supply chain bounded by a network of market transactions and flows along the chain; and second, the landscapes hosting oil palm plantations within specific territorial boundaries, which commonly are jurisdictional administrative units at the sub-national level with defined government systems.

- Actors are individuals and collectives exercising agency. The social actors in the palm oil sector are multiple. They include government officials, with different positions in the structure of government, and a diverse range of private actors involving consumer organizations, transnational and national palm oil companies. They also include diverse types of producers which constitute second- or third-party suppliers in the value chain, as well as indigenous communities, service providers and civil society organizations (Oosterveer 2015). All of these actors have a stake either in the value chains, or in the territories where oil palm is expanding.

- Architectures are comprised of institutional structures, systems and mechanisms defined by clusters of norms and principles aimed at regulating the behaviour of social actors and controlling social processes, in ways that comply with certain objectives embraced by those systems (Biermann et al. 2009). Governance architectures in the palm oil sector are composed by a mix of public regulations and private standards (Hospes 2014).

- Agreements and arrangements refer to the formal and informal interactions established by different individual or collective actors. While the formal interactions are established within formal governance architectures, by making use of the existing institutional systems and mechanisms, there are others established more informally, that is outside of those formalized institutionalized social spaces (Williamson 2009). Both types of formal and informal interactions take place in the value chains and the landscape's action arenas.

These constituent parts establish several interactions among themselves. For example,

the action arenas may contain specific type of interactions among actors struggling to

defend and/or advance their own positions in the value chains, which in turn leads to the

evolution of different architectures and institutional arrangements, something that also has

implications for specific landscape management challenges. The latter may, in turn, lead

to redefining the architectures and institutional arrangements linked to disparate state and

non-state actors' perspectives and interests in the value chains, which may have different

implications across landscape contexts.

The constituent parts of palm oil governance define different types of governance

problems or challenges. We follow Biermann (2014) in the selection of some key

governance problems that merit to be analysed in order to understand the politics of palm

oil governance when addressing the key performance issues facing the palm oil sector with

regard to differential yields among different types of producers and unequal economic

benefits distribution, land and social conflict, and negative environmental impacts. Major

problems addressed here are:

- Allocation of material resources (e.g. land and inputs) and benefits associated with the differential access that social groups have to diverse economic rents associated from the productive use of those resources and institutional rents linked to state incentives.

- Power that different social groups hold and exercise in the devising of rules as part of their role and influence in decision-making processes, and the means that they have at their disposal to impose those rules and affect the socio-environmental impacts.

- Accountability refers to the upward and downward accountability mechanisms, and the related checks-and-balances that are in place in order for social actors to become accountable for their actions and the associated outcomes. In addition, it implies to also have in place the mechanisms to punish deviant behaviours, and ways to appeal inappropriate decisions.

• Transparency in the monitoring and verification of individual or collective compliance of state regulations and/or self-regulations expressed in specific individual commitments or adherence to voluntary goals stated in collective processes or pledges.

Achieving progress in dealing with these different governance problems, while trying to improve the performance issues facing the palm oil sector, becomes critical for the governance architectures and frameworks – in ways that ensure equitable allocation and access to resources, fair access to decision-making processes by all stakeholders, and effective accountability on the outcomes of those decisions. Yet, this does not always work as expected, and different gaps can be found in the implementation process. Following Boström and colleagues (2015), we select four critical gaps that affect the governance system's performance. Below is a description of these gaps.

• Capacity gaps resulting from issues associated with articulating better supply chains and landscape management with broader consumers' expectations on sustainability and the capacities and resources held by upstream producers to uptake improved practices and standards. Capacities are required not only for the supply chain actors to effectively organize production, processing and marketing, but also for actors with territorial management authority to formulate and implement territorial planning, and secure tenure rights, among others.

• Cooperation gaps result from the lack of coordination between policy design and implementation across different levels of government from national to sub-national. These gaps also occur within decision-making in the corporate side, specifically between the parent company and their subsidiary groups, and third-party suppliers. Cooperation is prevented by increasingly decentralized administrative systems with no incentives to coordinate and it is challenged by the complexity and fragmentation along a commodity chain and across different jurisdictional levels.

• Compliance gaps linked to how able private actors are to follow their own selfregulations and pledges, as well as to comply with the mandatory public regulations enforced by the state in ways that are empirically verified, with the outcomes disseminated in transparent ways to a wider society. Many factors may prevent their effective implementation and lead to failures, and even to undesired direct outcomes, as well as indirect ones such as exclusion of poor smallholders or environmental impacts due to leakage effects.

• Credibility gaps associated with the effectiveness of public regulations in comparison to private standards, and of emerging institutional arrangements to address the problems facing the supply chains and landscapes due to palm oil expansion. This gap also refers to how widespread and durable are the solutions associated with these different policy instruments, regulations and mechanisms, and their benefits for the wider society.

The gaps observed in the governance complex, to some extent, reflects the inability of

the actors' agency, and institutional architectures and arrangements to overcome the

performance issues facing the palm oil sector, contributing to enlarge, or at least maintain,

the governance challenges preventing the sector from embracing enhanced sustainability

and inclusivity. In line with this framework, understanding the interactions between the

three dimensions (i.e. constituent parts, governance challenges and observed gaps) that

define the politics of palm oil governance is therefore critical. When related to supply

chains and landscapes, a major step is to explain what factors prevent change, and what

further public and private action is needed in order to either change the governance's constituent parts or minimize the observed gaps.

3 Constituent parts of the palm oil governance complex

3.1 Action arenas

The two action arenas shaping the development, and thus governance challenges for palm oil, are the global palm oil supply chain and the landscapes hosting the development of oil palm plantations. While the first action arena is related to a network bounded for a multiplicity of transactions of goods and services for oil palm development, the second is bounded for specific territorial boundaries. The two arenas host specific actors and institutional architectures and arrangements that ultimately shape the development and impacts of oil palm expansion.

The global palm oil supply chain has been growing in complexity over time. The palm oil sector is dominated by a handful of conglomerates involved in production, processing and trade (i.e. Wilmar, Musim Mas, Golden Agri-Resources (GAR), Cargill and Asian Agri in Indonesia and IOI, Sime Darby and FELDA in Malaysia). These groups source palm oil from their own plantations as well as from a large number of second- and third-party suppliers. According to the Malaysian Palm Oil Board (MPOB), in Malaysia there are 445 fresh fruit bunches (FFBs) mills, 44 palm kernel crushers, 52 refineries and 19 oleochemical plants (MPOB 2016). In Indonesia, according to information released by the five major corporate groups, these groups would control about 40 refineries, and source from about

850 mills and 1600 plantations. The official statistics present lower estimates (Statistik

Indonesia 2015). According to MPOB (2016), in 2015, about 5.6 million ha of oil palm had

been planted in Malaysia, of which 2.6 million ha were located in Peninsular Malaysia.

In Indonesia, 10.4 million ha of oil palm were planted by 2013, out of which about 42%

were cultivated by smallholders (Directorate General of Estates 2014).

The main companies processing and trading crude palm oil (CPO) supply to a diversified

number of end users, including a wide range of CGMs and retailers delivering a range

of products in the food, chemical, pharmaceutical and cosmetic industries. While much

processing and refining of CPO and palm kernel oil (PKO) take place in Indonesia, Malaysia

and Singapore, most manufacturing takes place in the countries of consumption and in

China, where transnational corporations manufacture products for consumers around the

world. The palm oil processing industry is well developed in Malaysia, where companies

maintain higher comparative advantage based on their efficiency (Abdullah et al. 2015),

yet over time Indonesian companies have been able to slowly expand their palm oil

refining capacity.

The landscapes where oil palm plantations tend to expand consist of places relatively well connected to ports, where refineries have been established, and with road infrastructure that makes possible the transport of CPO from the plantations to the mills. A key feature for the development of plantations is the establishment of palm oil mills, since production areas must be relatively closer to the processing facilities. In recent years, the number of mills and refineries has grown in Indonesia, which is contributing to greater sector integration and therefore improved efficiency. FFBs are transported from plantations to mills, where they are processed into CPO and KPO. Transportation is limited to an area of 50–100 km, due to the rapid deterioration of the fruit quality after harvesting. Once the FFB is milled, the resulting CPO is transported to the refineries, which are often located in the main export ports. Social exclusion of local indigenous groups has consistently accompanied the expansion of large-scale plantations in frontier lands, facilitating the dispossession of native populations that held customary rights over lands taken over by companies (Colchester et al. 2011; Li 2015; Gellert 2015). In addition, these plantations have attracted immigrant workers for both permanent and casual labour in the plantations, who may also look for land once they make enough savings. The latter were promoted by colonization programmes for securing the supply of workers to plantations such as FELDA in Malaysia and

Transmigration in Indonesia

(Potter 2015).

3.2 Actors and agency

CGMs and retailers in Western markets have been key drivers in shaping the governance

of the palm oil sector by introducing environmental concerns in the sourcing of palm

oil. In addition, environmental non-governmental organizations (NGOs) and advocacy

groups have targeted consumer brands such as Nestlé, Unilever, Ferrero, Krispy Kreme

and Dunkin' Donuts to leverage change among their suppliers (Pretty et al. 2008;

Dauvergne and Lister 2013; Bregman 2015). The challenge with the palm oil industry

is that the uptake of palm oil is highly fragmented. One of the biggest consumers is

Unilever, which uses 4% of the world's supply of palm oil (Unilever 2014). This means that

individual CGMs and retailers have limited influence and leverage on the supply chain and

the sustainability standards of production. Nonetheless, some major platforms, such as

the Consumer Goods Forum (CGF), embracing a large number of CGMs begun to adopt

policies promoting the adoption of sustainable sourcing (CGF 2013). Imposing standards

on producers is particularly challenging, as a large proportion of palm oil is manufactured

and sold in India and China, countries whose consumers are – so far – more price sensitive

and less concerned with sustainability.

Major plantation, processing and trading corporations responded to the pressures from CGMs and retailers by making public some collective commitments. In 2013, a wave of sustainability commitments began to emerge in the palm oil sector. The 'No Deforestation, No Peat, No Exploitation' movement was driven by a handful of international advocacy and civil society groups. Their message was simple and aimed to achieve what the Roundtable on Sustainable Palm Oil (RSPO) had failed to do – stop the deforestation of biodiverse and carbon-rich primary and secondary forests and peatlands. Campaigns targeted major oil palm traders such as Wilmar, GAR, Musim Mas, Cargill, Asian Agri and Astra Agro. These commitments differed from past sustainability policies in that they were applied to not only their operations but also their third-party suppliers. As such, commitments moved down the supply chain and were imposed on producers who had, until then, faced limited exposure to global sustainability demands.

The Government of Indonesia has made visible an important agency in the debates on palm oil, by eroding initiatives from the private sector, which could affect government's regulatory and control power. As a way to reinforce the role of the government, it has made the national regulations prevalent, around the Indonesian Sustainable Palm Oil

(ISPO) for regulating oil palm plantations development (Hospes 2014). Nonetheless, as a way to respond to international debates on climate change, and due to the detrimental effects of palm oil development in peatlands, the Indonesian government has also played an important role in supporting greater control of oil palm development in peatlands, and has supported an agenda of peatlands restoration. The government, however, is not a monolithic body, and it embraces antagonistic positions of different state agencies. In addition, the sub-national governments have also established some agencies and initiatives to formulate local regulations on sustainable plantation sector including palm oil. Some of the provincial governors such as those of Kalimantan also embraced sustainability initiatives such as the one promoted worldwide by the Governors' Climate and Forests Task Force (GCF), and the West and Central Kalimantan governments were signatories of the New York Declaration on Forests.

A much lower capacity of organization and agency is seen on the smallholder palm oil producers and customary local populations affected by the development of oil palm plantations (Brandi et al. 2015). This is likely due to the pressure exerted by the government while supporting the private sector, and the strong political patronage when the plantations were developed (Varkkey 2012). While there are smallholder associations in Indonesia – the Oil Palm Smallholders Union (SPKS) and the Oil Palm

Smallholders Association (APKASINDO), they have a relatively small membership base,

whose agency power is very limited. In addition, the indigenous organizations, notably

the Indigenous Peoples' Alliance of the Archipelago (AMAN), are mostly focused on

demands around recognition of customary tenure claims. Grassroots smallholder and

indigenous organizations, therefore, have a very limited capacity to build a movement

able to reach national scale with some capacity to contest the power of the private sector.

In addition, national producers, mostly medium-sized palm oil growers, are organized in

the Indonesian Palm Oil Association (GAPKI), which has a significant lobbying power over

the government.

3.3 Architectures

The institutional architecture underpinning the palm oil sector is structured by three major

elements. The first are the national policies and regulations in the oil-palm-producing

countries to incentivize or control the development of palm oil production, processing and

trade. The second are the import policies from consumer countries increasingly interested

in sourcing some verified sustainable supply. The third are a different range of private

standards, and self-regulatory commitments endorsed by the corporate sector to delink

their operations from supply associated with deforestation, and increasingly with violations

of workers' rights. These types of regulatory initiatives are creating a relatively complex

institutional architecture.

With regard to the public policy in Indonesia, in 2011 the government launched its

ISPO standard, a mandatory, third-party-audited, verification system, based on the

existing Indonesian regulations. The standard was introduced to ensure the adherence

of oil palm plantations to government laws and policies. Meeting the ISPO standard is

mandatory for all plantations and palm oil mills and voluntary for smallholders; so far, the

standard has fallen short in a number of respects since only 226 companies hold ISPO

certificates by March 2017 (ISPO 2017). ISPO has gone through a number of revisions

in relation to its timeframe for compliance, and in March 2015 it was rebranded as the

ISPO Certification System (Ministry of Agriculture et al. 2015). Currently, ISPO is under

the process of strengthening led by the Coordinating Ministry of Economic Affairs. The

Malaysian version, the Malaysian Sustainable Palm Oil (MSPO) standard, was introduced

in 2013. In contrast to ISPO, it is still voluntary, although a government statement on

February 2017 has announced a timeline for the mandatory implementation of MSPO

across the country by 2019 (MPOCC 2017).

The Government of Indonesia has also issued a number of policies to address

Indonesia's growing contributions to global greenhouse gas (GHG) emissions and climate change. The previous administration installed policies to protect primary forests and peatlands, notably the moratorium on issuing new permits on primary natural forest and peatland (Government of Indonesia 2013), which has been called into question (Busch et al. 2015), along with other regulations related to the land use planning, the protection and restoration of peatlands, and the One Map initiative, which aims to develop a unified map of land use agreed upon by all ministries. Most of these initiatives, while benefiting from the support of the central government, have yet to materialize. Furthermore, in reaction to the fire and haze crisis of 2015, the government issued a presidential instruction banning the clearance and exploitation of peatlands, and new planting in burned areas, as well as setting up a peatland restoration agency (BRG) with the goal of restoring about two million hectare of damaged peatlands in the next five years (Jong 2016). More recently, the Indonesian Government announced an additional moratorium on concessions for oil palm development, yet no decree was issued.

The new administration's commitments to empower rural communities and indigenous peoples' rights over the management of their land reflect the Constitutional

Court's Decision no. 35/PUU-X/2012. The court declared that customary forests are no

longer state forests, effectively returning the stewardship of these forests to indigenous

peoples. But the Ministry of Forestry has been slow to implement the necessary

changes (AMAN n.d.). In addition, a major issue constraining the governance of the

palm oil sector is that a large but still unknown portion of land under palm oil cultivation

is occupied illegally by smallholders, as these lands are still classified as state forests.

The government has made some efforts to regularize these settlements, but these

endeavours are still in their infancy (Sirait 2015).

One of the most significant regulations adopted by consumer countries is the European

Union Renewable Energy Directive (EU-RED) (Directive 2009/28/EC), which requires

all biofuel feedstocks, including biodiesel derived from palm oil, to meet the defined

standards. As such, a number of palm oil producers in Malaysia and Indonesia, mainly those

that are part of the largest palm oil conglomerates, certify their oil under the International

Sustainability and Carbon Certification (ISCC) standard. Additionally, 11 European

countries have adopted some form of sustainable palm oil commitment at the national

level, and three more will potentially follow this trend (Esselink and van der Wekken

2015). In October 2012, a number of UK sector associations with significant interests in the supply or use of palm oil made a public statement of their various commitments to

sourcing sustainable palm oil. In March 2016, France introduced a tax on noncertified

sustainable palm oil imports as part of a national biodiversity bill, yet it still has to be

reviewed and ratified in the upper house. Recently, a call from the European Parliament

recommended to phase out the use of palm oil for biodiesel by 2020 within the European

Union (European Parliament 2016), a move that has been challenged by the Indonesian

and Malaysian governments.

Biodiesel companies and product manufacturers in Europe have established the European

Sustainable Palm Oil (ESPO) initiative with a commitment toward 100% sustainable palm

oil in 2020. The agreement is supported by an alliance of refineries, and food and feed

manufacturers and retailers in the Netherlands, Denmark, France, Belgium, Germany, the

UK, Italy and Sweden. It is facilitated by three European sustainability organizations, that

is, Caobisco, FEDIOL and IMACE. The parties confirmed their commitment by signing

the Amsterdam Palm Oil Declaration on 7 December 2015, whose mission and objectives

are to support the uptake of more sustainable palm oil in Europe by working in close

collaboration with the national initiatives, RSPO and EU associations. It will do this by

encouraging the involvement of non-member companies, sectors and countries and the synchronization of activities. It is still not clear how influential ESPO will be in the global

palm oil market.

The third type of initiatives is related to the emergence of private standards. The

most prominent is the RSPO, which was formally established in 2004. It emerged

through a multistakeholder process, which included both private sector and civil society

organizations. Since its inception, the RSPO has seen a slow but steady uptake of the

standard, which now certifies roughly 21% of the total global supply (RSPO 2016). In spite

of its coverage of the palm oil market, the RSPO has received criticism regarding the

stringency of its principles and criteria and its ability to enforce companies' compliance

to standards on the ground. As a number of its corporate members have adopted

additional 'No Deforestation' commitments, the RSPO recently launched RSPO Next.

This is the second initiative to emerge from RSPO member companies and goes beyond

the principles and criteria of the original RSPO. The Palm Oil Innovation Group (POIG)

was another initiative promoted by Greenpeace and a few companies to demonstrate

companies' ability to not only mitigate negative environmental impacts, but also create

positive ones.

In September 2014, the growing number of 'No Deforestation' commitments spurred the

New York Declaration on Forests. This declaration, which includes national and sub-national governments (in Indonesia) as well as civil society and private sector organizations, aims to halve the rate of deforestation by the end of 2020. These commitments fostered regional- and local-level alliances such as the Malaysian-dominated Sustainable Palm Oil Manifesto (SPOM), while in Indonesia this took the form of the Indonesian Palm Oil Pledge (IPOP), an association of five companies working toward the same goal. Interestingly, since the inception of IPOP, the Indonesian government has strongly opposed it, branding it a cartel, in violation of Indonesia’s competition laws and ultimately threatening the government’s sovereignty, and also argued its negative impacts on smallholders (Anderson et al. 2005). IPOP was disbanded in July 2016, while companies kept their individual commitments to sustainable and deforestation-free palm oil production.

3.4 Arrangements

Despite the animosity over sovereign rights in relation to private standards in Indonesia, there have been attempts to find common ground between public and private standards. A recent joint study between ISPO and RSPO identifies a number of similarities and differences between the two standards. While there is a significant scope for alignment, particularly in the auditing process, key differences remain in the treatment and definition of high conservation value (HCV) areas within concessions, and the rules to follow for

developing new plantations, including the Free Prior Informed Consent (FPIC), which are

more stringent in RSPO vis-à-vis ISPO criteria (Ministry of Agriculture et al. 2015). By today,

however, it is not clear what steps will be taken by the two parties in order to promote

greater alignment of these two standards. Nonetheless, as mentioned, the Indonesian

government is conducting efforts to strengthen the ISPO standards in ways that could

close the existing gaps.

The commitments to deforestation-free supply chains led to the development of the High

Carbon Stock Approach (HCSA) by The Forest Trust (TFT), GAR and Greenpeace in order

to identify no-go areas for plantation development (Greenpeace 2013). This approach

somehow wanted to provide more clarity on which type of forests should be preserved

under more simple methodologies than those provided by the HCV methods, still based

on objective and verifiable criteria (Greenpeace 2014). In 2014, a separate group of major

palm oil producers known as the Manifesto group announced a voluntary moratorium on

clearance of HCS areas, based on empirically valid thresholds of carbon stocks, under the

so-called HCS+ approach, which deviated from the Greenpeace-initiated HCSA. Since

having in place two different criteria added some confusion, a process was initiated in

2015 to harmonize HCSA and HCS+, and in late 2016, a single set of principles was agreed upon by the involved stakeholders. In 2017, a HCSA toolkit that merges the two approaches will be finalized, which will be expected to be adopted by all major corporate stakeholders (HCSA 2016).

The challenge to implementing corporate and public sector sustainability commitments with new methods in place to comply with and verify progress has resulted in a range of organizations and associations emerging in the institutional landscape to help develop the methodologies and structures needed. One of the most prominent organizations is TFT, an NGO that works with companies to implement their zero deforestation commitments.

A number of organizations are also working to develop new business models and value chain structures to support the inclusion of smallholders in the value chains, while supporting the uptake of improved management practices. These include development organizations such as the Sustainable Trade Initiative (IDH) and the Netherlands Development Organisation (SNV), multilateral banks such as the International Finance Corporation (IFC), and private sector associations and working groups such as PISAgro and the SMART working group. Many of these models seek to increase transparency and traceability in the supply chain and aggregate smallholders in order to access the financial investments needed to replant and increase yields, as well as meet internationally

recognized sustainability standards.

In addition, private sector actors, NGOs, donors and development organizations

are making progress towards the adoption of arrangements at the sub-national level

inspired by approaches that embrace sustainability goals at the jurisdictional level. These

include efforts to map smallholders, and enable district-level monitoring, reporting and

certification (Wolosin 2016). Provincial-level regulations are also emerging in support

of market-based mechanisms for sustainability, such as the commitment by the South

Sumatra Provincial Government to turn South Sumatra into a sustainable province (IDH

2016) and the provincial regulation issued in 2011 by the Provincial Government of

Central Kalimantan, acknowledging the concept of HCV and allowing palm oil companies

to retain and protect areas within their concessions (Gnych and Wells 2014). Many such

governments hope that by supporting market-based sustainability standards, they will

encourage investment from responsible multinational corporations in their provinces or

districts, which will deliver economic development. Such jurisdictional-based view has

been championed by Unilever and Marks & Spencer, who in late 2015 launched the

'Produce and Protect' approach through which they commit to prioritize their commodity

procurements from areas that are implementing jurisdictional forest and climate initiatives

(CGF 2015).

Finally, it is important to highlight some arrangements that are being prompted by

financial actors, both in the international and national arenas. For example, the Banking

Environment Initiative (BEI), along with the CGF, has developed the Soft Commodities

Compact (CISL 2016), which consists of a set of technical guidelines to help the banking

industry transform soft commodity supply chains, including the elimination of deforestation,

through their clients. The main sustainability criteria for the palm oil sector rely on the

framework developed by RSPO principles and indicators. A complementary initiative

unfolding at a national level consists of the progress made by Indonesia's eight largest

commercial banks to adopting responsible lending practices across all their portfolios, in

the context of a Sustainable Financial Roadmap developed by the Indonesian Financial

Services Authority (OJK) (OJK 2014). A few international banks are supporting Indonesian

banks to develop the internal procedures and build internal capacities to implement these

responsible lending policies.

4 Critical problems affecting the palm oil governance complex

The governance of the palm oil sector, in spite of new regulations embracing the objectives

of environmental sustainability and peatland restoration, as well as wider recognition of the potential of private standards to foster the uptake of sustainability practices, still faces some critical problems. These problems are related with issues around uneven allocation and access to productive resources and finance, unequal distribution of power among different stakeholders involved in the sector, relatively poor accountability mechanisms, and opaque decision-making and sharing of information. These are explained in more detail below.

4.1 Allocation and access

Allocation of resources and access is relatively uneven when related to the palm oil sector since a few transnational corporate groups control a major portion of the markets and capital flows, yet over time there is an increasing number of small- and medium scale landholders, and other local investors, struggling to get access to land and other resources, such as finance and inputs, to make a profit from FFB production. In Indonesia, there is a strong legacy of policies, mainly on land allocation and fiscal incentives that privileged private investments for developing large-scale industrial plantations under wider discourses of agricultural modernization. For example, public policies have favoured the allocation of land to industrial plantations, while promoting production and services delivery agreements under different partnership schemes, between companies and local villagers and/or immigrants (Cramb and Curry 2012). The effects of these policies are contradictory, depending on the contexts.

Some local villagers suffered from land dispossession, while others were able to enter into agreements with companies, thereby benefiting from local employment and access to complementary sources of income (Cahyadi and Waibel 2015; Gellert 2015). Access to land in contexts where there is significant development of oil palm tends to also facilitate access to finance – formal or informal – and to some subsidized inputs, such as fertilizers (Rist et al. 2010; Diegues 1992). Nonetheless, still a major portion of smallholders cannot benefit from secure access to land and access to affordable finance, and thus are unable to make proper use of fertilizers to sustain their yields. There are emerging efforts to channel finance to smallholders for improving the uptake of management practices and increasing the yields; while a few pilot projects are emerging, it is unlikely that these initiatives will get impact at scale in order to foster substantive changes (Rainforests Alliance 2016).

4.2 Power distribution

Power is unevenly distributed among stakeholders in the value chain and within landscapes where oil palm tends to expand. A few corporate groups have enormous influence on the supply of FFB through contractual agreements with second- and third party suppliers. Influential individuals form palm oil consortiums that control oil palm production, marketing and distribution. These consortiums are using that power to impose the adoption of environmental standards through the supply chain, particularly those related to zero deforestation, in part responding to the pressure from traders, CGMs and retailers (Dauvergne and Lister 2013; Pichler 2013). The power of major corporate groups, however, has been contested by the Government of Indonesia, which in an attempt to reinforce national sovereignty is imposing the use of the ISPO standards over the international RSPO standards, or specific company standards (Hospes and Kentin 2014), and is making use of fiscal incentives, such as the ones linked to the CPO fund, to ratify its power in guiding the sector development, under some specific views on sustainability. This latter development has been accompanied by lobby from GAPKI, which is deploying initiatives in the Indonesian Parliament to safeguard the interest of national palm oil producers.

The power and authority in the landscapes, in a similar way, are shared between company actors, who have an important role in local economic development, and government officials from the provincial and district levels, who gained an important weight on the decisions about allocation of concession permits for oil palm development, and thereby on deciding who are the groups that can capture the economic rents originated from logging and forest conversion (Setiawan et al. 2016). In some cases, the

power concentrated by local elites at the district and provincial level tends to be used

to reinforce their privileged position, while in other cases it can also be used, as part

of patronage systems, to grant land and other public resources to local constituencies

in exchange of votes as a way to secure their power (Gellert 2015). In Indonesia, local

politics tend to largely be dominated by practices of patrimonial manipulation (Fukuoka

2013), which gives limited influence to organized local village or associations and

cooperatives in local decision-making. Their participation, in some cases, tends to be

regulated, for example, when defining FFB prices.

4.3 Accountability

Different accountability problems do persist in the governance of the palm oil sector.

Most are associated with the difficulties encountered by national government in

decentralized contexts to be accountable to provincial and district governments, as

well as for the district and provincial governments to make upper-level governments

more accountable (Setiawan et al. 2016). Major issues refer to very opaque decision

making process for land use planning, granting licenses to palm oil companies, taxes

collection from activities associated with timber extraction from land clearing and palm

oil production, and the use of such public resources. In most of these issues, tensions

exist among different levels and sectors of government due to intertwined interests

of local politicians and investors especially related to the local government election,

uneven law enforcement and government's desire to collect locally generated income

(Brockhaus et al. 2012). This leads to clashes between local and national interests around

oil palm development (Sahide and Giessen 2015), yet under very poor accountability.

In Indonesia, major government revenues from palm oil, such as value-added,

corporate income and export taxes, are channelled through the central government

in Jakarta, so they can be redistributed among provinces. In addition, many of the

national earnings from oil palm are captured through export taxes, which are collected

centrally and only a small fraction flows back to production provinces (Falconer et al.

2015). Other resources or benefits are transferred through social programmes. It is

often the case that local politicians and elites find ways to retain institutional rents at

the district or province level. Much of these rents are generated through land allocation.

There is a strong argument to see more of the fiscal revenues from palm oil retained in

the areas in which it is produced in order to support the mitigation of environmental

impacts as well as local infrastructure development. But the retention of profits is often distorted and corrupted by local political economies and self-interest, in scenarios

where local communities rarely benefit (McCarthy 2012). The institutional systems to

make government officials accountable for their decisions and public money are weak,

and many interests exist to prevent it from happening.

4.4 Transparency

Oil palm plantations have developed through consortiums involving political elites,

senior bureaucrats and businessmen ranging from the district to the national levels, thus

connecting private and public actors in complex and opaque processes of decision

making (Varkkey 2012, 2013). The system of political patronage under which oil palm has

expanded in Indonesia explains how many companies benefited from the weak policies

and corrupted processes of land allocation. This has made vast swathes of forested land

available for plantations at low cost (Bakker and Moniaga 2010). To some extent, this

opacity in land allocation prevents the government and companies to disclose information

regarding who holds what amount of land, how much land has been developed, what is

the magnitude of land banks held by corporate groups and how much of those have been

granted in peatlands. There have been attempts by environmental advocacy groups to

systematize this information, so to make publicly available the current land banks in the

hands of companies. In addition, some legal clause impedes the Ministry of Agriculture and the National Land Agency to disclose this information, particularly on company ownership. Civil society organizations have requested this information to be disclosed as part of debates of zero deforestation commitments. While some corporate groups (e.g. Wilmar and GAR) have made progress in disclosing information on their supply chain from mills to refineries, additional efforts are needed to trace upstream suppliers including third-party suppliers, and independent smallholders, and make that information open to the public.

5 Major gaps in the governance of the palm oil sector

The problems analysed above indicate the presence of several structural aspects that affect not only the overall social, economic and environmental performance of the sector, but also the governance architectures and arrangements to foster concrete changes in the material conditions and institutional structures shaping the sector's performance. This section explores four types of gaps that are observable in the governance of the palm oil sector, specifically capacity, cooperation, compliance and credibility gaps. These gaps have to be analysed in order to identify the public and private interventions with potential to reshape the action arenas, strengthen the agency of the most disempowered social groups, and improve the public and private rules and the arrangements to accommodate the diverse interests of the palm oil sector’s stakeholders.

5.1 Capacity gaps

The main capacity gaps result from uneven access to information and knowledge, as

well as the technical skills to embrace and put in place mechanisms and processes that

articulate better initiatives to improve supply chain management with others for enhancing

landscape management. Capacity gaps are important, since they influence the possibility

for linking more effectively the value chain interventions to territorial approaches to

sustainability, as well as may contribute to linking better monitoring of progress towards

sustainability in specific jurisdictions with expectations from CGMs and retailers on

addressing sustainability issues in accordance with certain agreed standards. In addition,

there is new demand for knowledge and technologies linked to the compliance with

sustainability commitments such as, for example, the identification and delimitation of

HCV and HCS areas, the implementation of traceability systems from upstream suppliers to

processing facilities, and the assessment of social and environmental risks, among others.

Currently, such capacity gaps are fulfilled by consultancy groups (e.g. Daemeter, TFT and

Aidenvironment) and environmental organizations (e.g. The Nature Conservancy (TNC)

and the World Wide Fund for Nature (WWF)), which are making use of new technologies and tools for remote sensing analysis, mapping, geo-traceability, data storage and analysis. Yet several specialized IT service providers are growing in number in order to fulfil this emerging demand. One of the most critical aspects is who is filling the needs of capacity building for local stakeholders including not only producer organizations but also district and provincial governments in order to use emerging knowledge for informing public-driven processes, which are essential to support sustainability at the jurisdictional level such as land use and spatial planning. Another set of capacities that are lacking are those related to enforcement capacities by state agencies in order to put in place the mechanisms to control and sanction regulations more effectively.

5.2 Cooperation gaps

The cooperation gaps in the palm oil governance complex are several, which in part depend on the incentives and motivations of stakeholder involved in the sector. There are issues of cooperation within different ministries influencing the palm oil sector governance, such as those between the ministries of agriculture, environment and forestry, and finance. In addition, there are significant coordination gaps between the central government and the provincial levels of government with regard to the implementation of specific policies, mainly those related to concession permits and spatial planning, and fiscal resources allocation. Furthermore, important coordination gaps exist between the public and the private sectors mainly with regard to the adoption of norms and procedures for supporting conservation of high-carbon and biodiversity-rich forests within state forestlands granted as oil palm concessions. In this regard, it is widely known that the government forced IPOP's disbandment as a way to reinforce its position of power in rules design and implementation, which was eroded by the major palm oil corporations. Finally, another cooperation gap is the one existing within the palm oil value chains, for example, those between manager of parent companies and plantation managers on the ground. It is not necessarily that managers along the value chain share the same perspectives of sustainability and ways to safeguard social and environmental risks, or implement existing policies and standards. In light of these different cooperation gaps, there is wide scope for improving collaboration not only within state agencies, but also across different levels of government, as well as between the government and the private sector, and along management operations in the supply chain.

5.3 Compliance gaps

Compliance gaps relate, on the one hand, to the capacity of companies to comply with their own pledges, and the rules and procedures in place to accomplish their commitments and, on the other hand, with their compliance with public regulatory frameworks in ways that can be empirically verified. In regard to the former, the aggressive move of companies to delink their supply chains from deforestation, accompanied by efforts to put in place traceability systems to monitor sources of supply as well as measures to avoid the exclusion of smallholders from their supply chains, raises doubts about effective compliance even more since companies have not defined clear targets and timelines. There are several obstacles that prevent effective compliance such as the difficulty for companies to put in place traceability systems that capture all their suppliers – mainly when smallholders are involved – and to design expansion plans that do not place additional pressure on peatlands. This is associated with the importance of putting in place monitoring systems that are able to trace the progress of compliance, while alerting on potential social and environmental risks. In some cases, however, compliance to these commitments requires complementarities with public regulations, particularly in regard to tenure legality and spatial planning. In addition, company commitments can produce leakage effects that can only be addressed with effective law enforcement. While likely large-scale companies are more prepared to make progress towards their commitments, and thus place pressure on their third-party suppliers, it is likely that the latter do not have the resources or the motivation to comply with those commitments. This raises the issue of the costs of compliance and who pays for it.

5.4 Credibility gaps

There are important credibility and legitimacy gaps, which refer to how effective private

self-regulations can be vis-à-vis public regulations in achieving goals of zero deforestation,

no expansion in peatlands and respect to local people's rights. Currently, the lack of

transparency, in the absence of independent verification of commitments, puts into

question the credibility of companies. Reducing credibility gaps is going to require an

increasing participation of independent civil society organizations in scrutinizing the

progress of companies. A similar situation occurs with regard to public interventions in

reversing the governance challenges in the palm oil sector, since the public sector is

largely discredited due to its inability to solve issues related to encroachment of state

lands, illegal tenure and opaque management of public money. The anti-corruption efforts

made by the government have contributed to address credibility gaps, yet more has to

be done. It will be important in the future that major palm oil corporate groups disclose

information regarding progress in implementing their own commitments (e.g. supplier and

production zones), and the approaches and methods used to verify them, as well as that

the state make public information that is critical to assess compliance, such as the status of concession permits as well as land banks held by companies. Additional information that

has to be shared with the society comprises the flows of fiscal resources related to palm oil

taxes, subsidies and incentives, and who are benefiting from them.

6 Conclusions

The present chapter was aimed at deciphering some aspects of the palm oil governance

complex, with strong emphasis on Indonesia. The major conundrum facing the palm oil

sector refers to how multiple agents' interests can be harmonized while addressing short

term development goals but embracing long-term environmental objectives. Recent years

have witnessed important changes in the policy frameworks regulating the palm oil sector as

well as a more active intervention of the private sector in embracing private standards and

commitments. This has led to a reconfiguration of the action arenas for sustainable palm oil.

Both value chains and landscapes have become spaces where public regulations and private

standards complement and/or conflict, as well as where public and private sector actors, and

other stakeholders, cooperate and/or compete when looking for the sector's sustainability.

This chapter tackles the issue of why is that in spite of evolving governance architectures and

arrangements there are still no major changes observed in the performance of the palm oil

sector. This analysis does not look at the performance of the palm oil sector but rather at the performance of the palm oil governance complex made of action arenas, actors, architectures

and arrangements that govern the sector.

We conclude that in spite of significant changes to improve the institutional architecture

as well as the agreements and arrangements established between public and private actors,

the governance complex faces several structural constraints that constitute governance

challenges. These constraints are related to issues of unequal allocation of and access to

resources; uneven power distribution across different players along the palm oil supply chain

as well as in the landscapes where oil palm expansion takes place; poor upward and downward

accountability; and limited transparency on how resources are allocated, who benefit from

those resources, and how those benefits are distributed. As result of this analysis, we have

identified some major gaps across different dimensions, specifically gaps in capacities,

cooperation, compliance and credibility. Addressing the specific challenges associated with

these gaps may lead to improved performance of the palm oil governance complex in order

to build more sustainable and inclusive oil palm supply chains and landscapes.

7 Where to look for further information

Additional information can be found in the following sources:

• Carbon networks • HCV network, https://www.hcvnetwork.org/

• Service providers • Daemeter,

http://daemeter.org/en/home • TFT, http://www.tft-earth.org/

• Research organizations • CIFOR, http://www.cifor.org/ • CIRAD, http://www.cirad.fr/en • ICRAF, http://www.worldagroforestry.org/

• Palm oil platforms • ZSL, https://www.zsl.org/

• Sustainability initiatives • ISPO, http://www.ispo-org.or.id/ • InPOP, http://www.foksbi.id/en/home/

• Private standards • RSPO, http://www.rspo.org/

• Monitoring of commitments • Supply Change, http://supply-change.org/

• Financial initiative

• Banking Environment Initiative, http://www.cisl.cam.ac.uk/business-action/sustainable-finance/banking-environment-initiative

• Corporate group commitments • Musim Mas, http://www.musimmas.co.id/ • Wilmar, http://www.wilmar-international.com/ • GAR, http://goldenagri.com.sg/

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5 Chapter 5 Advances in understanding oil palm reproductive development

1 Introduction

The African oil palm (Elaeis guineensis, Jacq.) is the highest-producing oil crop, with a mere

6% of cultivable lands planted with oil palm yielding one-third of the global vegetable oil

market share (FAO, 2015). However, the combination of a strong demographic pressure

and increased per capita income in developing countries (chiefly in Asian countries such

as China and India) puts a strain on the demand for edible oils, with its consumption

predicted to nearly double by 2050 (Corley, 2009; Murphy, 2014). Palm oil production,

on the other hand, is constrained by growing international concerns over the negative

impacts of plantations on both the environment and human communities. Changes in land

use from high conservation value, high carbon stock primary forests or peatlands to oil

palm plantations are paralleled by a drop in both biodiversity and carbon sequestration,

together with a rise in greenhouse gases emissions. Under the impulse of both

state-owned holdings and private companies, the implantation or expansion of large oil

palm plantations sometimes occurs at the expense of local populations and cases of illegal

land appropriation were reported, especially in Africa (Koh and Wilcove, 2007; Rival and

Levang, 2014; Wich et al., 2014). The relative stalling of plantations growth that ensues is becoming a pregnant problem in the two main oil palm producing countries, Indonesia

and Malaysia, which together account for nearly 90% of the world's supply of palm oil and

which rely on this commodity for their economic growth.

Consequently, strategies aiming at increasing oil yield per surface unit without increasing

agricultural inputs should contribute to increasing the sustainability of oil palm cultivation

by alleviating the need for continually expanding planted areas (Murphy, 2014). And

there is, indeed, a lot of room for improvement, considering that the average yield in

smallholder plantations, which contribute nearly half the palm oil production in Malaysia

and Indonesia, is estimated to be around 2–3 tons per hectare and that the average yield

in industrial plantations reaches 4–6 t/ha. By comparison, the theoretical yield that can be

expected from material resulting from decades of breeding is estimated to be 10–15 t/ha

(Barcelos et al., 2015; Murphy, 2014). Moreover, it has been estimated that over 25% of

the palms that are planted in Malaysia are approaching the end of their productive lifetime

while most of the remainder have reached or will soon reach their peak productivity Developmental step Research foci Effect on yield/production Sexual differentiation of the inflorescences. Positive correlation between yield and high sex ratio. Influence of environmental stresses on increased male flowering. Role of sources/sinks carbohydrate relationships. Inflorescence development. Yield losses associated with improper development of floral organs. Yield losses associated with inflorescence abortion. Molecular mechanisms underlying abnormal floral phenotypes. Role of sources/sinks carbohydrate relationships. Fruit development and maturation. Positive correlation between yield and mesocarp oil content. Yield losses associated with bunch abortion. Molecular mechanisms underlying fruit development, oil and metabolites synthesis. Role of sources/sinks carbohydrate relationships. Fruit shedding. Positive correlation between yield and synchronous shedding at fruit maturity. Negative correlation between yield and oil acidification resulting from fruit bruising. Molecular and cellular events underlying fruit abscission. Identification of the processes responsible for oil acidification.

Figure 1 Steps of reproductive development of the oil palm with an effect on yield, and associated

research interests.

(Murphy, 2014). Altogether, these observations suggest that the yield gap between actual

and theoretical figures could therefore be partially closed through the replanting of elite,

high-yielding material in ageing or low-yielding plantations.

As far as palm oil production is concerned, yield is influenced by a variety of parameters,

among which some are connected to the regulation of developmental processes affecting

the reproductive organs: the ratio of female to total inflorescences (sex ratio), inflorescence

development, fruit development, maturation (during which oil synthesis takes place)

and shedding (see Fig. 1). Obviously, a better understanding of such key steps in the

reproductive development of oil palm is of paramount importance so that the genetic,

molecular, physiological and environmental mechanisms or the stimuli controlling them

can be identified and, ultimately, used towards the optimization of oil production through both breeding and agricultural practices.

Beyond what can be achieved within the boundaries set by current planted areas and

climate conditions, how climate change may affect oil palm development and oil palm

cultivation must be anticipated so that food security can be ensured. In that aspect, it

is most urgent to explore how the present environmental conditions may influence the

reproductive developmental stages listed above. This way, we can better anticipate the oil

palm’s responses to future challenges, mitigate their negative impact on production and

elaborate appropriately adapted ideotypes.

2 Sex ratio

Oil palm is a monoecious species in which the emergence of male and female inflorescences

alternates on the same individual; hence, the term ‘temporal dioecy’ has been coined to

describe this type of reproductive development.

From the time oil palm reaches reproductive maturity, approximately 3–4 years after

planting, oil palm inflorescences are continuously produced from the single Shoot Apical

Meristem (SAM) of the plant and differentiate from the stem of the palm, at the axil

of each new leaf. The sexual determination of oil palm inflorescences occurs about

two years prior to flower maturity (anthesis) and 29–32 months before bunch harvest

(Adam et al., 2011; Combres et al., 2013; Cros et al., 2013; Durand-Gasselin et al., 1999).

Although, in principle, male and female inflorescences alternate so that self-pollination is prevented, various factors come into play and influence the actual outcome. Clues to the involvement of genetic factors can be found: the phenological comparison between different oil palm genotypes grown in the same environment shows substantial variations in the sex ratio (T. Durand-Gasselin, pers. comm.). Also, since fruit production is directly dependent on the rate of female flower emergence, elite oil palm genotypes obtained through breeding schemes tend to produce a higher number of female inflorescences, sometimes at the expense of pollen availability (Cochard et al., 2005; Durand-Gasselin et al., 1999).

In addition to these likely genetic determinants, non-genetic factors have long been known to exert a strong influence on sex differentiation in oil palm. The external application of growth regulators such as gibberellins resulted in increased male flowering (Corley, 1976a). Although the mechanism governing this phenomenon is as yet undetermined, it could be related to the direct or indirect action of growth regulators on the expression of the genes controlling the development of floral organs. A similar hypothesis has been suggested to explain the in vitro induction of stamen development in female date palm flowers submitted to variations of the balance between exogenously applied auxins and cytokinins (Masmoudi-Allouche et al., 2009).

Most strikingly, it has been shown that a variety of stress-related conditions may result in modifications of sex ratio in oil palm. For instance, the ablation of either leaves (defoliation), or inflorescences or fruit bunches (pruning) has opposite effects on the sex differentiation of inflorescences since they result in an increased number of male inflorescences and an increased number of female inflorescences, respectively (Corley et al., 1995; Corley and Tinker, 2016; Legros et al., 2009b). Also, it has been noted that the mutual shading of individual palms in areas with high-density planting patterns tends to stimulate the emission of male inflorescences (Durand-Gasselin et al., 1999), although the stress associated with competition for soil-associated resources such as nutrients and water may account partly for this effect. In order to account for these phenomena, it has been proposed that sex differentiation in oil palm was mainly driven by competitive supply-and-demand relationships between organs behaving mainly as producers (or ‘sources’) (i.e. photosynthetic leaves) or as importers (or ‘sinks’) of carbohydrates which include, but are not limited to, reproductive structures such as flowers and fruits. Indeed, Cros et al. (2013) showed that sex ratio is negatively correlated with bunch load. Thus, the increase in male inflorescence emission that is obtained in conditions of impaired photosynthesis (resulting from either shading or defoliation) could be attributed to the comparatively higher physiological ‘cost’ of female inflorescences (Combres et al., 2013). Conversely, the selective removal of sink organs through inflorescence or bunch pruning tends to increase sex ratio because of partial alleviation of the competition for photosynthetic assimilates (Corley and Tinker, 2016). In support to this model, recent publications analysing changes in the inflorescence transcriptome after defoliation treatment (Ajambang et al., 2015, 2016a, 2016b) showed an enrichment of differentially expressed genes with biological functions pertaining to carbohydrate metabolism and abiotic stress response pathways.

In oil palm, the water status of the plant at the time of sex differentiation of the inflorescence plays a significant role in the latter phenomenon. Indeed, sex ratio variability between planting sites under contrasting water regimes has long been reported by oil palm planters and breeders, with African plantations experiencing a marked seasonality, alternating dry and rainy seasons, displaying a higher frequency of male inflorescences than South East Asian locations under important and relatively stable rainfall (Corley, 1976b). Obviously, this difference in sex ratio cannot be explained solely by the use of different genotypes or the stronger prevalence of highly selected planting material in Asia, since it has also been observed with identical progenies planted in sites under distinct climatic conditions (Marcel de Raïssac, pers. comm.). In accordance with these observations, a positive correlation between sex ratio and water balance has been established and inter-cross variability in drought tolerance traits has been hypothesized to account for its variations (Cros et al., 2013). Also, the analysis of a Quantitative Trait Locus (QTL) explaining 11.3% of the phenotypic variation for sex ratio led to the identification of the EgAKR1 (aldo-keto reductase) gene with putative functions in response to abiotic stresses (Somyong et al., 2014). However, as pointed out by Corley and Tinker (2016), the induction of increased male flowering by drought periods occurring at different times along the inflorescence development process makes it likely that there is more than one period of sensitivity to sex determination-altering processes in oil palm.

3 Inflorescence and flower development

Following sex determination, inflorescence and then floral structures differentiate and develop through a process that culminates with the emergence and maturation of floral organs (Adam et al., 2005). In angiosperms, this chain of events is regulated through the sequential action of genes associated with inflorescence meristem, flower meristem and floral organ identities, respectively, as it has been elucidated through the study of the model plant species Arabidopsis thaliana (Fig. 2) (Liu and Mara, 2010; Ó’Maoiléidigh et al., 2014; Wellmer and Riechmann, 2010).

The occurrence of flower abnormalities, which negatively impact oil production, has been a strong incentive to tackle the question of flower development regulation in oil palm. The naturally occurring Poissoni phenotype, also known under the vernacular name diwakkawakka in Asia, displays an apparent feminization of male floral organs in inflorescences from both sexes (Adam et al., 2005; Hartley, 1988). This morphological variant, which has also been identified in the Latin American relative of oil palm (Elaeis oleifera), is assumed to result from a mutation, although this has not been formally demonstrated.

In contrast with these relatively rare occurrences of aberrant flower morphotypes affecting seed-derived palms, the mantled variation only arises in clonal progenies of tissue culture derived oil palms, where it affects 5% of the regenerants on average with unpredictable variations of both its frequency and its severity between genotypes and production batches (Eeuwens et al., 2002). Whereas the initial purpose of the somatic embryogenesis process was to generate a virtually unlimited number of in vitro-generated identical copies from high-yielding individuals, the mantled floral phenotype (which is morphologically similar to the diwakkawakka) makes the affected palms mostly unproductive due to fertility issues and impaired oil accumulation in the fruits (Corley et al., 1986). Visual detection of mantled palms is only possible from the time they reach the flowering stage, that is, 3–4 years from the time plantlets generated through the somatic embryogenesis protocol (which takes 2–3 years to complete and requires a highly qualified manpower) have been transferred to the field. Therefore, the mantled variation is not only costly in terms of oil production but also in human labour and plantation space. As a result, the large-scale use of clonal oil palms in plantations has been significantly hampered by the occurrence of the mantled variation. Obviously, finding markers enabling a screening of this phenotype as early as the in vitro culture stages is of high importance to the industry and might greatly facilitate the future adoption of somatic embryogenesis-derived material by end users (Rival et al., 2000).

The slow reversion of the mantled phenotype through time was an early indication that its source is not genetic, but more likely epigenetic and thus associated with changes in gene regulation mechanisms since these are commonly altered by tissue culture (Bairu et al., 2011; Kaeppler et al., 2000; Kaeppler and Phillips, 1993; Miguel and Marum, 2011).

Indeed, it was soon demonstrated that the genomic DNA of in vitro as well as adult

mantled tissues is significantly depleted in cytosine methylation (Jaligot et al., 2000, 2002,

2004; Matthes et al., 2001). Parallel investigations targeting oil palm genes belonging to

the MADS-box family of transcription factors involved in floral organ identity showed that,

consistently with the appearance of the mantled phenotype, the genes involved in male

organs (stamens) formation are downregulated throughout the development of variant

flowers (Adam et al., 2005, 2006, 2007). Further work on the regulation of one of these

stamen identity genes, namely EgDEF1, recently suggested that its expression defect in SAM IM E n v i r o n m e n t a l & d e v e l o p m e n t a l s t i m u l i Vegetative stage Reproductive stage IM FM Auxin accumulation through polar transport AP1 LFY MP BDL AGL24 SVP SOC1 GA signaling auxin signaling CAL FUL TFL1 TOE3 TEM1 TEM2 IM w1 w2 w3 w4 Floral organ identity genes EMF1 CLF WUS UFO AP2 AP3 PI AG JAG miR172 PAN TPL TPRs HDA19 LUG SEU BLR Organ boundaries factors SUP RBE other Transcription Factors & downstream targets CRC SHP1/2 Floral meristem identity genes

Figure 2 Summary of the flower development process (based on Liu and Mara, 2010; Ó'Maoiléidigh

et al., 2014; Wellmer and Riechmann, 2010). Pointed arrowheads: activation; blunt connectors:

repression; curved arrows: positive feedback loops. Abbreviations: SAM = shoot apical meristem;

IM= inflorescence meristem; FM = flower meristem; w1-w4: floral whorls 1 to 4; TFL1 = TERMINAL

FLOWER1; TOE3 = TARGET OF EAT3; TEM1/2 = TEMPRANILLO1/2; MP = MONOPTEROS; BDL =

BODENLOS; LFY = LEAFY; AP1 = APETALA1; AGL24 = AGAMOUS-LIKE24; SVP = SHORT VEGETATIVE

PHASE; SOC1 = SUPPRESSOR OF OVEREXPRESSION OF CONSTANS1 ; CAL = CAULIFLOWER;

FUL = FRUITFULL; EMF1 = EMBRYONIC FLOWER1; CLF = CURLY LEAF; PAN = PERIANTHA; UFO

= UNUSUAL FLORAL ORGANS; WUS = WUSCHEL; TPL/TPRs = TOPLESS/TOPLESS-RELATED;

HDA19 = HISTONE DEACETYLASE19; LUG = LEUNIG; SEU = SEUSS; BLR = BELLRINGER; AP2 =

APETALA2; AG = AGAMOUS; AP3 = APETALA3; PI = PISTILLATA; SUP = SUPERMAN; RBE = RABBIT

EARS; NZZ/SPL = NOZZLE/SPOROCYTELESS; JAG = JAGGED; CRC = CRABS CLAW; SHP1/2 =

SHATTERPROOF1/2.

mantled flowers might result from improper RNA processing caused by methylation loss

of a nearby transposable element (TE) (Jaligot et al., 2014; Ong-Abdullah et al., 2015).

While these studies propose a compelling molecular model for the flower phenotype in

adult clonal oil palms, much remains to be done to understand where, how and (perhaps

more importantly) when this epigenetic alteration arises during the tissue culture process

so as to provide a reliable basis for early detection tests that could be implemented in

commercial production units.

Beyond the specific issue of the mantled variation, understanding and reducing the

emergence of somaclonal variations is of considerable practical importance. Indeed,

because of their very low genetic variability and highly controlled culture conditions, clonal plants are a material of choice in the study of the response to environmental factors and stress adaptation mechanisms (Rai et al., 2011; Us-Camas et al., 2014; Wang and Wang, 2012). Moreover, it is crucial that the output of micropropagation protocols is under control in the prospect of developing efficient transformation and gene editing techniques, as such protocols always include an in vitro regeneration step (Etienne et al., 2016).

Studies carried out in both annual and perennial temperate plant species have shown that flowering responds to environmental cues so that the reproductive phase is adjusted to seasonal changes (Andrés and Coupland, 2012; Kudoh, 2015; Shrestha et al., 2014). As a matter of fact, many of the genes that play a role in either floral induction or flower development pathways respond to stimuli such as changes in photoperiod, light quality or temperature and can be affected by a variety of abiotic stresses (Liu and Mara, 2010; Ó'Maoiléidigh et al., 2014; Wellmer and Riechmann, 2010). It is likely that the balance between the different environmental signals required for flowering is different for a plant growing in tropical regions that are characterized by a narrower range in both temperatures and day length between seasons. However, Combres et al. (2013) proposed that the flowering rhythmicity of oil palm is influenced by photoperiod so as to minimize the adverse effects of strong seasonality on flower and fruit development: this effect is therefore

more significant in West Africa than it is in South East Asia. In line with the carbohydrate

partition model (see previous section), several studies have also concluded that seasonal

variations in oil palm production could be explained mainly through the negative effects

of environmental stresses such as drought on the availability of photosynthetic assimilates.

Such an imbalance would lead to a biased sex ratio, delayed inflorescence development

and enhanced inflorescence and fruit bunch abortions (Combres et al., 2013; Cros et al.,

2013; Legros et al., 2009a; Pallas et al., 2013). It has also been reported that a strongly

reduced carbohydrate supply such as that obtained through the reduction of the number

of source organs through severe defoliation might lead to a preferential abortion of female

inflorescences, thereby reinforcing the sex ratio bias (Pallas et al., 2013). However, data

are scarce and conflicting regarding this phenomenon and, just as with sex differentiation,

there might be several distinct stages of inflorescence development that show a critical

sensitivity to abortion-promoting signals (Corley and Tinker, 2016). In their recent paper,

Somyong et al. (2016) showed that the development of female oil palm inflorescences

likely involves ethylene-induced regulations and the action of non-coding regulatory

small RNAs. Because of the sensitivity of both this growth regulator and small RNA-based regulations to environmental challenges, this result can be considered as additional evidence regarding an environmental influence over reproductive development of oil palm.

4 Fruit development and maturation and oil composition

Once the female flower has been pollinated, the development of oil palm fruit (or drupe) is set in motion through steps that have been dissected at the transcriptomic and metabolomic levels in two important articles (Bourgis et al., 2011; Tranbarger et al., 2011).

The first phase of early fruit development, which runs up to 100 days after pollination (dap), includes a strong cell division and expansion activity and involves the action of the growth regulators such as gibberellins, cytokinins and finally auxins as well as the induction of the corresponding growth regulators-responsive genes. During the subsequent maturation and ripening phases, it is followed by an increase in both ethylene and abscissic acid production until the time when the fruit reaches full ripeness, around 160 dap (Tranbarger et al., 2011).

As demonstrated through the work of Legros et al. (2009b, 2009c), sucrose is exported from mature photosynthetic source leaves and temporarily stored as starch in the stipe (or pseudo-trunk) of oil palm. Sucrose is later imported to fruits where it provides precursors of oleosynthesis through the glycolysis pathway, with carbon allocation to oil

palm fruits amounting to about 30% of photosynthetic C fixation (Corley and Tinker, 2016;

Dussert et al., 2013; Lamade et al., 2016). Palm oil synthesis then occurs in the course

of the maturation and ripening phases through the massive transcriptional activation of

genes involved in fatty acids (FAs) biosynthesis, whereas the genes responsible for the

assembly of triacylglycerols (TAGs), the core components of the oil which are formed

from the esterification of these FAs, are not significantly upregulated (Bourgis et al., 2011;

Tranbarger et al., 2011).

A unique case among all the oleaginous plant species, oil palm synthesizes two oils:

palm oil, which accumulates in the pulp or mesocarp, and kernel oil, which is extracted

from the storage tissue (endosperm) of the stone. Both tissues rely on different members

of the WRINKLED (WRI) family of transcription factors to achieve the upregulation of FA

synthesis (Dussert et al., 2013). Ultimately, the markedly different regulations of their

respective oil synthesis pathways result in distinct oil compositions and global contents

in the tissues. While palm oil makes up 80% of the dry weight of the mesocarp and

includes a majority of palmitic (C16:0; 41%) and oleic (C18:1; 31%) acids, the endosperm

includes 50% of kernel oil made mostly of medium-chain FA such as lauric (C12:0; 49%)

and myristic (C14:0; 15%) acids. Finally, the embryo contains 27% of the oil with a higher

concentration of unsaturated FA: 25% palmitic acid, 35% oleic acid and 23% linoleic acid

(C18:2) (Dussert et al., 2013).

Now that a thorough characterization of the molecular events underlying fruit

development and maturation is available, the molecular basis of the yield gap between high

oil- and low oil-producing genotypes is being investigated. Teh et al. (2013) have compared

high oil- versus low oil-yield genotypes of oil palm for bunch and fruit morphological

traits, and the accumulation of primary and secondary metabolites during fruit maturation.

These authors conclude that morphological differences in number of bunches, mesocarp

weight per bunch and mesocarp oil content – which they assume result from genetic

variations between different crosses – account for most of the yield gap, with none of

the trade-off between fruit number and size that had been observed in previous works

(Cros et al., 2013; Pallas et al., 2013). The authors also observe a differential accumulation

of primary metabolites (amino acids, glycolysis intermediates and tricarboxylic acids) in

the mesocarp between high-producing and low-producing genotypes, which they suggest

may be indicative of differing strengths of carbon partitioning processes in favour of lipid

biosynthesis.

On the other hand, Guérin et al. (2016) have explored the regulation of oil synthesis in back-cross population between E. guineensis and E. oleifera. Indeed, the latter is

characterized by a lower oil accumulation in the mesocarp (15–25%) and a distinct

composition that includes nearly half as much palmitic acid (25%) and a higher

concentration of unsaturated FAs, which make this species a potential source of genes

of interest for the improvement of the nutritional value of palm oil (Barcelos et al., 2015;

Murphy, 2014). Using co-expression analyses, the authors confirm the negative correlation

between the expression of genes involved in starch and FA biosynthesis, and they identify

two additional transcription factors, namely NF-YB1 (nuclear factor Y) and ZFP1 (zinc

finger) with a significant influence in oil synthesis in different oil palm tissues, alongside

WRI family genes. In accordance with previous findings (Parveez et al., 2014), they further

highlight the central role of transcriptional regulations of the gene encoding the plastidial

enzyme β-ketoacyl-ACP synthase II (KASII, responsible for the elongation of C:16 FA to

C:18) in palmitic acid accumulation. These different genes provide potential targets for

breeding strategies aimed at altering palm oil FA composition through either introgression

or biotechnology In parallel, complementary research efforts are focusing on improving

the nutritional value of palm oil through its contents in metabolites such as carotenoids

and antioxidant compounds, in the aim of reducing vitamins

A and E deficiencies in

developing countries (Barcelos et al., 2015; Tranbarger et al., 2011).

5 Fruit shedding and oil acidification

Fruit abscission, the process through which the fruit becomes detached from the pedicel,

takes place once full maturity has been achieved, that is, about 160–180 dap. In plantations,

the presence of detached fruits at the foot of oil palm is used as an indicator that the

bunch is ready to be harvested (Corley and Tinker, 2016). However, premature abscission

occurring before both fruit ripeness and oil accumulation are optimal, as well as shedding

between harvest site and oil mill cause losses in production, prompting the need for a

better understanding of the mechanisms governing the abscission process.

In a first study of the cellular and tissular events associated with abscission of oil palm

fruit, Roongsattham et al. (2012) illustrated the differentiation of an abscission zone

(AZ) between the mesocarp and the pedicel of the fruit and showed the involvement

of polygalacturonases (PGs) and pectin depolymerization in the alterations of cell wall

composition leading to effective cell separation. They also demonstrated that the

sensitivity of this process to the stimulating effect of ethylene is acquired in the course

of the maturation process. In a later work, the same authors suggested that inter-cellular

exchange of signalling molecules between cell layers involved in AZ formation might trigger the coordinated changes in gene expression that are required in order to achieve cell separation (Roongsattham et al., 2016).

As a result of shedding or other mechanical shocks affecting the fruits over the course of transportation or processing, the activity of a lipase enzyme in the bruised mesocarp triggers the time-dependent release of Free FA (FFA). When their concentration reaches 5%, palm oil is deemed improper for human consumption and trade according to international standards. Fruit heating is used as a post-harvest treatment to inactivate the enzyme but it is unaffordable for many smallholders, especially in Africa, and it does not fully prevent oil acidification. The gene encoding the enzyme responsible for oil acidification has been mapped and characterized, paving the way for its use in marker assisted breeding schemes (Morcillo et al., 2013). It is expected that the generalization of oil palms with a ‘low-lipase’ phenotype in plantations will lead to substantial gains in productivity because of their extended ripening time frame and more flexible harvesting period on one hand, and through the decreased post-harvest costs on the other hand.

6 Future trends and conclusion

The ongoing climate change will have multiple consequences on oil palm culture, depending on the region that is considered.

Over the last 65 years, droughts have increased in frequency and length in Western

Africa (Spinoni et al., 2014), resulting in increased rainfall seasonality (Feng et al., 2013).

Climate models predict that drought intensity in Africa will further increase in the future

(Li et al., 2009). Meanwhile, in South East Asia, increased male and hermaphrodite flower

production has been recorded in plantations, in conjunction with erratic rainfalls, leading

to relative drought events in certain areas, whereas other regions experience increased

precipitations and flooding. Studies spanning the last decades show that drought duration

and seasonality tend to increase with time in this area (Feng et al., 2013; Li et al., 2009;

Spinoni et al., 2014). The occurrence of El Niño-Southern Oscillation (ENSO) events in

the Pacific Ocean has long been correlated with decreased precipitations and longer and

more intense droughts, bushfires and hazes, and thus a decline in productivity for oil palm

plantations in Indonesia and Malaysia (Corley, 2016). Opposite trends regarding the future

severity and the frequency of ENSO can be derived from climatic models because of the

overall poor predictability of this event (Collins et al., 2010). However, it seems that more

recent projection efforts point towards an increased frequency of extreme El Niño as a

result of climate change (Cai et al., 2014; Santoso et al., 2013). In any case, the exceptional

magnitude of the 2015/2016 event (the strongest recorded in the last 20 years) makes it a chief concern in this key producing region. As for oil palm-growing countries in Latin

America, the forecast is highly uncertain due to conflicting data (Corley, 2016).

The predicted rise in temperatures as a result of increased greenhouse gases (among

which is CO_2) concentrations in the atmosphere is not, in itself, an issue for oil palm. Up to a

point, rising CO_2 concentrations are predicted to result in increased yields due to improved

photosynthetic activity (Henson, 2006). However, high temperatures can become an issue

when occurring in conjunction with the relative drought conditions triggered by changes

in rainfall patterns. Indeed, the drier air around the leaves associated with such conditions

is associated with an increased Vapour Pressure Deficit (VPD), a parameter to which the

stomates of oil palm leaves are very sensitive and which leads to their closure (Henson,

1991; Smith, 1989). Closed stomates prevent not only excessive water evaporation but also

carbon dioxide uptake for photosynthesis, and extended drought periods are therefore

detrimental to photosynthesis and carbohydrate biosynthesis. In many crops, it has been

suggested that drought-related decreases in carbon allocation to reproductive structures

such as flowers and fruits may lead to decreased pollen fertility or flower abortion and

reduced grain or fruit filling (Albacete et al., 2014; Luquet et al., 2008; Pinheiro and

Chaves, 2011). Studies focusing on seasonal and inter-annual variations in phenology

and production seem to indicate similar trends in oil palm. The trophic competition

model between sink organs (Combres et al., 2013; Pallas et al., 2013) show that certain

stages of inflorescence and fruit bunch development display higher sensitivity to limiting

environmental and trophic conditions. It accounts well for inflorescence abortion under

limiting carbohydrate supply at the early stage of rapid inflorescence growth (ca. 10 months

before harvest), but it does not for earlier inflorescence abortion, nor for later bunch

failure occurring after anthesis. By contrast, data presented by Cros et al. (2013) are in

disagreement with some of these conclusions, highlighting the complex effects of seasonal

water deficit on production and, more specifically, on inflorescence abortion. Analyses of

oil palm inflorescence transcriptome have shown that the expression of genes involved

in carbohydrate metabolism was central to inflorescence development (Ajambang et al.,

2015) and that, conversely, carbohydrate deprivation triggered the expression of cell

death-associated genes, hinting at a possible connection with abortion (Ajambang et al.,

2016b). Furthermore, if the drought period overlaps with the fruit maturation process

during which the synthesis and accumulation of storage compounds is supposed to take

place, it might bear a significant negative impact on the final yield, as it has been shown in oil palm clones (Lamade and Setiyo, 1996). The transient storage of non-structural carbohydrates in the stem partially compensates/buffers the negative effects of small scale changes in environment on source-sink carbon balance and ensures oil synthesis in the fruit (and further, continuous fruit production) (Legros et al., 2009c); however, this mechanism is likely insufficient in true stress conditions (Combres et al., 2013). Water stress can also be anticipated to have a more qualitative influence on the accumulation of lipids, carotenoids and other metabolic compounds in fruits: since their synthesis is, in most plants, an adaptative trait that is strongly influenced by the environment, it is likely that the nature of the produced molecules might be altered (Murphy, 2014).

Although, ideally, the expansion of the areas planted with oil palm should be avoided, the adverse effects of climate change might prompt the need for growing oil palm outside of the region that is currently the most favourable for its culture, that is, within 20° of the equator (Barcelos et al., 2015; Corley and Tinker, 2016). Also, as Murphy (2014) notes, if oil palm is to provide an increasing share of the world's consumption in vegetable oils in the future, it might be desirable, from a strategical, food security perspective, to deconcentrate palm oil production from South East Asia. Oil palm has a threshold temperature for growth of 15°C (Corley and Tinker, 2016) which currently puts a limit to its cultivation in higher altitudes or lower latitudes, but this might change locally due to rising temperatures and lead to the cultivation of oil palm in moderate altitude (Andean plateaus and African Highlands) or outside of the tropics, in areas that are currently under a drier, more seasonal climate such as southern China (Barcelos et al., 2015).

Lately, several groups have set up to unravelling the molecular mechanisms underlying responses to either low temperatures or drought in oil palm (Azzeme et al., 2016; Ebrahimi et al., 2016; Lei et al., 2014; Silva et al., 2015; Xiao et al., 2014). In addition to genetic determinants, as highlighted by the inter-genotype variations that have been observed, there is a considerable phenotypic plasticity in stress response, which is made visible through the contrasting behaviours displayed by plants with equivalent genetic backgrounds. Overall, these studies have shown that the response to such abiotic stresses involves the activation of signalling pathways with key transcription factors (e.g. CBFs for cold stress) triggering the expression of downstream target genes acting for the mitigation of or the adaptation to the physiological effects of the constraint (e.g. the implementation of antioxidant strategies in drought conditions). In general, it is observed that stress-sensitive and -tolerant genotypes or individuals differ by the strength and/or the precocity of this response, or by their ability to recover more

promptly and with lesser long-term effects upon return to favourable growth conditions.

It must, however, be observed that stress response often occurs at the expense of

biomass production and growth. In the case of the breeding for drought tolerance in

particular, the traits that are favourable for enhanced water use efficiency (e.g. early

stomatal closure) may be partially incompatible with yield maintenance in low water

availability conditions (e.g. because of altered carbon allocation to the reproductive

organs) (Albacete et al., 2014; Pinheiro and Chaves, 2011). Ultimately, the goal is to

identify traits (in terms of plant architecture, physiology, gene expression, etc.) that

are associated with optimal production in a specific set of limited resource availability

conditions. These will be thereafter combined through new, adaptation-focused

breeding schemes in order to generate varieties that are either tailor-made to suit a

specific agro-climatic environment or highly plastic ones that will be able to face any

further change in conditions without significant yield loss. The involvement of epigenetic

regulations of gene expression in the response and adaptation to most environmental

constraints (Jaligot and Rival, 2015; Mirouze and Paszkowski, 2011; Richards, 2011) is

abundantly documented. It has been suggested that epigenetic variations might explain the phenotypic plasticity of these responses. The inclusion of the epigenetic information

'layer' as part of the multiple 'omics' approaches, fuelling these novel breeding schemes

as well as in field trial evaluation protocols, will thus be of paramount importance for the

elaboration of future adapted oil palm ideotypes.

7 Where to look for further information

developments on the subject of oil palm. Corley and Tinker's reference book The Oil Palm

is a most recommended starting point.

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6 Chapter 6 Diversity in the genetic resources of oil palm

1 Introduction

The oil palm is a monocotyledonous plant classified in the Arecaceae family, formerly

known as Palmae. There are two major species of oil palm, namely Elaeis guineensis and

Elaeis oleifera. Elaeis guineensis and Elaeis oleifera are native to West Africa and South

America, respectively (Corley and Tinker, 2003). Extensive natural or semi-wild varieties of

Elaeis guineensis (Fig. 1) are found along the west coast of Africa from Senegal to Angola

(Zeven, 1967), whereas Elaeis oleifera (Fig. 2) is distributed in Honduras, Nicaragua, Costa

Rica, Panama, Colombia, Venezuela, Suriname, Ecuador, Brazil and Peru (Meunier, 1975;

Ooi et al., 1981; Escobar, 1982; Rajanaidu, 1983; Julian Barba, 2012). These two species

are able to hybridize to produce fertile fruits. Hybrids are short with desirable oil quality

and fresh fruit bunch (FFB) yield.

This chapter discusses the rather narrow genetic base of current breeding materials and

the work undertaken by the Malaysian Palm Oil Board (MPOB) with the aim of broadening

Figure 1 African Elaeis guineensis.

Figure 2 American Elaeis oleifera.

this genetic base. It looks at ways of assessing genetic diversity in oil palm, through the

analysis of fruit forms and types, morphological traits and genetic markers. It also reviews methods for the conservation of oil palm collections and ways of utilizing germ plasm in order to develop improved varieties.

2 The genetic base of current breeding materials

Oil palm planting materials are based on an extremely narrow genetic base. The discovery of the genetic inheritance of shell thickness by Beirnaert and Vanderweyen (1941) formed the foundation for the production of dura × pisifera (DxP) planting material. It has been well documented that female sources are restricted to four Deli dura palms planted in Bogor Botanical Gardens, Indonesia, in 1848 (Hartley, 1988). The Deli dura population is the backbone of every oil palm breeding programme developed in the world. The genetic base of pisiferas is also limited. Both Deli dura and AVROS pisifera were imported to Malaysia via Indonesia. To date, the DxP hybrid known as tenera is the main planting material used and has resulted in a significant increase in oil palm yields. The selection of the thin-shelled teneras is due to the high oil-bearing content of the mesocarp (75–85%) compared to duras (20–65%) (Kushairi and Rajanaidu, 2000). Other important sources of pisiferas are the Djongo palm, Yangambi, Calabar, Ekona, La Me, URT and Pure SP540 (Fig. 3).

It has been generally recognized that the narrowness of the gene pool had been a major obstacle towards increasing yields in many crops including oil palm. The need to broaden the genetic base for continuous yield improvement has been recognized by the oil palm

industry worldwide. This concern provided the initial impetus for the MPOB to carry out

several expeditions to the various centres of diversity for oil palm in West Africa and South

America (Rajanaidu et al., 2000). From 1973 to 2010, the MPOB team collected Elaeis

guineensis germ plasm from the centres of origin in 11 countries, viz. Nigeria, Cameroon,

Figure 3 Major breeding materials in the seed production.

Figure 4 Germ plasm collection (Elaeis guineensis) sites in Africa.

Figure 5 Germ plasm collection (Elaeis oleifera) sites in South America.

Zaire, Tanzania, Madagascar, Angola, Senegal, Gambia, Sierra Leone, Guinea and Ghana

(Fig. 4). In the case of Elaeis oleifera, the collection effort covered eight countries, namely

Honduras, Panama, Costa Rica, Nicaragua, Suriname, Ecuador, Peru and Colombia

(Fig. 5). In addition, palms of economic interest such as Bactris, Jessenia, Oneocarpus,

Euterpe and Babassu were also sampled. Introducing these genetic materials will allow

new traits of economic interest to be discovered and subsequently introgressed into

current breeding materials in order to broaden the genetic base. Table 1 summarizes the

germ plasm collection activities developed at MPOB.

Table 1 List of germ plasm collections (Rajanaidu, 1994)

Country Year No. of accessions Collectors

Elaeis guineensis

Nigeria 1973 919 Rajanaidu, Arasu and Obasola

Cameroon 1984 95 Rajanaidu and Unilever

Zaire 1984 369 Rajanaidu and Unilever

Tanzania 1986 60 Rajanaidu and Ministry of Agriculture Officials, Tanzania

Madagascar 1986 17 Rajanaidu and Ministry of Agriculture Officials, Madagascar

Angola 1991, 2010 54, 127 Rajanaidu, Jalani Sukaimi, Mohd Din Amiruddin, Marhalil Marjuni and Ministry of Agriculture Officials, Angola

Senegal 1993 104 Rajanaidu, Jalani Sukaimi and Ministry of Agriculture Officials, Senegal

Gambia 1993 45 Rajanaidu, Jalaini Sukaimi and Ministry of Agriculture Officials, Gambia

Sierra Leone 1994 56 Rajanaidu, Ahmad Kushairi Din and Ministry of Agriculture Officials, Sierra Leone

Guinea 1994 61 Rajanaidu, Ahmad Kushairi Din and Ministry of Agriculture Offcials, Guinea

Ghana 1996 58 Rajanaidu, Mohd Rafii Yusof and Ministry of Agriculture Offcials, Ghana

Elaeis oleifera

Honduras 1982 14 Rajanaidu

Nicaragua 1982 18 Rajanaidu

Costa Rica 1982 61 Rajanaidu

Panama 1982 27 Rajanaidu

Colombia 1982 41 Rajanaidu

Suriname 1982 6 Rajanaidu

Peru 2004 4 Rajanaidu and Ahmad Kushairi Din

Ecuador 2004/06 10 Rajanaidu, Ahmad Kushairi Din and Noh Ahmad

Jessenia, Oenocarpus, Bactris, Euterpe

Peru 1981 50 Rajanaidu

Colombia 1989 182 Rajanaidu

3 Genetic diversity in oil palm: fruit forms

Genetic diversity in oil palm will be considered with reference to its distribution, fruit forms and fruit types, agronomic and morphological characters as well as using molecular markers. The phenotypic expression of traits in oil palm depends on around 32 000 genes, as estimated when sequencing the oil palm genome (Singh et al., 2013).

The oil palm fruit is a drupe, which consists of mesocarp, shell and kernel. A cross section of the fruit reveals the three fruit forms of the oil palm based on the presence or absence of shell: dura, pisifera and tenera (Fig. 6). Dura is homozygous-dominant ($sh^+ sh^+$) with a thick shell. Pisifera ($sh^- sh^-$) is a homozygous-recessive allele with no shell. As mentioned earlier, the cross between dura and pisifera produces a heterozygous hybrid, tenera ($sh^+ sh^-$), with a thin shell surrounded by a fibre ring (Beirnaert and Vanderweyen, 1941).

It is of paramount interest to explore genetic diversity in the natural oil palm groves of Africa in order to identify new economically important traits for further breeding. Recent oil palm collections provide information on the actual diversity of fruit forms that exist in such natural oil palm groves (Bakoumé, 2016). Based on MPOB oil palm germ plasm collection, the greatest proportion of fruit types in natural oil palm groves in Africa was duras (73.32%) followed by teneras (26.63%). Only one pisifera (0.05%) was found during collection expeditions in Sierra Leone (Table 2). Indeed, pisifera is considered rare by local communities and its scarcity has been attributed to the preference by local people for the other two varieties. Farmers tend to keep the tenera bunches for home consumption while selling the heavier dura bunches at markets because growers are paid by bunch weight (Rajanaidu, 1986). The frequency of dominant allele ‘D’ is higher (86.63%) in all the collections in Africa.

The data in Table 2 are further illustrated in Fig. 7 to show the frequency and distribution of dominant allele ‘D’ and recessive allele ‘d’ in various countries.

Figure 6 Characteristics of fruit forms (Source: MPOB).

Table 2 Fruit form frequency in natural oil palm populations

Year	Country	No of accessions	Genotype (%)			Frequency of alleles	
			Dura	Tenera	Pisifera	Allele ‘D’	Allele ‘d’
1973	Nigeria	919	595 (64.74)	324 (35.26)	0 (0.00)	1514 (0.82)	324 (0.18)
1984	Cameroon	95	58 (61.05)	37 (38.95)	0 (0.00)	153 (0.81)	37 (0.19)
1984	Zaire	369	283 (76.69)	86 (23.31)	0 (0.00)	652 (0.88)	86 (0.12)
1986	Tanzania	59	42 (71.19)	17 (28.81)	0 (0.00)	101 (0.86)	17 (0.14)

1986 Madagascar 17 17 (100.00) 0 (0.00) 0 (0.00) 34 (1.00) 0 (0.00)

1991,

2000 Angola 181 137 (75.69) 44 (24.31) 0 (0.00) 318 (0.88) 44 (0.12)

1993 Senegal 104 104 (100.00) 0 (0.00) 0 (0.00) 208 (1.00) 0 (0.00)

1993 Gambia 45 45 (100.00) 0 (0.00) 0 (0.00) 90 (1.00) 0 (0.00)

1994 Sierra Leone 56 52 (92.86) 3 (5.36) 1 (1.79) 107 (0.96) 5 (0.04)

1994 Guinea 61 58 (95.08) 3 (4.92) 0 (0.00) 119 (0.98) 3 (0.02)

1996 Ghana 58 49 (84.48) 9 (15.52) 0 (0.00) 107 (0.92) 9 (0.08)

Total 1964 1440 523 1 3403 525

(%) 100 73.32 26.63 0.05 86.63 13.37

Figure 7 The frequency distribution of ‘D’ and ‘d’ alleles in various germ plasm countries.

4 Genetic diversity in oil palm: fruit types

There are two types of fruits according to external exocarp colour, namely nigrescens

and virescens. It appears that virescens is controlled by a single dominant gene. The

homozygous-dominant and heterozygous hybrids express the virescens phenotype. Based

on the MPOB germ plasm collection, the frequency of virescens in natural oil palm groves

is extremely low even though the gene is dominant (Table 3). The percentage of virescens

was found to be 2.63% in natural oil palm groves, whereas the nigrescens proportion reached 97.34%. It is hypothesized that virescens is a recent mutation from NIGRESCENS

(recessive) to VIRESCENS (dominant). The highest frequency of virescens has been found

in Tanzania (16.95%) followed by Angola (14.12%) (Table 3). Hartley (1988) found a 0.7%

frequency for virescens in Angola. Rajanaidu (1986) found a high incidence of virescens

palms at certain sites in Cameroon (36%) and Democratic Republic of Congo (50%).

Hartley (1988) found an open-pollinated virescens bunch in Nigeria with 46% virescens

and 54% nigrescens.

Studies of phylogenetic characteristics and the transcriptome of virescens and nigrescens

suggest that the virescens gene controls exocarp colour by regulating the expression of

genes in the anthocyanin biosynthetic pathway (Singh et al., 2014). It is perhaps not surprising

that the gene might be found under the heterozygous condition since the frequency of the

recessive allele in natural oil palm germ plasm is significantly higher (98.69%) compared

to the dominant allele (1.31%). Based on the MPOB germ plasm collections, 3 out of 5

independent mutant alleles of the VIR gene in oil palm are present in material from Angola

and Democratic Republic of the Congo (Singh et al., 2014). The identification of alleles

Table 3 Fruit type frequency in natural oil palm population

Year Country No of bunches observed Genotype (%) Frequency of alleles Nigrescens Virescens Allele ‘V’ Allele ‘v’

1973 Nigeria 2112 2075 (98.25) 37 (1.75) 37 (0.01) 4187 (0.99)

1984 Cameroon 95 91 (95.79) 4 (4.21) 4 (0.02) 186 (0.98)

1984 Zaire 795 785 (98.74) 10 (1.26) 10 (0.01) 1580 (0.99)

1986 Tanzania 59 49 (83.05) 10 (16.95) 10 (0.08) 108 (0.92)

1986 Madagascar 17 17 (100.00) 0 (0.00) 0 (0.00) 34 (1.00)

1991,

2000 Angola 177 152 (85.88) 25 (14.12) 25 (0.07) 329 (0.93)

1993 Senegal 104 104 (100.00) 0 (0.00) 0 (0.00) 208 (1.00)

1993 Gambia 45 45 (100.00) 0 (0.00) 0 (0.00) 90 (1.00)

1994 Sierra Leone 55 54 (100.00) 0 (0.00) 0 (0.00) 108 (1.00)

1994 Guinea 59 59 (100.00) 0 (0.00) 0 (0.00) 118 (1.00)

1996 Ghana 58 50 (86.21) 8 (13.79) 8 (0.07) 108 (0.93)

Total 3576 3481 94 94 7056

Mean (%) 100 97.37 2.63 1.31 98.69

responsible for the virescens genotype allows breeders to develop paternal (pisifera) lines

that are homozygous virescens when crossed with homozygous Deli duras to produce a

100% virescens phenotype for future commercial planting. Planters prefer to plant virescens

because they find it hard to identify when nigrescens bunches move from being unripe

(black) to ripe (dark red). In contrast, virescens are green when unripe but turn to orange

when ripe, making it easy to identify ripe bunches, even in tall palms.

The data shown in Table 3 can be compared to Fig. 8 which shows the frequency and distribution of the dominant allele ‘V’ and recessive allele ‘v’ in various countries. We

further analysed the frequency of virescens in dura and tenera populations where most

of the dura and tenera palms are nigrescens (93.88% and 89.92%, respectively) (Table 4).

The mean frequency of virescens in dura and tenera palms is extremely low, at 6.12% and

10.08%, respectively.

4.1 Albescens (mescocarp colour)

The albescens fruit, which is characterized by a very low carotene level in the mesocarp,

has been found in Sierra Leone (1.79%). Corley and Tinker (2016) highlighted the presence

of albescens palms in Ghana, Democratic Republic of Congo, Angola, Nigeria and Cote

d’Ivoire, but it is very rare. Rajanaidu (1986) encountered one albescens palm at the

Yangambi Research Station, Democratic Republic of Congo (Fig. 9).

Figure 8 The frequency distribution of ‘V’ and ‘v’ alleles in various countries.

4.2 Mantled palm

An abnormal fruit known as mantled is a somaclonal variant due to an epigenetic

phenomenon which causes a malformation of floral organs in flowers from both sexes.

Mantled fruits produce little or no oil in the bunch (Shearman et al., 2013). Mantled fruits are

rare in natural oil palm groves. Where they occur, all the fruits in a bunch are stably mantled,

in contrast to mantled material originating from tissue culture in which reversion to normal

Figure 9 Albescens fruit (Reproduced from Hartley (1988)).

Table 4 Fruit type frequency in dura and tenera Fruit type

	Dura		Tenera	
Country	Nigrescens	Virescens	Nigrescens	Virescens
Cameroon	50	3	41	1
Tanzania	36	6	13	4
Madagascar	17	0	0	0
Angola	119	18	38	6
Senegal	104	0	0	0
Gambia	45	0	0	0
Sierra Leone	52	0	3	0
Guinea	58	0	3	0
Ghana	41	7	9	1
TOTAL	522	34	107	12
MEAN (%)	93.88	6.12	89.92	10.08

phenotype can occur and phenotypes of fruits can be diverse on the same bunch (Jaligot et al., 2000). Rajanaidu (1986) observed a natural mantled palm in Zaire and Nigeria (at site 10), while Zeven (1973) found mantled fruit constituting about 0.1% of bunches harvested in Nigeria and 0.16% in Angola. Hartley (1988) found some spontaneous mantled palms in Congo. When selfed, mantled palm resulted in the 75–100% mantled progeny. When crosses were made between mantled and normal palms, 50% of the progeny was mantled (Hartley, 1988). DNA hypomethylation was found to be related to the determinism of

mantled flower than fruit formation by several authors (Jaligot et al., 2000, 2014; Ong

Abdullah, 2015) (Fig. 10).

4.3 Leaflet variation (Idolatrica palm)

The leaflets in the idolatrica palm do not separate normally and they are fused. The centre

of distribution of the idolatrica palm lies is Ghana, Benin and western Nigeria (Corley and

Tinker, 2016). Rajanaidu (1986) found a number of idolatrica palms in the Boteka area,

Democratic Republic of the Congo, and also noticed idolatrica palms along the Edea/

Douala Road in Cameroon (Fig. 11).

Figure 10 (a) Normal fruit. (b) Cross section of normal fruit. (c) Mantled fruit. (d) Cross section of

mantled fruit.

5 Genetic diversity in oil palm: morphological traits

Although genetic diversity can be measured by using protein- and DNA-based markers,

morphological characteristics are still successfully used as a method to assess genetic

diversity in oil palm. Indeed, natural oil palm populations collected from Nigeria (1973)

by MPOB showed some considerable genetic variations in morphological traits, allowing

breeders to select individual palms with economically important traits (Table 5).

Genetic diversity within and among oil palm populations is measured using variance

component statistics. The genetic structure of oil palm populations shows that the variation within population ($\sigma^2 w$) is much higher than between population $\sigma^2 p$. $\sigma^2 w$ varies from 56.39

to 90.82% and $\sigma^2 p$ from 9.18 to 43.61%. The magnitude of $\sigma^2 p$ and $\sigma^2 w$ depends on the

traits. The highly heritable traits exhibit a higher level of $\sigma^2 p$. This information is useful to

oil palm breeders in helping them to allocate resources in the sampling of oil palm germ

plasm in various countries.

Principal component analysis (PCA) and cluster analysis have been used to understand

the oil palm populations collected at various sites and the influence of the environment.

Data involving 41 morphological traits of dura palms from 11 countries (Nigeria, Cameroon,

Zaire, Tanzania, Madagascar, Angola, Senegal, Gambia, Sierra Leone, Guinea and Ghana)

were retrieved from the MPOB Breeding Information System and analysed using PCA and

cluster analysis. In the PCA, the correlation matrix based on all traits was calculated with

respective eigenvalues.

The patterns of components 1 and 2 are shown in Fig. 12. A PCA plot of PC1 and PC2

showed that oil palm populations were grouped into four distinct clusters indicating the

differentiation among germ plasm material. The cluster analysis of the oil palm germ plasm

Figure 11 The idolatrica palm with fused leaflets (Adopted from Corley and Tinker (2016)).

Figure 12 PCA scores extracted from PC1 and PC2 based on 95% prediction ellipse.

Table 5 Variation for morphological characteristics in Nigerian collection (Trial 0.151) –Duras (Rajanaidu and Rao, 1988)

Bunch and vegetative traits	Variance components (%)	
	Between populations ($\sigma^2 p$)	Within populations ($\sigma^2 w$)
Bunch characteristics		
Fruit-to-bunch ratio (F/B) (%)	9.18	90.82
Oil-to-bunch ratio (O/B) (%)	27.96	72.04
Kernel-to-fruit ratio (K/F) (%)	36.00	64.00
Mean fruit weight (MFW) (g)	30.10	69.90
Mesocarp-to-fruit ratio (M/F) (%)	32.57	67.43
Vegetative characteristics		
Rachis length (RL) (m)	43.61	56.39
Leaflet number (LN)	23.56	76.44
Height/yr (H/yr) (m)	34.78	65.22
Harvest Index (HI)	17.67	82.33
Leaf area (LA)	37.91	62.09
Fresh fruit bunch (FFB) (kg/palm/yr)	20.00	80.00
Bunch no.	14.59	85.41
A bunch wt	31.81	68.19
Frond production (FP)	33.72	66.28

material revealed that the populations from Madagascar were distinct as measured by the characteristics used in the study. Surprisingly, the grouping of the populations reflects the original geographical collection sites.

Ward's method was used for the hierarchical clustering analysis since it is considered very efficient (Siracli et al., 2013). The samples were grouped according to their nearness

and similarity (Hossain et al., 2011). Based on the PCA, Ward's hierarchy clustered analysis

resulted in two major clusters (Fig. 13). The first cluster includes all the countries except

Angola and Nigeria which were present in the second major cluster. The first major cluster

consists of two subclusters. The first subcluster was formed by a minor cluster of Senegal

and Gambia materials reflecting their close proximity as shown in the African map, with

Madagascar being singled out. The oil palm populations from Tanzania and Zaire are

closely related since they are grouped together in the second subcluster. Oil palm from

Ghana and Cameroon as well as Guinea and Sierra Leone shared some similarities,

reflecting their geographical closeness.

6 Genetic diversity in oil palm: genetic markers

Morphological and agronomic characteristics are not always informative enough to

characterize diversity and they are often influenced by the environment. It is therefore

essential to use neutral markers such as molecular markers to investigate the genetic

structure of these materials to ensure a better utilization of present germ plasm in breeding

programmes. This information is also vital to guide breeders when planning breeding

programmes focused on crosses in order to develop new populations with sufficiently broad genetic base and degree of adaptability. A genetic marker is a DNA sequence

that is commonly recognizable by a restriction enzyme indicating a given chromosome

Figure 13 Dendogram of oil palm (cluster analysis tree chart) showing the relationship among 11

countries of germ plasm collections using 41 diverse characteristics.

(Hoelzel and Dover, 1991). A molecular marker or DNA-based marker is a DNA fragment

associated with a certain location within the genome.

Molecular markers used to analyse oil palm populations are as follows: • Microsatellite or Simple Sequence Repeat (SSR) (Billotte et al., 2000; Zulkifli et al., 2008). • Amplified Fragment Length Polymorphism (AFLP) (Kularatne et al., 2001). • Isozymes (Hayati et al., 2004). • Restriction Fragment Length Polymorphism (RFLP) (Barcelos et al., 2000; Rajanaidu et al., 2000). • Randomly Amplified Polymorphic DNA (RAPD) (Rajanaidu et al., 2000). • Single Nucleotide Polymorphisms (SNPs) (Ong et al., 2015).

These markers have proven to be useful in the investigation of oil palm genetic variability.

Each marker allows the reporting of allelic frequencies and other genetic variability

parameters such as the mean number of alleles per locus (Ao), mean effective number of

alleles per locus (Ae), the percentage of polymorphic loci (P), observed (Ho) and expected

(He) heterozygosity. Table 6 summarizes the genetic diversity for oil palm populations

using SSR, isozyme, AFLP and RFLP.

Significant intra-population genetic diversity has been found in natural oil palm

populations, irrespective of both the country of origin and the genetic markers used

(Table 7). Kularatne et al. (2000) employed AFLP markers when studying oil palm germ

plasm belonging to 11 African countries and Malaysia Deli dura and they revealed that the

higher proportion of total diversity was observed within populations (55%) than between

populations (45%). Similarly, the RAPD analysis of natural oil palms revealed a higher

proportion of diversity which could be attributable to within-population differences,

regardless of species (Rajanaidu et al., 2000).

Table 6 Genetic diversity of oil palm breeding and germ plasm material revealed by genetic markers

49 Natural oil palm

populations from 10

African countries and three

breeding materials of

Elaeis guineensis Bakoume et al. (2015) SSR 5.0 2.8 – 0.460 0.644

26 populations of

Elaeis guineensis from 100

African countries and Deli

dura Hayati et al. (2004) Isozyme 1.80 1.35 54.5 0.186 0.184

Four populations of breeding

materials maintained at

IOPRI (Indonesia) Purba et al. (2000) AFLP 19.2 – 61.0 – – Isozyme 1.81 – 36.4 0.332 0.300

Natural oil palm collections

from 11 African countries

and Deli dura Maizura et al. (2006) RFLP 1.66 – 53.0 – 0.199

The cluster analysis by Kularatne et al. (2001) resulted in oil palm populations divided

into three major groups (Fig. 14). The first major cluster belongs to oil palm from Ghana,

Nigeria, Cameroon, Democratic Republic of the Congo, Angola and Tanzania. Similar

results were observed when the analysis was carried out using isozymes by Hayati et al.

(2004) and RFLP by Rajanaidu et al. (2000). The palms originating from West Africa (Senegal,

Gambia, Guinea and Sierra Leone) were clustered in the second group indicating their

geographical closeness. Results based on the SSR analysis (Zulkifli et al., 2008) indicated

that Gambia and Senegal, as well as Guinea and Sierra Leone, were closely related to each

other. The uniqueness of Madagascar oil palm formed the third cluster, exhibiting low

genetic similarity with oil palms originating from other countries. The distinct relationship

of Madagascar oil palm from other countries was somewhat comparable to the results

based on other molecular analyses.

Phenotypic clustering analysis is slightly different compared to molecular analysis.

Indeed, Madagascar oil palm in the phenotypic analysis is related to Senegal and

Gambia, while Madagascar is totally distinct from other countries (Bakoume et al., 2015).

Madagascar is an island isolated from mainland Africa. The movement of pollen and

Table 7 Genetic diversity of oil palm breeding and germ plasm materials revealed by AFLP and RAPD

Natural oil palm collections from

11 African countries and Malaysia

Deli dura AFLP 0.55 0.45 Kularatne et al. (2000)

Natural

oil palm

populations

and Deli dura Elaeis guineensis populations RAPD 0.53 0.47 Rajanaidu et al. (2000) Elaeis oleifera populations 0.52 0.48

Figure 14 Dendogram of oil palm from different countries and Deli dura based on UPGMA analysis

and AFLP of simple matching similarities (Kularatne, 2001).

dispersal of seed through geographical barriers was thus limited, reducing gene flow.

This result shows the uniqueness of Madagascar oil palm as compared to other countries.

Palms from Madagascar are generally short with a high iodine value and linoleic acid

(C18:2) in oils (Rajanaidu et al., 2000).

Both phenotypic and molecular analyses showed similar results for oil palm from Gambia

and Senegal, as well as from Guinea and Sierra Leone. The grouping of Gambia and

Senegal has a strong geographical association since Gambia is actually a political enclave

of Senegal. The similarities between Guinea and Sierra Leone suggest that the main oil

palm belt begins in Guinea before spreading south through

Sierra Leone, Ghana and

other central African countries (Zeven, 1967). Significant genetic similarities of oil palm

between Tanzania and Zaire, and between Ghana and Cameroon, using both phenotypic

and molecular analyses, suggest a high migration rate between the regions. However, the

closer relationship between oil palm from Angola and Nigeria is quite difficult to explain.

Even though there are some differences in the clustering of populations using phenotypic

and molecular analyses, the information obtained from both analyses is important for

formulating a sampling strategy in order to establish a core collection of oil palm germ

plasm. Such analyses allow the conservation of oil palm germ plasm to be improved to a

manageable level to ensure the diversity of collections. Populations with sufficient diversity

can be used successfully for the development of new breeding populations.

7 Conservation of oil palm collections

Oil palm populations collected in various parts of the world can be preserved in in situ

and ex situ collections (Engelman, 1991). In situ conservation can be defined as the

conservation of species in their natural habitat, which is considered the most appropriate

way of preserving and managing biodiversity. In contrast, ex situ conservation relies on the

preservation of components of biological diversity outside their natural habitats.

7.1 Ex situ conservation

Ex situ conservation techniques include the following: • Field genebanks • Cryopreservation • DNA preservation • In vitro methods

The field genebank method is used for species which produce recalcitrant seed. Field

genebanks have the benefit that material is readily available for use. Field genebanks require

high maintenance costs, a large land area and they face possible exposure to diseases

and extreme weather conditions. In the case of oil palm, only 148 palms are planted per

hectare. To date, MPOB has successfully conserved approximately 100 000 palms collected

from West Africa and Latin America in an area covering nearly 500 ha (Fig. 15).

Cryopreservation is an alternative method to preserve oil palm tissues under extremely

low temperatures (-196°C) in liquid nitrogen. It was found possible to revive and germinate

oil palm zygotic embryo after freezing in liquid nitrogen (Grout et al., 1983). The plants

regenerated from frozen embryoids are predominantly normal as shown by Konan et al.

(2005). A simple desiccation stage should be conducted to reduce the moisture content

in the embryoids in order to prevent the loss of viability when stored in liquid nitrogen. In

comparison to ex situ preservation, this technique requires less space; lowers maintenance

costs; and protects the genetic materials from pests, diseases and extreme weather. For

long-term conservation, MPOB routinely stores zygotic embryos in liquid nitrogen. More than 34 000 zygotic embryos of accessions have been stored in the MPOB’s cryotank (Rajanaidu and Ainul, 2013).

DNA banking is an emerging technique which is aimed at ensuring the availability of genetic resources for oil palm improvement. Currently, MPOB runs a programme to preserve DNA samples of oil palm germ plasm in order to support molecular-based oil palm breeding. Readily available DNA samples are used for the verification of specific genotypes/crosses. DNA materials must be maintained under a stable condition at $-4^{\circ}C$ for long-term preservation (Mohd Din et al., 2014). Conservation of DNA from older palm and valuable genitors from seed production schemes is essential for future pedigree verification.

In order to preserve germ plasm, in vitro methods have also been used via embryo rescue, cloning and in vitro storage (seeds, embryo, polyembroid cultures and excised roots) (Rohani et al., 2000). The long-term preservation of oil palm collections via seed storage is not practical as the seeds can only be stored for two years (Rajanaidu, 1980).

7.2 In situ conservation

A sample of natural oil palm groves can be conserved on a long-term basis to represent various ecological niches. Natural palm groves in Africa harbour genetic diversity which is essential to plant breeders to develop high-yielding planting material. Such resources are rapidly disappearing in Africa because of the development and population pressures.

Under the guidance of FAO, MPOB has sought to preserve these resources for posterity

and safeguard the long-term interests of the oil palm industry in Malaysia and elsewhere

(Rajanaidu et al., 2000). Local population has supported the conservation of natural oil

Figure 15 Large-scale field planting of oil palm germ plasm in Malaysia.

palms since income can be generated and a variety of products be produced. Locals

have taken measures to protect and use natural oil palm groves, even though no or few

plantings have been carried out.

The concept of a core collection has been extensively studied by Brown (1989) and

Odong et al. (2013). As mentioned earlier, MPOB is conserving approximately 100 000

palms from West Africa and Latin America in a germ plasm collection occupying nearly

500 ha. The development of a core collection is cost-effective in increasing the efficiency of

conservation, characterization, use and regeneration of germ plasm. Various approaches

are used to preserve genetic diversity with a minimum number of accessions. As

recommended by Odong et al. (2013), MPOB studied the genetic distance of collections

using both molecular and phenotypic data. The study of genetic distances highlighted

gross differences between populations for core collections. In addition, breeders have also included some elite germ plasms in the core collection.

8 Utilization of germ plasm

MPOB runs the largest oil palm germ plasm collection in the world. Samples from all across

the oil palm belt have been sampled in order to capture the full range of genetic variation.

It is essential that germ plasm collections are maintained for the future. However, since this

strategy is costly, it is also essential that these collections are used effectively (Corley and

Tinker, 2016; Spraque, 1986). At MPOB, oil palm germ plasm has been evaluated and is

being utilized in a number of ways. These are discussed below.

8.1 Direct selection of individual elite palms

The breeding and selection of oil palm are time-consuming and difficult. Normally, newly

introduced genetic material has no potential for direct commercial use. It has to be

introgressed into another advanced material. The new gene pool will only be considered

for immediate use if it possesses interesting traits and acceptable yields. Elite palms which

are high-yielding and compact, such as P126, can be cloned.

8.2 Broadening the genetic base of Deli duras and teneras/pisiferas

Crossing Deli duras with Nigerian duras/teneras broadens overall genetic variability.

Increasing the amount of heritable variation for desired traits of these introgressed

populations is the basis for further selection and breeding. Selected palms need to possess one or a combination of desirable traits such as high bunch yield, superior oil and

kernel content, reduced height and superior oil quality.

8.3 Progeny testing of duras and pisiferas

Outstanding Nigerian tenera varieties were progeny-tested with a range of commercial

Deli duras varieties. The T × D or D × T hybrids and their dura and tenera parents are

selfed simultaneously. The purpose of the crossing programme is to progeny-test the

Nigerian teneras to study their combining ability. By using reciprocal recurrent selection,

the selfs can be used in the seed production (Jacquemard et al., 1981). The pisiferas

varieties are also progeny-tested to evaluate their combining ability with Deli duras.

8.4 New foundation of breeding programmes

Germ plasm is used to initiate entirely new breeding programmes aimed at producing

superior alternatives to Deli duras and modern breeding teneras. This is because of the

presence of teneras comparable to the best current material, produced from Nigerian

dura × Nigerian pisifera.

8.5 Development of elite DxP planting materials

The main objective of oil palm germ plasm collections is to make use of outstanding palms

with useful attributes and to introgress such genotypes into current breeding material.

The emphasis is on the attributes such as short stems, more liquid oil composition, high carotene content, long stalks and high kernel yield. Since 1992, 14 distinct genotypes

have been distributed successfully to the oil palm industry in Malaysia by MPOB (Table 8).

Recently, MPOB has released the PS14 genotype related to high protein kernel as an

alternative to imported ingredients for animal feed (Noh et al., 2015).

After undergoing extensive progeny-testing, the MPOB has been able to breed shorter

planting materials (PS 1.1) based on the MPOB-Nigerian population No. 12. Some of

such crosses were found to produce high oil yield and to be 30% shorter than the DxP

control (Rajanaidu et al., 2013). This characteristic makes bunch harvesting easier and

more amenable to mechanization, thus reducing production costs.

Table 8 Commercial oil palm planting materials and breeding populations transferred by MPOB to

the industry

No. PORIM series no. Trait Year of transfer Intended use of material

1 PS1 Dwarf 1992 Planting material

2 PS2 High iodine value 1992 Planting material

3 PS3 Large kernel 1996 Breeding population

4 PS4 High carotene (E. oleifera) 2002 Breeding population

5 PS5 Thin-shelled tenera 2003 Breeding population

6 PS6 Large-fruit dura 2003 Breeding population

7 PS7 High bunch index 2004 Breeding population

8 PS8 High vitamin E 2004 Breeding population

9 PS9 Bactris gasipaes 2004 Economic palm

10 PS10 Long stalk 2006 Breeding population

11 PS11 High carotene (Elaeis guineensis) 2006 Breeding population

12 PS12 High oleic 2006 Breeding population

13 PS13 Low lipase 2008 Breeding population

Source: Mohd Din et al. (2014).

9 Conclusion

International cooperation and collaboration are vital to collect and conserve oil palm germ

plasm which is the lifeline of the industry. International treaties such as the Convention on

Biodiversity and the International Treaty for Plant Genetic Resources, as well as the work

of the FAO Access and Benefit Sharing Working Group, govern the regulations on the

collection of oil palm germ plasm in foreign countries. Preservation of natural oil palm

germ plasm in situ needs international cooperation between developed and developing

countries in order to finance long-term conservation projects which are largely located in

farmers' fields.

10 Where to look for further information

Further information on the contents of this chapter can be obtained on the websites of: • Malaysian Palm Oil Board • Indonesian Oil Palm Research Institute • CIRAD • CINEPALMA, Colombia • ASD Costa Rica • International Treaty on Plant Genetic Resources for Food and Agriculture and Access and Benefit Sharing • Convention on Biological Diversity (CBD) • International Society for Oil Palm Breeders (ISOBP)

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7 Chapter 7 Advances in conventional breeding techniques for oil palm

1 Introduction

The oil palm has been grown in Africa for thousands of years. The oldest traces of oil

palm, in the form of pollen, date back to the Eocene period (Zaklinskaya and Prokofyev,

1971). Pollen has been found in all the current areas of oil palm cultivation in Africa from

the Miocene period (23.03 Ma to 7.246 Ma) (Zeven, 1964). Oil palm has been cultivated in

Egypt since 3000 BC (Friedel 1897 in Zeven, 1967).

Oil palm has played a fundamental role in the nutrition, technological, economic

and social development of many African forest peoples. For these populations, the oil

palm is central. It provides wine, oil and sauce from seeds. It is used to build houses,

provide flooring and weave hunting nets and traps as well as build dams to catch fish.

In short, ‘the oil palm has so many uses that cannot be counted’ (Haxaire, 1992). The

oil palm is also part of founding myths. For the Gouro people from Côte d’Ivoire, ‘That

Bali, the creator God has given to man before putting on earth is the palm. He gave

it to eat… The oil palm and man are the same, the palm is on earth, and humans are

on earth. God has given us oil palm to watch men’ (Haxaire, 1992). Despite such an

ancient and strong relationship between the oil palm and the populations of African

forests, the oil palm is mostly only semi-domesticated. No attempts were made to

propagate the palm by sowing seeds and/or transplanting seedlings (Zeven, 1972).

Hence, African populations almost never planted oil palms. This was the case in Guinea

(Madelaine, 2005), Côte d'Ivoire (Blanc-Pamard, 1980; Haxaire 1992), Togo (Tchamie,

1995), Cameroon (Baeke, 1996) and the Democratic Republic of Congo (Eggert, 1993).

When old oil palm stands were present, seedlings spontaneously sprouted and were

protected by clearing regularly around them so that they could receive enough light

(Haxaire, 1996). This clearing and elimination of some oil palm seedlings allowed a

natural expansion of the oil palm. Maley (1999) described two types of palm groves

used by the African populations: (i) forest regrowth where oil palm is a leading pioneer

species and (ii) sub-spontaneous oil palm groves near the villages, in fallows and other

type of vegetation disturbed by human activity.

At the beginning of the twentieth century, various authors reported that Ébriés in Côte

d'Ivoire (Bret, 1911 in Zeven 1967), and Togo (Grüner, 1904 in Zeven 1967), were able to

sow unselected seeds. Transplanting unselected palm was also done in Dahomey (now

Benin) (Zeven 1967) and in Ghana. At this time, selecting and planting seeds was a quite

rare practice, although it was done in Nigeria, Angola and Congo. In the middle of the

twentieth century, Tovey (1947) observed that the ratio of

Tenera 1 palms in Ufuma (Nigeria)

was higher than that in natural oil palm groves. Sparnaaij and Blaak (1963) had observed

the same situation in Nigeria. These abnormal ratios have also been described in Angola

and Congo (Zeven, 1967).

Therefore, oil palm could be considered as having not been subjected to breeding

historically, meaning that at the beginning of the twentieth century it was a semi-wild

crop. In the middle of the nineteenth century, oil palm was planted in different botanical

gardens and breeding started at the beginning of the twentieth century both in Africa and

Asia. In the present chapter, we will present the story of oil palm breeding which occurred

between the beginning of the twentieth century and the end of the 1950s, and then the

current state of oil palm breeding. Present breeding strategies will be described via the

various breeding schemes at work, traits observed, mating designs, and the experimental

designs used. The organization of seed production for oil palm will also be reviewed.

This chapter will mainly focus on oil palm breeding carried out by Institut de Recherche

pour les Huiles et Oléagineux (IRHO), CIRAD and now PalmElit, although oil palm

breeding activities by other companies will also be discussed. Finally, the future trends

in oil palm breeding will be explored.

2 Early history of oil palm breeding

Oil palm breeding is based on populations developed in different countries or in

different estates from the 1920s, and generally originated from a limited number of

founders. These populations have been named ‘breeding population of restricted

origin’ (BPRO) by Rosenquist (1986). Such populations are still now at the base of the

distinction between the principal seed suppliers. The main BPROs are presented in the

subsequent sections.

1. Tenera palms: oil palms with a thin shell. The shell thickness genetic determinism is important for oil palm breeding. It is explained

in Section 3.1.

2.1 Populations from Africa

Côte d’Ivoire

The botanical garden at Bingerville was established in 1900. Besides various food crops,

forestry species and introduction of accessions from several countries, the botanical

garden included a natural oil palm grove. In 1915, under the direction of Paul Teissonnier,

the garden focused its works on cocoa, oil palm, coffee, kola, rubber plants, plantain,

forest, fruit and ornamentals. In 1915 and 1917, selected oil palm were planted on

3.5 ha (Tourte, 2005; Houard et al., 1926). The first survey undertaken in the Bingerville

area (Bingerville botanical garden, Blachon concession, Granjean concession, Drevet

concession, Necker concession in M’Bato) resulted in the collection of 133 oil palms.

In 1925, the La Mé Experimental Station assessed 43 palms from which 20 palms were selected (Houard, 1926; Gascon et de Berchoux, 1964). Finally, 19 palms were ‘selfed’ and planted in La Mé Experimental Station between 1924 and 1930 (Cochard et al., 2006). In 2006, of these 19 palms, 6 selfed palms, namely M12, B205, B212, B247, TEIS3 and BRT10, survived. BRT10 is the base of the current breeding programme developed by CIRAD and PalmElit.

Cameroon

In 1904, trials and breeding of the Lisombé 2 were undertaken in the botanical garden of Victoria (Limbé) by Preuss. In some reports, it is said that 100 000 palms of Lisombé were received in the Kribi area and planted along the Kribi-Longji road. However, oil palm was rare in the Kribi area (Annet, 1921).

Before 1910, only a few concessions existed. Among these, the Deutsche Kautschuk Aktien Gesellschaft had planted oil palms in 1914, in Mpondo on the Mongo River near Ekona (Annet, 1921). The Ikassa Estate belonging to the Gesellschaft Süd Kamerun (Courade, 1978) was probably planted in 1913, using seeds from the Ekona 3 district (Corley and Tinker, 2003).

The history of Ekona BPRO has been described in detail by Rosenquist (1986). The United Africa Company planted oil palms from 1928 to 1933. Seeds were obtained from Calabar (Nigeria) and Ikassa Estate and selection started in 1933 in N'Dian. Seeds

from controlled pollinations were planted in N'Dian and the Cowan estates in Nigeria.

In addition, 800 palms were used to produce open-pollinated seeds for Cowan estate.

Selection on the two estates led to the selection of 19 teneras, 6 duras and 2 fertile

pisiferas. From this programme, 18 crosses and 5 selfs were planted in 1954/1955 in the

Lobé Estate in Cameroon which was newly designed for oil palm plantation. This was the

basis of the so-called Ekona population.

Democratic Republic of Congo

Here, breeding began with the creation of the Botanical Garden of Eala in 1900. The

Yangambi Research Station was created after the First World War (Drachoussof, 1989)

and, in 1921, Ringoet, the director of Yangambi, developed an interest in palms from

N'Gazi. Mr Tihon, a chemist from Eala, identified the famous 'Djongo' palm in the

2. Lisombé: Disombé or Lisombé was the name given by the Bakondo people to Elaeis guineensis var. Tenera, Beccari (Annet, 1921).

3. Possibly, it is the Ekona mentioned by Annet (1921).

'clonal' gardens. Ringoet planted these palms in a 4 ha field called the small 'plantation

de la Rive', now known as 'Palmeraie de la Rive'. Of the 1880 palms planted, 583

were kept after analysis (Ergo, 2013). This plantation would be complemented by four plantings: • The first one was done in 1924 with palms from N'Gazi, Yawenda and Isangi (Demol et al., 2002) and excess from the nursery dedicated to 'Plantation de la Rive'. • The second one was carried out in 1927 using seeds from N'Gazi. • The third one, in 1929, constituted of illegitimate seeds originating from oil palms of the 'Plantation de la Rive'. • Finally, the fourth one was planted in 1930 with one illegitimate progeny from the 'Plantation de la Rive' (Ergo, 2013).

These five selected oil palm groves constituted the basis of the Yangambi breeding

programme.

Nigeria

From 1911 to 1915, 800 oil palms were planted by E. Smith from the Nigerian Department

of Agriculture. Data for yield and bunch compositions were collected from 1922 to 1928

and nine dura and ten tenera palms were selected. Twelve palms were self-pollinated to

form the Calabar F1 generation. The progenies were planted between 1930 and 1935 on

four stations (Hartley, 1967).

In the 1920s, an oil palm selection programme was initiated in a 11 ha grove located

near Aba. Several thousand out-pollinated palms were established at the oil palm research

station near Benin City in 1939/1941 (Hartley, 1967).

Benin

Between 1922 and 1927, 38 oil palms were chosen in the sub-spontaneous oil palm groves

located near Porto Novo and Pobè (Gascon et de Berchoux 1964), and gathered in the

Pobè Research Station (Institut National de Recherche Agronomique du Bénin - INRAB).

Thirty-five palms were 'selfed' and planted in Pobè. Fourteen palms are still represented

in Pobè in 2016 by their 'self' (AG1, AS2, ED2, FAG1, J1, L10, Lo10, M9, MK5, OD1,

OD2, OL4, S2, S4). However, this population was never used in the current breeding

programme.

2.2 Other populations

Indonesia and Malaysia

Open pollination from the Djongo palm from the Eala botanical garden in Congo was

distributed to Sungei Panchur Research Station in Indonesia. Only 13 seedlings survived (8

duras and 5 teneras). One of the tenera was the SP540T. This palm is one of the pillars of

the Marihat (Indonesian Oil Palm Research Institute – IOPRI) breeding programme. SP540T

is also the basis of the so-called AVROS (Algemeene Vereniging van Rubber Planters ter

Oostkust van Sumatra) population; this population is also crossed by the name BM119,

planted in 1957 in Banting (Malaysia) (Corley and Tinker, 2003).

Deli populations

In 1848, four 1-year-old oil palm seedlings were introduced in Indonesia, at the Bogor

(Buitenzorg) Botanical Gardens. These four oil palms came from Bourbon Island (now La

Réunion Island, a French overseas region). Two seedlings came directly and two others

arrived via the Hortus Botanicus of Amsterdam (Rosenquist (1986) quoting Toovey and

Broekmans (1955), Hunger (1917) and Rutgers, (1922)). Hunger (1924) explained in detail

why there was confusion between Réunion Island and Mauritius, and therefore why he was

almost certain that the palms came from Réunion Island. Seeds from the Bogor Botanical

Gardens were sent to Sumatra in 1874 or 1875 to the Deli Maatschappij. Hunger (1924)

and Jagoe (1952) described in detail the early history of the development of the Deli

populations.

3 Oil palm breeding from the beginning of the 20th Century

3.1 Shell thickness

Chevalier and Beccari in the beginning of the twentieth century identified a number of oil

palm varieties which were classified by Professor Jumelle (Anet, 1921) according to shell

thickness: • Thick kernel (2–4 mm) from black fruit before ripening and red after, normal mesocarp of 2–3 mm, non-angular fruits, 35–40 mm: var. dura Becc. • Thin kernel (<2 mm) from black fruit before ripening and red after, fruit not beaked on the top, unwelded leaf segment, fruit length from 22 to 28 mm and fruit width from 18 to 22 mm, kernel throughout the length of the fruit: var. tenera Becc. • Thin kernel (<2 mm) from black fruit before ripening and red after, fruit not beaked on the top, unwelded leaf segment, fruit length from 23 to 28 mm and fruit width from 16 to 19 mm, reduced kernel across the top of the fruit: var. pisifera Chev.

African people also knew these different fruit forms, for instance: • Dura was called Dipobe (near Douala, Balong, Bakondo) in Cameroon (Annet 1921), possibly Dé-Yaya in Benin and Adé-Quoi for Ébriés in Côte d'Ivoire (Houard et al., 1927). • Tenera was called Sombé (Douala, Balong, Abo, Nyombé, Disombé or Lisombé (Bakondo) in Cameroon (Annet, 1921), Dé-Kla or Dé-Gbakoun in Benin, and AquoiSran or Adé-Sran for Ébriés in Côte d'Ivoire (Houard, 1927). • Pisifera was called Djoungoumea (Douala) in Cameroon (Annet, 1921), Votchi in Benin, and nothing for the Ébriés in Côte d’Ivoire (Houard, 1927).

It is clear from the above facts that botanists and the African people were able to distinguish

between different oil palm fruit forms, but did not understand the relationship between

them. It was only in 1941 that Beirnaert and Vanderweyen described how a single gene

controls the shell thickness of oil palm. Hence, the dura form was defined by sh + /sh + ,

tenera by Sh + /Sh – and pisifera by sh – /sh – . However, these authors observed in tenera x

tenera crosses or selfings some divergences from the 25% dura: 50% tenera: 25% pisifera

ratio. In addition, it is known that within such classifications, there is a polygenic variation

of the fruit form.

3.2 The ‘Experience Internationale’

Until the Second World War, breeding programmes implemented in Asia and Africa

were mainly carried out on local populations. Oil palm being a cross-pollinated plant, it

was considered interesting to assess crosses made between different populations. From

1946, the ‘Expérience Internationale’ was initiated with the aim of first testing different

combinations between African populations, and between the Deli population and African

populations. They were also interested in researching why the Deli dura generated better

yields (Ferrand, 1946 – internal notes): • Breeding dura is better than breeding tenera, • The weather conditions are better in Asia than in Africa for oil palm.

Genetic trials undertaken between 1950 and 1954 revealed that African populations

produced twice as many bunches than the Deli population. The average bunch weight

(ABW) in the Deli populations were found to be higher than that of the African populations.

Deli populations also produced the highest mesocarp to fruit (%M/F) ratio.

The fresh fruit bunch (FFB) measured in inter-origin crosses was significantly higher than

that of the parental origin. Number of bunches (NB) and ABW of inter-origin crosses were

intermediate to that of parental origins. The percentage of M/F and the percentages of

palm oil and of total oil in inter-origin crosses were intermediate to that of parental origins.

Finally, inter-origin crosses displayed a better annual oil yield than that of the parental

origins (Table 1) (Gascon and de Berchoux, 1964).

The improved performance of inter-origin crosses has been recorded, and breeding has

been directed towards improving these crosses. Hence, the reciprocal recurrent selection

(RRS) strategy presented by Comstock et al. (1949) was adapted with full-sib progenies Table 1 Results from the ‘Experience Internationale’ – oil yield (kg/palm/year) for inter-origin crosses and their parental origin. Average 5–6 years (Gascon and de Berchoux, 1964) Crosses Number of progenies Oil/palm/year (kg) La Mé × Deli 22 Dura Tenera 18.9 27.0 Yangambi/Sibiti × Deli 5 Dura Tenera 22.0 30.2 Deli × Deli 12 Dura 16.6 La Mé × La Mé 15 Dura Tenera 12.7 17.8 Yangambi/Sibiti × Yangambi/Sibiti 26 Dura Tenera 15.8 22.0

instead of half-sib progenies and with the addition of selfs (Gascon and de Berchoux,

1964).

3.3 Current breeding

Two major breeding methods were followed: • The RRS was adopted in 1957 by IRHO (Meunier and Gascon, 1972). The first cycle has been planted in the La Mé Station between 1959 and 1968 (Gascon et al., 1988). Between 1975 and 1986, the first set of the second cycle was planted in Aek Kwasan (Indonesia) and in La Mé (Côte d'Ivoire). It was followed by several sets of the second cycle of selection from 1995 until now. • The FIS was defined by Hardon (1970). This method was mainly adopted by South Asian companies and research institutes.

Some minor breeding methods also exist for oil palm breeding: • Pedigree selection has also been practised in Nigeria, Indonesia and Malaysia (Rosenquist, 1990). In several breeding programmes, a F3 generation (two generations of self) was obtained. This strategy is designed for the long term, with the aim of obtaining pure lines after 10 generations (80–100 years). As oil palm is an outcrossing species, the strategy takes into account the inbreeding depression effect. • Backcross breeding is also used for specific programmes. Dumpy Deli was introgressed into AVROS, which had been developed by backcrossing SP540T x Bangun with SP540T (Soh et al., 2006). This method is also used for specific traits such as dwarfness (Adon et al., 2001) and it is also commonly used with Elaeis oleifera by introgressing E. oleifera into E. guineensis.

4 Breeding objectives and methods

4.1 Breeding objectives

CIRAD and PalmElit have described major traits that need to be taken into account for

breeding programmes.

The first aim concerns increasing the oil yield. This is the first priority as it is the main

profitability factor for plantation companies. To do so, two principal components of the oil

yields are taken into account, namely FFB which is the weight of bunches per hectare for a

given period, and oil extraction rate (OER) which governs the quantity of oil in the bunch. • FFB is also the result of two components: the bunch number (BN) and the ABW, • OER is the result of three components: percentage of fruit to bunch (%F/B), percentage of mesocarp to fruit (% M/F) and percentage of oil to mesocarp (%O/M).

The second aim is to select for resistance to diseases. The first works were carried out on

Fusarium wilt which is mainly located in Africa. Early screening tests have been developed

from the initial work of Prendergast (1963) at the nursery stage. Renard et al. (1972) adapted

screening tests to the pre-nursery stage and this method is still used. In South East Asia,

and increasingly in Africa, basal stem rot affects plantations and an early screening test has

been developed for Ganoderma (Breton et al., 2006). Finally, in Latin America, a complex

of lethal bud rot damages plantations. It is possible that the causal agent is Phytophthora

at least in Colombia (Martinez et al., 2009; Torres et al., 2010), but this hypothesis still

needs to be confirmed. No early screening tests are routinely available and screenings are

done through planting in bud rot-infested zones. These resistance breeding objectives are

presented in detail in this book.

Tolerance to marginal cultivation conditions, especially to dry conditions, is becoming

increasingly significant due to climate change, and the necessity to develop this crop

under marginal conditions.

Other breeding objectives are to reduce height growth in order to increase the economic

life of a plantation, to reduce tree size in order to increase the density and therefore the oil yield, and to reduce lipase activity in order to have more time between harvesting and processing in the oil mill.

Soh et al. (2009) presented the priority list of desirable traits for the genetic improvement of oil palm in Malaysia. It includes characteristics such as high palm oil yield, dwarf stature, Ganoderma resistance and high oleic acid.

4.2 Breeding methods

Reciprocal recurrent selection (RRS)

RRS is based on the approach developed by maize breeders (Comstock et al., 1949), and relies on the development of two complementary populations. This method concentrates the desirable traits by increasing the frequency of these traits in the populations. It is well adapted to produce improved hybrids, and particularly to enhance low-heritable traits.

This method is composed of two cycles: a cycle of recombination or self, and a cycle of progeny testing (Fig. 1). These two cycles can be repeated over time.

Initially, populations have been divided into two groups (Gascon et de Berchoux, 1964): • Group A includes dura palms of the Deli origin, which have a small number of large bunches, • Group B includes pisifera of La Mé and Yangambi/Sibiti origins, which have a large number of smaller bunches.

Some other populations have been added later in the process (Meunier et Gascon, 1972) • Angola and Cameroon have been added to group A • Pobè, Yocoboué, Nigeria and also Cameroon have been added to group B

The test phase consists of assessing crosses between palms of group A and palms of group B. The DxT or DxP hybrids obtained are planted in comparative trials. This enables

the ranking of crosses (progenies) and corresponding parents, and highlights particular

combining abilities.

The recombination phase consists of crossing or selfing the best parents of the test

cycle. In group A, crosses are realized between the best duras (DxD) and selfs. In group

B, crosses are realized between the best tenera and pisifera, (TxT and TxP), and selfs of

tenera.

This method, with very minor modifications, was used by INEAC (Institut National pour

l'Etude Agronomique du Congo Belge) (Picel, 1956; Sparnaaij, 1958). The WAIFOR 4

(West African Institute for Oil Palm Research) adopted the same method, but the studied

population was more diverse and less inbred (Sparnaaij et al., 1963). Finally, Dami Oil Palm

Research Station also used this breeding method in Papua New Guinea (Dumortier, 2003).

Backcross: dwarfness

The introgression of slow vertical growth in improved oil palm populations is an example

of a backcross breeding programme for E. guineensis. In group A, the Dumpy Deli

population is known for its dwarfness. In group B, there is a progeny of the palm 1-2T (or

PO452T) originating from the Akpadanou region in Benin (Adon et al., 2001).

Amongst different crosses, Deli x Dumpy Deli and PO452T x

La Mé crosses were found

to display slow vertical growth. In trials planted in 1983-1985 at La Mé Station, Dumpy Deli

x Deli showed a vertical growth which was 28% lower than the control cross. For PO425T

self x La Mé self, the vertical growth rate was even lower, showing less than 42.7% to

the control cross. However, these crosses had a low oil yield (Adon et al., 2001), thus it

appeared necessary to develop a programme of backcross in order to combine the high

yield of the Deli and La Mé material with the dwarfness of Dumpy Deli and PO452T (Fig. 2).

4. WAIFOR is becoming the NIFOR, Nigerian Institute For Oil palm Research. Group A Populations Deli, Angola… Group B Populations La Mé, Pobè, Nigeria, Cameroon, Congo… Base Populations Dura selfs and DxD crosses TxT, TxP crosses T selfs 1 st Cycle 2 nd Cycle Improved Deli populations Improved La Mé, Pobè, Nigeria… populations DxT and DxP Hybrid test TxT, TxP crosses T selfs Improved Deli populations Improved La Mé, Pobè, Nigeria… populations DxT and DxP Hybrid test Dura selfs and DxD crosses

Figure 1 Recurrent reciprocal selection programme in PalmElit/Cirad.

Backcross: Elaeis oleifera

E. oleifera has been the focus of attention of oil palm breeders for a long time. E. oleifera was

introduced at Eala (DR Congo) in 1927 and its progenies at Yangambi in 1940/41 (Vanderweyen

and Roels, 1949). Elsewhere this happened in 1952 and 1956 in Indonesia (Lubis, 1988) and

then in La Mé Station in 1960 (Meunier, 1975). This palm presents interesting properties such

as tolerance to lethal bud rod in Latin America, oil fluidity, and slow vertical growth. In addition, some ecotypes seemed to display some good resistance to vascular wilt (Renard et al., 1980).

First, an interspecific hybrid improvement programme was set up: this has been

presented in details by Le Guen et al. (1991) and was initially designed by Meunier et al.

(1976). It consisted of: • Tests measuring combining ability between ecotypes, to determine which populations combined well with each other • Test of individual combining ability, to identify the best parents from both E. guineensis and each E. oleifera.

In La Mé (Côte d'Ivoire), Aek Kwasan (Indonesia), Pobè (Benin) and Rio Urubu (Brazil), 11

common E. oleifera and 7 E. guineensis have been tested. Quickly, it appeared that the

partial sterility of the interspecific hybrid was important (Arnaud, 1980). Bunch production

can be comparable to that of E. guineensis, although OER remained low in the interspecific

hybrid. However, interspecific hybrids are still the only solution for plantations affected by Group B La Mé, SP540, Yangambi DeliDumpy Backcross Trials Deli Trials Progeny tests Trials Improved Group B Group A Group A PO452T LaMé Deli, Angola Backcross Trials La Mé, SP540, Yangami Trials Progeny tests Improved Group A Trials Group B

Figure 2 Introgression of Dwarfness of Dumpy Deli and PO452T in improved populations.

lethal bud rot, through the introgression of E. oleifera's desirable qualities into the African

oil palm. A breeding strategy for interspecific hybrids and for backcrossing, with the aim

of introgressing E. oleifera's desirable qualities into E. guineensis, has been described by

Le Guen et al. (1991).

Many programmes of backcrossing have been undertaken, for example, in Nigeria

(Obasola et al., 1977), Costa Rica (Sterling et al., 1988; Escobar and Alvarado, 2003) and

Malaysia (Tam et al., 1977; Rajanaidu et al., 1983).

The major problem posed by interspecific backcrosses is the assessment of the yield. In

first generations, the value of the family does not have real significance (Durand-Gasselin

et al., 2009) and the problem is the same at the individual level (Soh, 2003).

Family and individual selection (FIS)

This method, called family and individual selection (or FIS; Hardon, 1970) or modified

recurrent selection (Soh et al., 2003), is widely used in South East Asia. The first step

is a mass selection: the selection of Deli dura parents is based on family and individual

palm performances. These parents can be used for both seed production and breeding

programmes. The tenera parent selection scheme follows the same method. However, for

the seed production, pisifera are needed, so they are selected on the basis of the tenera

sibling performance. Then a DxP progeny trial is implemented. This confirms the choice of

pisifera selected for seed production (Soh et al., 2009).

The choice of this method was based on several hypotheses. The number of palms

constituting the base population favours less genetic drift and inbreeding. The latter can

be considered as a reverse selection and it is also important to broaden the genetic base.

Under such conditions, the eigenvalue and the breeding value were found to show a good

correlation. It is for this reason that the method uses crosses between different BPROs, and

why relatedness is systematically avoided. Therefore, this resulted in an exacerbated GCA

(general combining ability 5), and forced the introduction of new germplasm (Soh et al.,

2009; Corley and Tinker, 2016).

4.3 Mating design

The test phase

The biparental mating design was used during the first cycle of the RRS and at the beginning

of the second cycle. At the end of the 1970s, NCM1 (North Carolina Model 1) was used for

a limited number of progeny testing trials. Since then, only incomplete factorial design was

used, and this was later complemented by adding testers. This model allowed estimations

of both the GCA and the SCA, although the GCA was largely predominant.

The recombination phase

In RRS, the focus is on the recombination phase, where most importantly the hybrid

crosses between group A and group B are assessed. This is because commercial seeds

are a representation of the best hybrids. For this step, the biparental mating design was

mainly used. There were a few attempts at using diallel design, but this did not last long.

5. General combining ability: it is the average genetic effect transmitted by an individual to its offspring.

The biparental mating design is mainly used as it allows the assessment of many more

crosses compared to the diallel mating design.

Soh et al. (2009) explained that for the FIS method, the biparental mating design is

used in the parental crosses. All the known genetic mating designs are used for dura x

dura, tenera x tenera and tenera x pisifera within population crosses and also for the dura

x tenera and the dura x pisifera inter-population progeny test crosses (biparental crosses,

NCM1, NCM2, diallels).

4.4 Experimental design

The test phase

The first experimental design was based on row planting: progenies were planted in rows,

generally with 3 replicates of 3 rows. Nowadays, the main experimental design is the lattice,

which is a balanced incomplete block design. Indeed, 16 or 25 crosses are tested, using 5 or

6 replicates of 12 or 16 palms per replicate. When the number of crosses differs from 16 or

25, the randomized complete block design is used with 6 replicates. Finally, the D-optimal

design has been tested which is an unbalanced incomplete block design. Instead of having

5 trials with connections or control crosses between trials, all the crosses can be tested in

the same trial. However, this design has proved difficult to manage in practice.

The recombination phase

All the crosses are planted by rows. In group A recombinations, progenies are often represented by 13 palms. However, progenies of the seed garden can also be considered

as recombinations. In this case, the number of palm per progeny can reach 300. In group B

recombinations, progenies are often represented by ca. 26 palms. As for group A, progenies

from the seed garden can also be considered as recombinations. Here, the number of

palms can reach 78. The maximum number was for the self of LM2T with 644 palms.

5 Data collection methods

5.1 Oil yield

The oil yield is measured through its two major components: the FFB yield and the oil to

bunch (O/B) yield.

FFB yield is collected for each palm, from the third year after planting to the end of the

ninth year. Every 7-15 days of the harvesting cycle, the number and weight of the ripe

bunches are recorded. This allows to record the NB, the total FFB and the ABW for a palm

each month and so for each year.

The O/B is estimated differently. For the test phase, O/B is determined at the progeny

level. For dura x tenera, all the teneras are analysed once at 5 years of age and once when

they reach 6 years old. For the dura x pisifera, 40 teneras are analysed when 5 and 6 years

old. In the recombination phase, for the dura x dura, all the palms are analysed at 5 and 6

years of age. For the tenera x tenera and tenera x pisifera, only the teneras are analysed when 5 and 6 years old. Depending on the progeny value, the number of bunch analyses

can be increased from 2 to 4, and even to 8 in some cases.

The bunch analysis method was derived from the method developed by Blaak et al. (1963)

at Waifor. For bunches under 14 kg, the ratio of the fresh fruit weight to the bunch (fresh fruit +

spikelet + stalk) weight (F/B) is determined for the whole bunch. For bunches over 14 kg, F/B is

estimated from half of the bunch. A sample of 30 random normal fruits is taken and weighed.

The mesocarp is scraped off. Nuts are then weighed. The ratio of the mesocarp to the fruit

(M/F) is then estimated. Finally, the oil to mesocarp (O/M) ratio is measured by extracting oil

with a solvent (hexane) in a giant Soxhlet apparatus. F/B x M/F x O/M give the O/B. Instead of

using the O/B ratio, we prefer to use the OER which is the O/B x 0.855. This correction factor

corresponds to an estimation of losses during extraction under mill conditions.

Palm oil yield is the result of NB x ABW x F/B x M/F x O/M x 0.855 or FFB x OER.

In addition, the kernel oil yield is determined. Kernel weight of the 30 fruits is recorded.

The kernel oil content is estimated to 50%. Kernel OER is the result of F/B x K/F x 0.5.

5.2 Oil quality

Iodine value is measured on oil samples after the bunch analysis procedure. This method

relies on a titration with a Hanus reagent and thiosulphate, which allows the unsaturated fatty acid content to be estimated.

5.3 Lipase activity

After harvesting, a rapid acidification of bunches occurs. This is due to a high endogenous

lipase activity that releases free fatty acids (FFA) in the mesocarp of bruised ripe fruits

(Sambanthamurthi et al, 1995). Low FFA is a requirement for good quality palm oil. A

FFA content of more than 5% is considered to be inadequate for human consumption

(Ngando-Ebongue et al., 2008). Identifying the genetic variability of this trait, is important

in order to facilitate harvesting and limit oil acidity. The oil acidity is estimated by FFA

titration. For this, the pressed mesocarp is placed in solution in a solvent mixture. FFAs

are titrated with an ethanol solution of potassium hydroxide containing phenolphthalein.

5.4 Vegetative traits

Vegetative traits are measured for each individual palm tree. Height is measured according

to Jacquemard (1979), mainly at 6 and 9 years old, although measurements at 12 and 15

years old can also be added. Canopy and leaf area index are measured at 10 years old.

Canopy is the average of the projection on the ground of the longest three leaves at

three directions measured at 1.5 m height. Leaf area index was adapted from the method

described by Tailliez and Ballo Koffi (1992).

6 Impact of reciprocal recurrent selection (RRS) on oil yield

6.1 The Expérience Internationale

In La Mé, Côte d'Ivoire, at the end of the 1940s, the oil yield per hectare reached 1.9 tons.

The main result of the Expérience Internationale was to highlight the interest of Deli x Africa

crosses with an oil yield increase of 58%, thus reaching 3 tons/ha (Gascon and Wuidart, 1975).

6.2 The first RRS cycle

The first cycle was implemented from 1959 to 1968 in La Mé and it was called 'Bloc 500'. On

500 hectares, 392 crosses of Deli x Africa were assessed. Almost 62 crosses were selected,

with an average oil yield per hectare and per year of 3.9 tons. Compared to the Expérience

Internationale, the gain was about 30%. Compared to the best crosses from the Expérience

Internationale, LM2T x DA10D, the gain was 18% (Gascon et al., 1981).

On these 62 crosses, a selection was carried out based on height growth. The average

height growth in the studied population ranged from 36 to 76 cm. It was decided to select

only crosses displaying a height growth lower or equal to 50 cm/year. Finally, the height

growth of the selected crosses was around 45 cm/year. However, this selection ended up

in the rejection of a large number of Deli x Yangambi crosses (Gascon et al., 1981).

The fatty acid composition of fruits sampled from 169 crosses originating from the first

cycle was studied. Palms from La Mé origin displayed the best unsaturated fatty acid

rate reaching 54.1%. This rate was 52.5% for Deli and only

49.2% for Yangambi origins.

These results were consistent with those from Eckey (1954), who described a gradient

between Sierra Leone (57.1%) and Zaire (52%) material (Gascon and Wuidart, 1975).

These differences were also shown in the Deli x Africa crosses. Indeed, the unsaturated

fatty acid rate was the highest in Deli x La Mé crosses (52.8%) and it was 50.6% for Deli

x Sibiti, 50.1% for Deli x Nigeria and 48.9% for Deli x Yangambi (Gascon and Wuidart,

1975).

6.3 The second RRS cycle

The second RRS cycle was implemented in eight locations between 1975 and 2012 (Table

2). Unfortunately, due to a severe drought, all the trials planted in Benin at Pobè Research

Station could not be fully monitored. For La Dibamba and Rio Urubu, only a very few

number of trials were completed.

The first results obtained for oil yield presented an average progress of 15% between

the second cycle and first cycle of RRS (Gascon et al., 1981). This progress was higher when

the tested Deli parents came from recombinations (Table 3). Crosses from selfed progenies

reflected more improvement of the cross than from the second cycle. However, these results

showed that improving a cross is possible, because there was enough variability within a first

cycle cross. These second cycle trials highlighted the importance of recombinations between

Deli parents. Such recombinations within group A are also based on the complementarity

between the number and the average weight bunch and these allowed the best progress.

Recombinations between parents of group B did not generate the same progress than that

obtained for recombinations between Deli parents. Indeed, in this case, recombinations

were not based on the complementarity between bunch yields components (Cochard et al.,

1993). On average, and compared to the standard cross LM2T x DA10D: • crosses between selfed progenies generated a progress of 3.9% • crosses between self of group A progenies and recombination between group B progenies displayed a progress of 1.4% • crosses between recombinations of group A progenies and self of group B progenies have enabled the highest progress, which was 13.6% • crosses between recombination of group A and group B progenies did not generate any progress (Fig. 3). However, there were only two examples of recombinations. Table 2 Experimental designs of the second RRS cycle conducted since 1975 Estate Company Country Years No. of trials No. of crosses No. of deli dura No. of tenera/pisifera Origins of tenera/pisifera Aek Kwasan PT Socfin Indonesia Indonesia 1975–1979 163272941 10 La Mé, Yangambi, SP540 La Mé IRHO, now CNRA Côte d'Ivoire 1975–1991 21714389242 La Mé, Yangambi La Dibamba IRHO, now IRAD Cameroon 1975–2000 12318257121 La Mé, Yangambi Bangun Bandar PT Socfin Indonesia Indonesia 1981–1991 31521224 6 La Mé, Yangambi Rio Urubu Embrapa Brazil 1984–1988 12256123 89 La Mé, Yangambi Aek Loba Timur PT Socfin Indonesia Indonesia 1995–2000 25571142 154 La Mé, Yangambi Pobè CRAPP de l'INRAB Bénin 1995–2002 91679496 La Mé, Yangambi Aek Kwasan II PT Socfin Indonesia Indonesia 2005–2012 25660 175147 La Mé, Yangambi, Ekona, Ekona x AVROS

Figure 3 Oil yield as a percentage of control cross: LM2T x DA10D. Results of the second cycle of

RRS mainly planted in Aek Kwasan (Indonesia) and La Mé (Côte d'Ivoire). From Cochard et al. (1993).

Table 3 Progress between second cycle and first cycle for crosses from selfed progenies and

recombined progenies (from Gascon et al., 1981)

Selfed progenies Progress Recombined progenies Progress

DA115D self x LM2T self 5-15% (LM404DxDA10D) x LM2T self 8-17%

DA10D self x LM2T self 9-12% (DA5DxDA3D) x LM2T self 13-21%

LM404D self x LM2T self 5-11% (DA10DxDA3D) x LM2T self 25-32%

Average 6-13% Average 15-23%

Table 4 Average and general combining abilities (GCA) of oil yield, FFB, OER and growth for the 4

independent groups tested in the Aek Loba Timur experimental design. GCA estimated for the x %

best crosses for oil yield. Oil yield: Tons/ha/year - FFB: kg/palm/year - OER: industrial percentage of

oil per bunch - i: intensity of selection

Group nb parents i Oil yield FFB OER Growth

Angola x La Mé Average 7.56 241.8 23.2 51.8 Angola 11 10% +8.7 % +4.0 % +4.8 % +3.1 % La Mé 11 10% +6.9 % -3.2 % +10.9 % +9.1 %

BBSP crosses Average 7.42 208.8 26.3 63.8 Deli 16 12.5% +5.3 % +5.0 % +0.4 % +4.7 % Group B 24 12.5% +8.5 % +10.1 % -1.2 % +6.9 %

Deli x La Mé Average 7.53 213.5 26.2 52.5 Deli 83 10% +7.7 % +2.7 % +4.5 % +4.8 % La Mé 102 10% +11.3 % +6.0 % +5.1 % +6.5 %

Deli x Yangambi Average 7.45 210.1 26.3 59 Deli 19 10.5% +8.1 % +8.4 % -0.1 % -3.7 % Yangambi 8 12.5% +8.3 % +3.0 %

+4.9 % -8.0 %

The last second cycle RRS experimental design for which results were obtained was the Aek Loba Timur's trials. For 571 crosses tested, the average oil palm yield was 7.4 tons/ha/year. This production level was equivalent to the standard cross LM2TxDA10D, showing all the genetic improvement achieved (Jacquemard et al., 2010). The best 10% crosses for palm oil yield displayed a production of 8.5 tons/ha/year, which still represent a gain of 15%. The best cross reached an oil yield of 9.2 tons/ha/year, which means a 24% improvement. For these best 10% crosses, FFB was 229 kg/tree/year (around 32.7 tons of bunches/ha/year) and the OER was 27.8. For the best cross, FFB was 231 kg/tree/year (around 33.0 tons of bunches/ha/year) and OER was 28.1. This result reflected the difficulties to combine both traits in order to obtain the best cross. Indeed, in this genetic experimental design, the best FFB was 256 kg/tree/year (around 36.6 tons of bunches/ha/year) and the best OER was 30.5.

Estimations of GCA were carried out in this experimental design (Jacquemard et al., 2010). They allowed the value of each tested parent to be assessed. When the additive value of each parent was compared to the average of all crosses, the value of non-tested crosses by adding the value of each parent, or approximately 10% of the best crosses, the oil yield gain was at least + 5.3%. Therefore, by combining the best crosses, the minimum

gain was around +10%. This total gain can be largely the result of an improvement in FFB,

or rather a gain on the OER, but also an almost equivalent gain for these two components

(Table 4). However, this oil yield increase was accompanied by a height growth increase.

Progenies that have a better FFB, a better OER, or a smaller growth than presented in

Table 4 exist, but with a lower oil yield improvement. Accordingly, the commercial supply

was segmented based on defined typologies.

6.4 The third SRR cycle

The third SRR cycle is presently being planted. The two first experimental designs have

been planted as rom 2010, in both Ecuador and Nigeria (Table 5). In addition, in order to

assess improved second cycle parents of Deli, La Mé and Yangambi origins, this third cycle

will have incorporated new Nigeria and La Mé x SP540 recombinations.

7 Impact of oil palm breeding on other traits and using other methods

7.1 Disease resistance

The second major objective of the oil palm breeding programme is to select for resistance

to major disease: Ganoderma for South East Asia, Ganoderma and Fusarium wilt for Africa,

and the complex of bud rot for Latin America.

Table 5 Experimental designs of the third RRS cycle established since 2010

Estate Company Country Years No. of trials No. of crosses No. of Deli Dura No. of Tenera/Pisifera

Cole Murrin Ecuador 2010-2015 23 413 125 96

Presco Siat Nigeria 2010-2016 29 690 182 116

7.2 Iodine value

The iodine value of palm oil usually ranges between 50 and 58 (Meunier and Boutin,

1975). Breeding has increased the average iodine value. Final results from the Aek Loba

Timure experimental design (Jacquemard et al., 2010) reported an average iodine value

of 53.8. The iodine value of the Deli material was approximately 52.6, but reached 56 for

progenies with LM404D as founder. The iodine value in palms of Yangambi origin was

lower than that in palms of La Mé origin (50–54 compared to 57–60). In each origin, it was

possible to obtain a 5% improvement for the iodine value.

7.3 Lipase

FFA and oil acidity were measured for several palms from various crosses by Ngando

Ebongue et al. (2008). The two E. oleifera palms from Monteria (Brazil) provided oil with low

acidity and a low % of FFA. For E. guineensis, few palms display a low % of FFA and low

acidity, on different origins, Deli x La Mé, La Mé and Deli. The differences were not at the

origin or at the progeny level but only at the palm level for some progenies. Morcillo et al.

(2013) explained that segregation of the low acidity trait was monogenic and recessive.

These studies were performed on a small number of progenies and origins and it is now necessary to study the genetic variation of this trait throughout the available genetic diversity.

Wong et al. (2016) have screened the Malaysian Palm Oil Board’s wild oil palm germplasm for lipase activity. At the population level, low FFA levels were measured in palms originating from Nigeria (2.55%), Guinea (7.99%) and Senegal (8.38%). Angola, Tanzania and Zaire displayed a high mean FFA value, which was higher than 20%.

7.4 Results from FIS

Dura x pisifera progeny tests are based on family and individual assessments of the dura x dura and tenera x tenera tests. Pisifera choice for the progeny test is based on the sib tenera performance. As the Deli dura is assumed to show little variability, work was focused on pisifera parent breeding value. Several performances of pisifera have been described and analysed (Hardon et al., 1987, Breure and Konimor, 1992; Lim et al., 2003; Teo et al., 2003; Noh et al., 2010; Junaidah et al., 2011; Noh et al., 2012).

Recently, results were published by Arolu et al. (2016) for Deli dura x Nigeria pisifera progeny tests. With a NCM I breeding design using 24 Deli dura nested into 10 Nigerian pisifera, and a randomized completed block design with two replicates of 16 palms per progeny, the authors described the performance of dura x pisifera crosses and GCA of the pisifera parents. Amongst the 10 pisifera tested, palms with the highest GCA for the FFB, displayed the highest GCA for the BN. This result suggests once more that the easiest way to increase FFB is to increase the BN, as Beirnaert already explained in 1935. When compared to the trials average results, the best pisiferas show an increase of 12% for oil yield.

Teo et al. (2003) described performance results of dura and pisifera tested under the design explained by Lim et al. (2003). They showed that AVROS pisiferas had higher oil yield but also displayed a rapid height increment and strong vegetative growth. Ekona pisiferas were equivalent or superior to those from AVROS origins, and Binga pisiferas were not as good as Ekona, on average. Pisiferas from Ulu Remis were found to display the poorest oil yield. Yields of duras, African duras, Deli duras or mixed duras have also been analyzed. The African and mixed duras produced more vigorous and higher yielding dura x pisifera progenies. Therefore, the authors concluded that there is no justification for persisting exclusively with pure Deli duras as seed parents.

8 Seed production

8.1 Methods

The first method for seed production established by IRHO, was based on the reproduction of the most successful crosses from the test phase of the first cycle of the RRS through the selfing of parents (Jacquemard et al. 1982). The most successful tested pisiferas were first crossed with the most successful teneras, and then pisiferas obtained from these most successful

tenera x pisifera crosses were used for seed production. A minimum of twelve duras and

twelve pisiferas were necessary to adequately reproduce the original cross. Between 12 and

20 crosses were enough to reproduce the initial cross (Jacquemard et al. 1981). This method

has the advantage of producing a large number of seeds representing the initial cross.

For the second cycle, it was difficult to implement this method because it required a

larger surface and a high number of crosses. In addition, Soh et al. (1989, 1990) found that

a trial of 6 replicates of 16 palms did not allow differentiation between crosses with less

than a 15% difference under Malaysian conditions. Under conditions in Indonesia or Cote

d'Ivoire, trials can differentiate between crosses with at lease a 10% difference. Therefore,

it is not possible to build the seed production only from the most successful crosses,

but from a set of the best crosses from each trial, thus increasing the number of crosses

involved in the seed production. The seed production based on the second cycle of SRR

has evolved: indeed, when possible, crosses are reproduced as the first cycle, otherwise it

is balanced at the grandparent level (Fig. 4).

With the FIS breeding method, the seed production is based on the duras selected on

their phenotypic performances, and on pisiferas selected on the phenotypic performances

of the duras and teneras sibs, or after a generation of progeny testing. Thus, seed production

is simply the combination of most successful parents identified on their phenotypes or

direct reproduction of the most successful crosses identified in the progeny tests.

8.2 Pollen availability

The CIRAD/PalmElit seed production process has the advantage of relying on many

pisiferas. However, they are not always enough to guarantee sufficient pollen production.

To overcome the problem of pollen deficiency, a drastic pruning method has been

developed which ensures a pollen production 20-24 months after pruning, depending on

the oil palm age (Durand-Gasselin, et al. 1999).

8.3 Seed preparation

Unlike in most plants, oil palm seeds cannot be delivered as such, seeds must be delivered

as germinated seeds. In order to obtain seed germination simultaneously, a long and

complex method has been developed.

Bunches originating from controlled pollinations are harvested as soon as one fruit becomes

naturally detached. At the seed production facility, bunches are chopped in order to separate

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mprovedGroupAImprovedGroupA2Im
provedGroupB2DuraDuraTeneraDur
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3Dura14Pisifera14Dura15Tenera1
5Dura16CommercialA1ixB1iDuraxP
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Dura112Pisifera152Dura113Pisif
era153Dura114Pisifera154Dura11
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p r o d u c e a c r o s s , f o r i n s t a n c e s e l f o f D u r a 1 4 w i t h t h e s e l f o f t e n e r a 1 5 ; i t m a y a l s o b e p o s s i b l e t o b a l a n c e a l l t h e c r o s s e s b e t w e e n t h e s e l f o f d u r a 1 1 , d u r a A 4 , d u r a 1 5 a n d t e n e r a 1 5 , a n d t e n e r a 1 5 x p i s i f e r a 1 5 . T h i s i s a r e p r o d u c t i o n o f a n i m p r o v e d s e c o n d c y c l e o f t h e g r a n d p a r e n t s d u r a 1 a n d t e n e r a 1 .

spikelets and rachis. Spikelets are put in boxes for 3–4 days and humidified during this

period in order to facilitate their destemming. Alternatively, chopping is continued in order to

separate fruit spikelets. Fruits are then placed into pools for 7 days to facilitate pulp removal.

The mesocarp of the fruits is removed using a depulping machine. Fresh seeds are then

cleaned of the adhering fibres, and white seeds, small seeds or floating seeds are eliminated.

Seeds of one-fifth of the crosses are observed for embryo conformity. If a cross shows less than

90% of normal embryos, it is eliminated. Seeds are then counted and treated with a fungicide.

Seeds are stored in an air-conditioned room. Hygrometry is maintained at 60–65% and

the temperature kept at 22°C. Seeds can be stored for a maximum of 18–24 months

otherwise their germination capacity becomes reduced.

The germination method includes two steps (Corrado and Wuidart, 1990): • the first step is to break dormancy by reducing moisture, down to 17 and 19% moisture on kernel fresh weight or 18 ± 0.5% moisture of the whole seed dry weight through heating • the second step is to ensure the development of embryos by placing the seeds at room temperature with a moisture rate on kernel fresh weight between 23 and 25% of a whole seed fresh 22 ± 0.5%

Seeds are removed from the storage room and soaked for 7 days. They are then wiped until they reach a dark grey colour, indicating a moisture content of 17–19% of fresh kernel

weight. Seeds are then placed in transparent polyethylene bags which are sealed and

placed in a germinator at a temperature of 39°C ± 0.5. They remain here for 80 days for

the Deli x La Mé crosses or 60 days for Deli x Yangambi crosses.

After heating, seeds are rehydrated by soaking for 5–7 days. Seeds are wiped a second

time until they reach a matte black colour, indicating a moisture content of 23–25% of

fresh kernel weight. Seeds are once again put in transparent polyethylene bags at room

temperature (25–27°C). Ten days later, the first set of seeds are collected followed by

a weekly collection during the next 4–5 weeks. Finally, collected seeds are packed in

batches of 100–200 germinated seeds inside plastic bags.

8.4 Seed delivery

CIRAD seeds are delivered as various categories based on a mix of crosses with the same

grandparents (Durand-Gasselin et al., 1999, 2000). Standard material is Deli x La Mé,

characterized by a high FFB and CPO production, and higher oil content of unsaturated

fatty acids compared to other planting materials. It also has a significant drought resistance

capacity and a low height increment which enables an economically profitable operation

over more than 25 years. During the past decades, CIRAD and PalmElit breeders have improved the Deli x La Mé material, in the aim of generating less bulky palms for high

density plantation, resistance against diseases and low lipase material. The other elite

materials on display are Deli x Yangambi and the interspecific E. oleifera x E. guineensis

hybrid (Turnbull et al., 2016).

In the future, the labelling of planting material will advertise specific characteristics: • resistant to bud rot disease, Ganoderma, Fusarium wilt, or drought • those with a very low height increment, with less bulkiness • those with a low lipase activity.

9 Future trends

For the future genetic improvement of the oil palm, conventional breeding will profit from

various different research area themes.

9.1 Breeding for resistance to drought

Countries and planters are increasingly interested in oil palm cultivation. Except in some

countries from Africa and Latin America, most of the remaining areas display unfavourable

environmental conditions. In addition, climatic change leads to an increase in uncertainty

about environmental parameters. It is therefore increasingly important to breed for the

resistance to drought.

Experiments have been implemented in Pobè (Benin), a place with a water deficit of

700 mm per year. In these conditions, the most relevant criteria is the percentage of

mortality. The Deli x Yangambi showed less mortality, but FFB was lower (43.5 kg/palm/

year) than in Deli x La Mé (65.8 kg/palm/year) (Houssou, 1985). A comparison between

crosses planted in Benin and Indonesia (North Sumatra) showed that OER components

stayed relatively unaffected (Nouy et al., 1999). For Deli x Yangambi, and Deli x La Mé

which display the same FFB yield in Indonesia, oil and FFB yields were found to be 50%

higher for Deli x La Mé compared to Deli x Yangambi in Benin (Nouy et al., 1999).

New trials are now implemented in different locations (Nigeria, Benin, Indonesia),

with different water deficits (200, 700 and 400 mm). Periodic observations are made

on this experimental design such as phenological monitoring of the appearance and

development of organs, morphological and biomass monitoring of all organs (including

roots). Also, bunch analysis, leaf photosynthetic capacity, and levels of non-structural

sugars in vegetative organs are measured. The intra-annual variations in phenology,

growth, functioning and production are thus analysed in the light of changes to climatic

factors such as water, temperature and radiation.

9.2 Improving the yield distribution over the year

Oil palms, when planted in locations where water deficit occurs, display a peak of

production. With no water deficit, the bunch production is spread over the year. To widen

this production peak, there is a means of estimating and representing the distribution of

production using the Gini coefficient and illustrating it by Lorenz curves. Hence, Cros et al.

(2013) showed differences between crosses as Gini coefficient varied between 0.382 and 0.699 for the bunch harvest. This coefficient summarizes the distribution of production and also highlights existing variability parameter to be taken into account for breeding, provided that crosses are at equivalent production levels.

9.3 Improving fertilizer's efficiency

The cost of fertilizer constitutes up to 60% of the plantation upkeep cost. Different methods are followed to reduce this cost, by recycling palm oil mill effluents, empty fruits bunches or compost. Foliar diagnosis is also used to assess nutrient status and fertilizer requirements (Foster 2003). The future of oil palm breeding can be based on improving the ability of palms to make better use of fertilizers. Genetic variability has been shown for nitrogen uptake at the nursery stage (Law et al. 2012). Ollivier et al. (2013) described contrasted leaflet concentrations for elements such as N, P, K and Mg between different genetic origins at measured plantations. Hence, there are optimum levels of nutrients for each genetic origin. For the same production level, the amount of mobilized nutrients may vary by up to 30–40% between genetic origins. Efforts must concentrate in the future on the fine-tuning of the critical levels using contrasted oil palm varieties to specifically adapt fertilization (Ollivier et al. 2017).

9.4 Improving pollination at a young age

In 1989, Meunier et al. showed that increases in oil yields mainly comes from the NB.

Corley and Tinker (2016) showed that the modern populations, after four generations

of selection, can display 16 bunches per palm per year. At 5–10 years of age the best

pisiferas can now produce more than 18 bunches per year (Arolu et al., 2016). In the

Aek Loba Timur project (PT Socfindo, Indonesia), on average, the NB per year in palms

aged 6–9 years was around 17. At the young age (3–5 years), this NB accounted for

one-third, with around 28 bunches per year. In these conditions, the number of male

inflorescences was rare at the young age. This lack of pollen and consequently a

bad fruit set of the female bunch, is being seen more frequently in the commercial

planting material, regardless of breeding strategy. In order to limit this drawback, two

possibilities exist: • The first option is to limit the NB at the young age while increasing the ABW. However, this solution also limits the NB at the adult age and therefore limits the yields. • The second option is to develop dioecious palms. Two kinds of palm will be developed: some with only female bunches and some with only male inflorescences. The latter, called supermale palms, will ensure adequate pollination of the other palms. The targets are to develop a supermale breeding programme and an appropriate design, with a defined and limited number of supermale palms per hectare.

9.5 Improving data analyses

Experimental and genetic designs have evolved considerably. As a consequence, data

analyses have also changed. At the beginning, the aim was to find the best crosses using

ANOVA. With genetic designs, the aim was to find the best parents by estimating mainly

GCAs and breeding values. Breure and Verdooren (1995) described different genetic

designs adapted for oil palm to estimate the GCAs and the breeding values of the

tested parents. In 1994, Soh estimated breeding value using BLUP (best linear unbiased

prediction). This method can integrate unbalanced data from experimental and mating

designs and it was also used to predict hybrid performance (Purba et al., 2001). With the

BLUP method, estimation of relatedness is facilitated by the knowledge of the oil palm

pedigree. Oil palm breeding methods are increasingly similar to animal breeding, hence

in breeding programmes BLUP approaches will be used more frequently. In addition, such

an approach in a well-studied pedigree could prove useful for the detection of QTLS

(Cochard et al., 2015; Tisné et al., 2015). This enables the implementation of marker

assisted selection or genomic selection (Cros el al., 2015a,b), which may help to shape the

future of oil palm breeding.

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8 Chapter 8 Advances in marker-assisted breeding of oil palm

1 Introduction

Oil palm is mostly cultivated in the tropical belt that lies between 10 degrees North and

South of the Equator (Godswill et al., 2016). Oil palm is unique, as it produces two types of

oil: palm oil from the mesocarp and palm kernel oil (PKO) from the kernel. Both oils have

different fatty acid profiles and hence separate applications. Palm oil from the mesocarp

is a major source of vegetable oils, while PKO has wide industrial applications, such as to

make soap, detergents and personal care products among others.

The oil palm industry has shown spectacular improvement in productivity over the past

50 years, with increases in production from 1.26 million tonnes in the early 1960s to about

45 million tonnes in the late 2000s (Abdullah and Wahid, 2010). Such a rapid improvement

was basically the result of (i) improved planting materials obtained via breeding, (ii) increase

in acreage cultivated with oil palm and (iii) more extensive and efficient use of fertilizers.

Among the three reasons, only the first is sustainable in the long term and is an area of

R & D across many oil palm-producing countries.

Thus far, conventional plant breeding has been in the forefront of producing elite

planting materials, helping the industry to achieve its status as the main source of

vegetable oils worldwide. Based mostly on phenotypic selection, commercial oil palm

breeding has largely focused on increasing palm oil yield. The effectiveness of the oil

palm breeding programmes is undeniable, where improvement in breeding lines has been

obvious over the past five decades, where improvements in oil yield at over 60% has been

observed between 1960 and 2010 (Durand-Gasselin et al., 2010; Cochard et al., 2015).

To help realize this, selection in breeding has focussed on genes of major effect that give

a clear measurable phenotype such as the ratio of fruit to bunch (FTB), mesocarp to fruit

(MTF) and oil to wet mesocarp (O/WM), which collectively determine the oil to bunch

(OTB) ratio of a particular palm (Yong, 1992). Oil yield is thus improved by increasing OTB

and the fresh fruit bunch (FFB) yield over several generations. Initially armed with a very

basic and limited genetic understanding of these complex traits, breeders have managed

to develop and select appropriate maternal dura and paternal pisifera lines which, when

crossed together, have successfully shifted the mean progeny response for the selected

traits in the desired direction.

Although effective, oil palm breeding faces several limitations, which include a long

generation time of 10–12 years (Mayes et al., 1997) and large land requirement, as

usually only 136–148 palms are grown per hectare of land. This makes breeding trials

an expensive endeavour, especially now as resources in arable land are limited even for

commercial cultivation. The advent of molecular marker technology and subsequent

advances in genomics-based technologies has provided an unprecedented opportunity

to improve oil palm breeding efficiency. The relationship between variation in gene

sequences and phenotypic observations in the field on mature palms provides a

powerful means of early selection for desired traits in juvenile plants, before the trait in

question is expressed. Referred to as marker-assisted selection (MAS), this approach is

especially important for oil palm indeed, where most of the phenotypic traits used for

selection in conventional breeding can only be evaluated 4–7 years after field planting.

Furthermore, phenotypic data collection, especially those related to bunch components,

is usually carried out over for several years in order to ensure an accurate estimation of

the palm productivity.

Application of markers in plant breeding was first demonstrated in the 1980s with

protein-based isozyme markers (Tanksley and Rick, 1980). This approach was extended

to DNA-based markers in the mid-1980s, when the applications of restriction fragment

length polymorphism (RFLP) were evidenced (Beckman and Soller, 1986). With respect

to oil palm, application of markers especially RFLP for DNA fingerprinting was initiated

in the 1990s (Cheah et al., 1993; Mayes et al., 1996). An

RFLP-based genetic map was

then constructed, which revealed markers linked to a pivotal monogenic trait – the shell

thickness of oil palm fruit (Mayes et al., 1997). The oil palm industry was for the first time

introduced to the power of molecular markers and its potential for improving breeding

efficiency. RFLP markers are cumbersome and expensive for large-scale screening, and the

fact that they were also not very tightly linked to the shell thickness trait at that time did not

encourage the large-scale application of such a promising tool in breeding programmes.

Research was also undertaken in order to make use of modified RFLP markers in the

search for the molecular determinism of the 'mantled' somaclonal variation affecting

flower and fruit structure in the oil palm (Jaligot et al., 2002). The RFLP approach did

however spur research in the direction towards the integration of DNA technology

within breeding strategies, which gained more popularity after the development of the

polymerase chain reaction (PCR) (Mullis and Faloona, 1987) and a whole generation of

PCR-based molecular markers. Indeed, using PCR-based random amplified polymorphic

(RAPD) markers, Moretzsohn et al. (2000) identified markers which proved to be more

tightly linked to the shell thickness locus. At about the same time, Singh and Cheah (1999)

described the application of amplified fragment length polymorphism (AFLP) markers for the assessment of the fidelity of controlled crosses in oil palm. Billotte et al. (2005) subsequently developed simple sequence repeat (SSR) markers for genetic mapping and produced 16 linkage groups to match the haploid chromosome number for oil palm. More importantly, these authors identified SSR markers flanking the gene influencing shell thickness, and the markers could predict the trait with over 95% accuracy. Research aimed at identifying markers linked to yield and vegetative components – which are quantitative in nature – was initially carried out using RFLP-based markers by Rance et al. (2001) and subsequently by Billotte et al. (2005), who evidenced links between SSRs markers and quantitative trait loci (QTLs) for yield and vegetative components in multi-parental linkage maps. Such pioneering works laid the basic foundation for the application of markers in oil palm breeding programmes. As the techniques for genotyping improve and the cost decreases (Poland, 2015), opportunities to incorporate MAS in oil palm breeding also increase. Such changes are also accelerated by increased expertise in basic molecular procedures across many oil palm-producing countries, especially in South East Asia and South America.

2 Application of markers for paternity testing in oil palm

Marker Assisted Selection (MAS) is yet to be widely implemented in oil palm breeding programmes. The major reasons which could explain such a situation could be that until

recently, there was a lack of trained staff, appropriate genomics tools and infrastructure in

many commercial plantation companies to implement MAS. The most basic application

of markers in oil palm breeding is probably testing for legitimacy within the progeny

of controlled crosses. This approach involves simple markers inherited in a Mendelian

manner in order to ensure that the palms within a family are of the correct parentage.

This is a very important information for breeding programmes, as parents are selected

based on family/progeny performance, and if illegitimates are present, wrong conclusions

can be drawn (Corley, 2005).

Although great care is taken to bag female flowers prior to anthesis, and in the collection,

documentation and subsequent storage of pollen, controlled pollination can still run into

problems due to various sources of errors as highlighted by Corley (2005). Problems with

controlled pollinations spiked with the introduction of the oil palm weevil (Elaeidobius

kamerunicus) in the early 1980s – when contamination rates as high as 20% were observed

(Rao et al., 1993; Corley and Tinker, 2003a). The illegitimate palms could be noticed even

without the use of molecular markers, especially in crosses involving the maternal dura

and paternal pisifera palms. Although only the hybrid tenera palms were expected from

such crosses, some contamination by dura palms could be observed, possibly due to

uncontrollable wind and/or insect pollination (Chin, 1995). Admittedly, contamination has

reduced tremendously in recent years due to improved quality control, but the problem

still persists to some extent (Ooi et al., 2016).

A number of reports in recent years have highlighted the application of PCR-based

markers in assessing the legitimacy of controlled crosses. Thongthawee et al. (2010)

reported that 7–8 SSR loci were sufficient to detect pollination errors confidently. More

recently, Hama-Ali et al. (2015) highlighted the problem with the assignment of parental

palms to families in an oil palm–controlled cross involving four half sib families. The

parental samples assigned to each family in their experiments were not corresponding

to the SSR profiles observed, thus highlighting the errors that occur especially when a

number of crosses are made at the same time. Although the authors managed to assign the

correct parents to the offsprings using a minimum set of five SSR markers and appropriate

statistical software, an illegitimacy rate of 1.5% was still observed. Without the use of

molecular markers for parentage analysis and assignment, the breeders would have made

a serious error in moving ahead with their breeding programme since family performance

is essential in determining the combining ability of the parental palms. Selecting the best

individual palm within a family in the presence of illegitimate palms can also have serious consequences. As such, the use of molecular markers to assess the fidelity of controlled crosses is of paramount interest, especially considering the mistakes that can happen at any stage of the crossing programme: from labelling of parental palms, pollen collection and storage to mix-up in the nursery as well as during field planting.

3 Genomic resources and tools for MAS

Research towards application of MAS in oil palm has been greatly assisted with the availability of the oil palm genome sequence (Singh et al., 2013a). Genomes of both the Elaeis guineensis and Elaeis oleifera species were uncovered, and at least ~45 000 genes were predicted. Together with the sequencing of the hypomethylated genome of eight individual palms from both species (Low et al., 2014) and the availability of expressed sequence tag (EST) sequences (Jouannic et al., 2005; Ho et al., 2007; Low et al., 2008; Chan et al., 2010), as well as transcriptome sequencing using next-generation sequencing technology (Tranbarger et al., 2011; Bourguis et al., 2011; Guerin et al., 2016), appropriate genomic resources and tools have been established for oil palm. More recently, sequencing of pooled DNA from 132 palms representing 59 different breeding lines at 35x genome coverage using Illumina Hi Seq 2000 (Teh et al., 2016) has added to the growing repertoire of genomic resources for oil palm. Such rapidly growing information

has allowed the mining of SSR (Singh et al., 2008; Ting et al., 2010; Tranbarger et al.,

2012; Xiao et al., 2014; Taeprayoon et al., 2016) and the highly valuable single-nucleotide

polymorphism (SNP) markers (Riju et al., 2007; Ting et al., 2014; Pootokham et al., 2015;

Kwong et al., 2016). Rapid advances in genotyping platforms and technologies have made

SNP markers especially valuable for the application in breeding programmes. As such, the

recent release of information on 4451 (Ting et al., 2014) and 200 000 SNPs (Kwong et al.,

2016) printed on an Illumina array provides a powerful platform for application in oil palm

genetic studies, especially in the efforts directed at identifying marker(s) for early selection

of a desired trait. The recent identification and in-depth description of long terminal

repeat (LTR) retrotransposons in the oil palm genome have also opened the opportunity

to assess the role of these elements in genome and transcriptome variations, especially

those resulting from the micropropagation of oil palm (Beule et al., 2015).

Proteomics- and metabolomics-based technologies are also now being deployed in

oil palm to obtain a comprehensive understanding of gene function related to disease

resistance (Syahanim et al., 2013) and yield differences in commercial material (Teh

et al., 2013). Although genomics-based technologies have played a key role in improving breeding efficiency in many perennial crops, there is growing evidence that molecular mechanism underlying some agronomic traits – especially those quantitative in nature – can be complex. Regulation of traits occurs over several layers, and observed phenotype may be influenced by post-transcriptional modification, protein–protein interaction, among others and give rise to certain metabolites that may not be predicted by the genome information. As such, phenotype prediction using proteins or metabolites – small molecules that are likely to be directly associated with the phenotype – can complement and enhance breeding efficiency. Although their use for practical application in oil palm is still very premature, the promise that these technologies have for oil palm improvement is undeniable. The establishment of appropriate methods (Tahir et al., 2013; Lau et al., 2015), relevant databases for oil palm (Nur-Ain et al., 2015) and the actual profiling of proteins and metabolites associated with Ganoderma infection (Al-Obaidi et al., 2014), as well as fruit development (Loei et al., 2013; Neoh et al., 2013) reflect the growing prominence of proteomics and metabolomics research in oil palm.

4 MAS for predicting monogenic traits

Monogenic traits are probably the most attractive for initial improvement via MAS. The two most important monogenic traits of interest to oil palm breeders, especially in the commercial species E. guineensis, are those related to fruit form and colour.

4.1 Oil palm fruit colour

The fruit of the oil palm can vary considerably based on external appearance, most notably

the colour of the fruit. By far, the most common type of fruit is known as nigrescens, in

which the fruits are deep violet to black at the apex and yellow at the base when unripe

and exhibit minimal change in colour upon ripening (Hartley, 1988; Singh et al., 2014a).

The other major fruit type is known as virescens, which changes colour from green to

light reddish orange at maturity. Currently, for nigrescens palms in commercial fields,

bunches are considered ready for harvest when loose fruits are observed on the ground

beneath the bunch (Corley and Tinker, 2003b). In practice, plantations prefer a minimum

number of loose fruits in order to reduce the cost and time spent collecting loose fruits.

Indeed, collecting loose fruits has been reported to occupy 28% of the total harvesting

time (Hitam et al., 1999). Inefficient collection of loose fruits can have repercussions on

the productivity of the oil palm industry. Furthermore, having a large number of loose

fruits from a bunch can also affect the oil quality, as the softer exocarp is easily bruised

and damaged, resulting in the oxidization and further generation of free fatty acids that

can seriously affect oil quality. In this respect, virescens palms can be more desirable to planters as the clear difference in colour between ripe and unripe bunches makes it easier

to identify ripe bunches and therefore facilitate fruit harvesting. As such, the identification

of the gene responsible for oil palm fruit colour has important implications in breeding

programmes. The virescens trait is most useful if incorporated into non-abscising palms

that have been observed in plantations (Donough et al., 1996). Ongoing research to

identify and characterize genes involved in oil palm fruit shedding (Roongsattham et al.,

2012), combined with increased knowledge on the morphogenesis of the abscission zone

(Roongsattham et al., 2016), will undoubtedly provide additional target genes for a more

effective MAS strategy.

Inheritance studies indicated that the fruit colour (Vir) trait is controlled by a single gene,

monogenic and dominant (Corley and Tinker, 2003a). More recently, Singh et al. (2014a)

assessed the inheritance of exocarp colour of oil palm fruits in a population derived from

the self-pollination of the tenera palm, T128, from the Malaysian Palm Oil Board’s (MPOB)

Nigerian germplasm collection. The data, as expected, suggested that one Mendelian

locus controlled the trait, and the position of the gene was determined on a genetic map

derived from the selfed T128 population. Subsequently, using the reference genome of

E. guineensis, the R2R3 MYB transcription factor was identified as the virescens gene (vir) that controls the exocarp colour of the fruit. VIR (R2R3-MYB transcription factor) was

shown to be homozygous wild type in nigrescens palms but, in virescens palms, was

heterozygous or homozygous for a nonsense mutation in the final exon of the gene (Singh

et al., 2014a). In order to further validate the association of the gene with fruit colour, the

entire gene was sequenced in over 500 palms from independent breeding populations as

well as germplasm collection. Four additional mutations were uncovered, each resulting in

the similar C-terminal truncation of the VIR protein giving rise to the virescens phenotype.

Whole transcriptome gene expression profiling in nigrescens and virescens fruit

demonstrated that the VIR truncation mutations result in a dominant-negative function

linked to anthocyanin deficiencies via impaired regulation of downstream anthocyanin

biosynthetic target genes (Singh et al., 2014a). A dominant-negative mutation in the same

gene was also found to be regulating fruit colour in the date palm (Hazzouri et al., 2015).

The discovery of the VIR gene facilitates genetic testing for fruit colour prior to planting.

More importantly it can be directly integrated in an MAS strategy, as it can be used

as a tool in oil palm breeding to differentiate seedlings that are heterozygous for the

dominant-negative mutation from those that are homozygous. This will allow breeders to

develop paternal pisifera lines that are homozygous for virescens for use in introgressing this desirable trait into elite breeding materials. The use of the VIR gene for application

in oil palm breeding via MAS was introduced by the MPOB recently (Singh et al., 2015).

4.2 Fruit form phenotype

Palm oil production is mostly based on the planting of hybrid tenera fruit form palms.

The tenera hybrids are obtained by crossing thick-shelled dura maternal palms to pisifera

paternal palms which are shell-less and typically female sterile. Tenera palms yield on

average 30% more oil than dura (Corley and Lee, 1992), while pisifera palms typically

do not produce any fruits. The monogenic, co-dominant inheritance of shell was first

discovered in the 1940s in Zaire, Africa (Beinaert and Vanderweyen, 1941), and it reflects

a classic example of single-gene heterosis (or single-gene hybrid vigour). Tenera palms

for commercial planting are produced via controlled crosses involving selected dura and

pisifera palms. Although great care is taken to make the controlled crosses, error-free

hybridization of the selected parental palms is often difficult to achieve in real-world

settings. This can result in unintentional planting of non-tenera palms for commercial

production. The presence of rudimentary anthers in maternal dura palms (Corley, 2005)

can also result in self-fertilization and subsequent dura contamination in commercial

plantings.

Over the past several decades, several attempts were made to identify markers linked

to the SHELL gene (Mayes et al., 1997; Moretzsohn et al., 2000; Billotte et al., 2005).

Despite such continuous efforts, marker(s) tightly linked to the SHELL gene and showing

a high level of predictability for the trait over different genetic backgrounds was never

made available for routine use, and the identity of the gene itself remained unknown for a

long time. However, using a combination of genetic mapping, homozygosity mapping by

sequencing and the oil palm whole genome sequence as a reference, Singh et al. (2013b)

identified the gene responsible for the three different fruit forms of E. guineensis. The

SHELL gene was revealed to be a type II MADS-box transcription factor homologous to the

Arabidopsis SEEDSTICK, which controls ovule, seed and lignified endocarp differentiation.

Singh et al. (2013b) further demonstrated that the expression level of SHELL was high in

the outer layers of the developing kernel in dura fruits, consistent with its function in

regulating the formation of the heavily lignified shell surrounding the kernel.

Palms bearing dura fruit form were found to be homozygous wild type at all nucleotide

positions. Initially, two similar but independent mutations were identified in the MADS

domain of the SHELL gene, which gave rise to the pisifera phenotype. These includes

the Congo-derived AVROS (sh AVROS) mutation which results in an asparagine substitution of a highly conserved lysine residue. The second mutation, the Nigerian T128-derived sh MPOB mutation, results in a leucine to proline substitution, two amino acids from sh AVROS in the N-terminal direction. Following the discovery of these two mutations, a small-scale national survey was carried out in order to determine the level of dura contamination among independent nurseries and smallholders in Malaysia. In the survey, additional three mutations were uncovered within the MADS domain of the SHELL gene. The additional mutations were sh MPOB2 lysine-to-glutamine substitution six amino acids N-terminal to sh MPOB , the sh MPOB3 alanine–aspartate substitution 10 amino acids C-terminal to sh AVROS and the sh MPOB4 lysine-to-asparagine substitution of the same amino acid altered by the sh MPOB2 mutation (Ooi et al., 2016). Palms that are heterozygous for any one of the five mutations are tenera fruit form, while palms that are homozygous mutant for any one of the five mutations (or compound heterozygous with different mutations on each of the two chromosomes) show the pisifera fruit form. More importantly, the discovery of the SHELL gene allowed the development of the first molecular diagnostic assay for oil palm which was named SureSawit TM SHELL (Singh et al., 2014b). The assay allows the prediction of the oil palm fruit form from the leaf, and testing can be carried out at the nursery. The discovery of SHELL and its application into a successful diagnostic assay facilitated the

measurement of non-tenera contamination rate in independent nurseries and plantings

which was found to reach 10% (Ooi et al., 2016). Although the scope of the survey

was limited to a small number of independent nurseries and plantings, it nevertheless

underscored the importance of genetic testing in order to avoid uncontrolled batches of

planting material derived from dura and pisifera crosses (DxP) reaching commercial fields.

This quality control strategy contributes to sustainability practices as screening with the

diagnostic assay will help ensure that the most appropriate materials are planted, resulting

in increased productivity per unit of land area.

The discovery of the SHELL gene and subsequent development of a simple diagnostic

assay will be most valuable to breeders in developing male parental lines for the

commercial production of tenera. Pisifera palms can now be identified early in the

nursery and planted separately for easier access and management. This way the planting

density of selected pisifera palms can also be adjusted to induce the development of

male inflorescence. The entire process of being able to separate out the male and female

parental lines early enables a more focused breeding programme that allows considerable

savings in land, labour and resources. This discovery provided a paradigm shift in assisting

oil palm breeders to reduce the length and the allocation of resources to the breeding and

selection cycle required to develop new and improved varieties.

5 MAS for predicting quantitative traits in oil palm breeding

Most traits of interest for oil palm breeding are polygenic in nature, as such traits are

influenced by many genes, with each likely having a small effect and interacting with

each other and the environment. Oil palm unlike other plants such as Arabidopsis, rice

and maize does not have visible mutants to study the complex traits and identify the

underlying genes. Instead, the ‘forward-genetics’ approaches such as QTL and association

mapping (AM) techniques have been embraced to help understand and dissect these

complex traits.

5.1 Oil palm QTL studies

One of the first QTL mapping studies in oil palm was reported by Rance et al., 2001,

who revealed QTLs linked to yield components and vegetative parameters. Marker

trait association was observed for 11 of the 13 traits analysed, some explaining a large

proportion of the phenotypic variance (in excess of 10%). The main setback with this initial

study was that the RFLP markers linked to the QTLs (or the corresponding sequences of

the markers) were not made available for further testing by other research groups and as

such could not be validated in independent studies. In addition, the use in this study of a selfed tenera cross, that gave rise to approximately 25% pisifera palms, also reduced

the number of palms that could be evaluated phenotypically in the mapping population.

Nevertheless, this research work did lay the foundation for QTL analysis in oil palm.

This was built on by Billotte et al., 2010, who used multi-parental populations involving

interconnected families to identify QTLs linked to yield and vegetative parameters. The

number of QTLs identified was definitely larger than those reported using the bi-parental

model of Rance et al. (2001). However, many of the QTLs identified within a family by

Billotte et al. (2010) did not go across families, even when sharing a common parent. The

authors speculated that this could be due to the size of the mapping population within

each family used in the study.

More recently, QTL studies were expanded for the commercial E. guineensis to include

those associated with oil yield components (Jeennor and Volkaert, 2014), production traits

(FFB, bunch number and bunch weight) (Tisne et al., 2015), sex ratio (Ukoskit et al., 2014)

and the height-associated trait (Pootakham et al., 2015; Lee et al., 2015).

The availability of the oil palm genome sequence (Singh et al., 2013a) has made it

possible to scan the QTL interval for interesting candidate genes linked to favourable traits

concerned. Among the QTL studies above, interesting candidate genes were identified for the vertical growth trait, which is of interest for incorporation into commercial breeding

lines in order to expand the economic life span of oil palm plantations (the slower the

vertical growth, the longer the economic life). Lee et al. (2015) identified a gene known as

asparagine synthase within the QTL interval for height, and this gene has been associated

with a dwarf phenotype in Arabidopsis. Meanwhile, Pootakham et al. (2015), using a

mapping population from a different genetic background, identified two interesting

but separate candidate genes associated with vertical growth within their QTL interval,

namely DELLA protein GAI1 and a putative gibberellin 2-oxidase 2. Both these genes

have been implicated in plant height by their involvement in regulating the gibberellin

signalling pathway. Although plant height is an interesting trait for improvement via MAS,

the incorporation of the reduced height trait into commercial breeding lines has to be

considered carefully in order to avoid any penalty in yield. This is because higher yielding

palms are usually taller and hence more competitive (Corley and Tinker, 2003a).

QTL studies involving interspecific hybrids and their backcrosses have also been carried

out mostly in relation to fatty acid composition. Indeed, there is a need to introgress

genes related to the lower level of saturation of fatty acids observed in E. oleifera into

E. guineensis through interspecific hybrid breeding. In this respect, Singh et al. (2009)

initially identified QTLs linked to palmitic (C16:0) and oleic (C18:1) contents in an

interspecific hybrid mapping family. Using a denser SSR-based genetic map, Montoya

et al. (2013) identified 19 QTLs linked to fatty acid composition in an interspecific first

generation pseudo-backcross. More importantly, the study identified key genes related

to the fatty acid biosynthesis pathway, namely acyl-ACP thioesterase type A (FATA) and

Δ9 stearoyl-ACP desaturase (SAD) in the QTL intervals linked to stearic acid (C18:0)

and C18:1 content. Expanding on this study, Montoya et al. (2014) compared the QTLs

identified in interspecific first-generation pseudo-backcross described above to those

identified in an intraspecific E. guineensis-based cross. The study identified only two

common QTL zones and two high-confidence QTL regions specific to E. guineensis and E.

oleifera in the comparison analysis. Nevertheless, Montoya et al. (2013) did conclude that

the results were specific to the mapping population used in the study and on the need

to further validate these findings in other independent populations segregating for fatty

acid composition. Recently, Ting et al. (2016) while working on the interspecific hybrid

mapping population described by Singh et al. (2009) but with a slightly bigger population

size and a much denser genetic map (involving mostly SNP and SSR markers) identified ten significant QTLs for six fatty acids and iodine value (IV). Taking one of the most significant QTL regions linked to IV, C16:0 and C18:1 content, Ting et al. (2016) mapped the QTL interval back to the oil palm genome sequence. Interestingly, the corresponding genomic region contained a number of genes linked to fatty acid biosynthesis pathway such as palmitoyl-ACP thioesterase (FATB) and also an AP2-like ethylene-responsive transcription factor (WRINKLED1). Additional SSR markers were designed from intronic regions flanking these genes, and they correspondingly mapped back to the QTL interval, improving the QTL peak for the traits. Interestingly, the same QTL interval was detected in two independent second-generation interspecific backcross 2 populations (Ting et al., 2016). This was the first report on the validation of QTLs identified in independent oil palm populations, although the validation populations were somewhat linked to the original population where the QTLs were initially uncovered. Nevertheless, the study also did report major QTL regions which were specific to the three crosses evaluated and did not correspond to regions described by Montoya et al. (2013). This implies as pointed out by Ting et al. (2016) that favourable alleles for fatty acid composition can be population specific, and this has to be considered carefully when implementing MAS.

The initial studies on QTL analysis using mapping populations in oil palm have demonstrated the need for larger mapping populations, especially for traits which usually

show lower heritability. Furthermore, small mapping populations also can cause an upward

bias on the phenotypic effect estimated for a particular QTL linked to a trait (Butcher

and Southerton, 2007). Interestingly, in order to address this issue, Cochard et al. (2015)

successfully demonstrated an innovative approach for genetic mapping in oil palm using

recombination found in three to four outbred pedigrees, paving the way forward for an

effective pedigree-based QTL analysis. Nevertheless, the most serious limitation on most

of the QTL analysis reported thus far for oil palm (with one exception) has been the lack

of validation in independent populations originating from a different genetic background.

It is therefore difficult to predict the accuracy or applicability of markers linked to the

traits. Nevertheless, these QTL studies have revealed valuable information on the position

and effect of QTLs underlying complex traits and provided confirmation that the traits

were actually governed by many genes. With the availability of the genome sequence,

several interesting candidate genes linked to vertical growth and fatty acid metabolism

have also been identified in the QTL interval, although the specific underlying genes are

yet to be identified. However, a point to take into account is that in hybrid crosses (either

inter or intra), recombination rates are expected to be low, especially when compared to

wild populations; the QTLs detected, especially for low heritability traits, are likely to be

population specific. Furthermore, the cost factor must be considered when developing

advanced bi-parental oil palm breeding lines to an extent that sufficient number of meiosis

are available. As such, alternative methods have to be explored.

5.2 Association mapping studies

In recent years, owing to the limited size of the available mapping populations and the

need to dissect complex traits in a more robust manner, oil palm geneticists have started

to move on to AM analysis. AM was initially developed and used in human and animal

genetics research, where there is also a serious limitation in terms of number of individuals

available per family. Currently, AM analysis is being actively applied in a wide range of

crops and is often complementary to the traditional QTL analysis (Korte and Farlow, 2013).

AM analysis involves determining the genotype of wild or unadapted populations where

the phenotype has been characterized, followed by the use of specific statistical software

to determine population structure and subsequently marker-trait association. AM analysis

can exploit natural populations where recombination events in the distant past would

have selectively maintained association between a QTL and markers that are tightly linked

to it (Abdurakhmonov and Abdukarimov, 2008). The so-called rapid decay in linkage

disequilibrium is advantageous as once discovered and validated could be quite effective

in an MAS programme. Nevertheless, for an effective discovery and implementation

process, high marker density or a carefully selected set of candidate genes are required

for genome-wide association (GWA) analyses (Neale and Kremer, 2011).

In the first association study published for oil palm, Teh et al. (2016) used a 200 000 SNP

array to genotype over 2 000 palms, and they identified three significant QTLs on

chromosome 5 linked to an important yield component trait which is the oil to dry mesocarp

(O/DM) ratio. Interestingly, QTLs linked to other yield component traits such as MTF, OTB

and FTB were also observed previously on the same chromosome using bi-parental families

(Billotte et al., 2010; Jeennor and Volkaert, 2014). An interesting candidate gene pyruvate

kinase was also identified near the SNP markers, and the gene had been previously

linked to fatty acid biosynthesis and oil accumulation (Bourgis et al., 2011). In a powerful

demonstration on the resolution of AM analysis in oil palm, Teh et al. (2016) also showed

that the progeny containing the favourable allele for the most significant SNP marker in a

homozygous form had elevated amounts of O/DM. It is only natural that this information

is being exploited in an MAS programme to develop elite parental palms that carry the favourable allele, which in return will help generate planting materials with higher O/DM (Teh et al., 2016). Using the same SNP array which was applied in a separate GWAS analysis – involving 312 palms from four different populations – Kwong et al. (2016) identified several SNP markers around a region in chromosome 2 influencing the percentage of shell to fruit (S/F), an important determinant of shell thickness which in turn influences mesocarp and subsequently oil content. This is a convincing confirmation of the capability of AM analysis at dissecting complex traits in oil palm and making MAS for polygenic traits a tangible reality. More importantly, this technique provides the opportunity to exploit the genetic diversity available in the oil palm germplasm collections assembled (Barcelos et al., 2015). Unique traits (such as long stalk, slower vertical growth and balanced fatty acid composition, among others) that are not segregating in advanced lines could be readily associated with markers within a selected germplasm. The information will be vital to effectively introgress these desirable traits into the current commercial material.

Progress in the area of genomic selection (GS) for oil palm has also been promising (Cros et al., 2014) and can further expedite the selection of palms with desirable traits. GS uses genome-wide molecular markers to estimate the breeding value of individual palms for complex traits. In contrast to MAS, GS will likely detect small-effect QTLs, especially for the quantitative traits governed by multiple loci (Spindel et al., 2015).

The results thus far obtained for QTL analysis of oil palm, either using traditional QTL

or AM analysis, will likely induce significant progress in MAS programme designed to

improve speed and efficiency and also reduce the cost of existing conventional breeding

programmes. The markers linked to QTLs associated with yield parameters for example

can be used to screen maternal dura lines which were preselected phenotypically, to

identify those carrying favourable alleles. The dura palms carrying the desired genotypes

can be selfed or intercrossed to develop an elite line of dura materials homozygous for

most of the favourable alleles (Rance et al., 2001). In fact, these ‘improved dura’ palms

could be selected early in the nursery for field planting. Similarly, pisifera palms can also

be selected based on favourable alleles present in their tenera sibs, which may be more

efficient and cost-effective than random selection (Rance et al., 2001).

In interspecific hybrid and backcross breeding programmes, the main goal is to introgress

favourable alleles related to fatty acid composition from E. oleifera into E. guineensis.

Although the QTLs identified thus far can allow for selection of palms with favourable

alleles for higher levels of unsaturation of the oil in specific genetic backgrounds, the

challenge will be to avoid unfavourable genes within the

QTL confidence interval being

incorporated at the same time (linkage drag). Identifying the causal gene(s) influencing

fatty acid composition or using additional markers close to the QTL region to assist with

E. guineensis genome recovery (Rance et al., 2001) will help avoid linkage drag. To help

unravel the complexities of fatty acid synthesis (FAS), Guerin et al. (2016) recently revealed

a gene coexpression network that regulated FAS in the oil palm. It was demonstrated that

a number of genes associated with plastid biogenesis, glycolysis, starch metabolism and

sugar sensing were co-ordinately transcribed with FAS genes. The most interesting finding

in the study was that low level of β-ketoacyl-acyl carrier protein synthase gene (KASII)

transcript is in fact responsible for the accumulation of C16: 0 in the mesocarp of oil palm.

Interestingly, this is in agreement with earlier biochemical evidence by Sambathamurthi

et al. (1999, 2000) that KASII in mesocarp is rate controlling and responsible for

C16:0 accumulation. They also showed positive correlation between the activity of the

KASII enzyme and the level of unsaturated fatty acids, in both the oil palm species and

their hybrids. In fact, upregulating the expression of KASII is a major strategy employed

to produce higher C18:1 palms via the genetic engineering route (Sambanthamurthi

et al., 2000; Parveez et al., 2015). The combined findings from QTL analysis, biochemical analysis and gene expression profiling will facilitate the development of appropriate MAS strategies for producing palms with the desired fatty acid composition.

6 MAS in oil palm tissue culture

The production of elite planting material via the vegetative propagation of palms with superior characteristics will expedite oil palm improvement. However, genotype dependency of the cultured leaf explants results in low callogenesis rate of 19% (Corley and Tinker, 2003c) and an average embryogenesis rate of between 3 and 6% (Wooi, 1993; Ho et al., 2008). Moreover, the tissue culture process itself also induces somaclonal abnormality which results in the production of clonal palms with abnormal fruit set and flower characteristics (Rohani et al., 2000). Owing to these challenges, molecular research was initiated with a mission to unravel the molecular mechanisms controlling tissue culture amenity and the trueness-to-type of clonal regenerants.

In terms of clonal abnormality, a major breakthrough was achieved recently, when it was shown that a reduction in methylation of the retrotransposon Karma which lies within the EgDEF1 gene causes the ‘mantled’ phenotype (Ong-Abdullah et al., 2015), a result which built on the previous work published by Jaligot et al. (2014). This discovery paves the way for the development of a diagnostic assay that will allow the culling of abnormal mantled palms prior to cultivation in the commercial fields. Now the interesting question

which has to be addressed is how to correlate demethylation of Karma evidenced in

inflorescences from mature palms with epigenetic events occurring during the various

differentiation/dedifferentiation phases during in vitro micropropagation through somatic

embryogenesis (SE). This putative 'gene'-assisted selection will provide confidence for

large-scale commercial planting of oil palm clones, once an efficient diagnostic assay is

made available. An added booster will be the ability to predict if a palm can be successfully

micropropagated through SE.

The oil palm indirect SE process is initiated from leaf explants, which dedifferentiates

into callus followed by somatic embryo development. The candidate gene approach was

initially used to identify potential SE genes. This approach resulted in the association of a

putative peroxiredoxin, EgPER1 (Ong, 2001) and AINTEGUMENTA-like (AIL) gene, EgAP2

1 (Morcillo et al., 2007) with oil palm SE. In order to have an improved understanding of

genes expressed during tissue culture, ESTs were generated from suspension cell cultures

(Ho et al., 2007; Lin et al., 2009; Roowi et al., 2010), leaf-derived embryogenic callus

(EC), non-embryogenic callus (NEC) and embryoid (EMB) (Low et al., 2008; Chan et al.,

2010). Potential gene expression markers for embryogenesis such as EgPK1, a member of

serine/threonine kinase family (Ong-Abdullah and Ooi, 2007;

Ooi et al., 2008); EgHOX1,

a HD-Zip II subfamily member (Ong-Abdullah and Ooi, 2007; Ooi et al., 2010); OPSC10,

coding for aminocyclopropane-1-carboxylate oxidase (Ong-Abdullah and Ooi, 2007; Ooi

et al., 2010); EgLSD, a putative lignostilbene-α,β-dioxygenase (Roowi et al., 2010); EgER6,

a putative ethylene-responsive 6 (Roowi et al., 2010); and Eg707, an unknown protein

(Thuc et al., 2011) were identified from these ESTs.

Transcript profiling of ESTs during the tissue culture process was made possible by the

DNA microarray technology. The EST DNAs were printed on a glass slide, and relative

gene expression data were obtained through differential co-hybridization between test and

reference samples. Preliminary work focused on the identification of differentially expressed

genes across EC, NEC, EMB and shoot (Ooi et al., 2001; Chan et al., 2005; Low et al., 2006)

prior to early stages of tissue culture process. A total of 76 unigenes whose expression

was upregulated in NEC as compared to EC/EMB and shoot were identified (Low, 2009).

Research was subsequently directed at targeting a group of hormone-responsive genes

such as EgIAA9, a putative Aux/IAA to predict for embryogenic competency (Ooi et al., E m b r y o g e n i c m o l e c u l a r m a r k e r s f o r t i s s u e c u l t u r e a m e n i t y Somatic embryo Shooting Rooting Nursery Field Markers to predict for callogenesis Markers to predict for early somatic embryogenesis Markers to predict for late somatic embryogenesis Markers to differentiate normal and mantled palms Markers to predict for embryogenic potential Leaf explants Callogenesis Non-embryogenic calli Embryogenic calli M o l e c u l a r m a r k e r s f o r c l o n a l a b n o r m a l i t y

Figure 1 Application of molecular markers during the oil palm tissue culture process. Molecular

markers can be used at specific stages to predict for amenity and clonal abnormality.

2012). At the same time, genes such as EgBrRK, a putative brassinosteroid leucine-rich

repeat receptor kinase; EgCKX, putative cytokinin dehydrogenase; and EgRR1, a putative

response regulator type A gene were also linked to the callogenesis potential of uncultured

leaf explants (Ooi et al., 2013). Several of the genes listed above were used to develop

the first-generation markers to predict for oil palm tissue culture amenity, for which 15

candidate markers were made available to the industry in 2010 (Ooi et al., 2010). As shown

in Fig. 1, markers can be applied at specific stages of the tissue culture process to predict

for amenity and the ‘mantled’ clonal abnormality. Today, in-depth collaborative research is

required to identify a more robust set of markers that can be used to accurately predict for

tissue culture amenity and clonal abnormality across different genetic backgrounds with

high confidence.

7 Factors contributing to large-scale application of MAS in oil palm

The considerable progress achieved in the last few years in oil palm genomics has

now made it possible for MAS to be deployed as an integral part of oil palm breeding

strategies. Fig. 2 illustrates where molecular markers can potentially be integrated into oil

palm breeding, specifically in the modified recurrent selection scheme, which is widely

utilized in Malaysia. A major factor that will contribute to the successful application of

MAS in oil palm improvement is the cost involved. Not many publications in oil palm have

attempted to address this issue. Lim and Rao (2004) were the first to attempt at quantifying

the benefits of applying DNA markers in oil palm breeding. These authors had estimated

in 2004, when the availability of genomics resources and strong marker-trait association

was still at their infancy, that establishing a marker laboratory as an adjunct to a breeding

programme would add about 10% to the programme cost but will provide savings up to

30%, through the earlier detection of plant material of interest. More recently, Ooi et al.

(2016) developed an economic model which was able to show that for an average of ~8%

dura palms weeded out from independent commercial plantings using the SHELL gene

assay, an increased revenue of about US$89M was predicted for the oil palm industry in

Malaysia only.

Nevertheless, cost will still continue to be under scrutiny, especially for the private oil

palm breeding companies, when applying MAS. As such, steps have to be taken in order

to reduce cost where possible. A major hurdle in terms of cost is actually DNA extraction.

The availability of a high-throughput, efficient and cheap

DNA extraction system for

oil palm can be considered as the major bottleneck for large-scale application of MAS

programmes. High-quality DNA preparation in oil palm has been somewhat challenging,

due to high level of polyphenols and polysaccharides present (Rahimah et al., 2006;

Suzana et al., 2015) in oil palm tissues. DNA obtained from leaf tissues is most feasible

for early selection, while DNA from seeds (although utilized in some plant species) is not

suitable for MAS in oil palm. Oil palm seeds consist of a thick shell and kernel, and the

kernel in turn consists of endosperm. Shell is a maternal tissue (Corley and Tinker, 2003a)

and as such, the sample has to be taken from the endosperm to determine the genotype

of the palm that will eventually emerge. High cost of penetrating the thick shell to get into

the endosperm without damaging the embryo makes the process impractical. In addition,

up to 20% of seeds may eventually be culled as off-types at the various developmental

stages, making testing at this stage not cost-effective. Furthermore, seeds are also not

appropriate for DNA-based quality control in the tissue culture process, as clonal materials

are not seed derived. DxD trial TxT or TxP trials Markers applied to • Confirm legitimacy • Identify D palms carrying favourable alleles (eg. bunch component trait) Markers applied to • Confirm legitimacy • Discard D • Segregate T and P Cross D and P Markers applied to • Confirm legitimacy • Confirm T fruit form Markers applied to • Confirm legitimacy Selected D Plant T and P separately Markers applied to • Identify P carrying favourable alleles (e.g. Homozygous for vir, vertical growth) Selected P Plant and progeny test D x P For seed production Field plant New introductions Markers applied to • Access genetic diversity • Identify palms with favourable alleles

Figure 2 A simplified diagram describing integration of markers in the modified recurrent selection

breeding scheme (D: dura, T: tenera, P: pisifera).

As the plantations belonging to an oil palm company can be spread out over several

locations around a country, samples must be efficiently collected, tagged and brought to

a central DNA testing facility. An efficient sample collection kit, allowing sample tracking,

is essential for a large-scale MAS programme. More importantly, investment in developing

an efficient sample tracking system similar to laboratory information management system

is important. Tracking samples from the field to the DNA testing lab and subsequently

correlating the genotype profile obtained in the laboratory back to the original sample is

time consuming and can be error-prone if not managed well (Xu and Crouch, 2008). This

is especially true for oil palm, for which breeders tend to establish, evaluate and manage a

large number of crosses at any one time that are spread out over several locations. Careful

management of sample collection, DNA extraction, data generation via an efficient

tracking system at a high-throughput level will contribute significantly to cost-effective

and successful MAS programmes for oil palm in the long run.

Undeniably, a huge amount of data is going to be generated by genotyping samples of interest in MAS programmes, and this dataset must be integrated with other databases, [e.g.

breeding or genotype by environment (GxE) database] to make informed decisions accurately.

Although many tools are currently available in oil palm breeding and tissue culture, they were

almost developed independently, with separate data formats and in different operating systems.

If not synchronized, decision-making in a timely manner will be hampered and may restrict

effective communication between geneticists working in the laboratory as well as breeders and

agronomists in the field, hampering efforts at implementing MAS for oil palm improvement.

8 Future trends

Advancements in proteomics- and metabolomics-related technologies are essential to obtain

a more complete understanding of the determinism of complex traits such as yield and disease

resistance (Murphy, 2014), which are both major targets of oil palm breeding. Admittedly,

research in oil palm proteomics and metabolomics is relatively at its infancy. Nevertheless,

pioneering efforts have been made to elucidate fatty acid biosynthesis and lipid metabolism in

oil palm mesocarp (Hasliza et al., 2014; Lau et al., 2015; Lau et al., 2016) using gel-based and

nanoLC–MS/MS technologies. Proteomics platforms have also been utilized in understanding

the biological processes involved in palm oil production by analysing the fruits harvested at

different time points during maturation. This is with a view to identify key temporal changes in the mesocarp proteome that contribute to oil production (Neoh et al., 2013; Teh et al., 2013).

At present, proteomics and metabolomics studies are beginning to identify various group of

metabolites from the oil palm (Tahir et al., 2012; Tahir et al., 2013) and reveal the relationships

between specific proteins and/or metabolic changes associated with Ganoderma boninense

infection, which causes the basal stem rot disease (Syahanim et al., 2013; Nurazah et al., 2013).

Efforts are already underway to develop proteome- and metabolome-related databases (Nur

Ain et al., 2015) in order to have a centralized data repository system, which will facilitate

access to data and dissemination of relevant information.

9 Conclusion

In oil palm breeding and micropropagation, the adoption and utilization of MAS have

not yet met expectations. Even if markers for DNA fingerprinting to assess the fidelity

of controlled crosses have been available for at least a decade, widespread application

is lacking. Most of the efforts had actually been channelled at developing appropriate

genomic resources and finding marker-trait association for both monogenic and

quantitative traits of interest. The significant achievements which occurred in the last 3–4

years, especially in deciphering the oil palm genome and in identifying genes linked to

the two important monogenic traits of oil palm, namely fruit form and colour, will likely

pave the way for MAS in oil palm. The identification of these genes and subsequent development of a diagnostic assay for SHELL has opened up the prospects for error-free early selection in oil palm breeding. The identification of the gene linked to the expression of the ‘mantled’ clonal abnormality has also opened up the prospects for the use of markers for quality control during the oil palm micropropagation process. In the medium term, the advances made in conventional QTL analysis and association genetics in identifying markers linked to economically important polygenic traits will facilitate improvement of quantitative traits via MAS. MAS undoubtedly will be most effective where phenotyping is difficult or expensive for the polygenic traits. The emerging technologies of proteomics and metabolomics will also likely contribute to the long-term goal of routine selection via MAS. With the right support structure in place, in terms of sample collection, processing and tracking, MAS will facilitate the exploitation of the genetic variation available in exotic germplasms to improve yields and provide considerable value addition for sustainable development of the industry.

10 Where to look for further information

Additional information on oil palm genome assembly, transcripts, gene annotation and genetic markers is available at the Genomsawit website ‘http://genomsawit.mpob.gov.my’.

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9 Chapter 9 Advances in the genetic modification of oil palm

1 Introduction

Transgenic crop modification uses recombinant DNA methods to alter gene expression

in order to create new varieties for breeders that may be either difficult or impossible to

produce using conventional approaches. Over the past few decades, transgenic methods

have been successfully applied to develop genetically modified (GM) varieties of the major

oilseed crops, soybean, rapeseed and sunflower. In this section, the research efforts for

production of GM oil palm plants over the past 20 years will be reviewed. Although these

efforts have yet to result in stable lines of commercially useful GM varieties of oil palm,

there are good prospects that the greatly improved knowledge of genomics, coupled with

advanced technologies such as genome editing, will be successful in the future (Murphy,

2015).

Since the advent of scientific breeding in the early twentieth century, many novel

methods have been applied to agricultural improvement (Murphy, 2011). The term ‘genetic

modification’ is popularly applied to the use of recombinant DNA methods for the creation

of new varieties of plants, animals or microbes. Strictly speaking, however, humans have

been using genetic modification as part of crop and livestock breeding for over 10 000

years. Initially, such breeding efforts involved controlled reproduction followed by rigorous

selection of progeny by farmers so that new types of domesticated plants and animals

were created. In many cases the human-selected versions of their crops and livestock were

radically different from their wild ancestors that had only been subject to Darwinian natural

selection. Indeed, most domesticated organisms are unable to compete in the ‘natural’

world and would soon become extinct without their human guardians.

During the twentieth century, breeding methods became increasingly scientifically

based and even further removed from so-called natural selection. Such methods include

the use of DNA-damaging chemicals, for example alkylating agents and azides, or

gamma irradiation, for instance from cobalt-60 or caesium-137, to create large numbers

of mutations in plant or animal genomes. While the vast majority of such mutations

have adverse consequences, and are often lethal, a few may be useful to the breeder if

they result in phenotypes that are more adapted to agriculture. In other cases, breeders

have forced different species to breed together via wide crosses. The progeny of such

interspecific sexual crosses are normally non-viable, but they can sometimes be grown

to maturity using in vitro cell and tissue culture methods referred to as embryo rescue.

These and other highly intrusive breeding technologies have been widely used in plant breeding since the 1930s with little or no controversy (Murphy, 2011). Indeed, they are

often collectively referred to as ‘conventional breeding’ and are not classified as genetic

modification – despite the fact that their express purpose is to use laboratory techniques

to modify crop genomes.

2 Early and current genetically modified (GM) crop varieties

The first GM bacteria were created in the 1970s, and the first GM plants in the early 1980s.

In many cases, GM methods are faster, more specific and safer than alternative breeding

techniques such as mutagenesis. GM methods also have the advantage for commercial

breeders that the resultant crop varieties can be patented under more rigorous legislation

than is available for the protection of non-GM varieties (Murphy, 2007). Interestingly, GM

methods are now used routinely and without controversy in a host of medical applications,

such as the production of life-saving recombinant therapeutic products including human

insulin and blood-clotting factors. In contrast, however, the use of GM technologies in

agriculture has caused substantial (if arguably unwarranted) public concern. The concern

about GM crops has resulted in an effective ban on their cultivation in most of Europe

although they are increasingly being grown in the Americas, Africa and Asia (Murphy,

2016).

The earliest commercial transgenic oilseed crop was a variety of rapeseed (canola)

produced by the biotech start-up company, Calgene, and first grown under licence

by farmers in the USA in 1995 (Murphy, 2006). Interestingly, this transgenic rapeseed,

termed Laurical™, had been modified to produce a high-lauric oil with the aim

of replacing imported palm kernel oil in US markets. Laurical™ was produced by

transferring a gene encoding a C12-specific thioesterase from the California Bay plant,

Umbelluria californica, into rapeseed. Although yields of lauric acid were relatively low

in the early versions of Laurical™, the addition of additional transgenes eventually

enabled Calgene breeders to produce a seed oil that contained in excess of 60% w/w

lauric (Voelker et al., 1996).

However, even this relatively lauric-rich oil crop was unable to compete commercially

with the standard commodity lauric oil, which was (and still is) obtained from the far

cheaper and more plentiful (and non-GM) palm kernel oil. Therefore, the Laurical™ brand

of transgenic rapeseed was a commercial failure and was only grown for a few seasons

during the mid-1990s in the southern United States. This demonstrates some of the major

challenges involved in producing transgenic crop varieties that also apply to oil palm. In

the case of Laurical™, the technical challenges to produce a high-lauric oil were eventually

resolved but the unfavourable commercial realities of trying to compete with palm kernel

oil prevented the crop from succeeding in the marketplace.

Remarkably, since the mid-1990s there have been no further releases of GM crops

specifically modified to produce novel oils, and none of the major ‘first generation’

GM crops released between 1996 and 2010 were modified for output traits such as oil

composition. The reasons for this include the technical challenges in producing GM oil

crops with acceptable fatty acid contents, plus the lack of markets for such modified

oils. Moreover, even if these technical and commercial hurdles could be overcome,

new transgenic varieties would still face problems due to the public opposition to GM

crops that has existed in some parts of the world since 1999. Such opposition has been

particularly intense in Europe right up to the present day. Hence, in late 2015, many local

regions in the EU took advantage of a change in regulations and instituted formal bans on

the cultivation of all GM crops, this even included varieties that had been approved by the

European Commission (Nelson, 2015). In the case of a long-lived perennial tree crop like

oil palm, all three of these challenges, namely technical feasibility, commercial prospects

and anti-GM sentiment, are potentially more severe when compared with annual oil crops

such as rapeseed and soybean.

In 2015, GM crops were grown on 180 million hectares or about 10% of the global arable crop area (James, 2015). Over half of this area was in developing countries, with

Brazil, Argentina, India and South Africa emerging as increasingly important centres of

GM crop breeding as well as cultivation. Interestingly an increasing number of GM crop

varieties are being developed by public-sector organizations, such as EMBRAPA (Murphy,

2016) in Brazil. This is beginning to challenge the dominance of the major agbiotech

multinationals, such as Monsanto, Dupont and Syngenta, that have hitherto been the major

sources of seeds for GM crops. Indeed, in 2016, a Chinese government-owned company

called ChemChina acquired Syngenta in a development that many analysts regarded as

signalling the beginning of a large-scale deployment of GM (and other biotech-derived)

crops in China, while several other large agbiotech companies also announced merger

plans (Clapp, 2016).

3 GM oil palm in Malaysia

During the 1980s and 1990s, the oil palm industry in Malaysia was expanding rapidly

with a trebling of oil output between 1980 and 1995 (Abdullah, 2005). During this period

Malaysia was also aspiring to develop into a leading high-tech economy as outlined by

then prime minister, Dr Mahatir, as part of the ‘2020 vision’ for the country (Murphy 2003).

This coincided with the development of transgenic (GM) methods for oil modification in annual crops by several biotech companies, including Calgene, Dupont and Monsanto.

Production of the first experimental transgenic plants was reported in 1983 and over the next two decades many hundreds of transgenes were inserted into dozens of plant species. The late 1990s were a relatively optimistic time for GM technology, with the first large-scale crop releases occurring in 1998 and with the backlash from anti-GM groups was still in the future. At this time there was considerable pressure against imported palm oil from activist groups, such as the US soybean industry. The major criticism of what was referred to as ‘tropical oils’ was based on the perceived nutritional disadvantages of relatively highly saturated oil.

Existing accessions of oil palm were from a relatively restricted genetic base and did not display much variation in fatty acid profile, which ruled out a conventional breeding programme. A mutagenesis approach would also be complicated by the need to manipulate several independent genes (see Fig. 1). Given the success of Calgene in using GM methods to modify high-oleic rapeseed into a high-lauric variety after a few years of research and development, the prospect of creating a transgenic oil palm with a lower amount of saturated fatty acids was very enticing (see below).

Moreover, if it was possible to manipulate acyl content at will, other more niche novel oil varieties could be created, such as high stearate for solid fat markets or ultra

high laurate for cosmetic/cleaning products (Barcelos et al., 2015; Murphy, 2014;

Sambanthamurthi et al., 2009).

This led to the launching of a research programme to produce GM oil palm with target

traits that included oil composition plus several additional key agronomic characters.

This research was carried out at the Palm Oil Research Institute of Malaysia (PORIM) –

and later the Malaysian Palm Oil Board (MPOB) (Cheah et al., 1995; Sambanthamurthi,

et al., 2009). Even at this early stage, it was recognized that the choice of target traits

was important and that disruption of the existing highly successful commodity palm oil

products should be avoided. It was also recognized that oil palm transformation was a

multi-decade endeavour that was unlikely to bear fruit before the 2020s. This is illustrated

by the following quote about the goals of the GM oil palm programme from the leader of

the PORIM/MPOB transformation group, GKA Parveez: Among these targets are high-oleate and high-stearate oils, and the production of industrial feedstock such as biodegradable plastics. The efforts in oil palm genetic engineering are thus not targeted as commodity palm oil. Due to the long life cycle of the palm and the time taken to regenerate plants in tissue culture, it is envisaged that commercial planting of transgenic palms will not occur any earlier than the year 2020. (Parveez et al., 2000)

Figure 1 Metabolic pathway for the biosynthesis of C16 and C18 fatty acids in plants.

4 Improving the fatty acid composition of palm oil

By far the most important target trait for transgenic oil palm is to have a significantly

increased oleic acid content in the mesocarp oil. Existing commercial varieties of oil

palm produce a mesocarp oil that typically contains only about 40–45% oleate whereas

competitor crops such as rapeseed, olive, soybean and sunflower have varieties containing

well above 60% and in some cases as high as >90% oleate (see Table 1). The main reason

for the low oleate content of palm oil is that the mesocarp has a highly active palmitoyl-ACP

thioesterase that results in C16 palmitate being channelled towards TAG accumulation

instead of being elongated to stearate and desaturated to oleate (see Fig. 1).

In order to change the mesocarp oil into a high-oleate profile, it is therefore necessary

to manipulate at least three, and possibly more, genes. First, palmitoyl-ACP thioesterase

needs to be downregulated to stop palmitate being diverted to TAG. Secondly, the

key elongation gene, KASII needs to be upregulated so that the palmitate is efficiently

converted to C18 stearate. Thirdly, the stearoyl-ACP desaturase needs to be upregulated

so that stearate is efficiently desaturated to oleate. Experience with other crops, such

as the transgenic Laurical™ rapeseed described above, has shown that it may also be

necessary to transfer additional acyltransferase genes to ensure that the new fatty acids

are efficiently assembled onto triacylglycerols. For example, evidence from several plant

species suggests that the type-2 acyl-CoA:diacylglycerol acyltransferase (DGAT2) can

stimulate accumulation of exotic fatty acids in storage TAG (Kroon et al., 2006; Shockey,

2006).

Due to these complications, until very recently, the levels of the novel fatty acids in most

transgenic plants have been relatively modest and were far from achieving commercial

viability (see reviews by McKeon, 2005; Murphy, 2006; Cahoon et al., 2007; Dyer and

Mullen, 2008). This means that it is likely to be some time before an ultra-high oleate trait

can be created in oil palm, but this goal is still important due to the usefulness of oleate

rich feedstocks for both food and non-food applications (Murphy, 2014). It also means

that the engineering of oil palm for more minor fatty acid traits, such as high palmitate

or palmitoleate, or for acyl derivatives such as bioplastics (Parveez et al., 2015; Yunus et

al., 2008) is going to be even more problematic. Given that these will be niche products

with much more limited markets, it may be appropriate to question whether large R&D

investments in a transgenic strategy aimed at such targets are justified at this stage.

Table 1 The ‘big four’ major global oil crops and their potential for ultra-high oleate varieties

Type of oil Global production, Mt Global production, % Ease of producing GM varieties Highest % oleate achieved

Palm oil 65 40 + 50

Palm kernel oil 7 4 + 15

Soybean oil 50 30.5 ++++++ 75

Rapeseed oil 27 16.5 +++++++ 75

Sunflower oil 15 9 +++ >90

Data from USDA website, 2015.

In addition to oil modification, transgenic approaches can, in principle, be applied to

any other trait where suitable genes have been identified. This means that there is a long

list of possible GM varieties of oil palm, but high research and development costs are

likely to limit their development to traits with a guaranteed agronomic and commercial

potential. For example, expression of Bt insecticidal proteins has been proven to be an

effective strategy to control certain insect pests in a range of annual crops and is also being

investigated in oil palm (Lee et al., 2006). A much more important threat to oil palm yields

is the fungal pathogen, Ganoderma boninense, and the possibility of modifying lignin to

make oil palm plants more resistant is being examined (Paterson et al., 2008). As of 2016,

progress in addressing any of these traits has been limited and the high costs of existing

transgene technology mean that scarce resources would arguably be better targeted to

addressing the major key trait of high-oleate mesocarp oil where the biochemical basis

of the trait is reasonably well understood and there is a guaranteed global market for the resulting oil (Murphy, 2014).

5 Progress to date in oil palm transformation

Early work on oil palm transformation was initially focused on the assessment of suitable

tissue culture systems transformation and suitable vectors for transgene delivery. This work

was based largely at PORIM/MPOB with additional input from several university-based

groups in Malaysia, as outlined in Abdullah (2005). During the 1990s, Agrobacterium

mediated gene transfer was still largely restricted to dicot plant species. At this time

a few monocots such as rice and maize had been transformed, but oil palm was well

outside the host range of Agrobacterium so initial strategies for oil palm transformation

used the newer method of biolistics, which could in principle be applied to any plant

species (Parveez 1998; Parveez and Christou, 1998; Parveez et al., 2000). A disadvantage

of biolistics is that it often results in the integration of multiple transgene copies or even

fragments of transgenes, whereas Agrobacterium-mediated transformation is more likely

to introduce either single-copy or low-copy-number transgenes. Nevertheless, it was

possible to bombard oil palm cultures with marker genes such as GUS and achieve transient

expression of the transgene (Parveez et al., 1997). It was also possible to experiment

with different gene promoters in order to investigate levels of gene expression and tissue

specificity (Chowdhury et al., 1997).

In order to improve transformation efficiency, new tissue culture systems were developed

in order to have a suitable starting material for transformation. One of the best systems

was found to be immature oil palm embryos and these were used as the target tissue for

both biolistics and Agrobacterium-mediated transformation experiments (Ruslan et al.,

2005; Bhore and Shah, 2012). This resulted in transformed tissues that expressed marker

transgenes such as those encoding Bacillus thuringiensis (Bt) insecticidal proteins (Lee et

al, 2006) and the cowpea trypsin inhibitor (CpTI) (Ismail et al, 2010). Unfortunately, these

experiments required the transformation of thousands of tissue-culture samples. Even

after several stages of selection and regeneration, there were many hundreds of plants

that required housing in containment facilities and subsequent analysis. It took 3–5 years

to generate transgenic oil palm plants by either particle bombardment or Agrobacterium

mediated transformation and that both processes were highly inefficient. The frequency

of escapes and chimeric plants was high because of the long selection process during

callus formation and the fact that somatic embryogenesis encourages the growth of

non-transformed cells (Masani et al., 2014). This meant that the logistics of establishing

and maintaining such large numbers of tissue explants and regenerating plantlets was

extremely challenging.

Despite several decades of intensive research, the development of transgenic oil palm remains a relatively young science and is fraught with many technical and logistical challenges. For example, it is still unclear whether biolistics or Agrobacterium-mediated gene transfer will be the gene delivery method of choice (Izawati et al., 2012; Parveez and Bahariah, 2012). The choice of plant material is also crucial with some of the best options including various types of callus and embryo culture. Then there is the issue of which gene promoters to use. Unlike most existing commercial transgenic crops where constitutive viral promoters are used, the manipulation of palm oil composition will probably require deployment of strong mesocarp-specific or kernel-specific gene promoters, ideally sourced from the oil palm genome itself.

Also, in order to achieve high oleic oil phenotypes, it will probably be necessary to downregulate some genes while adding or upregulating other genes. Even when the primary transgenic plantlets have been produced they will still need to be grown on for three to five years to obtain fruits that can be screened for oil content. Finally, these primary transformants will need to be taken through several sexual generations, backcrossed with existing elite lines and then multiplied via micropropagation before any new commercial transgenic varieties can be released. Some recent strategies for achieving transgenic oil palm are listed below: • Improved transformation vectors for oil palm (Yunus, and Parveez, 2008) • Development of positive selectable marker systems such as phosphomannose isomerase (Bahariaha et al., 2013) and 2-deoxyglucose-6-phosphate phosphatase (Izawati et al., 2015) • Transforming oil palm protoplasts by PEG-mediated transfection and microinjection (Masani et al., 2014) • Using more rigorous molecular analytical methods to detect transgene presence (Nurfahisza et al., 2014) • Improved tissue-specific gene promoters for mesocarp expression (Taha et al., 2012)

Given the gradual rate of progress to date, it seems likely that the development of

routine methods for transforming oil palm with gene constructs optimized for commercial

phenotypes will take more than a decade from the present time. The initial target of

having commercial transgenic oil palm varieties under cultivation in the 2020s is now

looking rather optimistic. However, a target date in the late 2020s is not necessarily totally

unrealistic, especially if new genome-editing technologies prove useful, as discussed

below. Meanwhile it is important that efforts at using classical and/or more modern

genome manipulation technologies are continued for oil palm. This is because there are

likely to be several important genetic traits that cannot be created using non-transgenic

approaches. For example, although it may be possible to create a medium-high (55–65%)

oleic oil phenotype via conventional methods (e.g. by using identified accessions obtained

from Africa (Murphy, 2014)), a more desirable ultra-high (80–90%) oleic trait might only be

possible via transgenic technology. Another example where the use of transgenic methods

is essential is the production of completely novel compounds, such as biopolymers like

polyhydroxyalkanoates, in oil palm.

6 New technologies for genome editing – an alternative to 'classical GM'

During recent years, biological advances have started to make it much easier to

manipulate genomes in more radical and precise ways than were possible with traditional

late twentieth-century GM technologies (Murphy, 2016). For example, several new forms

of plant and animal (including humans) GM technologies known as 'genome editing' have

recently been developed. Probably the most powerful is the CRISPR (Clustered, Regularly

Interspaced, Short Palindromic Repeats) system (Hsu et al., 2014; Mao et al., 2013). In 2015,

the CRISPR/Cas9 system was described in a Nature article as 'the biggest game changer

to hit biology since PCR' (Ledford, 2015a). Applying this method to crop improvement

has opened up many new possibilities for radical genome modifications (Belhaj et al.,

2015; Zhang et al., 2014). Genome editing will greatly accelerate crop breeding by

enabling precise and predictable genetic modifications directly in elite individuals as well

as simultaneous modification of multiple traits.

This means that breeders will progress well beyond the random insertion of single or

small numbers of genes into a genome (as in traditional GM) to the highly precise insertion into a defined location of large numbers of genes, chromosome segments or pseudo

segments encoding entire metabolic pathways into virtually any plant species. Methods

such as TALEN (Transcription Activator-Like Effector Nucleases) and CRISPR/Cas9 can be

used for gene knockouts, for example, to eliminate unwanted genes that adversely affect

food quality or confer susceptibility to pathogens or that divert metabolism away from

valuable end-products. An example reported in 2014 was the use of both TALEN and

CRISPR/Cas9 to target the genes of the mildew resistance locus in wheat. This resulted

in the production of plants resistant to powdery mildew disease, which is a serious crop

disease (Wang et al. 2014). Throughout 2015 and 2016, improved versions of CRISPR have

been reported that will enable the technology to be used more widely and effectively to

create new crop phenotypes (Ledford, 2015b; Zetsche et al., 2015).

In addition to transgenic approaches, modern breeding is able to profit from a host

of advanced technologies such as association genetics (Rafalski, 2010) and molecular

mutagenesis, including TILLING (TargetIng Local Lesions IN Genomes) (Shu, 2009) and

marker-assisted selection (Ribaut et al., 2010). Deployment of these technologies is

already enabling breeders to begin to address complex traits such as drought tolerance

and disease resistance (Tuberosa and Salvi, 2006; Xu, 2010). Such technologies could be used together with GM methods to develop additional useful traits such as dwarf trees, increased oil content in mesocarp and kernel tissues, and wider resistance/tolerance profiles to a range of pests and pathogens (Murphy, 2014).

7 Conclusions and future prospects

Despite a lack of clear scientific evidence to support adverse claims from anti-GM activists, many politicians in Europe remain wary about allowing GM crops or products to be grown or imported into the region (Nelson, 2015). Given that oil palm already suffers from an image problem (especially in Europe) due to its perceived environmental impacts, the industry is rightly cautious about possible future GM developments. Indeed, in many cases palm oil producers actually stress that the crop is entirely non-GM at the present time.

However, the current status of GM crops may change radically over the next decade as the technology becomes ever more refined and globalized and is applied to more crops with traits that have better consumer appeal than current GM varieties (Murphy, 2016). In line with this prospect, it was announced in mid-2016 that CRISPR-edited crops (which some would regard as being GMOs) will be able to be cultivated and sold in the USA without regulatory oversight by the USDA (Waltz, 2016).

By 2016, over half of all GM crops were being grown in developing countries, including several countries in Africa. There has been an increasing tendency for transgenic crops to be developed by public-sector institutions in developing countries and then distributed at low cost to poorer farmers. An example is golden rice developed by IRRI in the Philippines and scheduled for release to farmers in 2016–17 (Kowalski, 2015; Moghissi et al., 2015). As developing countries produce new varieties of GM crops with traits such as improved nutritional quality drought tolerance and disease resistance, it will become increasingly difficult to defend the 1990s-era argument that GM crops represent a tool for the imposition of global food hegemony by Western governments and multinationals (Engdahl, 2007). These factors of improved genome-editing technologies, ability to alter many more traits, more public-sector and public-good research and development, and increased attractiveness to consumers around the world mean that the coming decades are more likely to see an expansion in the number and range of GM crops and traits. For these reasons, one can be cautiously optimistic about the future of transgenic oil palm and the possibility that commercial releases might be carried out before the end of the 2020s.

8 Where to look for further information

The most reliable source of information about this topic for researchers is the peer reviewed literature and especially the articles cited below. In some cases there may also be useful

web-based information from bodies such as FAO and national scientific academies such

as US National Academy of Science and the Royal Society in the UK.

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12 Chapter 12 Maintaining soil health in oil palm cultivation

1 Introduction

In West and Central Africa, initiatives to set up organized oil palm plantations were

reported as early as the nineteenth century (Berger and Martin, 2000). However, the first

modern plantations to contribute significantly to oil and fat production only appeared after

World War II in the Belgian Congo, Côte d'Ivoire, Nigeria, Ghana and Cameroon (Corley

and Tinker, 2016). The first plantations in Southeast Asia were created between 1910 and

1920. The areas increased rapidly and, after World War II, Malaysia and Indonesia were

definitively the leading region in the world in terms of areas planted (Rival and Levang,

2014). In Latin America, plantations started appearing in the 1950s in Colombia and

Ecuador, and more recently in Brazil and Central America.

The climatic requirements of the crop mean that the cultivated areas are mainly located

in an equatorial band between the latitudes ten degrees North and South. This area is

also the home of equatorial and tropical rainforests. Oil palm plantations set up after

cutting primary or secondary forests were therefore very frequent at the beginning of the

twentieth century in Africa and Asia. After an initial cycle of around 30 years, replanting

with oil palm started while the rapid spread of cultivated areas in Southeast Asia continued

to take place with the conversion of natural forests or forests managed for timber. In

Indonesia and Malaysia, depending on regions, it is estimated that 55–90% of the areas

planted have been established on forests (Pauli et al., 2014).

In tropical soils under forest, the topsoil is where the fertility lies due to its physico

chemical properties, developed through an accumulation of organic matter (OM) and

intense biological activity. That layer is protected by the plant cover and the formation

of a humus-bearing layer. Erosion and sediment transportation processes are minimal

under tropical forests, despite being subjected to high rainfall (Hartemink, 2006a). The

quality of soils inherited from forests converted to oil palm plantations led to high palm

oil yields, which contributed to the crop expansion. In Côte d'Ivoire, Ollagnier et al.

(1978) investigated the changes arising from cultivation by comparing soil properties at

different ages (up to 14 years) with those still under forest, down to a depth of 90 cm. They

concluded that after a rapid change in the first four years after felling of the associated

trees, the topsoil evolved towards a new chemical state corresponding to 60–90% of

the initial state depending on the variables examined (C, N, CEC, pH and exchangeable

cations). According to these authors, the observed changes towards a new stable state did

not constitute a degradation likely to have an adverse effect on yield potential over the long term if the best management practices at the time were respected.

The main challenges for soil health were thus established to preserve, or even improve,

physico-chemical properties that enable high yields. Along with preserving the chemical

reserves of soils, protecting them from the risks of physical degradation through erosion

also needs to be added. Finally, cultivated soil under oil palm should not be a threat to the

environment, which can occur when leached mineral nutrients contaminate water tables

and courses.

2 Key issues and challenges

2.1 Soil: an essential factor for crop sustainability

Although yields depend on several factors, especially of genetic and climatic order, the

physico-chemical properties of the topsoil down to a depth of 30 cm play an essential role

in influencing the crop's supply in water and nutrients. Oil palm is grown on a wide range

of soils whose profiles differ depending on their origin (nature of the parent material,

climate and topography) and how they evolve after planting. So, in each situation, the

properties of the different layers of the soil profile and the limitations for the crop will vary.

Several authors have proposed keys for understanding to define classes in which

potential yield is reduced by certain limitations. Indeed, Olivin (1968) defined a framework

of five agronomic classes based on texture, the existence of coarse elements, the adequacy of drainage and chemical fertility. Such classification gave good results in Africa where the

criteria had been defined. Paramanthan (2000) developed a similar approach involving

five ability classes based on several precise variables, taking into account topography

and other factors that seemed more specific to Asia, such as soil salinity or the existence

of an acid sulphate horizon. Setting aside these two aspects, which are not particularly

widespread in the oil palm world, the variables identified by Olivin and Paramanthan

converge to describe the main functions of soil for the crop, which are: (i) to provide a

sufficient water supply for the compensation of evaporative demand, especially during

periods of low rainfall. Besides, soil water saturation must not be excessive and drainage

must be adequate enough to avoid the establishment of an anaerobic environment over

long periods during the rainy season; (ii) to constitute a reservoir of nutrients which must

be both available for the plant and minimally exposed to losses through leaching; and (iii)

to protect the soil from erosion and run-off, which contribute to losses of both sediment

and OM.

The ecosystem functions of soils linked to their biological activities also need to be

added to the above functions.

2.2 Soil and water supply

The oil palm is highly susceptible to water deficits that occur in climates with a marked dry

season, especially in Africa. As soil is the reservoir that helps to mitigate drought effects,

its depth is one of the most important physical properties which govern that function. The

topsoil is most colonized by roots, though primary and secondary roots have been found

down to a depth of more than 6 meters (Jourdan, 1995). The absence of an indurated

horizon in the first 2 meters is considered as favouring adequate rooting.

The soil texture also plays an essential role in the occurrence of structures which are

able to promote an adequate water reserve. The quality of such structure (dimensions of

aggregates and voids, porosity, stability of aggregates) determines the volume of water

available over a given depth and is highly dependent on several other parameters, notably

the biology of the soil, plant cover and cultural practices. Both the depth and structure

properties of the soil determine the available water reserve at a given stage of the crop

under given climatic conditions.

2.3 Soil and nutrient supply

The chemical properties of the topsoil, which are used by most authors as an indicator of

soil fertility, are the amounts of OM and N, the cation exchange capacity (CEC), the pH

and the amounts of exchangeable potassium (K), calcium (Ca) and magnesium (Mg), along

with base saturation.

Some authors also mention soil phosphorus (P) reserves as an indicator of fertility,

although this aspect of soil chemical fertility is mainly related to the management of

crop fertilization. Soil salinity problems are rare and the methods to be implemented for

keeping a saline water table at a suitable depth do not call for a specific approach for the

oil palm. Moreover, sodization of the soil profile is controlled by usually abundant rainfall

which naturally keeps sodium at a depth if soil drainage is effective.

Tropical soils undergo the process of weathering and leaching of cations and

anions due to heavy rainfall and high temperatures which are typical of the oil palm

cultivation zone. These phenomena, combined with the frequent presence of 1:1 layer

clay minerals, mean that the CEC is generally weaker than in soils developed under a

temperate climate. OM therefore plays a more important role when the texture is sandy

and the pH is acidic.

Finally, erosion processes directly reduce the ability of the soil to provide the crop with

water and nutrients by altering the topsoil horizon, which is by far the most useful. This

also leads to the decay of fine absorbing roots once they are exposed to the open air.

The factors that increase erosion are described, and rainfall intensity, slopes and soil cover

were found to be the most important (Hartemink, 2006b). It is practically impossible to control the intensity of incident rainfall at the plantation scale; the installation of terraces and suchlike along contour lines can help in some cases to overcome slopes, although such techniques are expensive and usually limited in area. This is why one should be focusing more on managing biomass under oil palm in order to protect the soil from erosion. These techniques are all the more promising in that they can be applied to even the gentlest slopes.

3 Management practices and soil health in oil palm plantations

Operations in oil palm plantations modify soil properties throughout the life span of the crop by creating distinct zones with various different activities (Fig. 1A). Although many configurations exist, in most cases a distinction is made between at least three management zones (or management units, Nelson et al., 2015): the chemically weeded circle (WC); the harvesting path (HP), which is mostly used for harvesting and dispersion of fertilizers; and the area in which pruned fronds are deposited (FP-Frond pile), which is where herbaceous or woody regrowth is generally more abundant. In some plantations, in order to avoid accident due to the spiny petiole, this part of the leaf is separated to form a petiole stack (PS). Some authors also distinguish an intermediate zone (BZ – Between Zone) which is the area located outside the transit zones (HP and WC) but which is not covered by pruned fronds. The relative sizes of each of the sectors do vary with the practices adopted by each plantation manager and with the planting density of oil palms: with a radius of between 2.0 and 2.5 metres, WCs account for around 20% of the area planted; with a width of 3 metres, HPs account for around 20%; and the FP areas vary from 20% to 30% depending on the spreading adopted. In theory, this zone may be expanded to cover the entire area, apart from the circles, that is 80% of the planted area. BZs cover the additional area.

In addition to these different zones individualized by management practices, it is also necessary to consider the effect of fertilizers which are applied to specific areas and the

Figure 1 Various types of frond disposal. (a) traditional with alternate frond piles (FP) and harvesting path (HP), (b) U-shaped frond disposal, (c) frond disposal in the centre of the interrow exposed to erosion processes and petiole stacks (PS), (d) random disposal and petiole stacks.

periodic recycling of mill by-products in the form of fresh empty fruit bunches, compost, and in some cases even the dispersion of liquid effluents or sludge. Depending on the choices adopted for all these practices, the physico-chemical properties of soils will change either negatively or positively. Interaction with other characteristics which are site specific (soil texture, topography, rainfall pattern) may also increase the resulting differentiation from the properties of the original soil.

3.1 Effect of pruned frond recycling on some soil properties

In a survey conducted on smallholdings in Benin, Aholoukpé et al. (2016) compared soil

properties under frond piles with those of soils where all fronds were removed from the

plot. The purpose of the study was to assess the long-term effects of this practice, which

consists in using pruned fronds as domestic fuel by local populations. The effects of fronds

recycling on the total C, total N, water pH and exchangeable K variables depending on

soil depth are recapped in Fig. 2. A very clear improvement in pH, total organic C, total N,

CEC and exchangeable cations can be observed even at a depth of 25 cm, beyond which

the effect of frond OM becomes negligible.

Figure 3 describes a lower soil density under frond piles (0–20 cm) than without

OM recycling. Frond recycling therefore helps in increasing soil porosity and available

water reserves in the horizon immediately below the frond layer. The same layer is

also the one colonized by fine roots, and it is essential for the supply of water to oil

palm.

Pruned fronds amount to an average ten tonnes of dry matter per hectare in mature oil

palm plantations (Redshaw, 2003). They provide a source of OM which is cheaply available

on site. This biomass has long been spread in every other inter-row (Fig. 1A), the idea being to limit the area covered by fronds so as not to hinder operations (upkeeping,

fertilization, harvesting).

Figure 2 Effect of recycling pruned fronds (RT) compared to bare soil without recycling (RN) on 4 soil

properties in Benin (according to Aholoukpè et al. 2016). Each mean is presented with the confidence

interval (at $p < 0.05$).

The results obtained for OM effects on soil properties have led growers to adapt how

they position the fronds, seeking to amplify their beneficial effects. Depending on the

local situation and constraints, several effects may be sought after: • Better topsoil porosity and colonization by roots: The increase in pH and in CEC, and the appearance of organic humus compounds promote the generation of a stable structure enabling adequate aeration and drainage conditions. To a certain degree, this area will be protected from evaporation by a mulch effect due to the plant debris, which is useful under a climate with a marked dry season. Among smallholders, who do not have the constraints of mechanized operations, unlike agro-industrial estates, virtually the entire area, apart from the weeded circles, can be covered by fronds (Fig. 4 and Fig. 1D). • Greater ability of the topsoil to retain fertilizing inputs: This function is all the more efficient as the amended area promotes the development of absorbing roots. Although fertilizers are sometimes spread over the surface of the weeded circle, it is recommended that they be applied on the areas covered by OM as an improvement in the pH and CEC values will favour cation fixation on the surface and thus will reduce the risk of leaching. • Erosion and run-off control (Fig. 5): Pruned fronds can be laid on areas subject to runoff, in order to create obstacles which will reduce the flow rate and curb the erosion process (Quencez, 1986). This is generally the first step that encourages further colonization by plants whose roots will fix the soil. In addition to pruned fronds, which sometimes need to be fixed to the soil, other sources of OM can be used, notably EFB.

Figure 3 Changes in soil bulk density under total recycling (RT) and no recycling (RN) for the 0–50 cm soil layer under mature palms (13–24 years) (according to Aholoukpè et al. 2016). Each mean is

presented with the confidence interval (at $p < 0.05$). • Finally, and this is definitely the most essential aspect over the long term to provide a habitat for soil organisms that contribute to several soil-based goods and services (Wall, 2012). Among the most important are soil OM synthesis linked to the conversion of organic C, the nutrient cycle and soil structure maintenance (Kibblewhite and Ritz, 2008).

These services involve the arthropods, nematodes, fungi and bacteria making up the soil

biota (Carron et al., 2016; Tao et al., 2016).

3.2 Effects of some mineral fertilizers on the chemical properties of soils

Fertilization trials are conducted to assess the requirements of the plant in order to reach

or approach the maximum yield. These are determined for each situation by several

variables, notably the climate and the planting material. The experimental designs

selected will serve in determining the leaf contents that will be considered as optimum

Figure 4 Frond disposal in Ecuador.

Figure 5 Run-off and erosion processes in Ivory Coast.

for reaching yield targets. By using an indicator of the mineral composition of the foliage

in each plantation block (25–50 ha), annual fertilizer requirements will be determined.

This scheme totally ignores the status of the soil’s reserves, and no accurate decision

making tool has been proposed based on soil analyses for the industrial management

of fertilization (Goh, 2004). However, although managing mineral nutrition of plantations

using leaf analyses provides satisfactory results in terms of both vegetative growth and oil

yields, the fact that a stable composition for the aboveground organs can be maintained

does not guarantee that an equivalent balance exists in soils. It is therefore reasonable

to explore changes in the soil's mineral reserves on the long term. Apart from changes in

the physical properties of soils that are linked to cultural practices (e.g. compaction due

to the passage of agricultural machinery) and are not covered in the present chapter, two

questions are frequently recurring about the chemical fertility of soils under oil palms: (i)

Does mineral fertilization modify soil chemical properties such as pH or cation balances?

(ii) On the long term, are the so-called mining effect processes occurring that alter the soil

nutrient reserves that feed the soil solution?

In Ecuador, Dubos et al. (2016) used two long-term fertilization trials in order to investigate

these issues. After ten years of urea and KCl applications using different protocols (Tables 1

and 2), the topsoil (0–20 cm) was analysed while distinguishing between the zones directly

receiving fertilizers and those deprived of treatment.

In both trials, N application did not improve FFB production (data not shown), but the

consequences for the chemical properties of the fertilized soils were substantial, since it

resulted in a drop in pH following cation depletion. The effects were greater when the

CEC and pH values in the original soils were high, as shown in CP08 trial. To explain the variation in pH found between the two trials, the authors proposed that leaching of excess N occurred under the form of nitrates towards the underlying horizons.

The consequences of KCl applications on the fertilized soil were also marked: the exchangeable K content increased very significantly and could exceed 1 cmol kg^{-1}, which is a very high value (Goh, 2004) for the types of tropical soils where oil palm is grown. This

Table 1 Effects of N fertilizer on pH and exchangeable cations in the fertilized zone after 10 years of application (according to Dubos et al. 2016)

	CP06				CP08		
	N0	N1	N2	P-value	N0	N1	P-value
N applied (kg $palm^{-1}$ yr^{-1})	0	0.45	1.35		0	1.35	
pH water	4.95	4.80	4.63	0.089	5.88	4.71	0.000
Ca cmol kg^{-1}	1.563a	0.751b	0.500b	0.002	4.953	1.805	0.000
Mg cmol kg^{-1}	0.538	0.390	0.306	0.088	1.101	0.525	0.001
K cmol kg^{-1}	0.426	0.438	0.370	0.776	1.108	0.785	0.054
Al cmol kg^{-1}	1.637b	2.374ab	2.972a	0.016	0.028	0.946	0.002
H cmol kg^{-1}	0.089b	0.106ab	0.126a	0.008	0.015	0.109	0.000
CEC cmol kg^{-1}	5.89	5.73	5.86	0.770	7.50	4.90	0.000

P-value: significant results are shown in bold. Means followed by the same letter are not significantly different, according to Tukey's test.

imbalance affected Ca and Mg contents, whose significant drop compensated for the increase in K (CP08).

The harmful effects of N and K fertilizers on the chemical properties of soils were found

to increase in line with application rates. Indeed N and K are the two nutrients most used

by oil palm, be it by the aboveground vegetative organs or by the FFB. The observed

changes in exchangeable cations may be reflected in the unfavourable evolution of

the soil structure, as seen in Côte d'Ivoire (Caliman et al., 1987). When replanting oil

palm plantations in savannah in the Dabou region, these studies showed that a drop in

productivity between the first and second cycles was linked to the unfavourable evolution

of the topsoil structure, which limited its colonization by roots. The measures that were

successfully tested consisted in restoring the structure by subsoiling and applying gypsum

to rebalance the monovalent:bivalent cation ratio.

Environmental risks are directly linked to the leaching of excess nitrates and K. Indeed

the decrease in CEC observed for fertilized soil increases the risk of water table pollution,

particularly as NH 4 and K adsorption is low. It is therefore definitely worth not over-fertilizing

the plants, meaning that the mineral status of plants and soil in oil palm plantations needs

to be accurately assessed, ensuring that fertilizer uptake efficiency is optimum and losses

are limited. Foong (1993) estimated maximum N and K losses by leaching at 5.8 and 4.4%,

respectively, in mature plantations in Indonesia, which seem to be low values. However,

Banabas et al. (2008) estimated N losses under the root layer at 47% when incident rainfall

was very intense. Further studies would therefore be worthwhile (Corley and Tinker, 2016)

in the aim of determining the conditions that tend to reduce the risks of leaching. There

are roughly two mechanisms that promote cation retention in the soil, and which can help

in reducing NH 4 , K, Ca and Mg losses: a high CEC and the presence of fine absorbing

roots. OM applications do promote both mechanisms, which leads us to recommend

applying fertilizers on the areas which are the richest in OM, that is, as a priority in the frond

spreading zones, but also in zones where oil mill by-products are spread when practised.

The favourable effect of fertilizer dispersion can also be added to the advantages of OM.

In the two trials examined above, the fertilizers were applied over an area not exceeding

10 m² per palm, which is small when compared to the 70 m² potentially available with a

planting density of 143 palms per ha. A theoretical calculation was made for a fertilizer

area of 30 m² on a soil with a bulk density of 1.3 and a useful layer of 25 cm for absorbing

roots. K application equivalent to 1 kg of KCl, that is, 1282 cmol, only amounts to 2.6% of

Table 2 Effects of K fertilizer on exchangeable cations in the fertilized zone after 10 years of application

(according to Dubos et al. 2016) CP06 CP08 K0 K1 K2 P-value K0 K2 P-value

K applied (kg palm -1 yr -1) 0 0.5 1.5 0 1.5

Ca cmol kg -1 1.090 0.903 0.821 0.343 4.041 2.716 0.007

Mg cmol kg -1 0.366 0.419 0.449 0.660 0.986 0.640 0.012

K cmol kg -1 0.030 b 0.193 b 1.010 a 0.000 0.261 1.631 0.000

Total cmol kg -1 1.49 1.52 2.28 5.29 4.99

P-value: significant results are shown in bold. Means followed by the same letter are not significantly different,

according to Tukey's test.

the total CEC of the volume of fertilized soil if the CEC measured is 50 cmol/kg. This level

for CEC, which is very low, is that of a very sandy soil propitious to leaching. However, the

degree of disturbance caused by KCl application is intuitively acceptable when considering

the risk of displacing other cations from the exchange surface.

In a study of soil properties after repeated applications of N and K fertilizer, Dubos

et al. (2016) also considered soils that were not fertilized. The idea was to compare the

soil reserves under unfertilized treatments with those from treatments balancing N and K

requirements of the palms with fertilizer applications. After ten years without fertilizers,

no mining effect could be measured, as the soil reserves were not significantly lower. This

conclusion does not mean that no soil impoverishment took place, but rather that the

degree of take-off over ten years was not enough to be detected given the measurement

system and the accuracy of the analysis methods in the laboratory. Nevertheless,

maintaining the chemical reserves of soils remains as a concern over the long term.

4 Optimizing biomass recycling: the promising way to increase yields and sustainability

Recycling available biomass is a powerful way of restoring, preserving or improving the

properties of soils. OM conservation begins as soon as the crop cycle is created by adopting

non-destructive practices (especially zero burning), unlike what was sometimes done in

previous centuries. The recycling of oil mill by-products has become a widespread practice,

be it under the form of EFB or compost. At the outset, it was a strategy to substitute mineral

fertilizer with organic fertilizers, thus enabling some use of by-products while providing

a technical solution for their recycling. At the plantation scale, the improvement in soil

fertility was confirmed in blocks under organic fertilization, thus reflecting in an increase in

pH, in organic C, in the CEC and in exchangeable cations (Comte et al., 2013). However,

palm oil mill by-products, whose effects can be expressed differently depending on the

nature of the soil, cannot be spread over all areas, unlike pruned fronds which are available

everywhere without any need for transportation. At the palm tree scale, EFB application

over a very limited zone (the harvesting path) leads to marked changes compared to

application in the other zones (Rosenani et al., 2011). However, OM applications bring into play complex mechanisms that go beyond the foreseeable effects due to the chemical composition of the recycled matter. For what concerns chemical parameters, an increase in pH, Ntotal, Corg, CEC and exchangeable cations is generally measured in the application zone. However, those changes may come about through an imbalance, especially for P, K and Mg and the pH. As regards biological parameters, it was found that EFB applications impacted the communities of living organisms making up the biota of the soil, especially earthworm communities, whose movements followed variations in nutrient availability or stress associated with the application of organic by-products (Carron et al., 2015a).

An analysis of the variability in soil parameters after applying organic waste brought out three distinct periods: 1) a period of strong disturbance lasting around six months, with an increase in pH, base saturation, K and the macrofauna density (especially ants), but a decrease in earthworms, centipedes and nematodes; 2) a period of resilience lasting around 12 months; and 3) a period of stimulation lasting around eight months with an increase in macrofauna (earthworms, centipedes and nematodes) activity and some improvement in the soil fertility parameters (Carron et al., 2015b). Beyond two years’ time, the analysis of physical, chemical, morphological or biological indicators of soil quality revealed that EFB application helped to restore the soil under the harvesting path and thereby homogenized properties of the different zones, which were no longer different for

these parameters at the palm tree scale (Carron et al., 2016).

Of the four ecosystem services identified by Brussaard (1997), OM decomposition,

bioturbation and nutrient recycling are the most capable of ensuring that soil health is

maintained over the long term. The soil biota, especially earthworms, break down OM,

redistribute it at depth, and increase aeration and water infiltration. Some bacteria

(Rhizobia group) facilitate nitrogen fixation by developing nodules on plant roots

(regrowth, legume cover crop). Several studies have indicated that soil biodiversity is a

key factor for maintaining ecosystem services (Wall, 2012). It also seems that the stability

(i.e. resistance and resilience) of ecosystem services in relation to disturbance and stress

generally appears to be more strongly related to species richness (Brussaard et al., 2007).

Soil biodiversity cannot be modified directly by introducing individuals and, for that

reason, improving environmental conditions that are favourable to biodiversity increase

seems to be the most promising strategy.

5 Future trends in research

Two avenues are opened up for going beyond the effect of OM on chemical properties

and for understanding how the services provided by soil can influence crop functioning.

Studies on how EFB application rates and frequencies affect the biodiversity of soils

(Carron et al., 2016) have only made it possible to describe changes in the communities of

organisms at a given instant, but not to measure the impact of those changes on the plant

itself. These results therefore need to be extended by linking the diversity of the soil biota

to the functions that are decisive for carbohydrate production. The crop’s water supply,

nutrient cycle and root biomass should therefore be observed over sufficiently long time

lapses for the properties of the soil and the composition of the biota to be stabilized.

Long-term monitoring of cultivated soils under oil palm is a recent concern for growers.

It is often suggested that soil analyses should be carried out periodically, once every 3–5

years, in order to assess the reserves of the soil and its ability to retain nutrients (i.e. OM

and CEC) (Paramananthan, 2015). It is also covered by the principles and criteria governing

certification through voluntary Roundtable for Sustainable Palm Oil (RSPO) standards. Until

now, the decision of undergoing or not a long-term monitoring of soil health belongs to

plantation managers only and no standard has been issued for interpretation over the long

term. Yet, as already mentioned, the accuracy of observations depends on the accuracy of

analyses delivered by laboratories and this would probably not be enough to guarantee

an objective analysis of the sustainability of soil reserves over a time lapse as short as 5 years. Nelson et al. (2015) proposed a simple method for directly taking composite samples

proportionally representing the different zones of the crop cycle and of the preceding cycle

in the case of replanting. This method seems to be particularly appropriate for very long

time lapses (decade, culturing cycle). It can be used to calculate directly the overall reserves

of the planted area (e.g. 1 ha) for a given depth. One might question the ability of this

single variable (overall evaluation) to measure the sustainability of plantation management

when the planted area is structured in different zones with different soil properties. Cultural

practices, primarily fertilization, locally modify soil reserves (Paramananthan, 2015). It may

also be a matter of transfers via the recycling of pruned fronds whose composition depends

in return on the fertilization regime (Dubos et al., 2016). Ultimately, among the various

zones that are gradually created while oil palm plantations are ageing, some are likely to

be exposed more rapidly to two worrying phenomena: (1) an impoverishment of reserves

and (2) an enrichment for certain nutrients, up to concentrations that could lead to some

leaching towards deeper zones and water tables. One could therefore just as easily choose

to monitor unfertilized zones that are not subjected to changes linked to agricultural activity

(e.g. weeded circle and harvesting path) in order to detect the impoverishment of reserves

or, conversely, to consider zones enriched by fertilizers and/or pruned fronds in order to

assess potential environmental impacts. There are therefore some important choices to be

made when sampling soils for a long-term monitoring.

Hartemink (2006b) gave considerable thought to the difficulties encountered when

estimating the decline in soil fertility in the tropics under tree crops. In particular, he

emphasized the consequences of the choice of analysis laboratory and of the methods

used. Each laboratory has its own signature which is linked to its equipment and

methods and that signature can change over time with the renewal or upgrading of the

equipment. For each nutrient, there are several analysis methods that are supposed

to estimate the fraction which is available for the plant. For instance, there are more

than ten methods estimating available P. Besides, exchangeable cations are frequently

extracted with ammonium acetate with a constant pH close to neutral, although cobalt

hexamine extraction at a variable pH close to that of the soil solution seems to be suitable

for generally acid tropical soils. For Indonesian soils, Foster and Prabowo (1996) found

that K extraction with boiling HCl better reflected the K reserves available for oil palms

than cation extraction with acetate. The proposed method would be more suitable for

assessing K reserves in soils with a low sand content. There is therefore every reason to

believe that the methodological search to optimize the most suitable analysis methods for

estimating reserves available to oil palm will impact on the diagnoses to be made in the

coming decades.

In this perspective, it seems necessary to set up rapidly some reference situations for

plantations whose long-term fertility needs to be assessed and it might be necessary

to collect samples from varied zones. Such samples describing an initial situation are

particularly important when converting forest cover to oil palm plantations.

In order to compensate for a change of laboratory or the adoption of new analysis

methods, it is wise to keep duplicate soil samples of the reference situations under

excellent preservation conditions for possible future re-analysis.

6 Where to look for further information

General information and educational documents on soil health concepts (assessment and

management) can be found in the website of the United States Department of Agriculture

(http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/).

General information and data (soil data and soil mapping) can also be found on the

ISRIC website (http://www.isric.org/). ISRIC – World Soil Information is an independent,

science-based foundation set up on the initiative of the International Soil Science Society

(ISSS) and of the United Nations Educational, Scientific and Cultural Organization

(UNESCO).

In Malaysia, AAR (Applied Agricultural Resources Sdn. Bhd) is a research centre working

on tropical tree crops, particularly oil palm. It produces summaries of R&D findings, some

of which are devoted to soil management (http://www.aarsb.com.my/).

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13 Chapter 13 Use of palm oil for biofuel

1 Introduction

1.1 Introducing biofuels

Fossil fuels are refined from coal, oil and gas, of which there is a limited global supply.

Their consumption also releases stored CO_2 into the atmosphere. By contrast, biofuels

are derived from renewable biomass and are carbon neutral since their consumption

releases CO_2 previously absorbed from the atmosphere by growing the original feedstock.

Humans have been using 12 to 20% of total terrestrial plant-based net primary production

(Haberl et al., 2007). Terrestrial plants essentially produce sugars, starch and oils, while

their main constituents are lignocellulose and water. Only 10% of them are used to

provide energy, with the remainder being used for animal feed (58%), materials (20%) and

human food (12%) (Krausmann and Kowalski, 2008). Consequently, any additional uptake

of terrestrial biomass for bioenergy use could increase the pressure on ecosystems if it

means producing and harvesting more sugar, starch or oil than is already the case. This

pressure on ecosystems lies at the heart of the potential adverse effects arising from the

development of biofuels.

1.2 The sustainability of biofuels

The major objections to the use of biofuels are deforestation, competition with food

production and uncertainties about their ability to meet some or all of their stated

objectives. The global production of biofuel was more than 100 billion litres in 2010

(Wilkinson et al., 2013) raising issues about its competition with food and arable land.

Over the last decade, grain and edible oil prices have increased by 70–120%. World

food prices reached their peak in 2008, causing world food markets to experience their

largest price shock in 30 years, a development which has been linked in part to biofuel

production (Bailis and Baka, 2011; Meyer, 2009).

Biofuel production currently uses around 2–3% of arable land globally (Wilkinson et

al., 2013). However, several assessments have shown how biofuels can contribute to

large-scale land use change (Fargione et al., 2008). Competition occurs through direct

land use change which decreases the production of food on arable lands by replacing

existing crops (e.g. food or feedstock) with energy crops. Competition can also occur

through indirect land use change where biofuel crops change market conditions,

either resulting in crops and livestock areas being less profitable, or diverting existing

production from food to energy. They may also have other unexpected negative

effects: for example, some biofuel production systems emit more greenhouse

gases (GHGs) than fossil fuels (Bailis and Baka, 2011). All these direct and indirect

effects interact through complex feedback loops connecting agriculture, food and

energy systems (Fig. 1). Such complexity is represented in Table 1 which provides a

suggested (but not exhaustive) list of sustainability criteria required for responsible

biofuel production. Technologies, technical itineraries, yields Competition in demand: Food Versus Feed Competition for resources: Land, water input, labour Higher prices for food and feed Food access Higher farm income Farm subsistence Urban income Higher rural income Investments Increase of production Infrastructures Rural development Jobs Demand / Policies National Macroeconomic variable Local use in energy Fossil energy savings Energy security and bill Commercial balance Balance of payments Food availability Feed availability Biofuel feedstocks Exports Transformation Energy

Figure 1 Main impacts and feedback in the food, agriculture and energy systems following the

introduction of biofuel demand (adapted from Wilkinson et al., 2013).

2 Trends in biofuels

Biofuels can be first-, second- or third-generation depending on the raw material and

conversion technology used. First-generation biofuels refer to fuels that are derived from

crop sources such as sugars, starch and vegetable oil. Second-generation biofuels are

essentially based on lignocellulosic biomass or industrial and urban waste. Lignocellulosic

biomass is derived from crop residues found in fields, plantations or forestry residues.

Technically all biomass can be connected to second-generation pathways and processes

(Fig. 2). Third-generation biofuels essentially refer to oils obtained from algae.

Table 1 Biofuel sustainability requirements (adapted from

Anon., 2008)

Sustainability criteria Policy criteria

Do biofuels threaten food security? Protecting the poor and food-insecure

Can biofuels help promote

agricultural development? Taking advantage of opportunities for agricultural and rural development

Do biofuels help reduce greenhouse

gas emissions? Ensuring environmental sustainability and a national system to support sustainable biofuel development

Can biofuels help achieve energy

security? Reviewing existing biofuel policies Products Transformation Raw materials 2 nd generation 1 st generation Lignocellulosic biomass Thermochemical conversion (pyrolysis, gasification) Ethanol 2G BTL fuels 2G Oil Soy Palm Rapeseed Starches Maize, Wheat, Potato, Barley, Cassava Bioethanol Biodiesel Vegetable oil Lignocellulose Softwood, Hardwood, SRC, Miscanthus, Switchgrass Conventional commodity crops Transesterification Direct oil extraction Fermentation Distillation Crop residues Co- products Co- products Sugars Sugarcane Sugarbeet Biochemical conversion (enzymatic, chemical)

Figure 2 Pathways for producing first- and second-generation biofuels (adapted from Naik et al.,

2010).

In the aftermath of the oil crises of 1973 and 1979, the United States and Brazil

encouraged first-generation biofuel technology to convert corn and sugarcane into

bioethanol and biodiesel. This early start gave the United States and Brazil a leading

role in the biofuel sector, though other countries followed later. Between 2005 and 2008,

major biofuel programmes were initiated in the European

Union and the United States. By

2012, around 60 countries had targets in place to promote biofuel production for energy

security, improving the balance of payments in their countries, creating new sources of

income and employment, developing rural areas and reducing GHG emissions. In 2014,

the United States and Brazil still dominated global biodiesel production with 78% of

the world production, but the European Union has since become a major player. 72%

of the world's biodiesel sources remain temperate rapeseed oil and soybean oil despite

the growth in the use of other sources of biodiesel such as palm oil (Fig. 3) (Neslen, (a) (b) United States, 52% Brazil, 26% China, 8% European Union, 7% India, 2% European Union, 42% United States, 19% Brazil, 11% Argentina, 9% Indonesia, 7% Thailand, 4% Colombia, 3%

Figure 3 Major world producers of bioethanol and biodiesel in 2014 (OECD, 2015). (a) Bioethanol (113

billion L). (b) Biodiesel (30 billion L).

2016; Dings, 2016). Bioethanol production really took off after 2001 and biodiesel quickly

followed. In 2014, the world production of bioethanol and biodiesel reached 143 billion

litres (Fig. 4) with 7–8% growth per year on average since 2001.

However, there was increasing concern that first-generation fuels could easily become

unsustainable if produced in large quantities because of the potential stress that global

production would place on food commodities (Gomez et al., 2008). Consequently, there

has been a shift towards second-generation biofuels to mitigate the disadvantages of first

generation biofuels. Even though second-generation biofuels are theoretically attractive,

a number of technical hurdles still exist and profitability needs to be improved. Besides the

issue of profitability, their sustainability also needs to be more fully investigated. Among

potential impacts are effects on GHG emissions, biodiversity loss, soil degradation, effects

on food security, rural development issues, health hazards and social conflict (Gomez et

al., 2008).

Second-generation biofuels from lignocellulosic raw materials are now produced on

an industrial scale in the United States and Brazil, but still at lower volumes than first

generation biofuels. Second-generation biofuels represent less than 1% of overall biofuel

production in most countries apart from Brazil (International Energy Agency, 2013; Anon.,

2014). Very few tropical countries have the resources to develop second-generation

biofuels given the often proprietary nature of this technology, the high capital investment

required and the need for infrastructure, logistics and human capital (Wilkinson et al.,

2013). In 2016 Indonesia announced its plans to invest in the production of significant

volumes of lignocellulosic second-generation biofuels but simultaneously announced new

plants for first-generation biodiesel production, the technology which has been in place

for about a decade (Erni Ginting, 2015). World ethanol production World biodiesel production World ethanol trade World biodiesel trade

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Figure 4 Growth of world production and trade of bioethanol and biodiesel (OECD, 2015).

3 Production of palm-based biofuels

Oil palm fruits produce a lot of cellulosic waste and two main types of oil, palm oil from

the fibrous mesocarp and kernel oil from the fruit kernel (Fig. 5). A few products have

been developed on a very small scale such as solid residues for combustion, charcoal,

etc. Currently, there is no large-scale second-generation biofuel produced from palm oil

waste. When occasionally these wastes are used, some of the cellulosic waste (core of

the trunks and part of the fronds) is sold for animal feed for a higher price than second

generation biofuels would incur. Another part of the waste is sometimes gasified in existing

plants generating electricity. Some palm oil processing plants produce methane through

treatment of liquid palm oil mill effluents (POMEs). Since such plants are located in remote

parts of Indonesia and Malaysia, they are too distant from the grid for profitable electricity

commercialisation and the excess gas is burnt (flared). Currently, the only palm oil-based

biofuel developed on an industrial scale is first-generation biodiesel.

Only one tonne of kernel oil is extracted compared to 8–9 t of palm oil (Fig. 5). Kernel

oil is sold at much higher prices than palm oil. Even though biodiesel production from

the kernel is technically feasible, palm oil is the first choice for biodiesel production.

In the conventional milling process, the fresh fruit bunches are first sterilised and then

steamed in vessels pressurised up to three bars to halt natural fermentation and to have

the fruits ready for the subsequent processes. The sterilised bunches are then stripped of Full fruit bunches (FFB) 85 Mt Palm oil mill residues Fresh fruit Empty fruit bunches (EFB) 19.2 Mt Press cake Crude oil Fibre 11.7 Mt Nuts Kernel 4.3 Mt Dry kernel oil 2 Mt Shell 5.4 Mt Dry palm oil 17 Mt POME 34.6 Mt Stripping Pressing Nut cracker Clarification Depericarping

Figure 5 Oil palm mill processing flow chart in Malaysia (Roda et al., 2015).

the fruitlets in a rotating drum thresher before being conveyed to the press digesters. In

the digesters, the fruits are heated using live steam and stirred continuously to loosen the

oil-bearing mesocarp from the nuts and break open the oil cells present in the mesocarp.

The digested mash is then pressed, extracting the oil using screw presses, and the pressed

cake is conveyed to the kernel plant where the kernels are recovered. At this point empty

fruit bunches can be collected. The oil from the press is diluted and pumped to vertical

clarifier tanks where the clarified oil is fed to purifiers to remove dirt and moisture before

being dried further in the vacuum drier. POME is unsuitable for biodiesel. Crude palm oil

is a commodity that is processed directly or sold on international markets mostly for food

and cosmetics as well as for biodiesel.

In theory, vegetable oils could be used in diesel engines without the need for a

biorefinery. Rudolph Diesel, who wanted farmers to be able to produce their own fuel,

invented the diesel engine specifically to run on vegetable oils: ‘The diesel engine can be fed with vegetable oils and would help considerably in the development of agriculture of the countries which use it.’ ‘The use of vegetable oils for engine fuels may seem insignificant today. But such oils may become in the course of time as important as the petroleum and coal tar products of the present time.’ (Diesel, 1912)

In practice, the heterogeneous nature of vegetable oils and their sensitivity to cold weather

prevent efficient carburation. Biorefining allows the production of a quality-controlled and

consistent product, tolerant of low temperatures, which is a perfect substitute for petrol-

based diesel.

The biorefinery process for all major oils and fats is similar. The same generic technology

applies to vegetable oils, animal fats and waste fats or oils. All these products are essentially composed of triglycerides in varying proportions. These triglycerides are themselves

made of chains of fatty acids of varying lengths. The controlled chemical breakdown of

the triglycerides into their components and transformation of the acid chains into methyl

esters are the bases of the technology. This process of converting a fatty acid chain from

an ester to a simple alcohol is called transesterification (Fig. 6). It is a reversible reaction,

facilitated by a catalyst. Pure biodiesel consists of an array of fatty acid methyl ester chains

of various lengths (Capareda and Press, 2014). The product is named ‘FAME’ – Fatty Acid

Methyl Esters. Its properties and energy values are close to those of petrol-based diesel,

allowing its use with various blends of fossil fuel. The major vegetable oils (soybean, C Fatty_Acid_Chain 1 C 3 H O C Fatty_Acid_Chain 3 OH OH O O C 3 H OH CH 3

C 2 H CH O C Fatty_Acid_Chain 3 C Fatty_Acid_Chain 1 OH O O O O CH 3 OH

C 2 H C 2 H CH 3 C 2 H O O C Fatty_Acid_Chain 2 O

CH OH O C 3 H C Fatty_Acid_Chain 2 100 kg of biodiesel (methyl esters x)+ + 100 kg of refined vegetable oil 10 kg of methanol 10 kg of glycerine catalysis

Figure 6 Generic reaction of transesterification (adapted from Capareda and Press (2014)).

rapeseed, sunflower and palm) share a similar generic composition, the difference being

in the proportion of chains of given lengths. These differences in proportion are important

for specific food applications (for example, the property of being solid or liquid at ambient temperature), but they are completely neutral for biofuel end uses. All these oils are

transesterified into FAME the generic formula of which is $CH_3(CH_2)_nCOOCH_3$. Consequently

they are completely interchangeable for energy use. Most recent car engines are certified

by the manufacturers for blends containing up to 30% biodiesel and in Germany a sizeable

fleet of vehicles runs on pure biodiesel (B100 biodiesel).

4 Biodiesel economics

Biodiesel prices are entirely determined by vegetable oil prices. In a typical palm oil

biorefinery, for example, palm oil would represent 80–90% of the overall cost of the

biodiesel (Ong, 2012). Before the increase in biodiesel demand and volatility in petrol

prices, supply and demand were the main drivers in agrifood markets. When the demand

for fossil fuel began to rise consistently at the beginning of the millennium, it was the main

cause of variations in the price of vegetable oil (Fig. 7). At the same time, motivated by

both climate change and energy independence concerns, political interest in biodiesel

grew and production of biodiesel quickly followed. Biodiesel is designed to be a

substitute to petrol-based diesel. Fuel costs and environmental concerns are the main

reasons behind this substitution. The production cost of biodiesel depends mainly on

upstream plantation costs: yields, diseases, fertiliser and fossil fuel costs. Yields account

for the main differences between the four major vegetable oils. Per hectare, palm oil is the

most productive by far (Rival and Levang, 2014). Therefore, structurally it is the cheapest

of the four (Fig. 7). Regardless of the yields, fossil fuel costs directly impact fertiliser and Palm oil Rapeseed oil Soybean oil Sunflower oil Crude oil

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Figure 7 International prices of palm, rapeseed, soybean, sunflower and fossil crude oil.

other agricultural costs. Consequently, the international prices of all vegetable oils from

industrial plantations are very similar and this has been apparent since the beginning of

the millennium (Fig. 7).

In 2016, Indonesia and Malaysia produced over 85% of the total global palm oil supply.

Asia accounts for more than 63% of the palm oil demand, followed by Africa (more than

13%) and Europe (more than 12%). In all the consuming countries, palm oil demand is driven

by end uses as food and animal feed. Only around 27% of global palm oil production is for

'industrial domestic consumption'. Part of this industrial consumption is for biodiesel and

part is for industrial non-food uses such as cosmetics. In the case of the five countries that

represent 75% of the global palm oil ‘industrial domestic consumption’ (Indonesia, Europe

[EU-27], Malaysia, China and Thailand), the breakdown of fuel and non-fuel uses is given

in Table 2. Total palm oil-based biodiesel production uses around 12% of the palm oil

grown. Interestingly, although Europe consumes more than 42% of all biodiesel globally, it

only uses 2.8% of world palm oil production for biodiesel. The amount of palm oil used by

Europe for biodiesel appears disproportionately small compared to the significant amount

of research that has been on the adverse effects of European use of this biodiesel: indirect

deforestation, climate change, loss of biodiversity and direct competition with European

vegetable oil (Sihvonen, 2016a; Neslen, 2016; Dings, 2016).

The main limitation to palm oil-based biodiesel globally is the competitiveness of

crude palm oil and fossil fuel prices. With an increasing demand for palm oil in food and

cosmetics, it is frequently more expensive than the petrol-based diesel it is supposed to be

substituting. This creates an economic barrier in countries where fuel policies impose very

low or zero excise duties on gasoline and diesel, such as the United States. In countries

with full or partial subsidies on gasoline and diesel, such as Malaysia, Indonesia and

India, it is even more difficult to run biodiesel refineries based on palm oil feedstock. For

example, in 2006, the Malaysian government introduced the use of B5 blended biodiesel – 95% petroleum diesel and 5% biofuels (Lee and Ofori-Boateng, 2013). Between 2006 and 2007, 92 biodiesel projects were approved in Malaysia but by 2012, most of them had been halted due to high feedstock prices and competition in demand for raw oil by the agro-food sector. To revive these projects, in 2013, the Malaysian government announced that B10 blended biodiesel would become mandatory but this has yet to be implemented. Altogether, only 30 biomass transformation plants are currently operating; most of them are located in the states of Johor and Selangor. Conversely, in countries applying high excise duties on gasoline and diesel such as most of the European Union

Table 2 Breakdown of palm oil feedstock for biodiesel production in 2016 for the five major palm oil industrial domestic consumers (Flach et al., 2016)

Palm oil (1000 T)	Indonesia	EU-27	Malaysia	China	Thailand
Industrial domestic consumption	3500	3040	2400	2050	1520
Use for biodiesel	2250	1790	360	500	885
Other non-food industrial uses, such as cosmetics	1250	1250	2040	1550	635
% of world palm oil production used as biodiesel	3.5%	2.8%	0.6%	0.8%	1.4%

members, converting vegetable oils into biodiesel is much more competitive. The result has not necessarily been that these countries have become large importers of palm oil based biodiesel, but it is clear that such conditions are better for biorefineries using local

vegetable oil.

The magnitude of possible excise duties largely determines the price range of the major

vegetable oils. Regardless of the existing biofuel policies or vegetable oil trade, in every

country fossil fuel policies are the first factor determining the competitiveness of biofuels.

Taking as examples the United States (near the lower end) and France (near the higher end

of excise duties), Fig. 8 shows how fossil fuel policies overlap with vegetable oil prices.

Palm oil prices have been close to, or lower than, US diesel prices for extended periods,

but higher than any subsidised petroleum diesel (as in Malaysia, for example). Soybean

oil has occasionally been cheaper than the US diesel price, but prices are typically similar.

This price proximity explains why the United States relies mostly on soybean as its main

temperate oil feedstock. Conversely, even costly oils like rapeseed are almost always lower

than the price of French petroleum diesel and the occasions when it is more expensive

coincide with dips in rapeseed production in Europe.

5 Imports and defiscalisation: the odd alliance

As noted earlier, Europe has become the main global producer and consumer of biodiesel.

This has been due to biodiesel ‘defiscalisation’ (i.e. removal of relevant taxes and use of

subsidies) and high petroleum diesel prices (since all European Union members apply Palm oil Rapeseed oil Soybean oil Sunflower oil US petroleum diesel French petroleum diesel

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Figure 8 International prices of palm, rapeseed, soybean and sunflower oils, compared with diesel

prices in France and in the United States.

very high gasoline and diesel excise duties compared to countries such as the United

States). The aim of the defiscalisation policy was to promote locally produced rapeseed

oil, especially on fallow ground. In 2003, Europe made a major commitment to support

biofuels with dedicated EU legislation. In 2004, total defiscalisation of biodiesel in Germany

accelerated several years' growth of rapeseed oil and rapeseed biodiesel (Fig. 9). German

rapeseed production quickly became dominant in Europe, followed by France (which

carried out partial defiscalisation). Rapeseed plantations are quite sensitive to weather

and disease and, in Northern Europe, the crop is prone to temporary tensions between

supply and demand, with subsequent volatility in rapeseed oil prices. The slow or delayed

response of rapeseed production to price variations creates opportunities for cheaper vegetable oil imports from international markets, typically soybean and palm oil. After

the initial increase in industrial domestic consumption of rapeseed oil, a surge in soybean

oil imports from the United States was observed. The European Union did set up specific

anti-dumping policies to address this issue, transforming the surge into a temporary peak

which is visible from 2004 to 2011 (Fig. 9). This led to the substitution of large soybean oil

imports from the United States by lower volumes of imports from Argentina. At the same

time, cheaper palm oil (already imported in large quantities for European food) helped

to offset local variations in vegetable oil supplies within Europe. Rapeseed oil production

levelled off from 2009, because of diminishing biodiesel defiscalisation. In Germany and

France, defiscalisation rates began to decrease in 2007 but it appears that the critical level

was crossed in 2009 (Table 3). Palm oil Rapeseed oil Soybean oil Sunflower oil I n d u s t r i a l d o m e s t i c c o n s u m p t i o n (x 1 0 0 0 t o n n e s) 0 1000 2000 3000 4000 5000 6000 7000 8000 Years 2000 2002 2004 2006 2008 2010 2012 2014 2016

Figure 9 Trends in industrial domestic consumption of oils in Europe.

Table 3 Amount of biodiesel defiscalisation per hL, in France

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015
Euros/hL	25	22	15	11	8	8	8	4.5	3

During this period, there was a European debate as to whether palm oil was an

economic substitute for rapeseed oil with mixed evidence according to the years of

reference. What was critical was the price of rapeseed oil and the level of defiscalisation for

biodiesel. A simple econometric test called ‘cross price elasticity of demand’ and shown

as E c (Equation 1) shows that if two goods are substitutes for each other, independent or

complementary to each other: E Q Q P P c A A B B = ▯ ▯ . (1)

with Q A being quantity of commodity A and P B being price of commodity B. R 2 : 0.98 R 2 : 0.001 P a l m o i l c o n s u m p t i o n (x 1 0 0 0 T) 0 500 1000 1500 2000 2500 3000 3500 Rapeseed oil price (Euros/T) (a) (b) 400 600 800 1000 1200 1400 P a l m o i l c o n s u m p t i o n (x 1 0 0 0 T) 0 500 1000 1500 2000 2500 3000 3500 Rapeseed oil price (Euros/T) 400 600 800 1000 1200 1400

Figure 10 Variation of palm oil industrial domestic consumption in Europe according to rapeseed oil

price. (a) from 2000 to 2008. (b) from 2009 to 2016.

The cross price elasticity of palm oil demand in Europe was 3.1 from 2000 to 2008 on

average and 0.07 from 2009 to 2016. This meant that, from 2000 to 2008, the quantity of palm

oil changed by 3.1% when the price of rapeseed oil changed by 1%. Each time the price of

rapeseed oil increased for any reason, such as a temporary reduction in production anywhere

in Europe, palm oil imports and consumption were stimulated. This shows that industrial

palm oil consumption in Europe was completely driven by rapeseed oil prices between 2000

and 2008. It was then a perfect economic substitute to rapeseed oil. During the second

period, the quantity of palm oil changed by 0.07% when the price of rapeseed oil changed by 1%. When the defiscalisation of biodiesel decreased, the market saturated, rapeseed oil

production levelled off and the consumption of palm oil became completely independent

from the price of rapeseed oil (Fig. 10). At the same time, there was still a large international

supply of cheaper soybean and palm oil where prices were driven by non-European markets.

In Europe, palm oil has come to act as a substitute when biodiesel is defiscalised, and, if not,

as a commodity independent of the price of competing rapeseed oil.

While the main European producers of rapeseed oil are Germany and France, the

main European consumers of palm oil for biodiesel are Italy and Spain, with palm oil

representing 95% and 90%, respectively, of their vegetable oil use for biodiesel (Sihvonen,

2016b). From a bioclimatic perspective, rapeseed is as exotic to these countries as palm

oil is to Germany and France. While subsidising rapeseed oil production makes sense in

Germany and France, it does not in Italy and Spain and market forces prevail. In Italy and

Spain, it is more rational to import palm oil available relatively cheaply at any harbour,

rather than transport it by road from Northern Europe and compete with German and

French consumption of rapeseed oil.

6 The geopolitics of agribusiness: competition between

productions systems

Soybean, rapeseed and sunflower are originally temperate-grown oilseeds. These

commodities are dominated by agribusiness mega-corporations all originating from

western countries. They form the ‘ABCD Empire’. There are four of these large groups:

Archers Daniel Midlands, Bunge, Cargill and Louis Dreyfus, and they dominate the trade in

agricultural commodities. Despite its temperate origin, soybean is also grown in subtropical

and tropical areas in Brazil thanks to new varieties. Even in Brazil, the majority of soybean

plantations are directly or indirectly under the control of the ‘ABCD Empire’. Conversely,

palm oil production and trade are more diverse, shared between a number of smaller

corporations originating in Southeast Asia (Table 4). Figure 11 illustrates the divide between

north and south, or between temperate and tropical systems of production. The fact that

soybean varieties have been improved to grow in subtropical and tropical conditions blurs

the picture slightly. However, with 60% of Brazilian soybean being dominated by Archers

Daniel Midlands and Bunge (Anon., 2015), it remains undeniable that oil crops are a source

of competition between western and Southeast Asian agribusiness corporations.

Another factor in this competition is the difference in productivity per hectare for

these crops. Figure 11 shows that the area required by palm oil is disproportionately

small compared to its production. A clearer picture of the ‘space footprint’ of palm oil versus other major oils is given in Fig. 12. Today, productivity per hectare differentiates Hectares 1000000 5000000 10000000 Sunflower oil Rapeseed oil Soybean oil Palm oil Tonnes 1000000 10000000 30000000 Sunflower oil Rapeseed oil Soybean oil Palm oil (b) (a)

Figure 11 Global location of major vegetable oil production in 2013. (a) Hectarage. (b) Tonnage.

Table 4 Agribusiness corporations controlling 70% of the palm oil world market in 2010 (Bureau Van Dijk, 2015)

Company	Country of headquarters	Market capitalisation (million USD)	Land bank (ha)	% of world market	% of world land bank
Wilmar	Singapore	14 565	243 138	25	6
Sime Darby	Malaysia	12 175	986 824	21	26
IOI Corp	Malaysia	7147	217 918	12	6
KL Kepong	Malaysia	6203	270 040	11	7
Indofood	Indonesia	5410	224 083	9	6
Golden Agri	Singapore	3360	451 063	6	12
Astra Agro	Indonesia	2427	297 862	4	8

the vegetable oils in terms of cost per tonne. It makes palm oil the most competitive in any temperate biodiesel business. The production of Brazilian soybean oil hardly affects this situation since Brazilian biofuel production revolves around ethanol. In the future, and as agricultural land becomes scarcer, the difference in area required to produce one tonne of oil could become the main competitive factor. In recent decades, the size of plantations for all vegetable oils has increased tremendously to meet growing global demand (Fig. 13). Conversely, the hectarage of palm oil has grown quite modestly and,

especially in comparison to its main competitors in biodiesel production (Fig. 13).

7 Conclusions

A global perspective of vegetable oils means looking at their market share on a global

scale (Fig. 14). Supported by US policies, the global market share of soybean oil peaked

at the end of the 1970s and has decreased ever since. That of rapeseed oil increased

until the 1990s and started to decrease at the turn of the millennium. European biodiesel

policies subsequently encouraged a revival, but rapeseed oil seems to have stagnated

since 2009. After a peak at the end of the 1960s, the global sunflower market share has

been constantly on the decline. A striking figure is the steady and seemingly irresistible

growth in the market share of palm oil since 1970 (Fig. 14). Looking at the competition

between southern and northern production systems, palm oil is clearly threatening the

other oil production systems.

However, as noted earlier, fossil fuel prices and domestic interests play a major role in the

use, or not, of vegetable oils for biofuel. Comparative cost competitiveness of fossil fuel

remains critical in the development of palm oil-based biodiesel, but energy independence

is also a major factor to consider. For example, Indonesia, once a net producer of fossil

fuel oil, is now a net importer. A new Energy Bill passed in 2015 committed to a mandate 0 20 40 60 80 0 50 100 150 200 World production of oil crop plantations (million tonnes) W o r l d a r e a o f o i l c r o p p l a n t a t i o n s (m i l l i o n h e c t a r e s) Soybean+Rapeseed+Sunflower Oil palm Soybean Rapeseed Sunflower

Figure 12 Progression of global plantation area versus production of the major oil crops.

of 30% of biodiesel blend in all diesel consumption by 2025. This means that between 7

and 8 million tonnes of palm oil-based biodiesel should be blended into Indonesian fuel

per year by this date. Such quantities would completely transform the balance of global

biodiesel economics. It remains to be seen if the Indonesian bill will be implemented soon. 1960 1970 1980 1990 2000 2010 0 100 200 300 400 500 Years A r e a o f o i l c r o p s (m i l l i o n h e c t a r e s) Oil palm All other oil crops 1960 1970 1980 1990 2000 2010 0 50 100 150 200 Years A r e a o f t h e 3 o t h e r m a j o r o i l c r o p s (m i l l i o n h e c t a r e s) Oil palm Sunflower+Rapeseed+Soyabean (a) (b)

Figure 13 Oil palm planted area in perspective with other oil crops from 1961 to 2015. (a) All oil crops.

(b) Sunflower, rapeseed and soybean.

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Figure 14 Progression of global palm oil production percentage versus other vegetable oils

percentages from 1961 to 2015.

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