



Review article

Yield gaps in oil palm: A quantitative review of contributing factors



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ABSTRACT

Oil palm, currently the world's main vegetable oil crop, is characterised by a large productivity and a long life span (≥ 25 years). Peak oil yields of $12 \text{ t ha}^{-1} \text{ yr}^{-1}$ have been achieved in small plantations, and maximum theoretical yields as calculated with simulation models are $18.5 \text{ t oil ha}^{-1} \text{ yr}^{-1}$, yet average productivity worldwide has stagnated around $3 \text{ t oil ha}^{-1} \text{ yr}^{-1}$. Considering the threat of expansion into valuable rainforests, it is important that the factors underlying these existing yield gaps are understood and, where feasible, addressed. In this review, we present an overview of the available data on yield-determining, yield-limiting, and yield-reducing factors in oil palm; the effects of these factors on yield, as measured in case studies or calculated using computer models; and the underlying plant-physiological mechanisms. We distinguish four production levels: the potential, water-limited, nutrient-limited, and the actual yield. The potential yield over a plantation lifetime is determined by incoming photosynthetically active radiation (PAR), temperature, atmospheric CO_2 concentration and planting material, assuming optimum plantation establishment, planting density (120–150 palms per hectares), canopy management (30–60 leaves depending on palm age), pollination, and harvesting. Water-limited yields in environments with water deficits $>400 \text{ mm year}^{-1}$ can be less than one-third of the potential yield, depending on additional factors such as temperature, wind speed, soil texture, and soil depth. Nutrient-limited yields of less than 50% of the potential yield have been recorded when nitrogen or potassium were not applied. Actual yields are influenced by yield-reducing factors such as unsuitable ground vegetation, pests, and diseases, and may be close to zero in case of severe infestations. Smallholders face particular constraints such as the use of counterfeit seed and insufficient fertiliser application. Closing yield gaps in existing plantations could increase global production by 15–20 Mt oil yr^{-1} , which would limit the drive for further area expansion at a global scale. To increase yields in existing and future plantations in a sustainable way, all production factors mentioned need to be understood and addressed.

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1. Introduction

African oil palm (*Elaeis guineensis* Jacq.) has its centre of origin in the humid lowland tropics of West Africa. Wild oil palms are uncommon in primary forests but rather grow in disturbed and very wet locations, such as swamps and river banks, where sunlight is abundant and water available throughout the year (Zeven, 1967). The oil palm is a member of the monocotyledonous palm family (*Arecaceae*). The woody stem carries a single terminal growing point, from which leaves appear at regular intervals in a double spiral (Rees, 1964). Each leaf supports a single inflorescence, which can be either male or female. The harvested product is a fruit bunch comprising 1500–2000 fruitlets. Crude palm oil (CPO) is extracted from the orange-yellow mesocarp, and palm kernel oil (PKO) from the white kernel.

Over the last 100 years, oil palm has changed from a small-holder agroforestry crop and ornamental palm into the world's most important vegetable oil crop. Current worldwide production is estimated at 63 Mt crude palm oil per year, or 36% of the total world vegetable oil production (USDA, 2014). Expansion of oil palm plantations has been suggested as a key cause of deforestation in both Indonesia (Carlson et al., 2012; Stibig et al., 2014) and Malaysia (Miettinen et al., 2011; Stibig et al., 2014), although other drivers such as logging also play a major role (Laurance, 2007; Lambin et al., 2001). The increasing demand for palm oil over the coming decades will probably be met both through expansion of the area planted and increased productivity (Carter et al., 2007; Corley, 2009).

Since oil palm expansion may lead to the displacement of bio-diverse rainforests (Gaveau et al., 2014), increased productivity, combined with targeted expansion into degraded areas (Fairhurst and McLaughlin, 2009), are the preferred strategies to meet the growing demand for palm oil. Increasing productivity does not, *per se*, lead to reduction in deforestation unless supporting policies are in place and are properly enforced (Angelsen, 2010), but is a necessary step towards reducing pressure on land. A thorough understanding and quantification of the contribution of different

production factors to oil palm yield is urgently needed to estimate the scope to increase productivity in existing stands, and in ongoing (re)planting programs.

Yield gap analysis has been commonly used as a tool to explore the possibilities for improving land productivity (Lobell et al., 2009; van Ittersum et al., 2013; see also www.yieldgap.org). The 'yield gap' is defined as the difference between potential and actual yield (van Ittersum and Rabbinge, 1997), with the upper limit of productivity per hectare being the 'potential yield'. This potential yield is defined as the theoretical yield at a given temperature, ambient atmospheric CO₂ concentration, and incoming photosynthetically active radiation (PAR), with optimum agronomic management and without water, nutrient, pest and disease limitations (van Ittersum and Rabbinge, 1997). It refers to current germplasm or to the best currently available material.

Yield gap analysis has been carried out for a range of annual crops such as wheat (Aggarwal and Kalra, 1994; Bell et al., 1995; Anderson, 2010), cassava (Fermont et al., 2009), rice (Yang et al., 2008; Laborte et al., 2012), and cereals in general (Neumann et al., 2010). A limited number of perennial cropping systems has been subjected to yield gap analysis, including coffee (Wairegi and Asten, 2012), highland banana (Wairegi et al., 2010), and cocoa (Zuidema et al., 2005). Perennial crops such as oil palm are structurally different from annual crops in several ways. In annual crops, growers can take advantage of new seeds with each growing season. By contrast, the yield potential for perennial crops, with a lifespan of up to several decades, is fixed for each planting cycle. Events early in the plantation lifetime, especially in the nursery and at planting, may have strong effects on yield in later years, which complicates the interpretation of yield data (Breure and Menendez, 1990). In addition, oil palm fruit bunches take several years to develop, and there is a time lag of 20–30 months between the onset of stress factors and their impact on yield. This makes it difficult to separate and quantify the effects of individual factors (Adam et al., 2011).

Quantitative data on yield responses of oil palm to different production factors, particularly planting density, irrigation, and fer-

tiliser use, are available from trials carried out by companies or research stations. Results of many such trials are reported only in the grey literature and can be difficult to access, but [Corley and Tinker \(2016\)](#) provide a very complete overview. Recently, [Fairhurst and Griffiths \(2014\)](#) performed a yield gap analysis in oil palm from a practical planters' perspective, with a step-by-step guidance on the identification and resolution of yield constraints in the field. However, an assessment of the underlying causes of yield gaps in oil palm production systems worldwide is lacking. In this review, we explore existing knowledge on oil palm productivity from a plant physiological perspective, to provide a coherent picture of factors contributing to yield gaps in oil palm. We start with a discussion on plantation life cycle, vegetative growth, and leaf area development in Section 2. In Section 3 we provide a detailed assessment of bunch production, focusing on bunch number and bunch weight, the two main determinants of yield. In Section 4 we review the yield gap concept and the different production levels (i.e. potential, water-limited, nutrient-limited, and actual yield), and discuss the different factors that affect generative productivity in oil palm, including climatic factors, nutrition, and the main pests and diseases. In Section 5 we consider the most important constraints to yield in the oil palm producing regions around the world, with focus on both large-scale commercial and smallholder systems. Finally in Section 6 we identify the existing knowledge gaps and propose directions for future action and research.

2. Plantation life cycle and vegetative growth

In this section we discuss the oil palm production system, the different yield profiles during the plantation life time and the vegetative growth of the oil palm, with a focus on leaf area development.

2.1. Plantation life cycle

Oil palms are commercially grown in plantation systems, with a density of 120–150 palms per hectare. Pre-germinated seeds are raised in polybags in a nursery for 6–12 months ([Rankine and Fairhurst, 1999a](#)), after which the seedlings are planted in the field at final density with limited options for replacing plants that do not survive or prove to have less-desirable properties beyond the first 12 months. Plantations have an average lifetime of 25 years, of which 21–23 are productive. Four yield phases have been described ([Fig. 1](#)): 1) the immature or 'yield building phase', up to 2–3 years after planting (YAP), before harvestable production begins and when the canopy is not yet closed; 2) the young mature phase or 'steep ascent yield phase', 4–7 YAP, when leaf area and yield increase linearly; 3) the mature or 'plateau yield phase', 8–14 YAP, when yield and leaf area are stable; and 4) a phase of yield decline, 15–25 YAP ([Ng, 1983; Goh et al., 1994; Fairhurst and Griffiths, 2014](#)).

The first year of harvest typically yields 10–15 t fruit bunches ha^{-1} (with and oil to bunch ratio of 10–15%) under favourable circumstances; initial yields of >20 t fruit bunches ha^{-1} have been achieved in commercial plantings ([Rao et al., 2008](#)). Under favourable conditions, bunch production peaks 6–7 YAP, with typical peak yields of 35 t fruit bunches ha^{-1} ([Ng, 1983; Donough et al., 2009](#)). Maximum yields of 60 t fruit bunches ha^{-1} have been obtained with selected clonal planting materials ([Ng et al., 2003](#)). During the mature phase, bunch production stabilises somewhat below the peak achieved at six YAP, with typical commercial yields of 25–30 t fruit bunches ha^{-1} in well-managed plantations ([Ng, 1983; Donough et al., 2010](#)). In the phase of yield decline, leaf production rate and bunch numbers decrease, but increased bunch size partly compensates for the reduction in bunch number ([Hardon et al., 1969; Goh et al., 1994; Jacquemard and Baudouin, 1998](#);

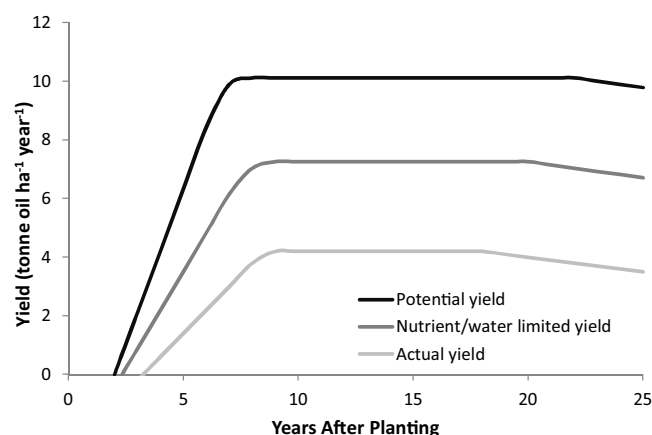


Fig. 1. Development of oil palm yield over time in three hypothetical plantations (after [Ng, 1983; Goh et al., 1994; Fairhurst and Griffiths, 2014](#)). The light grey (bottom), dark grey (middle) and black grey (top) lines show the yield progress at different productivity levels: actual yield (average 3.5 t oil $\text{ha}^{-1} \text{year}^{-1}$), nutrient/water limited yield (average 6.1 t oil $\text{ha}^{-1} \text{year}^{-1}$) and potential yield (average 8.9 t oil $\text{ha}^{-1} \text{year}^{-1}$), respectively, with a large gap between the three levels. The yield building (no yield), young mature (increasing yield), mature (plateau) and yield decline phase can be discerned.

21). Oil palms continue to produce fruit bunches until death, but replanting is required at 20–25 YAP when palms become too tall for economic harvesting or when yields decline due to the loss of palms to pests and diseases.

2.2. Vegetative growth

The average yearly above-ground dry matter production per hectare for mature palms (> 10 YAP) planted with triangular spacing at planting densities of 120–150 palms ha^{-1} ranges from 19 t DM $\text{ha}^{-1} \text{yr}^{-1}$ in Nigeria ([Rees and Tinker, 1963](#)) to 32 t DM $\text{ha}^{-1} \text{yr}^{-1}$ in Malaysia ([Corley et al., 1971a](#)). Dry matter production can be described by the following equation:

$$\text{DMP} = \text{PAR} \times f \times \text{RUE} \quad (1)$$

where DMP = dry matter production ($\text{kg m}^2 \text{yr}^{-1}$), PAR = yearly photosynthetically active radiation ($\text{MJ m}^2 \text{yr}^{-1}$; 50% of total incoming solar radiation ([Monteith, 1972](#))), f = fraction of radiation intercepted by the canopy, and RUE = radiation use efficiency ($\text{kg DM MJ}^{-1} \text{PAR}$) ([Monteith, 1977; Corley, 2006](#)). Estimated values for RUE are 0.6–1.3 $\text{g MJ}^{-1} \text{PAR}$ ([Rees and Tinker, 1963; Squire, 1986; Squire and Corley, 1987](#)). RUE does not change with age in oil palm ([Squire and Corley, 1987](#)) but is decreased in dry climates and on poor soils and enhanced by fertiliser use (15–30% increase in response to the application of N-P-K) ([Squire, 1986](#)). Radiation interception (f) depends mainly on the leaf area index (LAI), i.e. the area of leaves per surface area ($\text{m}^2 \text{m}^{-2}$), although leaf orientation with respect to light angle can modify effective interception. The LAI increases linearly from planting until 5–6 YAP and peaks around 10 YAP, when the leaves reach their maximum size ([Gerritsma and Soebagyo, 1999](#)). The maximum LAI typically varies between 4 and 6 depending on genotype ([Gerritsma and Soebagyo, 1999; Breure, 2010](#)), environment ([Corley et al., 1973](#)), planting density ([Corley et al., 1973; Gerritsma and Soebagyo, 1999](#)), pruning ([Squire and Corley, 1987](#)), fertiliser use ([Breure, 1985; Corley and Mok, 1972](#)), and general agronomic management. In plantations where old leaves are not removed, LAI may exceed 10 ([Squire and Corley, 1987](#)). At an LAI of 4.5 interception of PAR is at least 80%, increasing up to 90–95% at an LAI of 6–7 ([Gerritsma, 1988; Breure, 1988](#)). Yields are reduced when LAI exceeds a value of 6 due to competition among palms ([Breure, 2010](#)).

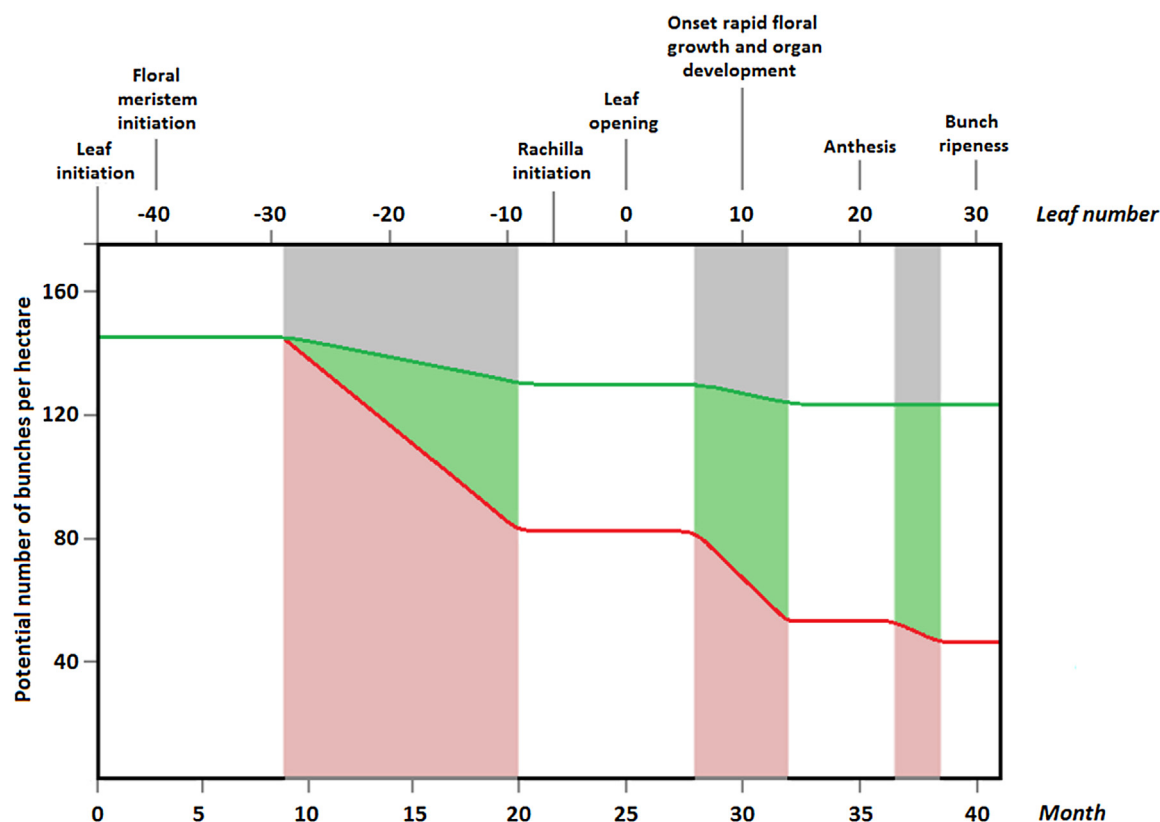


Fig. 2. Schematic representation of inflorescence and bunch development, showing key developmental stages and the effects of stress on potential bunch number (after Uexküll and Fairhurst, 1991; Corley et al., 1995; Adam et al., 2005). Time starts at leaf initiation (point zero) and progresses until bunch ripeness, and is indicated in months since leaf initiation (bottom x-axis) and leaf number (upper x-axis, assuming an average phyllochron length of 1.9 month⁻¹). The y-axis shows the number of potential bunches per hectare. The two lines show the progress of two hypothetical batches of potential bunches, starting at one per palm in a plantation with a planting density of 142 palms per hectare. Over time the number of potential bunches decreases as the batches pass through several critical phases. Severe stress (bottom line) leads to larger reductions in bunch number than mild stress (top line). The bars represent the stress-sensitive periods: sex determination (left), inflorescence abortion (middle) and bunch failure (right).

In older plantations, most of the standing biomass is contained in the trunk (Rees and Tinker, 1963). Of an estimated gross primary production of 160 t DM ha⁻¹ yr⁻¹ in 10-year-old palms in Malaysia, around 70 t ha⁻¹ yr⁻¹ was allocated to trunk, root, and rachis respiration, and 55 t ha⁻¹ yr⁻¹ allocated to leaflet respiration, leaving 30–35 t ha⁻¹ yr⁻¹ of dry matter production (Corley, 1976b). Estimates of standing root biomass at 15 YAP from different experiments were listed by Henson and Chai (1997), ranging from 9 t DM ha⁻¹ (Corley et al., 1971a) to 20 t DM ha⁻¹ (Teoh and Chew, 1988). Under conditions without water limitation, about 10–12% of assimilates are allocated to the roots (Henson and Chai, 1997), but under water limited conditions, assimilate allocation to roots may be up to 35% (Dufrène et al., 1990; van Noordwijk et al., 2015).

In productive palms planted at standard densities, about 45–50% of the aboveground dry matter production is allocated to generative growth (male inflorescences and female inflorescences and bunches; Corley et al., 1971b). It has been proposed that allocation of assimilates to inflorescences and bunches will not occur until demands for vegetative production are met (the “overflow” model; Corley et al., 1971b). Yet later research has shown that both vegetative and generative growth are source-limited and that competition occurs between the different sinks, although priority is given to vegetative growth (Corley and Tinker, 2016: 103).

3. Fruit development

A number of key stages can be distinguished during inflorescence and fruit bunch development (Fig. 2; for a detailed review,

see Adam et al., 2005). Oil yield depends on the number of harvested bunches, the bunch weight, and the oil content of the fruit (Breure et al., 1990). These factors are discussed in detail below.

3.1. Bunch number

The number of ripe bunches available for harvest is determined by 1) the number of inflorescences initiated (which in turn depends on the rate of leaf production; Gerritsma and Soebagyo, 1999); 2) sex ratio (Corley et al., 1995; Adam et al., 2011; Heel et al., 1987); 3) abortion of female inflorescences before anthesis (Pallas et al., 2013); and 4) failure of developing bunches between anthesis and bunch ripeness (Combres et al., 2013).

3.1.1. Number of developing inflorescences

Leaf initiation rate determines directly the potential number of inflorescences, as a single inflorescence is initiated in the axil of each leaf. An average oil palm carries 45–50 unopened leaves in varying stages of development and 32–48 opened leaves (Breure, 1994). The youngest fully opened leaf is denoted as Leaf 1, with unopened leaves being numbered negatively (Fig. 2). Leaf initiation rate is determined primarily by palm age (Broekmans, 1957), with opening rates declining rapidly in the first 10 YAP (Gerritsma and Soebagyo, 1999). Typically 40–45 leaves palm⁻¹ year⁻¹ are produced at two YAP, 25–35 leaves year⁻¹ at six YAP, 20–25 leaves year⁻¹ at 12–14 years YAP (Broekmans, 1957; Gerritsma and Soebagyo, 1999) and 17–20 leaves year⁻¹ at 21 YAP (Broekmans, 1957; Rafii et al., 2013). Leaf initiation rate may vary between dif-

ferent planting materials by ± 1 leaf palm⁻¹ year⁻¹ (Gerritsma and Soebagyo, 1999) or three days per phyllochron (the time elapsed between the appearance of two consecutive leaves) (Lamade et al., 1998). Leaf initiation rates of individual palms respond positively to light availability: initiation rates increased by 19% two years after thinning of palms 11–15 YAP at high density (186 palms ha⁻¹; Breure, 1994). Sink limitation in 13 year old palms, resulting from complete removal of developing fruits, reduced phyllochron length from 17 days to 15 days (Legros et al., 2009b), possibly because of increased carbohydrate availability to young leaves. This suggests that oil palm is able to respond to abundant carbohydrate supply by increasing its rate of inflorescence initiation (Pallas et al., 2013). The rate of leaf opening is reduced rapidly in response to drought (Chang et al., 1988), resulting in the accumulation of unopened leaves in the centre of the palm crown (Broekmans, 1957; Nouy et al., 1999). Drought may also reduce leaf initiation rates (Chang et al., 1988; Breure, 1994).

3.1.2. Sex determination, inflorescence abortion, and sex ratio

In contrast to other palms, such as coconut, that carry male and female flowers in the same inflorescence, sex is determined at inflorescence level in oil palm. The earliest morphological difference between male and female inflorescences is the increased number of bracts initiated on male rachillae (Leaf -6; Corley, 1976a; Heel et al., 1987; Adam et al., 2005). The timing of sex determination varies among experiments, research sites and planting material, ranging from 29 to 30 months before harvest (Broekmans, 1957) to 20 months before harvest (Breure and Menendez, 1990; Fig. 2). Corley et al. (1995) found that the timing of sex determination varies among clones: either at bract initiation, Leaf -29, or just before first rachilla initiation, Leaf -10, or both. This led Corley and Tinker (2016: 121) to speculate that sex differentiation occurs at Leaf -29 but is reversible up to Leaf -10 (Cros et al., 2013). The physiological mechanisms underlying sex determination and the role of carbohydrate balance and plant hormones remain poorly understood (Corley, 1976a; Corley and Tinker, 2016: 120; for a review on the effects of environmental factors on sex determination see Adam et al., 2011).

Sex ratio (i.e. the ratio of female inflorescence number to total inflorescence number) is affected by both sex determination and the preferential abortion of female or male inflorescences; the two effects are difficult to separate (Corley, 1976a). In the absence of severe stress, the average sex ratio is 0.9–1.0 in the first four YAP (Henson and Dolmat, 2004), 0.6–0.9 until 12 YAP (Jones, 1997; Henson and Dolmat, 2004), and then steadily declines (Corley and Gray, 1976). Severe water deficit, such as occurs in the dry season in West Africa, can reduce the sex ratio to 0.1–0.2 (Broekmans, 1957; Bredas and Scuvie, 1960; Corley, 1976a). Sex ratio, particularly inflorescence abortion, is affected by fruiting activity (Corley and Breure, 1992). The combined effects of environmental and internal signals result in annual oscillations in sex ratio and yield (Cros et al., 2013). Developing inflorescences are most sensitive to abortion 4–6 months before anthesis, which coincides with the onset of floral organ development and elongation (Broekmans, 1957). Whereas several authors reported a preferential abortion of female inflorescences during (part of) the sensitive period of inflorescence development (Bredas and Scuvie, 1960; Breure and Menendez, 1990; Pallas et al., 2013), others observed preferential abortion of female inflorescences only in specific lines (Corley et al., 1995), preferential abortion of male inflorescences (Legros et al., 2009b), or equal abortion rates for inflorescences of both sexes (Henry, 1960). Inflorescence abortion rates of 25–40% were measured in young mature palms that experienced prolonged dry seasons in Nigeria, decreasing to 5–10% in palms >15 YAP (Broekmans, 1957). Much smaller abortion rates of 2–13% were measured in palms

of 4–17 YAP planted on deep peat soils with a high water table in Malaysia, and no clear age trend was observed (Henson and Dolmat, 2004). A reduction in source availability through defoliation down to 16 leaves increased inflorescence abortion rates in Leaves +2 to +12 from 10% to 40%, on average, in clonal palms of 9 YAP in Malaysia (Corley et al., 1995). While the sex ratio at the moment of peak abortion did not change significantly in all clones but one, the average percentage of leaf axils with male inflorescences increased from 50% in the control to 60% in the pruned palms, in the period 11–25 months after defoliation. Conversely, a decrease in sink activity induced by fruit pruning in palms of 14 YAP in Sumatra increased the fraction of female inflorescences in the trough and the peak season from 0.15–0.6 in the control to 0.25–0.8 in the pruned palms. Simultaneously, the aborted fractions decreased from 0.2–0.6 to 0.1–0.2, and the number of male inflorescences in the trough season increased from 0.1 to 0.5 (Legros et al., 2009b). Thresholds of specific assimilate availability that trigger sex determination and floral abortion responses remain to be identified, due to the large variation in response among planting materials, research sites, and experiments (Breure, 1987; Corley and Breure, 1992; Corley et al., 1995; Cros et al., 2013).

3.1.3. Bunch failure

Bunch failure, the abortion of a bunch before full ripening, occurs 2–4 months after anthesis (Sparnaaij, 1960). Bunch failure may be caused by poor pollination or acute and severe assimilate shortage, usually caused by lack of water or radiation (Corley and Tinker, 2016: 125; Combres et al., 2013). Bunch failure rates between 1.5% (Corley, 1973b) and >25% (Sparnaaij, 1960; Corley and Tinker, 2016: 124–125) have been observed, but the available data is scarce, and the phenomenon remains poorly described and understood (Corley and Tinker, 2016: 124–125).

3.2. Bunch weight and oil content

Bunch weight and oil content are less responsive to stress than bunch number, but have a major impact on yield. We briefly describe inflorescence and bunch development, and then discuss the regulation of the various components of bunch weight and oil content.

3.2.1. Inflorescence and bunch development

Both male and female inflorescences consist of a peduncle, carrying spikelets on which the flowers are set, each subtended by a single bract. The male peduncle and spikelets are 40 and 10–30 cm in length, respectively, and each of the 100–300 spikelets carries 400–1500 male flowers 3–4 mm in length. The female peduncle is shorter (20–30 cm) and thicker and carries around 150 spikelets, each 6–15 cm in length. A spikelet carries 5–30 flowers that are subtended by a bract in the shape of a sharp spine (Jacquemard and Baudouin, 1998). The number of spikelets and the number of flowers per spikelet increase with palm age but reach a plateau at 10–12 YAP (Corley and Gray, 1976). The number of female flowers that develops into fruitlets ranges from 30–60% (Corley and Tinker, 2016: 49) to 80% (Harun and Noor, 2002) when insect pollinators are present. In palms 10–15 YAP, bunches contain 1500–2000 fruitlets. The bunch maturation time (from anthesis to bunch ripeness) varies from 140 to 180 days, depending on both genetic and environmental factors (Lamade et al., 1998; Henson, 2005). Fruit maturation starts two weeks after anthesis and occurs in several distinct phases (Oo et al., 1986). Oil starts to accumulate in the endosperm of fruitlets about 12 weeks after anthesis, and four weeks later the endocarp and endosperm (which together form the kernel) have hardened (Oo et al., 1986; Sambanthamurthi et al., 2000). Oil deposition in the mesocarp begins around 15 weeks after anthesis and continues until fruit ripeness, 5–6 months after anthe-

sis (Oo et al., 1986), when fruitlet mesocarp oil content is about 60% and water content has decreased from more than 80% to less than 40% (Bafar and Osagie, 1986; Bille Ngalle et al., 2013).

3.2.2. Regulating mechanisms of bunch weight and oil content

The main components that determine bunch weight are the number of spikelets, number of flowers per spikelet, fruit set, weight per fruitlet, and weight of non-fruit bunch components (Broekmans, 1957). Bunch fresh weight (with 53% dry matter, on average; Corley et al., 1971b) increases with palm age, starting at 3–5 kg at 24 MAP and increasing to over 30 kg by 25 YAP (Lim and Chan, 1998, cited by Corley and Tinker, 2003: 113; Sutarta and Rahutomo, 2016). All components of bunch weight respond positively to increased assimilate availability (Breure and Menendez, 1990; Corley and Breure, 1992; Pallas et al., 2013). Removal of 75% of the inflorescences in palms of 4–7 YAP increased total bunch weight to 12.7 kg from 7.6 kg in control palms, resulting from an increase in all components mentioned above (Corley and Breure, 1992; Breure and Corley, 1992). Fruit set is determined mainly by pollination efficiency (4.2.8).

Oil content is primarily affected by planting material (4.2.4). A single gene determines kernel shell thickness, which in turn affects the thickness of the mesocarp and therefore fruit bunch oil content (Beirnaert and Vanderweyen, 1941). Wildtype oil palm (*dura*) has a thick shell and a typical oil extraction rate of 16–18%, whereas the *tenera* hybrid, a cross between *dura* and the shell-less *pisifera* mutant, has an intermediate shell thickness and oil extraction rates of 22–30% (Jalani et al., 2002; Rajanaidu and Kushairi, 2006). Fertiliser use affects bunch oil content (Ochs and Ollagnier, 1977), with increased tissue chloride concentrations leading to an increase in kernel-to-fruit from 7.8 to 9.3%, and a reduction in mesocarp-to-fruit from 81.7 to 79.2% in palms of 8 YAP in Papua New Guinea (Breure, 1982). Oil content is negatively correlated with rainfall, and positively correlated with available radiation; high rainfall in Malaysia in 1996 resulted in a 0.8–1.5% decrease of oil extraction rate (OER) compared with 1993 (Hoong and Donough, 1998). It is positively related with the concentration of Mg in leaf tissue (Ochs and Ollagnier, 1977) but sometimes negatively correlated with the application of potassium chloride (Ochs and Ollagnier, 1977; Zin et al., 1993), probably as a consequence of increased Cl concentrations in the plant tissue resulting in increased kernel-to-fruit ratio (Breure, 1982).

4. Magnitude, causes, and management of yield gaps

Oil palm is grown in large-scale monoculture plantations or as a smallholder crop, with fruit bunches as the primary output and crude palm oil (CPO) and palm kernel oil (PKO) as the final products. Productivity is best measured as oil yield (t ha^{-1}), calculated from the yield of fruit bunches (t ha^{-1}) and the extraction rate (%). In this review yields are expressed either in t ha^{-1} fruit bunches (with 53% DM) or in t ha^{-1} oil. PKO is not considered, as it is a by-product which is extracted and traded by a limited number of mills. Kernel extraction rate is usually about 5% (Carter et al., 2007).

4.1. The different yield gaps in oil palm

In production ecology, three production levels are commonly distinguished: the potential yield (Y_p) determined by yield-defining factors (PAR, temperature, ambient CO_2 concentration, and crop genetic characteristics); the water-limited (Y_w) and nutrient-limited yield (Y_n) determined by yield-limiting factors (water and nutrition); and the actual yield (Y_a) determined by yield-reducing factors (weeds, pest, diseases) (van Ittersum and Rabbinge, 1997). Yield gap analysis is the analysis of the difference between Y_p (assuming genotype and management are optimal)

and Y_a in a particular physical environment (van Ittersum and Rabbinge, 1997; for recent reviews on yield gap analysis see also Lobell et al., 2009; van Ittersum et al., 2013).

We define the potential yield as *the yield of a cultivar, when grown in environments to which it is adapted; with nutrients and water non-limiting; and with pests, diseases, weeds, lodging and other stresses effectively controlled* (Evans, 1993). The theoretical limit to genetic gain in crop yield can be calculated using simulation models (Lobell et al., 2009). This number is sometimes also referred to as the 'potential yield' in oil palm literature (Breure, 2003; Corley, 2006), and can be used to set a target for breeders and to explore future scenarios, such as for land use. Oil palm management literature refers to the "site yield potential" (Tinker, 1984; Goh et al., 2000), defined as *the yield obtained on a specified site, with natural water supply, nutrients supplied at optimum rates, and agronomic and disease control measures implemented to a high standard* (Corley and Tinker, 2016: 322). This is similar to what we call the water-limited yield, but includes management decisions taken at planting, specifically planting material and density. For thorough reviews on the approach to yield gap analysis from the oil palm management perspective, see Goh et al. (1994); Griffiths et al. (2002), and Fairhurst and Griffiths (2014), among others.

Accurate analysis of yield gaps depends on the correct assessment of the various production levels (Fig. 3). The yield-determining, yield-limiting and yield-reducing factors relevant in oil palm and their quantitative effects on productivity are discussed in detail below.

4.2. Potential yield and yield-determining factors

The potential oil yield, as defined by fruit bunch yield and oil content, is determined by PAR, temperature, ambient CO_2 concentration, and crop genetic characteristics, under perfect crop management (van Ittersum and Rabbinge, 1997; Table 1). We discuss the different factors that determine the potential yield in further detail below.

4.2.1. Available radiation and PAR

As a perennial with a permanent leaf canopy, oil palm is able to intercept radiation throughout the year, which is one of the main reasons why its productivity is so large compared with other vegetable oil crops. In the tropics, available radiation is mostly limited by cloudiness. The range of total daily incoming short-wave radiation and sunshine hours per day in oil palm growing regions are shown in Table 1.

A minimum of $15 \text{ MJ m}^{-2} \text{ day}^{-1}$ total solar radiation (equivalent to $\sim 7.5 \text{ MJ m}^{-2} \text{ day}^{-1}$ PAR) or 5.5 h day^{-1} of sunshine is optimal for oil palm growth, indicating a lesser yield potential in parts of Africa and the Americas (Paramananthan, 2003). Modelling work by Kraalingen et al. (1989) indicated that each hour per day of bright sunshine results in 15–20 kg bunch dry matter production $\text{palms}^{-1} \text{ year}^{-1}$ in excess of the bunch dry matter produced under cloudy circumstances, assuming a planting density of 110 palms ha^{-1} . Thus potential yields in regions with eight sunshine hours per day would be >60% larger than in regions with three sunshine hours per day (Kraalingen et al., 1989). Light saturation in oil palm leaves typically occurs at a photosynthetic photon flux density (PPFD) of $>1100\text{--}1200 \mu\text{mol m}^{-2} \text{ s}^{-1}$, roughly equivalent to 250 W m^{-2} PAR (Dufrène et al., 1990). A light-saturated net assimilation rate of about $20 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ was measured at $1100 \mu\text{mol m}^{-2} \text{ s}^{-1}$ PPFD in leaf 8 and 9 of palms planted in Ivory Coast (Dufrène and Saugier, 1993), which is similar to the average rate of $17.8 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ found in palms 12–13 YAP in Malaysia (Henson, 1991b). Reduction of available PAR due to haze, caused by forest burning, is a common issue in Indonesia. Forest burning occurs mostly during the dry season when available radiation is at its peak, and is

Table 1
Yield-determining factors in oil palm systems: potential yield (Yp).

Yield-determining factors	Range in oil-palm growing areas	Yield effects measured in case studies	Selected references															
Radiation: solar radiation	<ul style="list-style-type: none">All regions: average 15 to 23 MJ total radiation m⁻² day⁻¹Africa and parts of the Americas: < 10 MJ m⁻² day⁻¹ during the wet season	<ul style="list-style-type: none">Modelled increases of 1.7–2.1 t fruit bunches ha⁻¹ yr⁻¹ per additional MJ m⁻² day⁻¹Modelled 15–20% annual yield loss after two months reduction from 15 to 12 MJ total radiation m⁻² day⁻¹ due to haze	(Paramananthan et al., 2000) (Henson, 2000) (Goh, 2000) (Caliman et al., 1998)															
Radiation: sunshine hours day ⁻¹	<ul style="list-style-type: none">Asia: 5.3–6.9Americas: 2.2–7.7Africa: 3.6–6.3	<ul style="list-style-type: none">Productivity constraints if <5.5 h day⁻¹One additional hr day⁻¹ yields an additional 15–20 kg bunch DM palm⁻¹ yr⁻¹ compared with productivity under cloudy conditions	(Hartley, 1988: 100–101) (Kraalingen et al., 1989) (Paramananthan, 2003)															
CO ₂ concentration	<ul style="list-style-type: none">1960: 317 ppm1980: 339 ppm2000: 370 ppm2015: 399 ppm	<ul style="list-style-type: none">Modelled bunch DM production (t ha⁻¹ yr⁻¹) in site without water deficit: <table><tr><th>Bunch DM</th><th>CO₂ (ppm)</th><th>Temperature (°C)</th></tr><tr><td>11</td><td>350</td><td>+0</td></tr><tr><td>30</td><td>550</td><td>+0</td></tr><tr><td>18</td><td>550</td><td>+2</td></tr><tr><td>10</td><td>550</td><td>+4</td></tr></table>	Bunch DM	CO ₂ (ppm)	Temperature (°C)	11	350	+0	30	550	+0	18	550	+2	10	550	+4	(Ibrahim et al., 2010) (Henson, 2006) (Tans and Keeling, 2015)
Bunch DM	CO ₂ (ppm)	Temperature (°C)																
11	350	+0																
30	550	+0																
18	550	+2																
10	550	+4																
Temperature	Lowest monthly minimum: 17.7 °C (Bahia, Brazil) Highest monthly maximum: 34.6 °C (Aracataca, Colombia)	<ul style="list-style-type: none">Undefined strong yield reductions at minimum monthly average temperatures of less than 18–19 °CSeedling growth inhibited at 15 °C, seven times slower at 17.5 °C and three times slower at 20 °C than at 25 °CImmature period in cold conditions up to 1 year longer	(Hartley, 1988: 102–103; 110) (Henry, 1958) (Olivin, 1986)															
Planting material	<ul style="list-style-type: none"><i>Tenera</i> clones<i>Tenera</i> semi-clonesDxP <i>tenera</i> seed<i>Dura</i> seedSeed of unknown origin	<ul style="list-style-type: none"><i>Tenera</i> clones: 15.7 t oil ha⁻¹ yr⁻¹ at 7 YAP<i>Tenera</i> semi-clones: 11.1 t oil ha⁻¹ yr⁻¹ at 5 YAPDxP <i>tenera</i> seed: 8.9 t oil ha⁻¹ yr⁻¹<i>Dura</i> seed: ~ 35–50% reduced bunch oil contentSeed of unknown origin: reductions potentially very large depending on percentage <i>pisifera</i> in population (zero yield from <i>pisifera</i> palms) and potential of parent materials	(Simon et al., 1998) (Ng et al., 2003) (Rajanaidu et al., 2005) (Sharma, 2007)															
Planting density	<ul style="list-style-type: none">110–156 palms ha⁻¹ in favourable environments160–170 palms ha⁻¹ in unfavourable soils	<ul style="list-style-type: none">Optimum fixed planting density: 140–160 palms ha⁻¹; optimum LAI: 5.5–6.01–2% reduction in cumulative plantation yield when density ± 10 palms from optimumOn deep peat: higher optimum densities (> 160 palms ha⁻¹)Yield increase of 4 t fruit bunches ha⁻¹ yr⁻¹ from 9 to 16 YAP in response to thinning from 160 to 120 palms ha⁻¹ at 8 YAP compared with no thinning or a fixed density of 143 palms ha⁻¹ in Thailand	(Corley and Tinker, 2016: 282) (Breure, 2010) (Corley, 1973a) (Breure, 1977) (Gurmit et al., 1986) (Goh et al., 1994) (Uexküll et al., 2003)															
Culling	<ul style="list-style-type: none">Good: 20–30% of seedlings removedPoor: incorrect or insufficient culling	<ul style="list-style-type: none">No culling: 20–30% abnormal seedlings producing 40–100% less yield than normal seedlings	(Tam, 1973) (Gillbanks, 2003)															
Pruning	<ul style="list-style-type: none">50–60 leaves at 0–3 YAP40–50 leaves at 4–10 YAP32–40 leaves at >10 YAP	<ul style="list-style-type: none">Over-pruning palms 8–12 YAP planted at 138 palms ha⁻¹ in Malaysia: <2, 12, 19, 24, and 25 t fruit bunches ha⁻¹ with 8, 16, 24, 32, and 40 leaves palm⁻¹, respectivelyUnder-pruning: direct but unquantified yield loss due to reduced harvesting efficiency	(Hartley, 1988: 441–442) (Henson, 2002) (Corley and Hew, 1976)															
Fruit set and pollination	<ul style="list-style-type: none">Pollinating weevil present in all regionsAverage fruit set 70–80%	<ul style="list-style-type: none">Quadratic asymptotic relation between fruit set and bunch weight with an average bunch weight of 24, 20 and 14 kg at 90, 50 and 20% fruit set, respectivelyQuadratic relation between fruit set and oil to bunch ratio with an average O/B of 25, 20 and 13% at a fruit set of 75, 40 and 20%, respectively	(Harun and Noor, 2002) (Syed et al., 1982) (Rao and Law, 1998) (Henson, 2001)															
Harvesting frequency	<ul style="list-style-type: none">Plantations: 7-day, 10-day or 14-day harvesting intervalSmallholders: usually 14 or 15-day harvesting interval, sometimes up to 30 days	<ul style="list-style-type: none">Yield increase of 5–20% when reducing length of harvesting round from 14 to 10 days	(Donough et al., 2013) (Lee et al., 2013) (Corley, 2001) (Donough, 2003)															
Crop recovery in the field	<ul style="list-style-type: none">Varying from near complete recovery to less than 70% of fruit	<ul style="list-style-type: none">Reported yield losses of up to 5 t fruit bunches ha⁻¹ due to poor crop recoveryYearly losses under strict harvesting regime at 7-day interval: 200 kg fruit bunches ha⁻¹ unharvested bunches and 65 kg ha⁻¹ uncollected loose fruitsIncomplete collection of loose fruit: on average >5% yield loss~30% less oil yield from unripe bunches	(Fairhurst and Griffiths, 2014: Chapter 6) (Donough et al., 2013) (Corley, 2001) (Wood, 1985)															

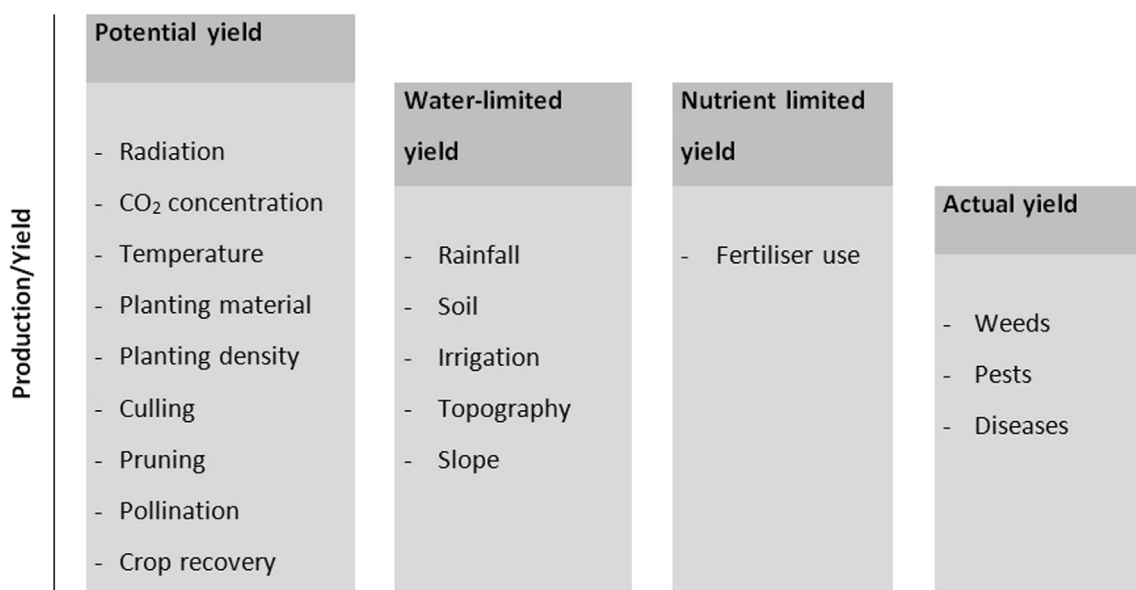


Fig. 3. Different oil palm production levels and the contributing factors.

likely to reduce yields significantly (Table 1). In Africa, dust from the Harmattan and smog cause periodic reductions in radiation.

4.2.2. CO₂ concentration

Under current circumstances the rate of photosynthesis in C3 crops such as oil palm is limited by the availability of CO₂. Yield increases of 10–30% in response to doubling atmospheric CO₂ concentrations have been observed in other C3 crops such as wheat (Kimball et al., 1993; Fuhrer, 2003), and may be expected in future in as oil palm is well adapted to high temperature-environments (Dufrène and Saugier, 1993). Increases in photosynthetic rates in oil palm seedlings from 5 to 12 $\mu\text{mol m}^{-2} \text{s}^{-1}$ have been observed in response to changes in atmospheric CO₂ concentrations from 400 to 800 ppm (Ibrahim et al., 2010). Whether increased rates of photosynthesis are translated into improved yields depends on multiple factors, particularly the source/sink balance (e.g. Paul and Foyer, 2001) and the air temperature (4.2.3). Mature palms are usually source-limited (Breure, 2003) making an actual yield response to rising CO₂ concentrations likely, if the temperature remains stable. No research has been carried out to date on the actual effect of available CO₂ on oil palm yield in mature plantations. The expected effects of climate change on worldwide palm oil production are reviewed by Corley and Tinker (2016, Section 17.3).

4.2.3. Temperature

The temperature range in the oil palm growing regions is shown in Table 1. The upper temperature limit for efficient photosynthesis in oil palm leaves is >38°C, provided that vapour pressure deficit is small (Dufrène et al., 1990; Dufrène and Saugier, 1993; Paramanathan, 2003). Temperature and maintenance respiration in plants are strongly positively related, with an average factor two increase in maintenance respiration at every 10°C temperature rise (Amthor, 1984; Ryan, 1991). Whether this estimate holds for oil palm remains unclear, and yield responses to increasing temperatures have not been quantified (Henson, 2004, 2006). Oil palm is sensitive to cold (Table 1). In cooler regions such as in Bahia (Brazil) and Tela (Honduras), strong reductions in yield occur during the second half of the cold season and the beginning of the warmer season, and in Sumatra low temperatures at higher elevations were found to extend the immature period by at least one year (Hartley, 1988: 110).

4.2.4. Planting material

Estimates of theoretical ceiling oil yields (with future planting materials under the best possible environmental and management condition) range from 10.6 (Breure, 2003) and 14.0 (Henson, 1992) to 18.5 t oil ha⁻¹ yr⁻¹ (Corley, 1998, 2006) on average over the plantation lifetime. While the larger estimates may be based on some unrealistic assumptions (Breure, 2003), best yields achieved in small plantations or experimental fields already fall within the estimated range (Table 1). Non-clonal planting materials, raised from seed, consist of a population of offspring from a *dura* mother and a *pisifera* father (DxP), and individuals vary in terms of potential for vegetative growth and productivity (Okwuagwu et al., 2008). Potential yields of DxP planting materials have increased by an estimated 1.5% per year through breeding with specific male/female parent combinations that show an early track record of performance: this trend in yield increase is expected to continue (Soh, 2004; Corley, 2006). Breeding has particularly improved photosynthetic conversion efficiency (Corley and Lee, 1992) and bunch oil content (Corley and Lee, 1992; Prasetyo et al., 2014; Soh, 2015). Varieties with improved tolerance for cold (Chapman et al., 2003) and drought (Rao et al., 2008) are being further developed.

Clones from carefully selected ortets can outyield conventional seed material by 20–30%, due to a combination of better uniformity, increased fruit bunch yield and greater oil to bunch ratio (Khaw and Ng, 1998; Simon et al., 1998; Kushairi et al., 2010; Soh, 2012; Table 1). Although field experiments have confirmed the superior yields of selected clones under circumstances of rigorous culling, key issues with multiplication of embryos and somaclonal variation limit the current planting of clones at commercial scale (Soh, 2004; Soh et al., 2011). The recent finding of the epigenetic factor underlying the *mantling* phenotype (a floral malformation that results in failure to form fruitlets or reduced fruitlet oil content) is likely to boost the planting and performance of clonal oil palm (Ong-Abdullah et al., 2015).

4.2.5. Planting density

Planting density is an important determinant of potential yield (Corley, 1973a; Breure, 1977, 1982; Uexküll et al., 2003). An optimum planting density (Table 1) balances the requirement for rapid canopy closure in the immature phase with a large number of palms (i.e. bunches) in the young mature phase and limited inter-palm

competition for light in the mature phase. On deep peat, vegetative growth is reduced and denser planting has been recommended (Table 1; Gurmit et al., 1986). High-density planting followed by selective thinning at 8–9 YAP is an effective strategy for yield maximisation (Uexküll et al., 2003; Palat et al., 2012; Table 1).

4.2.6. Culling

The quality and uniformity of field palms depends on the planted material and on the selection of individuals during the nursery phase, termed ‘culling’ (Tam, 1973). Due to genetic diversity and stresses during the nursery and field planting phase, large differences in productivity between palms have been observed even when rigorous culling has been carried out (Okwuagwu et al., 2008), with the most productive individuals yielding two to three times more than average, and the least productive individuals yielding no bunches (Yeow et al., 1982; Hartley, 1988: 222). Normally the prevalence of stunted or abnormal seedlings is 20–30%. Abnormal seedlings, identified by phenotypic selection in the nursery phase, give strongly reduced yields when planted out (Tam, 1973; Table 1). All abnormal seedlings should be removed during the nursery phase or replaced within 12 months after planting (Gillbanks, 2003; Jacquemard and Baudouin, 1998: 56).

4.2.7. Pruning

Pruning, the removal of selected leaves, is a management practice specific for perennial crops. Pruning aims to optimise source availability while minimising loss of assimilates due to respiration in senescing leaves. Newly-opened leaves in oil palm show a stable or slightly increasing photosynthetic activity until 4–10 months after opening (in palms of 3 and 10–12 YAP, respectively), after which activity decreases until the leaves senesce and die (Corley, 1983, 1976b). Leaves at the bottom of the canopy remain photosynthetically active and are net sources until senescence (Henson, 1991a), and retaining all living leaves but removing senescing leaves is the best way to maximise assimilate availability irrespective of plantation age (Hartley, 1988: 441; Henson, 2002). Pruning in immature and young mature palms is usually limited to the removal of senescing or dead leaves, as reductions in leaf area have a strong negative effect on light interception and total assimilate availability during this phase (Gerritsma, 1988; Breure, 2003). Yield penalties when pruning from >48 down to 32–40 leaves per palm in mature plantations are not significant (Corley and Hew, 1976) and sufficient pruning of tall palms to facilitate complete and correct harvesting and quick recycling of nutrients is recommended (Fairhurst and Griffiths, 2014).

4.2.8. Pollination

A quadratic function describes the relationship between fruit set and bunch weight, with a maximum bunch weight at 90%, and a maximum oil to bunch ratio at 75% fruit set (Harun and Noor, 2002; Table 1). Seasonal episodes of poor (10–20%) fruit set have been observed in Malaysia, caused by strong reductions of pollinating weevil populations due to excessive rain, absence of sufficient male flowers and infection with parasitic nematodes (Rao and Law, 1998). As a consequence oil extraction rate (OER) fell from 21.2 to 18.8%, and kernel extraction rate from 4.7 to 3.5% in Malaysia between 1993 and 1996. A minimum of two male palms per hectare in plantations with a high sex ratio is thought to supply sufficient pollen and maintain weevil populations (Rao and Law, 1998).

4.2.9. Crop recovery

The goal of harvesting, or crop recovery, is to collect all fruit bunches at the moment of optimum ripeness (i.e. maximum oil content with a minimum concentration of free fatty acids in the extracted oil; PORLA, 1995). Infrequent, incomplete or incorrect harvesting practices (i.e. harvesting unripe or overripe bunches)

directly reduce both the quantity of fruit and the oil quality (Donough et al., 2010; Table 1). The harvesting interval (i.e. the number of days between two harvesting rounds) should be adapted to the speed at which loose fruits detach from the ripe bunch, to minimise losses from uncollected loose fruit and overripe bunches (Gan, 1998). An optimal harvesting interval of 10 days has been proposed (Gan, 1998; Rankine and Fairhurst, 1999b; Donough et al., 2010). Harvesting of unripe bunches is likely to affect the source/sink balance as bunch sink requirements increase strongly towards the last phase of ripening (Henson, 2007), but this has not been quantified.

4.3. Water-limited yield and yield-limiting factors

The water-limited yield (Y_w ; Table 2) is an important benchmark as most oil palm cropping systems are rain-fed (Ludwig et al., 2011). Water availability depends on rainfall and soil characteristics and is strongly site-specific (Lobell et al., 2009; van Ittersum et al., 2013). Y_w can be approximated by crop simulation models using plausible physiological and agronomic assumptions (Evans and Fischer, 1999), by field experiments, estimates of best farmers' yields, or growers' contests (van Ittersum et al., 2013).

4.3.1. Rainfall

Oil palm transpires about 6 mm water day⁻¹ under non-limiting conditions, and requires sufficient rainfall throughout the year (Table 2). Average actual transpiration rates in oil palm plantations are 4.0–6.5 mm day⁻¹ in the rainy season and 1.0–2.5 mm day⁻¹ on dry days (Carr, 2011). Moderate to severe water stress strongly suppresses yield (Table 3). Oil palm leaves do not wilt, but the opening of new leaves is delayed in response to water stress, and stomatal opening is strongly affected by air vapour pressure deficit (VPD) and soil water availability (Smith, 1989; Caliman, 1992). Henson and Harun (2005) measured potential evapotranspiration rates of 1.3 mm day⁻¹ at 1.9 kPa VPD and 75% available soil water content, in palms of 3 YAP planted at a site with a regular dry season in Malaysia. In another site, an increased VPD from 0.4 to 2.0 kPa resulted in a decline in photosynthetic rate from 18–19 to 10–12 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in palms of 1–2 YAP, even under conditions of sufficient soil water availability (Henson and Chang, 1990).

A linear relationship between applied water volume and yield has been found in irrigation trials in drier environments (Corley, 1996; Palat et al., 2008; Carr, 2011; Table 2). Although yield responses to irrigation have been observed in areas with occasional dry spells in Malaysia, irrigation is not always economically feasible (Corley and Hong, 1982; Henson and Chang, 1990). Critical water deficit thresholds at different stages of palm development and optimum volumes of water to be applied remain to be defined (Carr, 2011).

4.3.2. Soil

Soil water availability depends on the influx of water (rainfall, irrigation, and groundwater), the loss of water (evapotranspiration, drainage, and surface water run-off), and the previous soil water reserve. A simplified calculation was proposed by Surre (1968) to allow for a quick assessment of the suitability of soil-climate combinations for oil palm development. This calculation is based on the following equation:

$$B = Res + R - Etp \quad (2)$$

where B is the water balance at the end of a period, Res is the soil water reserve at the beginning of a period, R is rainfall and Etp is the potential evapotranspiration (Surre, 1968). Using this equation, Olivin (1968) estimated water-limited yields in Africa for five scenarios of water deficit on five soil classes ranging from

Table 2
Yield-limiting factors in oil palm systems: water-limited yield (Yw).

Yield-limiting factors	Range in oil-palm growing areas	Yield effects measured in case studies	Selected references
Total rainfall and distribution	Rainfall (mm year ⁻¹) <ul style="list-style-type: none"> Malaysia and Indonesia: 1700–4000 Africa: 1200–3500 Americas: 1600–3500 Dry months (less than 100 mm rain month ⁻¹) <ul style="list-style-type: none"> Malaysia and Indonesia: 0–3 Africa: 3–6 Americas: 0–5 	<ul style="list-style-type: none"> Yield reduced if rainfall <2000 mm yr⁻¹ or >3500 mm yr⁻¹ and/or <100 mm month⁻¹ Yield reductions in relation to water deficit: <ul style="list-style-type: none"> None if water deficit is less than threshold of 50–200 mm yr⁻¹, depending on local conditions; 10–20% yield loss per 100 mm deficit after the threshold; Exponential decline down to <10 t fruit bunches ha⁻¹ yr⁻¹ at water deficits of >500 mm See also: Table 3 	(Dufrène et al., 1990) (Hartley, 1988: 98–99) (Paramanathan, 2003) (Goh, 2000) (Olivin, 1986)
Irrigation	<ul style="list-style-type: none"> Most areas are rain-fed Plantations in Thailand, parts of Africa, and parts of the Americas use irrigation Some smallholders in the Americas and Thailand use irrigation; rare in other areas 	<ul style="list-style-type: none"> Estimated response according to IRHO method for calculating soil water deficit: 20–30 kg ha⁻¹ year⁻¹ fruit bunches per mm irrigation water in areas where the potential soil water deficit is 200–600 mm year⁻¹ Approximately linear relationship between water volume (mm water dry day⁻¹) and yield response (t fruit bunches ha⁻¹ year⁻¹) in irrigation trial in Thailand (soil water deficit 235 mm year⁻¹ over 3–4 months): <ul style="list-style-type: none"> 18 t fruit bunches at 0 mm 24 t fruit bunches at 3.2 mm 28 t fruit bunches at 6.4 mm 	(Palat et al., 2008) (Ochs and Daniel, 1976) (Carr, 2011)
Soil type	Most common soil types (according to the USDA soil taxonomy) <ul style="list-style-type: none"> SE Asia: ultisols, oxisols and histosols Africa: oxisols, ultisols and mullisols Americas: oxisols and ultisols 	Most soil types are not constraining apart from: <ul style="list-style-type: none"> Shallow soils (Malacca series and Baiayo family): <30 t fruit bunches ha⁻¹ yr⁻¹ Coarse textured soils (psamments): yield 'poor' but not quantified Biochemically constrained soils (saline soils, peat soils, acid sulphate soils): 20–30 t fruit bunches ha⁻¹ yr⁻¹ when managed well 	(Goh et al., 1994) (Gurmit et al., 1986) (Paramanathan, 2013) (Mutert et al., 1999) (Paramanathan, 2000)
Soil texture	<ul style="list-style-type: none"> Sandy soils to heavy clay 	<ul style="list-style-type: none"> Large but unquantified yield losses in very sandy soils and in heavy clay soils 	(Paramanathan, 2003) (Paramanathan, 2013)
Topography and slope	<ul style="list-style-type: none"> Flat to hilly 	<ul style="list-style-type: none"> Slopes >20° are considered unsuitable; slopes 10–20° require soil conservation measures Estimated 10–30% yield reduction on slopes of 2–7° without conservation measures Measured 20–30% yield increase (mature plantation; 3-month dry season) after implementation of soil conservation measures on slope of 2–5° 	(Paramanathan, 2003) (Paramanathan, 2013) (Balasundram et al., 2006) (Kee and Soh, 2002) (Murtlaksono et al., 2011)
Waterlogging	<ul style="list-style-type: none"> Common in low-lying areas in all regions Localised flooding or water logging for several days to months per year 	<ul style="list-style-type: none"> Mortality of up to 75% of immature palms in regions of frequent inundation Yield losses of 20–30% in poorly drained mature plantations Yield increases of >5 t ha⁻¹ fruit bunches after drainage of frequently flooded fields 	(Lee and Ong, 2006) (Abram et al., 2014) (Henson et al., 2008) (Chuah and Lim, 1992; cited by Lim et al., 1994)

Table 3
Water-limited yield in Africa related to soil class and water deficit, assuming all other production factors are sufficient (after [Olivin, 1968](#)).

Soil class		Water deficit (mm)				
		0	100	200	300	400
		Yield (t fruit bunches ha ⁻¹ yr ⁻¹)				
I	Very suitable	≥27	24	18	14	12
IIa	Suitable	25	20	16	13	10
IIb	Moderately suitable	25	20	16	11	8
III	Somewhat suitable	22	16	13	9	6
IV	Unsuitable	16	13	9	6	4

I (excellent, such as young alluvial soils) to IV (unsuitable, such as very sandy or gravelly soils; [Table 3](#)). In Malaysia, yields of >30 t fruit bunches ha⁻¹ have been reported on most soil types apart from shallow soils, which cause problems such as reduced root proliferation, increased susceptibility to drought and waterlogging, and risk of palms falling over ([Goh et al., 1994](#); [Fairhurst and McLaughlin, 2009](#); [Paramanathan, 2013](#); [Table 2](#)). On peat soils, yields of 30 t fruit bunches ha⁻¹ have been reported ([Gurmit et al., 1986](#)) but yields are generally less than on mineral soils

because of palms leaning or falling over, waterlogging, and soil drying ([Paramanathan, 2013](#)).

4.3.3. Topography and slope

Cultivation on slopes increases surface run-off which reduces the amount of water available for the crop. A maximum slope of 10° without soil conservation, or 20° with terraces, has been proposed to maintain economic yields ([Paramanathan, 2003](#)), but yield responses to soil conservation on slopes of 2–10° have been

reported (Table 2). Water losses by run-off varies from zero to >30%, with erosion and fertiliser loss occurring mostly from weeded circles and harvesting paths where soils are bare and become compacted (Comte et al., 2012; Bah et al., 2014; Banabas et al., 2008). Water and fertilisers flow from summits and side slopes to valleys, creating heterogeneity in soil fertility and yield (Balasundram et al., 2006), as well as environmental problems (Comte et al., 2012).

4.3.4. Waterlogging

Oil palm is tolerant of temporary flooding, which may be partly due to the ability of the roots to form pneumatodes (Purvis, 1956; Jourdan and Rey, 1997). However, submerged roots are unable to respire normally, leading to impaired water and nutrient uptake, delayed frond opening, and reduced carbohydrate availability (Corley and Tinker, 2016: 109). Henson et al. (2008) demonstrated that photosynthetic activity and transpiration rates are 3–4 times less in oil palms under waterlogged conditions compared with palms in well-drained soils. Waterlogging is a common problem in plantations in Southeast Asia (Paramananthan, 2003; Lee and Ong, 2006) and severe, but poorly quantified, reductions in yield have been observed (Abram et al., 2014; Carr, 2011; Table 2). Data on effects of drainage on productivity in waterlogged fields is scarce (Table 2). In peat soils and acid sulphate soils, sufficient drainage while maintaining the water table at 40–50 cm below ground level or above the acid sulphate layer is critical to prevent soil degradation, reduce greenhouse gas emissions, and obtain high yields (Toh and Poon, 1981; Othman et al., 2011).

4.4. Nutrient-limited yield and yield-limiting factors

The nutrient-limited yield (Y_n ; Table 4) is location dependent, mostly due to the effects of soil properties on nutrient availability.

The nutrient needs of oil palm are well-researched and reviewed (Uexküll and Fairhurst, 1991; Goh et al., 2003; Ng, 1977; Breure, 1982). Oil palm requires particularly large quantities of potassium, as well as nitrogen, phosphorus, magnesium, and boron (Table 5). Fertilisation with copper and zinc is required on peat soils. In case of severe deficiencies, foliar symptoms become visible (Broeshart et al., 1957; Table 5). Critical tissue nutrient concentrations that indicate nutrient deficiencies have been established (Uexküll and Fairhurst, 1991), but are site and soil specific (Foster and Chang, 1977; Foster, 2003). The availability, uptake, and allocation of the different nutrients are strongly interdependent (Tohiruddin et al., 2010; Foster and Prabowo, 2002). In order to provide correct fertiliser recommendations, accurate measurements of the concentrations of N, P, K and Mg in both the leaflet and the rachis tissues are required (Foster and Prabowo, 2006; Prabowo et al., 2011).

In oil palm plantation systems, nutrients are removed through harvesting of fruit bunches, leaching, run-off, and immobilisation in the trunk; recycled through pruned fronds and male inflorescences; and supplied by rainfall, soil nutrient stocks, mill waste products, and fertilisers (Ng et al., 1999). Chemical fertilisers are usually required to maintain the balance between nutrient removal and supply. Yield responses to chemical fertiliser application are location dependent and vary widely, and numerous randomised factorial N-P-K(-Mg) fertiliser experiments are described in literature (see Tohiruddin et al., 2006 for a good overview of results from Sumatra). Three experiments are summarised in Table 6 to highlight the type of yield responses observed. The range of nutrient use efficiencies (NUE) at different levels of fertiliser use was 0–45, 0–20, and 15–90 kg fruit bunches per kg nutrient $\text{ha}^{-1} \text{yr}^{-1}$ for N, P, and K, respectively, when comparing no fertiliser with average applications (Treatment 0–1; Table 6). When quantities of nutrients applied were increased from average to large quantities (Treatment 1–2; Table 6), NUE became negative in some cases, and maximum

NUE were 13, 0, and 8 kg fruit bunches per kg nutrient $\text{ha}^{-1} \text{yr}^{-1}$ for N, P, and K, respectively.

In none of the experiments in Table 6 a clear yield response to phosphorus application was observed, but yield increases of 50–100% in response to P fertilisers have been observed elsewhere (Vossen, 1970; Ng, 1986; Sidhu et al., 2001). Yield increases of up to 45% in response to magnesium application as kieserite were observed on yellow podzolic sandy loams in north Sumatra (Akbar et al., 1976). Because of the variability in NUE, site-specific factorial fertiliser experiments are required to optimise fertiliser applications (Tohiruddin et al., 2010; Webb, 2009).

4.5. Actual yield and yield-reducing factors

The actual yield (Y_a) is the water and nutrient limited yield, reduced by weeds, pests, and diseases (van Ittersum and Rabbinge, 1997). The cumulative yield over the plantation lifetime is the most important productivity indicator, which takes into account the duration of the unproductive yield-building phase. This has similarities to milk production from cows, but while individuals in a dairy herd can be replaced at any time (van der Linden et al., 2015), abnormal palms can only be replaced during the nursery phase and the first 12 months after planting. The yield-reducing effects of pests and diseases in oil palm unfold over a period of at least three years (Corley and Gray, 1976; Corley, 1976b; Legros et al., 2009a; Adam et al., 2011). This time lag, combined with seasonal variations in fruit production, complicates the interpretation of oil palm yield data (Legros et al., 2009a). The calculation of 'rolling yields' over a 12-month period is useful to filter out seasonal variability when analysing yield trends (Uexküll and Fairhurst, 1991). Pest and disease damage early in the plantation lifetime often have a large effect on total yield, especially when they lead to palm death. The different yield-reducing factors are summarised in Table 7 and are further discussed in the sections below.

4.5.1. Weeds

Weeds protect the soil against erosion and provide a habitat for natural pest enemies, while interacting with the water and nutrient cycles (Table 7). If weeds are allowed to grow uncontrolled, physical access to the plantation is reduced resulting in incomplete and inefficient harvesting. Certain weeds, especially woody and creeping weeds and speargrass (*Imperata cylindrica*), compete strongly with oil palms for water and nutrients (Wood, 1977; Surre, 1968). Weeds in immature plantations can reduce yields by overgrowing the young palms and thus limit available radiation (Table 7). In mature plantations the actual yield response to various weed populations remains unknown. Shade-tolerant legumes as well as certain soft grasses and *Nephrolepis* spp. are preferred as undergrowth in mature plantations because they are easy to manage, able to out-compete woody weeds once established, and not very competitive (Samedani et al., 2014b). Legumes provide an additional advantage because of their capacity to fix nitrogen. A well-established legume cover crop can provide over 150 kg N $\text{ha}^{-1} \text{year}^{-1}$ in the first 4 years after field planting (Agamuthu and Broughton, 1985; Giller, 2001; Giller and Fairhurst, 2003). Livestock integration, practiced regularly by smallholders, improves weed management and plantation productivity (Devendra and Thomas, 2002; Devendra, 2009).

4.5.2. Pests

Leaf-eating insects are present in all oil palm producing regions and large-scale outbreaks periodically occur, especially of bagworm (*Psychidae* spp.) and nettle caterpillar (*Lamicrodidae* spp.) in Southeast Asia (Wood, 1968) and leaf miner (*Coelaenomenodera* spp.) in West-Africa (Mariau, 1976; Mariau and Lecoustre, 2000). Effects of mild infestations are small but yields can be strongly affected when severe defoliation reduces the LAI to less than 5 (Wood, 1977; Table

Table 4
Yield-limiting factors in oil palm systems: nutrient-limited yield (Yn).

Yield-limiting factors	Range in oil-palm growing areas	Yield effect	Selected references
Fertilisation	In kg ha ⁻¹ year ⁻¹ , assuming 140 palms ha ⁻¹ <ul style="list-style-type: none"> • N: ≤260 kg • P: ≤130 kg • K: ≤350 (up to 430 on peat soils) • Mg: ≤70 • B: ≤20 • Cu (on peat): ≤10 • Zn (on peat): ≤10 • Mn, Cl, Ca, Fe, S: occasionally applied 	<ul style="list-style-type: none"> • For N, P, K, and Mg: see Table 5 • B: yield reductions of >35% in palms with severe B deficiency symptoms • Cu (on peat): 10–25% yield increase • Zn (on peat): 10–80% yield increase 	(Rankine and Fairhurst, 1999b) (Rajaratnam, 1973) (Cheong and Ng, 1977) (Gurmit, 1988) (Osman and Kueh, 1996) (Ng, 2002)

Table 5
Role of key nutrients in oil palm physiology.

Element	Physiological role	Effect of deficiency on oil palm growth and yield	Visual deficiency symptoms	Selected references
Nitrogen	Formation of chlorophyll, amino acids, DNA, and ATP	Suppressed net assimilation rate; decreased vegetative dry matter production; increased phyllochron time; decreased bunch weight and number	Chlorosis in younger leaves; stunting	(Corley and Mok, 1972) (Bah Lias, 2011)
Phosphorus	Formation of DNA, RNA, and ATP	Yield decrease on some soils; reduced yield response to N and K fertiliser	Conical trunk shape	(Kraip and Nake, 2006) (Bah Lias, 2011) (Ng, 1986)
Potassium	Transport of photosynthates; control of stomatal opening	Decreased vegetative dry matter production; strongly decreased bunch weight and number	Yellow spotting in older leaves	(Corley and Mok, 1972) (Bah Lias, 2011) (Braconnier and d'Auzac, 1985) (Zakaria et al., 1990)
Magnesium	Chlorophyll formation; ribosome aggregation; enzyme functioning	Yield decrease on some soils; reduced yield response to N and K fertiliser; reduced oil/bunch ratio	Yellow/orange colour in leaflets of older leaves exposed to sunlight	(Dubos et al., 1999) (Härdter, 1999) (Shaul, 2002)
Boron	RNA formation; pollen formation; flavonoid synthesis; seed and cell wall formation	Decreased LAI (occurrence of 'little leaf'); decreased bunch number and yield when leaf deficiency symptoms are present	Crinkling of leaflets in older leaves; stunting of young leaves ('little leaf')	(Rajaratnam, 1973) (Rajaratnam and Lowry, 1974)
Copper, zinc	Electron transport; photosynthesis	Reduced photosynthesis (Zn); decreased vegetative dry matter production (Zn); reduced bunch number and size (Zn, Cu)	Yellowing and necrosis in older leaves starting at the leaflet tip	(Cheong and Ng, 1977) (Gurmit, 1988) (Osman and Kueh, 1996)

Table 6
Effects of N, P, K and Mg on yield in three different fertiliser experiments. Significant responses are printed in bold.

Source	Corley and Mok (1972)			Kraip and Nake (2006)			Bah Lias (2011)					
Location	South Johore, Malaysia			Milne Bay, PNG			South Sumatra					
Soil type	Sandy clay loam granite-derived red-yellow oxisol (Rengam series)			Recent alluvial sandy clay loam (fluvent)			Low-pH loamy kaolinitic inceptisol (typic dystrodept)					
Palm age	10–20 YAP			5 YAP			14 YAP					
Duration of trial	10 years			7 years			> 14 years					
Palms ha ⁻¹	114			127			143					
Treatments (kg palm ⁻¹ yr ⁻¹)		0	1	2		0	1	2		0	1	2
	N	0	0.8	1.5	N	0	0.4	0.7	N	0	0.9	1.8
	P	0	0.9	1.7	P	0	0.2	0.2	P	–	0.2	0.5
	K	0	1.8	3.7	K	0.4	1.2	2.2	K	0	1.0	2.0
	Mg	0	0.4	0.8					Mg	0	0.2	–
Yield (converted to t fruit bunches ha ⁻¹)		0	1	2		0	1	2		0	1	2
	N	25	29	30	N	31	31	29	N	15	20	21
	P	27	29	28	P	30	30	–	P	–	19	18
	K	26	29	29	K	28	31	32	K	10	23	22
	Mg	27	28	29					Mg	19	18	–
Remarks				Significant K effect 4 and 5 YAP, but not 6 and 7 YAP			Significant yield increases by application of P and Mg at the highest levels of N and K					

Table 7

Yield-reducing factors in oil palm systems: actual yield (Ya).

Yield-reducing factors	Range in oil-palm growing areas	Yield effects measured in case studies	Selected references
Ground cover management	<ul style="list-style-type: none"> • Good practice: closed legume cover plant canopy in the first six YAP; afterwards a closed canopy of soft weeds without noxious or woody weeds • Common practices: clear-weeding (companies, smallholders) or no weeding (smallholders) 	<ul style="list-style-type: none"> • Uncontrolled weed growth: 50–60% yield reduction in young plantations at first harvest; no data for mature plantations • Clear weeding: up to 50% yield reduction in plantations 4–6 YAP • Planting of legume cover crops: yield increase of 10–20% in first productive years compared with non-leguminous weeds 	(Ojuederie et al., 1983) (Samedani et al., 2014a) (Wood, 1977)
Pests: Leaf-eating insects	<ul style="list-style-type: none"> • Common in all regions • In case of severe infestation complete defoliation of palm clusters can occur 	<ul style="list-style-type: none"> • Yield loss in case of complete defoliation: ~50%, 25% and 15% in year 1, 2 and 3 after defoliation, respectively 	(Wood, 1977) (Wood et al., 1973)
Pests: <i>Oryctes</i>	<ul style="list-style-type: none"> • Common in immature plantations in all regions 	<ul style="list-style-type: none"> • Yield reductions of 50% in first year and 20% in second year of production following severe attacks in young plantations • Rarely: death of severely damaged immature palms • In mature stands: yield reductions when LAI reduced below 5 (rare) 	(Wood, 1977) (Wood et al., 1973) (Cahyasiwi et al., 2010) (Sushil and Mukhtar, 2008)
Pests: Rats	<ul style="list-style-type: none"> • Common in all regions • In case of severe infestation populations reach >300 individuals per hectare 	<ul style="list-style-type: none"> • Estimated 5% loss of oil (130–240 kg oil ha⁻¹ year⁻¹) in mature plantations with rat populations at ‘saturation’ level • Death of immature palms leading to incomplete stand or extended immature period 	(Wood and Liau, 1984) (Wood and Chung, 2003) (Puan et al., 2011)
Diseases: <i>Ganoderma</i>	<ul style="list-style-type: none"> • Common in all regions, especially Southeast Asia • Potentially severe in Malaysia and Sumatra with up to 80% mortality at >15 YAP 	<ul style="list-style-type: none"> • Palm losses of up to 30–40% at 12 YAP and >50% at 25 YAP in affected areas • When >10% of stand lost: yield reduction of 0.16 t fruit bunches ha⁻¹ per additional palm death • Around 35% yield loss at 50% palm mortality • One-year fallowing before replanting: 4% reduction in cumulative yield due to one-year increase of unproductive period; infection rate down from 30% to 3–6% at 9 YAP 	(Flood et al., 2000) (Idris et al., 2004) (Ariffin et al., 2000; Cooper et al., 2011) (Cooper et al., 2011) (Flood et al., 2002) (Virdiana et al., 2010)
Diseases: bud rot	<ul style="list-style-type: none"> • Common in South America with up to 100% mortality in severe outbreaks 	<ul style="list-style-type: none"> • Disease progress: linear phase (several years, ~1% of palms lost/year, limited or no yield effects), exponential phase (destruction of up to 100% of palms, complete loss of yield) • When >10% of stand lost: yield reduction of 0.16 t fruit bunches ha⁻¹ per additional palm death 	(Uexküll et al., 2003) (De Franqueville, 2003) (Cooper et al., 2011) (Lopez, 2010)

7). Rhinoceros beetle (*Oryctes rhinoceros*) is a pest in both immature and mature oil palm plantations (Bedford, 1980). Whereas the effects are usually limited in mature plantations, rhinoceros beetle is a problem in young plantings as it is capable of reducing growth by damaging the growing point, and on rare occasions killing the immature palms (Table 7). The effects are a delay in time to maturity or an incomplete stand of productive palms and hence a reduction in yield during the beginning of the productive phase (Wood et al., 1973). Rats (*Rattus* spp.) are common in all oil palm producing regions in the world, with unchecked populations reaching over 300 individuals per hectare in mature plantations. Rats eat the developing fruitlets and cause direct losses in oil yield (Wood and Liau, 1984; Wood and Chung, 2003; Table 7). In the immature phase, rats can eat through the bole of seedlings and destroy the growing point, causing palm death.

4.5.3. Diseases

Two diseases cause significant yield losses in oil palm plantations: basal stem rot in Southeast Asia and Africa, and bud rot in Latin America. Basal stem rot, caused by the pathogenic fungi *Ganoderma boninense*, can devastate old plantations (Flood et al., 2000; Flood and Hasan, 2004; Idris et al., 2004; for a review on previous research see Paterson, 2007). The onset of infection happens earlier at each replanting if no sanitation measures are taken, and can occur as soon as 1–2 years after planting when oil palm is planted after oil palm or coconut (Ariffin et al., 2000). The implementation of a one-year fallow can significantly reduce infection rates, but increases the immature/fallow to mature ratio from 0.12 to

0.15 (Virdiana et al., 2010; Table 7). Sanitation, the removal of diseased material, has been recommended as a management strategy in mature plantations (Chung, 2011; Hushiarian et al., 2013) but there is no experimental evidence that shows conclusively that it reduces disease incidence (Idris et al., 2004; Hoong, 2007). Breeding for resistant planting material is an important strategy to prevent future yield losses (Durand-Gasselin et al., 2005; Ho and Tan, 2015). Bud rot is a fatal disease in the Americas, with incidental outbreaks having caused the destruction of complete stands across thousands of hectares since the 1960s (De Franqueville, 2003). The causal agent of bud rot in Colombia may be the oomycete *Phytophthora palmivora* (Martínez et al., 2010), but other pathogens such as the fungus *Fusarium* and the bacterium *Erwinia* spp. have also been associated with the occurrence of bud rot symptoms, as have the pest *Rhynchophorus palmarum* and a variety of abiotic factors (Benítez and García, 2014). Remediation and prevention measures are available but expensive and labour-consuming (Fontanilla et al., 2014).

4.6. Interactions between stress factors

While each production factor has certain quantifiable effects on yield, in reality multiple factors interact. For example, good ground cover management increases water retention in the soil, prevents the establishment of more competitive weeds, increases the population of natural enemies to pests, and reduces *Oryctes rhinoceros* breeding, each of which may affect yield. In order to close yield gaps it is necessary to take these interactions into consideration

and to address multiple stresses simultaneously. Examples of such efforts are the Maximum Exploitation of Genetic Yield Potentials (MEGYP) approach (Henson and Chang, 1990) and the Best Management Practices (BMP) approach (Griffiths and Fairhurst, 2003; Witt et al., 2005). The accurate recording of yields, input use and climatic and environmental factors is an essential component of all yield improvement strategies in oil palm (Griffiths et al., 2002).

5. Current causes of yield gaps and future outlook

In this section, the main factors contributing to the worldwide yield gaps are discussed with special attention to smallholders, who face a number of unique constraints. Smallholders, with a plantation area of <50 ha, produce about 40% of the total CPO volume worldwide (RSPO, 2015).

Potential palm oil yields in the main palm oil producing countries are shown in Table 8. Specific estimates have been made for Indonesia, Malaysia and Ghana using the PALMSIM model (Hoffmann et al., 2014; Rhebergen et al., 2014). For the other countries no potential yield profiles are available but data from best-yielding trials or plantations can provide a benchmark. Large variations in potential yields may exist within countries, depending mostly on radiation (cloudiness) and elevation (temperature).

The actual yields achieved in the 16 largest oil-palm producing countries in the world in 2013 are shown in Table 9. Worldwide average yields have been rising steadily and are currently around 15 t fruit bunches or 3.0 t oil ha⁻¹, but yield increases are slow compared with other crops (Fry, 2009; Murphy, 2009). When comparing the numbers in Table 9 with the potential yields as estimated in Table 8, it is clear that the yield gaps in most countries are large. In Southeast Asia the average oil yield from the top producing plantation companies is 5.5 t oil (23 t fruit bunches) ha⁻¹ yr⁻¹ (Fairhurst and Griffiths, 2014). The estimated average production from smallholder plantations in Indonesia is only 13 t fruit bunches ha⁻¹ yr⁻¹ (Molenaar et al., 2013; FAO, 2013), but positive exceptions exist, such as the Ophir scheme smallholders in West Sumatra who consistently achieved yields of 22–29 t fruit bunches ha⁻¹ yr⁻¹ (Jelsma et al., 2009). In Africa average actual yields are less than 8 t fruit bunches ha⁻¹ yr⁻¹ (Table 9).

The water-limited yields in currently planted areas are around 3.5 t oil ha⁻¹ yr⁻¹ in Africa (e.g. Rhebergen et al., 2014), 4.5 t ha⁻¹ yr⁻¹ in the Americas (e.g. Melling and Henson, 2011) and Thailand (e.g. Palat et al., 2008), and 5.5 t ha⁻¹ yr⁻¹ in Indonesia and Malaysia (e.g. Corley, 2009). Current yield gaps range from 2 to 4 t oil ha⁻¹ yr⁻¹ in smallholder systems and from 1 to 3 t oil ha⁻¹ yr⁻¹ in large plantations. Closing these yield gaps to only 80% of Yw could realistically increase global production by 15–20 Mt oil yr⁻¹—the equivalent to clearing 4–6 Mha of new land.

Traditional village plantations in Africa are usually planted with 100% *dura*, which partly explains the poor oil extraction rates found in most African countries (Table 9). In Indonesia, *dura* presence in smallholder plantations is likely to be common, with an estimated 50% of independent smallholders in some areas having planted non-hybrid materials (Molenaar et al., 2013). Early replanting (i.e. replanting before the 25 year cycle has been completed) with new, high-yielding varieties is an important strategy to improve productivity. In Malaysia, slow replanting has led to aging of oil palm plantations and resulting declines in yield (Wahid and Simeh, 2010; USDA-FAS, 2012). The production in 25–30 year old palms is estimated to be 60–90% of peak productivity (Goh et al., 1994). For smallholder farmers, delayed replanting due to lack of financial means is a serious threat to current and future productivity (Government of Malaysia, 2011; Molenaar et al., 2013). On the other hand, the ratio of immature to mature plantations is high worldwide due to area expansion. In Indonesia 22% of the planted

area in 2014 was immature (USDA-FAS, 2015), while in a static area that is replanted every 25 years, 12% of the area is immature.

Drought is a key constraining factor to yield in Africa, parts of Latin and Central America, and parts of Southeast Asia. To allow for expansion into drier areas or for further yield improvements, irrigation has been used successfully in Ecuador (Mite et al., 1999a), Thailand (Palat et al., 2008; Univanich, 2011) and India (Prasad et al., 2010), but is uncommon (and uneconomic) in most plantations. As a consequence of global warming, irrigation is likely to become increasingly relevant due to projected increases in frequency of droughts, especially in Africa and Latin America (Fischer et al., 2007; Paeth et al., 2009; Marengo et al., 2009). The costs and benefits of different irrigation regimes under a range of environmental conditions need urgent further investigation. Waterlogging and flooding are largely un-quantified yield limiting factors which are likely to suppress yields especially in Malaysia and Indonesia (Lee and Ong, 2006; Malay Mail Online, 2015). Whether these are serious issues in other oil palm growing regions is unclear, and research efforts on the effects of flooding and waterlogging on yield in the different phases of the plantation life cycle are needed. Due to scarcity of suitable land, 2.1 Mha of peatlands in Southeast Asia were cleared for oil palm planting by 2010 (Miettinen et al., 2012; Koh et al., 2011). Proper water management in peat soils requires the establishment of drainage canals, dams and flood gates over a larger area (Othman et al., 2011; Lim et al., 2012). Smallholders cannot implement such practices at field scale and are therefore likely to obtain poor yields, especially in deep peat areas. Due to subsidence, drainage, and fire, cultivated peat soils progressively degrade, which threatens the future livelihoods of farmers established on peat areas (Könönen et al., 2015) and causes serious environmental problems including estimated greenhouse gas emissions of 60 Mg CO₂ ha⁻¹ yr⁻¹ in the first 25 years after forest clearing (Murdiyarso et al., 2010). Carbon stocks in mineral soils planted with oil palm remain stable, provided that pruned fronds are recycled within the plantation (Khasanah et al., 2015) and trunks are left in the field at replanting (Khalid et al., 2000).

Total N, P and K fertiliser use in oil palm in 2010 as estimated by the International Fertilizer Industry Association (Heffer, 2013) for Indonesia, Malaysia and Thailand are presented in Table 10. Applications are far less than optimal, ranging from 40 to 90% of recommended rates (Rankine and Fairhurst, 1999b). Almost double the amount of P and K are applied on plantations in Malaysia than in Indonesia, and three times more K than in Thailand, yet the average K application is still insufficient to replace the nutrients removed with a yield of 30 t fruit bunches ha⁻¹ (Corley and Tinker, 2016: 365). Data for other countries are not available.

In smallholder plantations in Indonesia (Molenaar et al., 2013; Lee et al., 2013; Woittiez et al., 2015) and Africa (Raffleau et al., 2010; Kim et al., 2013; Nkongho et al., 2014) limited amounts of mineral fertilisers are applied, with potassium application rates being especially small (Raffleau et al., 2010; Woittiez et al., 2015). Site-specific recommendations are usually not available because tissue analysis and on-site fertiliser experiments can only be implemented when fields are managed and sampled collectively (Jelsma et al., 2009). Organic fertilisers from mill waste streams may not be accessible for smallholders due to competition or lack of infrastructure. Alternatively, smallholders sometimes integrate livestock within their oil palm systems and therefore have access to manure.

Pest problems in oil palm are relatively mild, apart from leaf miner in West Africa (Chung, 2015). In Malaysia, the estimated incidence of *Ganoderma* in 2009 was around 3.7% of the mature area, with a yearly increase in incidence rate of >10%, corresponding to an estimated 270,000 ha of affected palms in 2015 (Roslan and Idris, 2012). In Indonesia, *Ganoderma* is most prevalent in Sumatra, and losses of 40–50% of the palms at the time of replanting are reported to be common in North Sumatra (Cooper et al., 2011). In Latin Amer-

Table 8

Potential yields over the plantation lifetime in six selected countries from Southeast Asia, Africa, and the Americas.

Country	Potential yield (t ha ⁻¹ yr ⁻¹)		Remark	Source
	Fruit bunches ^a	Oil ^b		
Indonesia	32–40	8–10	Low-lying areas, modelled	(Hoffmann et al., 2014)
	16–32	4–8	Higher elevations, modelled	(Hoffmann et al., 2014)
Malaysia	38	9.5	Progeny trial	(Rajanaidu and Kushairi, 2006)
	24–32	6–8	Low-lying coastal areas, modelled	(Hoffmann et al., 2014)
	8–24	2–6	Inland, modelled	(Hoffmann et al., 2014)
Thailand	36	9	Progeny trial	(Univanich, 2011; Rao et al., 2008)
Ghana	30–36	7.5–9	Modelled	(Hoffmann et al., 2015)
Ecuador	28	7	At research station	(Mite et al., 1999b; Pulver and Guerrero, 2014)
Costa Rica	36	9	Progeny trial	(ASD de Costa Rica, 2014)
Guatemala	32	8	Progeny trial	(ASD de Costa Rica, 2014)

^a Peak yields in single years were converted to 25-year averages by assuming that yield over plantation lifetime = 0.8 × yield from peak year (adapted from Goh et al., 1994).^b Assumed oil extraction rate: 25%.**Table 9**

Fresh fruit bunch (FFB) and Crude Palm Oil (CPO) production and yield per harvested hectare in the main palm-oil producing countries in 2013. Sources: FAO (2013); USDA-FAS (2016). Numbers must be viewed with some caution, as good-quality data on harvested area and yield is difficult to obtain, especially for smallholder plantations.

Country	Area harvested ¹ (Mha)	Annual production (Mt)		Yield (t ha ⁻¹ yr ⁻¹)		OER ² (%)	Data source
		FFB	CPO	FFB	CPO ³		
Indonesia	7.1	120	26.9	17	3.8	22.4	FAO, unofficial figure
	8.1		30.5		3.8		USDA
Malaysia	4.6	95.7	19.2	21	4.2	20.0	FAO, unofficial figure
	4.5		20.2		4.5		USDA
Nigeria	3.0	8.0	1.0	2.7	0.32	12.0	FAO, estimate
	2.5		1.0		0.39		USDA
Thailand	0.63	12.8	2.0	20.5	3.1	15.1	FAO, official data
	0.66		2.0		3.0		USDA
Colombia	0.45	5	1.0	20	3.5	17.5	FAO, official data
	0.34		1.0		3.1		USDA
Ghana	0.36	2.1	0.12	5.8	0.30	5.2	FAO, estimate
	0.37		0.49		1.3		USDA
Guinea	0.31	0.8	0.05	2.7	0.20	7.4	FAO, estimate
	0.31		0.05		0.16		USDA
DRC (Congo)	0.28	1.8	0.30	6.6	1.1	16.7	FAO estimate
	0.18		0.22		1.2		USDA
Côte d'Ivoire	0.27	1.7	0.42	6.5	1.5	23.1	FAO, unofficial figure
	0.27		0.42		1.5		USDA
Ecuador	0.22	2.3	0.33	10.6	1.5	14.2	FAO, official data
	0.22		0.57		2.6		USDA
Papua New Guinea	0.15	2.1	0.50	14	3.3	23.6	FAO, unofficial figure
	0.15		0.50		3.4		USDA
Cameroon	0.14	2.5	0.23	18.2	1.7	9.3	FAO, unofficial figure
	0.13		0.29		2.2		USDA
Honduras	0.13	2	0.43	16	3.4	21.3	FAO, unofficial figure
	0.13		0.46		3.7		USDA
Brazil	0.11	1.3	0.34	11.5	3.1	27.0	FAO, official data
	0.12		0.34		2.8		USDA
Guatemala	0.07	1.5	0.40	22.8	6.2	27.2	FAO, unofficial figure
	0.10		0.43		4.3		USDA
Costa Rica	0.07	1.3	0.30	17.5	4.0	22.9	FAO, estimate
	0.06		0.21		3.5		USDA
World	18.1	266.5	54.4	14.8	3.0	20.3	FAO, aggregate
	18.6		59.4		3.2		USDA

¹ Area harvested excludes immature area.² Oil extraction rate (OER) was calculated from the yield data ($\text{ton CPO/ton FFB} \times 100$).³ CPO yield was calculated by dividing production over harvested area ($\text{Mton CPO/mHa harvested area}$).**Table 10**

Fertilizer use (N, P and K) on oil palm in Indonesia, Malaysia, and Thailand in 2010/11 (Heffer, 2013). Data for other oil palm producing countries were not available.

Nutrient	Application, total (1000 t year ⁻¹)			Application per hectare (kg ha ⁻¹ year ⁻¹) ^a			Nutrient removal ^b (kg ha ⁻¹ year ⁻¹)
	Indonesia	Malaysia	Thailand	Indonesia	Malaysia	Thailand	
Nitrogen (N)	548	374	41	95	91	72	146
Phosphate (P)	61	78	9	11	19	16	19
Potassium (K)	643	821	39	111	199	69	248

^a The application per hectare was calculated by dividing the total application over the oil palm area in 2010 (FAO, 2013).^b The final right column shows the nutrient removal, assuming a yield of 30 t fruit bunches ha⁻¹ (Corley and Tinker, 2003: 358).

ica bud rot disease remains an important cause of yield loss (Benítez Sastoque, 2011). The disease currently affects an estimated 15% of the oil palm area in Colombia (Fontanilla et al., 2014) and similar areas in other Latin American countries (Tapia and Velasco, 2015; Gálvez Intriago, 2014).

Lack of labour, especially for harvesting, is a key issue in Malaysia, and to a lesser extent in Indonesia, leading to longer harvesting rounds, which result in reduced oil extraction rates, loss of loose fruits and unharvested bunches (Murphy, 2014). Plantations in Malaysia report manpower shortages of 20–30% and consequent yield losses of 15% (Murphy, 2014). In South and Latin America, labour is more expensive leading to a competitive disadvantage. Mechanisation options for spreading fertilisers, spraying pesticides, and harvesting are being developed but have not yet been sufficiently successful to resolve labour shortages (Carter et al., 2007; Yahya et al., 2013; Khalid and Shuib, 2014).

6. Conclusions

Yield gaps in oil palm plantations are large, and there is considerable scope for improving yields and environmental performance. Yield responses to waterlogging, drainage, micronutrient fertilisers, and biotic stresses in mature plantations are poorly understood. A number of basic processes underlying bunch production need further investigation, especially sex determination and bunch failure. Also, the signalling pathway leading to drought stress responses needs to be unravelled, so that breeding and irrigation strategies can be further developed. Considering that smallholders produce 40% of the world palm oil supply, but often lag behind in terms of yield, particular effort should be put into understanding all the factors that limit yield in smallholder plantations, and to identify effective ways in which large numbers of smallholders can be supported to improve the sustainability and yield in their plantations. Increasing global yields to 80% of Yw could substitute the clearing of 4–6 Mha of new land. Improving yields in existing plantations in ways that are environmentally sound, while targeting expansion of oil palm cultivation into degraded lands only, appears to be the most responsible way forward for producing sufficient palm oil to meet future demands while preventing further loss of tropical rainforests.

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