On Yield Gaps and Better Management Practices in Indonesian Smallholder Oil Palm Plantations

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Abstract

Palm oil is currently the most important vegetable oil in the world, and Indonesia is the world's largest producer. Oil palm plantations are an important source of revenue, but rapid expansion has led to deforestation and loss of biodiversity. Forty per cent of the plantation area in Indonesia is owned by smallholders, whose yields are relatively poor. The objective of this thesis was to investigate the yield gaps and agronomic practices in Indonesian smallholder oil palm plantations, with a focus on fertiliser application, and to propose and test better management practices that can contribute to sustainable intensification. The research consisted of an in-depth literature review, several surveys, the collection of samples in smallholder plantations, and a three-year experiment with 14 smallholder farmers.

In yield gap analysis, three yield levels are recognised: potential, limited, and actual yield. The potential yield in a plantation is determined by radiation, CO_2 concentration, temperature, planting material, culling, planting density, pruning, pollination, and crop recovery (harvesting). The yield-limiting factors are rainfall, irrigation, soil, waterlogging, topography, slope, and nutrition. The yield-reducing factors are weeds, pests, and diseases. In smallholder plantations, the yield gap is mostly explained by poor planting material, poor drainage, sub-optimal planting density, poor culling (leading to large variability and the presence of unproductive palms), infrequent harvesting, soil erosion, poor nutrient management, and rat damage, but the effects of these factors on yield vary depending on local conditions.

The survey data showed clear evidence of insufficient and unbalanced fertiliser applications, and visual nutrient deficiency symptoms were observed in many plantations. Leaf sample results showed that 57, 61 and 80% of the plantations in Jambi and Sintang were deficient in N, P and K, respectively. In Riau, 95, 67 and 75% of the plantations were deficient in N, P and K. The implementation of better management practices (including harvesting, weeding, pruning, and nutrient application) in 14 smallholder fields for three years resulted in palms with significantly larger leaves and heavier bunches compared with palms under farmer management, but improvements in yield were small and not statistically significant, and financial returns on better practices were negative. Possible causes of the small yield response were good starting yields, increased inter-palm competition for sunlight, and environmental constraints (particularly the 2015 El Niño event and waterlogging in Jambi).

On the basis of our findings on yield gaps, nutrient limitations and better practices, we discuss how Indonesian smallholders may be supported to achieve sustainable intensification at a larger scale, and we reflect on the broader implications of our findings for a future supply of truly sustainable palm oil.

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List of abbreviations

B	Boron
BBC	Black bunch count
BD	Bonai Darussalam
BMP	Better Management Practice
CPO	Crude palm oil
CRH	Central Rokan Hulu
EFB	Empty fruit bunches
FFB	Fresh fruit bunches
GAP	Good Agricultural Practice
ISPO	Indonesian Sustainable Palm Oil
IQR	Inter-quartile range
K	Potassium
LAI	Leaf area index
LPI	Large peat investors
LRF	Large resident farmers
MAP	Months after planting
Mg	Magnesium
MLF	Medium local farmers
MMF	Medium migrant farmers
MSPO	Malaysia Sustainable Palm Oil
N	Nitrogen
NUE	Nutrient use efficiency
OER	Oil extraction rate
P	Phosphorus
PAR	Photosynthetically active radiation
PCA	Principal component analysis
PCS	Petiole cross-section
PKO	Palm kernel oil
POME	Palm oil mill effluent
RP	Rock phosphate
PPFD	Photosynthetic photon flux density
RSPO	Roundtable on Sustainable Palm Oil
SMF	Small migrant farmers
SMPF	Small and medium peat farmers
SP-36	Double super phosphate
TJB	Tanjung Jabung Barat

TLC	Total leaf cations
TSP	Triple super phosphate
VPD	Vapour pressure deficit
Ya	Actual yield
YAP	Years after planting
Yn	Nutrient-limited yield
Yp	Potential yield
Yw	Water-limited yield
ZA	Sulphate of ammonium

Nana korobi ya oki
Fall down seven times, get up eight times

CHAPTER 1

General introduction

1.1 A brief history

In 1896, the 3000-year-old Egyptian tomb of Osiris was discovered in Abydos (Amélineau, 1898). In the enormous tomb, many valuable and interesting artefacts were found. Among the treasures was a 'mass of several kilograms, which still had the shape of the vase that had contained it, and which was covered by a sort of black crust' (Friedel, 1897). After some detailed chemical analyses, Mr. Friedel concluded that the main ingredient of the mysterious vase-shaped mass was palmitic acid, which is found in many plant and animal species but occurs at particularly high concentrations in palm oil.

The 3000-year-old mass discovered by Amélineau is the first historical evidence of the use of palm oil, but the Egyptians were not the ones who discovered it. The oil palm (*Elaeis guineensis* Jacq.) is native to the humid tropical regions of Western Africa and thrives in open spaces in the forest, on forest edges, and along river banks where it is well supplied with water and sunlight (Zeven, 1964). It is likely that the prehistoric hunters in the African rainforests were able to identify edible fruits based on the diet of monkeys and other animals. As orang-utans in Asia enjoy oil palm fruits (Ancrenaz et al., 2014), we can imagine that monkeys in Africa did likewise, and that prehistoric hunters collected palm oil fruits and carried them as food on hunting trips (Irvine, 1948). During the very gradual domestication of the oil palm, migrating tribes probably carried the seeds to new areas and regions, and in this way the oil palm spread through Western Africa (Zeven, 1964).

For hundreds (or even thousands) of years, local communities in Africa harvested oil palm bunches from home gardens or natural groves and pressed out manually the tasty liquid reddish oil for cooking and for skin and hair care (Aghalino, 2000). When the Europeans colonised Africa, they recognised the usefulness of palm oil, and its first mention is from Guinea around the 1450s, in a record written by the Portuguese (Zeven (1964) and references therein). In the year 1848, two oil palm seeds from the botanical gardens of Amsterdam and two seeds from Mauritius were planted in the botanical gardens of Bogor, Indonesia. The Dutch brought the oil palm to Indonesia mostly because of its ornamental value, but in the second half of the 19th century the British trade in palm oil (mostly produced in Nigeria) increased strongly, both to replace the slave trade, and to feed the increased demand for lubricants to grease the developing industrial revolution (Dike, 1956). The Dutch did not want to be left behind, and the first commercial palm oil plantation in Indonesia was established in 1911 in North Sumatra, close to Medan

(Figure 1.1). The first plantation in Malaysia followed in 1917. In 1935 the 'Dutch Indies' became the world's leading palm oil exporter, for the first time surpassing Nigeria with 35% of global export, derived from 74,000 hectares of oil palm (Rowaan, 1936). But it was not until after World War II that the expansion of oil palm in Southeast Asia really took off (Figure 1.2). In 2008 Indonesia achieved its long-desired goal of surpassing Malaysia again as the world's largest producer (McCarthy, 2010; Varkkey et al., 2018).

Figure 1.1 A mature oil palm plantation near Medan, Sumatra.

In the 21st century palm oil has become ubiquitous. It is an ingredient of biscuits, soap, ice cream, instant noodles, chocolate, shampoo, and a wide range of other supermarket products. In Asia, palm oil is also very important as a cooking oil and as a biodiesel. In 2017/18, around 70 million metric tonnes of palm oil were produced globally, compared with 58 and 29 million metric tonnes of soy and rapeseed oil, respectively (USDA, 2018; Figure 1.3). In Chapter 2 of this thesis, the current production of palm oil in different parts of the world is discussed in more detail.

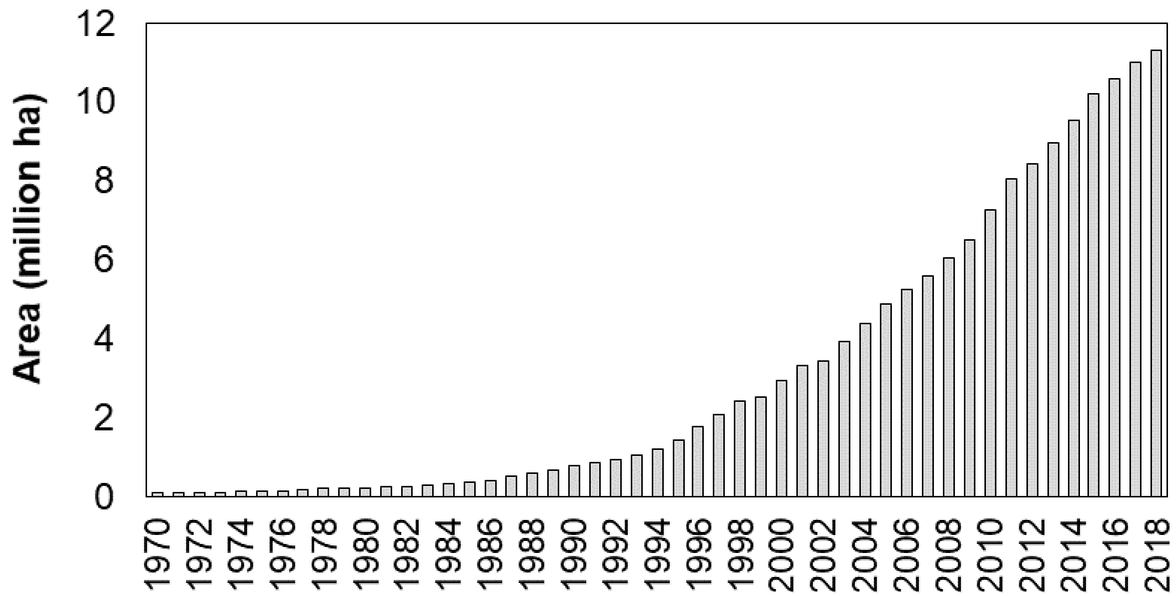


Figure 1.2 Oil palm area (1000 ha) in Indonesia between 1970 and 2018. Adapted from USDA-FAS (2018).

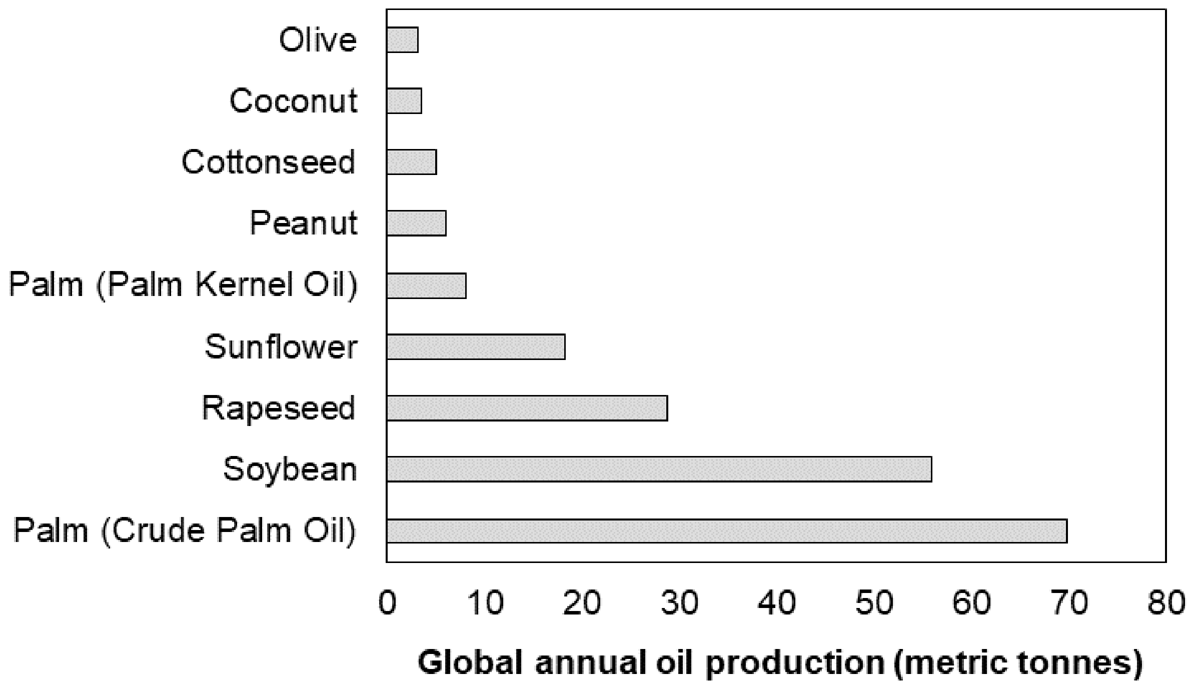


Figure 1.3 Global annual vegetable oil production in 2017/18, adapted from USDA (2018).

1.2 Palm oil production and sustainability

Palm oil comes from the fruits of the oil palm. The fruits grow in spiny bunches (Figure 1.4, left) which can easily weigh 20 kg or more. The fruitlets have a thick orange flesh (the mesocarp) around a seed with a woody shell (the endocarp) and a white endosperm in the centre (Figure 1.4, right). The mesocarp contains up to 60% oil, which is known as crude palm oil (CPO), and the endocarp also contains oil, known as palm kernel oil (PKO). The CPO can be pressed from the fruits by hand, as it was traditionally done in Africa, but currently most oil palm extraction takes place in factories referred to as a 'palm oil mills'. After pressing and clarification, the oil that remains is clear and reddish in colour. The PKO is pressed out in different factories and in much smaller volumes. Further processing of CPO and PKO is done in refineries, to create a range of palm oil products that can be used for many different purposes, particularly food, cooking oil, soaps and biofuels.

Figure 1.4 A ripening fresh fruit bunch on the left, and half a *tenera* fruit on the right, showing the orange-yellow mesocarp with the crude palm oil and the white kernel with the palm kernel oil.

The increased demand for palm oil has mostly been met through expansion (Varkkey et al., 2018), which has led to tropical deforestation and loss of biodiversity (Koh and Wilcove, 2008; Carlson et al., 2012; Stibig et al., 2014; Figure 1.5) and to large greenhouse gas emissions from drained peat soils (Murdiyarso et al., 2010). In 2015, oil palm expansion was the third largest driver of deforestation in Indonesia, after pulp-and-paper and logging (Abood et al., 2015). The oil palm produces 35% of the global vegetable oil volume on 10% of the total land area allocated to vegetable oils, because it is an extremely efficient oil producer (Meijaard et al. (2018) and Chapter 2 of this thesis). In this situation, replacing palm oil with other oil types would shift deforestation elsewhere (particularly to the Americas; Meijaard et al., 2018) and destroy the livelihoods of millions of farmers in the process (Byerlee et al., 2017: 184). As much as some may dislike it, palm oil appears to be the best option we have to meet the world's demand for vegetable oils. Western consumers have been made aware of the tropical deforestation linked with the expansion of oil palm plantations in Asia by some very influential public campaigns in the 1990s and after (Pye, 2012). In response to consumer pressure, the Roundtable on Sustainable Palm Oil (RSPO) was established in 2004, with the ambition to 'transform markets to make sustainable palm oil the norm' (RSPO, 2018a). Currently, about 20% of the global palm oil volume is RSPO certified, meaning that it is produced according to the RSPO sustainability guidelines (RSPO, 2013). Triggered by the influence of the RSPO, Indonesia and Malaysia created their own sustainability guidelines: the voluntary Malaysian Sustainable Palm Oil standard (MPOCC, 2018), and the mandatory Indonesian Sustainable Palm Oil certification scheme (Hidayat et al., 2018). Like the RSPO, these standards focus on legality, good agricultural practices, and some form of environmental sustainability. But despite the presence of these different standards, the oil palm sector is still causing deforestation and is associated with other issues such as contamination of waterways (Abdullah et al., 1999), land grabbing (McCarthy et al., 2012), exploitation of labourers and child labour (Amnesty International, 2016). There is an urgent need to improve further the sustainability of the sector, so that it can provide income for producing countries and farmers without causing social conflict or irreversible damage to important ecosystems.

Figure 1.5 Oil palm plantations and forests in West Kalimantan.

1.3 Smallholder oil palm plantations in Indonesia

In Indonesia, the rapid expansion of oil palm started in the end of the 1970s and happened alongside the efforts of the government to re-settle people from the over-crowded island of Java on the Indonesian 'outer islands' (particularly Sumatra) to speed up the development of these islands (Budidarsono et al., 2013). The trans-migrants were provided with two hectares of land and with financial support and extension services to plant the land with oil palm. These so-called nucleus-estate schemes coupled to the transmigration schemes facilitated the production of palm oil by smallholders while at the same time providing a labour force to the companies and boosting rural development (Budidarsono et al., 2013). In the 1990s, the Indonesian government made a transition towards policies that were more focused on attracting private investments and creating an open market. From then on, companies engaged directly with the local population to gain access to land. The companies planted oil palm on the land of local owners in exchange for use of another part of their land to create a company-managed nucleus estate (McCarthy and Cramb, 2009).

The historical and current collaborations between scheme smallholders and companies have not been trouble-free. Land conflicts were (and are) particularly common, usually due to the perceived unfairness in company-smallholder partnership agreements (McCarthy and Cramb, 2009). Still, local land owners have mostly been willing to participate in the oil palm boom, because of the financial benefits of oil palm cultivation (Zen et al., 2005; Feintrenie et al., 2010a; Feintrenie et al., 2010b). Since the 1980s, a rise in palm oil processing capacity in Indonesia led to an increasing number of independent smallholders, who planted oil palm without the support or interference of a company (Papenfus, 2002; Vermeulen and Goad, 2006; Bissonnette and De Koninck, 2015). Currently 41% of the oil palm area in Indonesia is owned by smallholders (DJP, 2015) and a large majority of these smallholders can be classified as 'independent' (Jelsma et al., 2017a; Figure 1.6).

Although the distinction between 'scheme' and 'independent' smallholders sounds logical, the reality is much more nuanced. For instance, many scheme smallholders own independent fields as well, so they belong to both groups (Molenaar et al., 2013). Even without the 'independent' or 'scheme' prefix, the definition of an 'oil palm smallholder' is not straightforward. For the Roundtable on Sustainable Palm Oil (RSPO), for example, a smallholder is a family farmer who owns a maximum of 50 hectares (RSPO, 2018c). For the Indonesian government a 'real' smallholder owns no more than 25 hectares, but the law also recognises a category of smallholder businesses that are 25 to 250 hectares in size (Jelsma et al., 2017a). Considering that there are millions of oil palm smallholders in Indonesia, it is easy to recognise that there is an enormous diversity among them (Jelsma et al. (2017a), and Chapters 4 and 5 of this thesis), which is one of the reasons why the sector is poorly understood (Molenaar et al., 2013) and difficult to change (Glasbergen, 2018).

Partly because smallholders are so numerous and so diverse, sustainability standards are struggling to reach and certify smallholders. The RSPO has certified 73,000 smallholder farmers globally (300,000 hectares) up to today, of whom around 4,250 farmers (21,000 hectares) are independent (RSPO, 2018b). Reaching more smallholders is an important aim, because smallholders have poor yields and a large potential for intensification compared with companies (Molenaar et al., 2013), have access to land (Colchester et al., 2006), provide a large share of the labour (McCarthy and Cramb, 2009) and are able to harvest the direct benefits of oil palm cultivation (Budidarsono et al., 2012; Kubitza et al., 2018a) instead of waiting for a 'trickle-down' that may never happen (Dabla-Norris et al., 2015). For these reasons, smallholders should be included in all efforts to make the oil palm sector more sustainable.

Figure 1.6 An immature independent oil palm plantation with a vegetable intercrop in Sintang, West-Kalimantan.

1.4 Better (or Best) Management Practices in oil palm plantations

One of the key aspects of sustainability in agriculture is the process of sustainable intensification, where *yields are increased without adverse environmental impact and without the cultivation of more land* (The Royal Society, 2009). Intensification allows for more production on less land, so that the demand for an agricultural product (like palm oil) can be met with limited expansion of the planted area (Corley, 2009a; Fairhurst and McLaughlin, 2009). This does not mean that sustainable intensification in oil palm plantations automatically leads to reduced deforestation, as should be the case according to the Borlaug hypothesis (Borlaug, 2007). On the contrary, better yields can lead to more profitability, which gives farmers and companies additional incentives to expand their plantations (Byerlee et al., 2014). Or, if production efficiency increases, the price of palm oil may go down and the demand and production may increase; this is known as the Jevons paradox (Alcott, 2005). For intensification to contribute to reduced deforestation, it needs to go hand in hand with the successful implementation of policies that regulate environmental protection and target expansion to degraded areas in order to have a direct, positive impact on nature conservation (Angelsen and Kaimowitz, 2001; Lambin et al., 2001; Byerlee et al., 2017; Varkkey et al., 2018).

Norman Borlaug said: ‘There are no miracles in agricultural production’. Improvements in yield and sustainability need to be built upon an in-depth and solid understanding of the agricultural system. To make this system more understandable, it can be divided into smaller components. For example, the productivity of a field or plantation can be divided into three elements: plant genotype (G), environment (E), and management (M). Yield (Y) is a function of these three factors: $Y = G \times E \times M$. To achieve the best possible productivity, the best available genotype should grow in the best possible environment with the best possible management.

As the genotype of palms in a plantation is selected once every 25 years and the environment is mostly beyond human control, the focus for sustainable intensification is on the management, unless the field is replanted, in which case the best genotype can also be selected. For oil palm, as well as for other crops, sets of good agricultural practices (GAP) or best management practices for plantations have been defined through experiments and practical experience (Rankine and Fairhurst, 1999c; Figure 1.7). From the perspective of a large oil palm plantation, it is sensible to aim for near-maximum yields, provided that the long-term price of CPO is sufficiently high so that the additional benefits outweigh the additional costs (Griffiths and Fairhurst, 2003; Fairhurst and Griffiths, 2014). Smallholders have less benefits of scale, less access to capital and knowledge, and have less control over issues such as water management and infrastructure (Molenaar et al., 2010). For this reason, ‘best management practices’ designed for large-scale plantation companies are not necessarily very applicable or very fitting in smallholder plantations, and I propose to use the term ‘better management practices’ (BMP) instead. Better management practices are practices that increase yield or the environmental performance or both, without aiming for (or claiming) the absolute best.

Figure 1.7 Better Management Practices implemented in a plantation in Ghana.

Although the average productivity of Indonesian oil palm smallholders may be slightly better than the rather low estimate of 13 t fruit bunches ha^{-1} provided by Molenaar et al. (2013), there is great scope for improvement. Several authors have reported sub-optimal management practices, such as the use of poor planting material (Papenfus, 2002), delayed replanting (Koczberski and Curry, 2003), infrequent harvesting (Lee et al., 2013; Euler et al., 2016a), and limited fertiliser use (Papenfus, 2002; Koczberski and Curry, 2003; Euler et al., 2016a). There are few reports on practices that have been tested in oil palm smallholder fields to achieve better yields. The projects described by Fairhurst (1996) and Jelsma et al. (2017b) showed that smallholder farmers can get very good yields, but only if they are part of a well-functioning organisation, in which case they operate almost as a company. A project reported by IPNI (2015) showed large yield increases in Ghana due to farm maintenance only, particularly when the starting yields were very poor. Hutabarat et al. (2018) proposed that yield increases are feasible when following GAP recommendations from the RSPO, but the exact practices that were implemented were not defined.

1.5 Research questions, hypotheses, and outline of the thesis

This thesis aims to dig deeper into the agronomic practices of Indonesian oil palm smallholders, with a focus on fertiliser application, and to propose and test Better Management Practices that can contribute to sustainable intensification. The thesis is structured around four main research questions (Figure 1.8):

1. What are the causes of yield gaps in oil palm plantations, and how large are their effects on yield?
2. To what extent are nutrient deficiencies prevalent in Indonesian smallholder oil palm plantations, and what are their effects on yield?
3. What yield-determining, yield-limiting, and yield-reducing factors can explain the large yield gap in Indonesian smallholder oil palm plantations?
4. What is the scope for sustainable intensification in mature Indonesian smallholder oil palm plantations?

The research questions are accompanied by four hypotheses:

1. The effects of yield-determining, yield-limiting, and yield-reducing factors, on yield of oil palm in plantations vary greatly depending on the local biophysical and socio-economic conditions.
2. Nutrient deficiencies are prevalent in smallholder plantations and have a strong yield-limiting effect.
3. Yield gaps are mostly explained by poor planting material, poor drainage, infrequent harvesting, and poor nutrient management, but the factors vary depending on the local biophysical and socio-economic conditions.
4. There is large scope for ustainable intensification in mature smallholder plantations through the implementation of better management practices, which will result in both economic and environmental benefits.

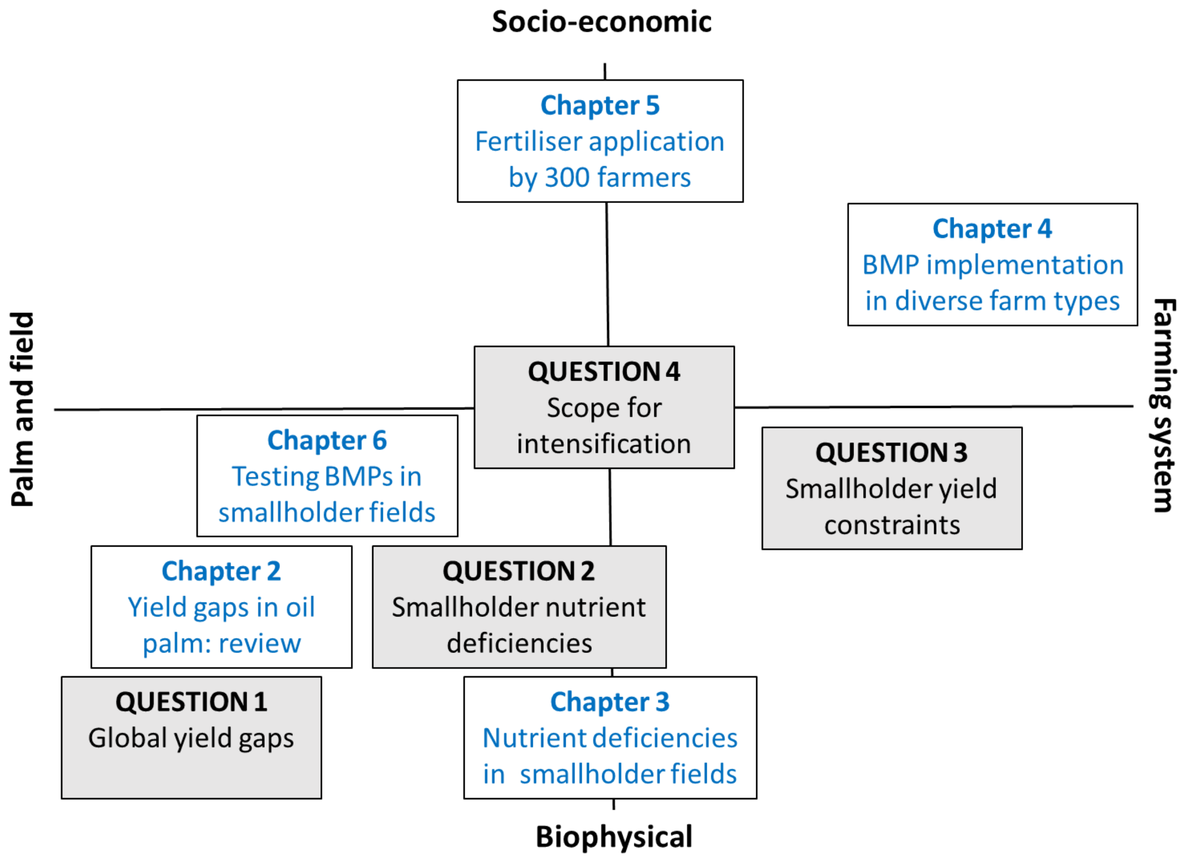


Figure 1.8 Position of the four research questions and the five research chapters on two axes: the scale axis (from palm/field to farming system) and the topic-related axis (from biophysical to socio-economic).

To answer my research questions and test the hypotheses, I have used descriptive and experimental research approaches, and I have focused on both the biophysical and the socio-economic aspects of oil palm production. The thesis has five research chapters, combining the different approaches and aspects mentioned above (Figure 1.8).

- Chapter 2 of the thesis reviews the existing knowledge on oil palm productivity from a plant physiological perspective and tries to provide a comprehensive, coherent, and quantitative analysis of factors contributing to yield gaps in oil palm. This chapter focuses on global oil palm production systems, which includes both large-scale plantations and smallholder farms.
- Chapter 3 zooms in on a small sub-set of smallholder plantations in Jambi and West-Kalimantan to identify nutrient deficiencies and their effect on palm growth and, potentially, on productivity. This chapter focuses on the use of soil and leaf samples for diagnosing nutrient deficiencies and shows that smallholder plantations are particularly deficient in potassium.

- Chapter 4 and Chapter 5 both aim to understand agronomic practices in smallholder oil palm plantations in Indonesia. Chapter 4 focuses on differences in management practices among different farmer types in Riau, and Chapter 5 looks at the nutrient management and other agronomic practices of smallholders in Jambi, Riau and West-Kalimantan, and aims to assess the effect of training on fertiliser application. Chapter 5 also explores where farmers get their knowledge on oil palm farming and how this knowledge spreads within communities.
- Chapter 6 describes an experiment in which several interventions were tested in smallholder fields. This chapter aims to estimate the production potential on existing smallholder oil palm plantations in Indonesia; to provide insight in the response of mature oil palm to fertiliser application; and to formulate recommendations on suitable practices to improve productivity, profitability and sustainability of smallholder oil palm plantations.

The thesis ends with a general discussion, which consists of a critical reflection on the lessons learned from the different chapters, and their implications for the research community and for the Indonesian oil palm smallholders. I hope my thesis provides the readers with new knowledge and insights, and that it will contribute to improving the livelihoods of the oil palm smallholders and increasing the sustainability of the palm oil sector.

CHAPTER 2

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

Woittiez, L. S., van Wijk, M. T., Slingerland, M., van Noordwijk, M., Giller, K. E. (2017). Yield gaps in oil palm: A quantitative review of contributing factors. European Journal of Agronomy 83: 57–77.

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 t ha^{-1} $year^{-1}$ have been achieved in small plantations, and maximum theoretical yields as calculated with simulation models are 18.5 t oil ha^{-1} $year^{-1}$, yet average productivity worldwide has stagnated around 3 t oil ha^{-1} $year^{-1}$. 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 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 $year^{-1}$, 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.

Contents

2.1 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 is 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 smallholder 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 (Lambin et al., 2001; Laurance, 2007). 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, 2009a). Since oil palm expansion may lead to the displacement of biodiverse rainforests (Gaveau et al., 2014a), 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 it 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 CO_2 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 fertiliser 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 2.2. In section 2.3 we provide a detailed assessment of bunch production, focusing on bunch number and bunch weight, the two main determinants of yield. In section 2.4 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 2.5 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 2.6 we identify the existing knowledge gaps and propose directions for future action and research.

2.2 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.

2.2.1 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 (Figure 2.1): 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 an 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 weight partly compensates for the reduction in bunch number (Hardon et al., 1969; Goh et al., 1994; Jacquemard and Baudouin, 1998: 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.

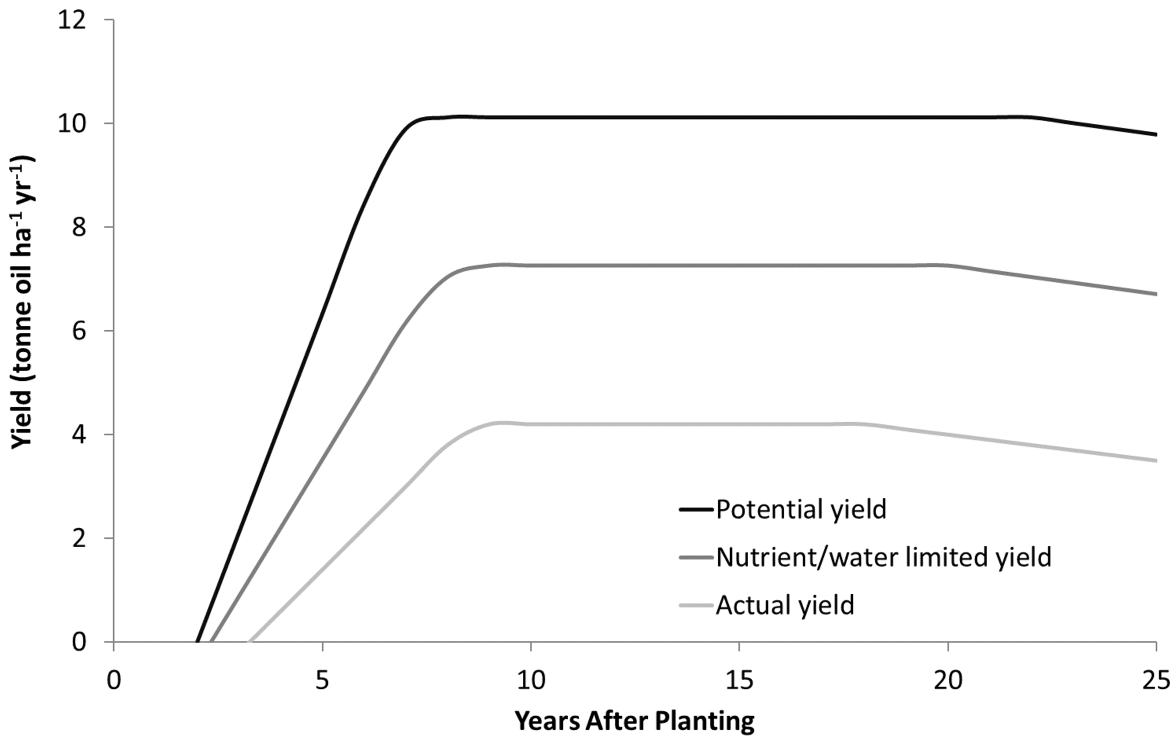


Figure 2.1 Development of oil palm yield over time in three hypothetical plantations (after Ng, 1983; Goh et al., 1994; Fairhurst and Griffiths, 2014). The light grey (bottom), dark grey (middle) and black grey (top) lines show the yield progress at different productivity levels: actual yield (average 3.5 t oil ha^{-1} year^{-1}), nutrient/water limited yield (average 6.1 t oil ha^{-1} year^{-1}) and potential yield (average 8.9 t oil ha^{-1} 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.

2.2.2 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 ha^{-1} year^{-1} in Nigeria (Rees and Tinker, 1963) to 32 t DM ha^{-1} year^{-1} in Malaysia (Corley et al., 1971a). Dry matter production can be described by the following equation:

$$DMP = PAR \times f \times RUE \qquad \textit{Equation 2.1}$$

Where DMP = dry matter production (kg m^{-2} $year^{-1}$), PAR = yearly photosynthetically active radiation (MJ m^{-2} $year^{-1}$; 50% of total incoming solar radiation; Monteith, 1972), f = fraction of radiation intercepted by the canopy, and RUE = radiation use efficiency (kg DM MJ^{-1} PAR; Monteith, 1977; Corley, 2006). Estimated values for RUE are 0.6–1.3 g MJ^{-1} 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 (m^2 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 (Corley and Mok, 1972; Breure, 1985), 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 (Breure, 1988; Gerritsma, 1988). Yields are reduced when LAI exceeds a value of 6 due to competition among palms (Breure, 2010).

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} $year^{-1}$ in 10-year-old palms in Malaysia, around 70 t ha^{-1} $year^{-1}$ was allocated to trunk, root, and rachis respiration, and 55 t ha^{-1} $year^{-1}$ was allocated to leaflet respiration, leaving 30–35 t ha^{-1} $year^{-1}$ 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 maybe 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).

2.3 Fruit development

A number of key stages can be distinguished during inflorescence and fruit bunch development (Figure 2.2; 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.

2.3.1 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 (Heel et al., 1987; Corley et al., 1995; Adam et al., 2011); 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).

Number of developing inflorescences

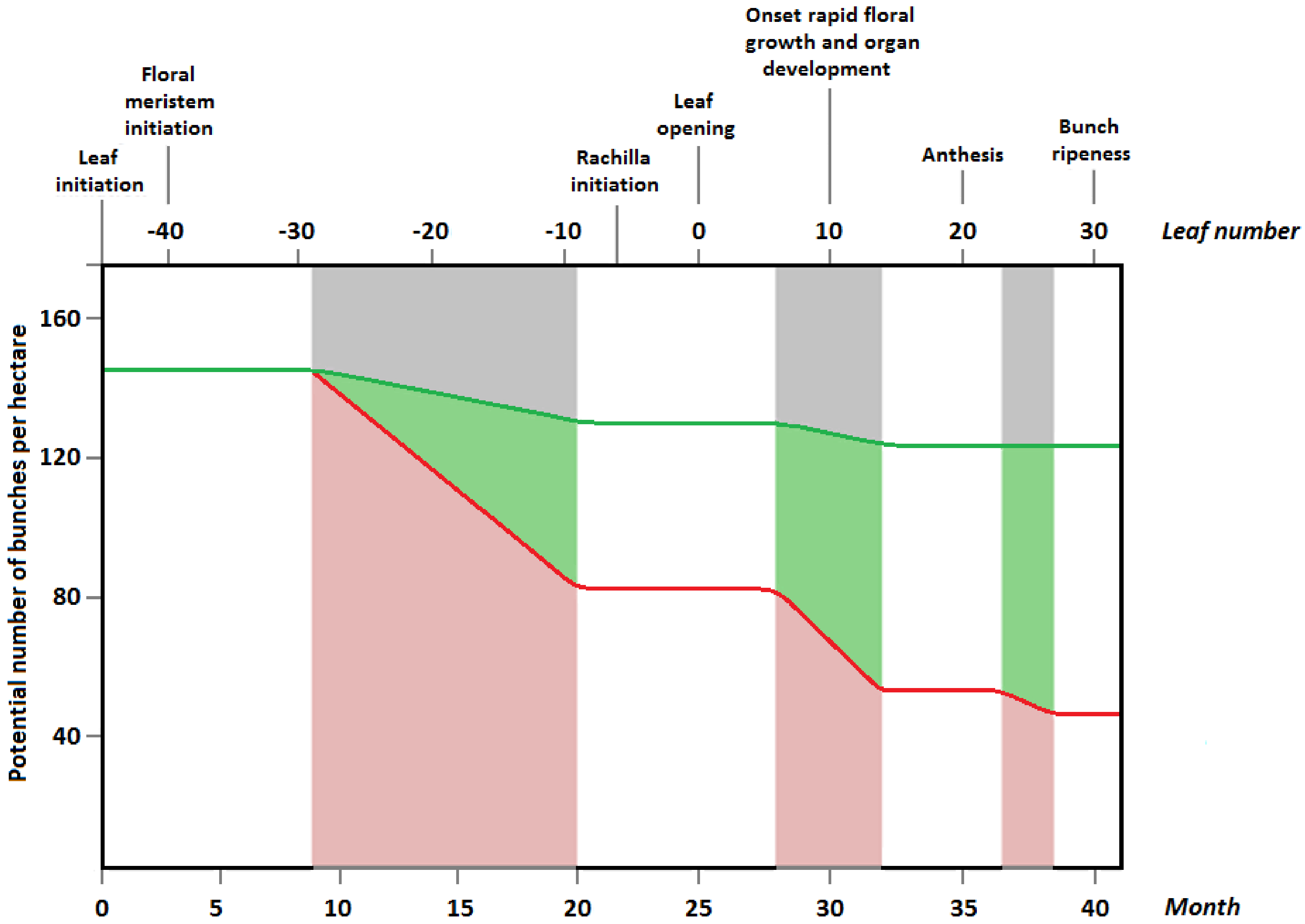
Leaf initiation rate determines directly the potential number of inflorescences, as a single inflorescence is initiated in the axil of each leaf. An average oil palm carries 45–50 unopened leaves in varying stages of development and 32–48 opened leaves (Breure, 1994). The youngest fully opened leaf is denoted as Leaf 1, with unopened leaves being numbered negatively (Figure 2.2). 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 different 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).

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 materials, ranging from 29 to 30 months before harvest (Broekmans, 1957) to 20 months before harvest (Breure and Menendez, 1990; Figure 2.2). 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., 20.

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 fraction 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).

Figure 2.2 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).



Leaf initiation
Floral meristem initiation
Rachilla initiation
Leaf opening
Onset rapid floral growth and organ development
Anthesis
Bunch ripeness
-40
-30
-20
-10
0
10
20
30
Leaf number
160
120
80
40
Potential number of bunches per hectare
0
5
10
15
20
25
30
35
40
Month

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 (Combres et al., 2013; Corley and Tinker, 2016: 125). 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.

2.3.2 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.

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 anthesis (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% (Bafor and Osagie, 1986; Bille Ngalle et al., 2013).

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 (Breure and Corley, 1992; Corley and Breure, 1992). Fruit set is determined mainly by pollination efficiency.

Oil content is primarily affected by planting material. 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). 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). Fertiliser use affects bunch oil content (Ochs and Ollagnier, 1977); increased tissue chloride concentrations led 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 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.

2.4 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).

2.4.1 The different yield gaps in oil palm

In production ecology, three production levels are commonly distinguished: the potential yield (Yp) determined by yield-defining factors (PAR, temperature, ambient CO_2 concentration, and crop genetic characteristics); the water-limited (Yw) and nutrient-limited yield (Yn) determined by yield-limiting factors (water and nutrition); and the actual yield (Ya) determined by yield-reducing factors (weeds, pests, diseases; van Ittersum and Rabbinge, 1997). Yield gap analysis is the analysis of the difference between Yp (assuming genotype and management are optimal) and Ya 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 (Figure 2.3). The yield-determining, yield-limiting and yield-reducing factors relevant in oil palm and their quantitative effects on productivity are discussed in detail below.

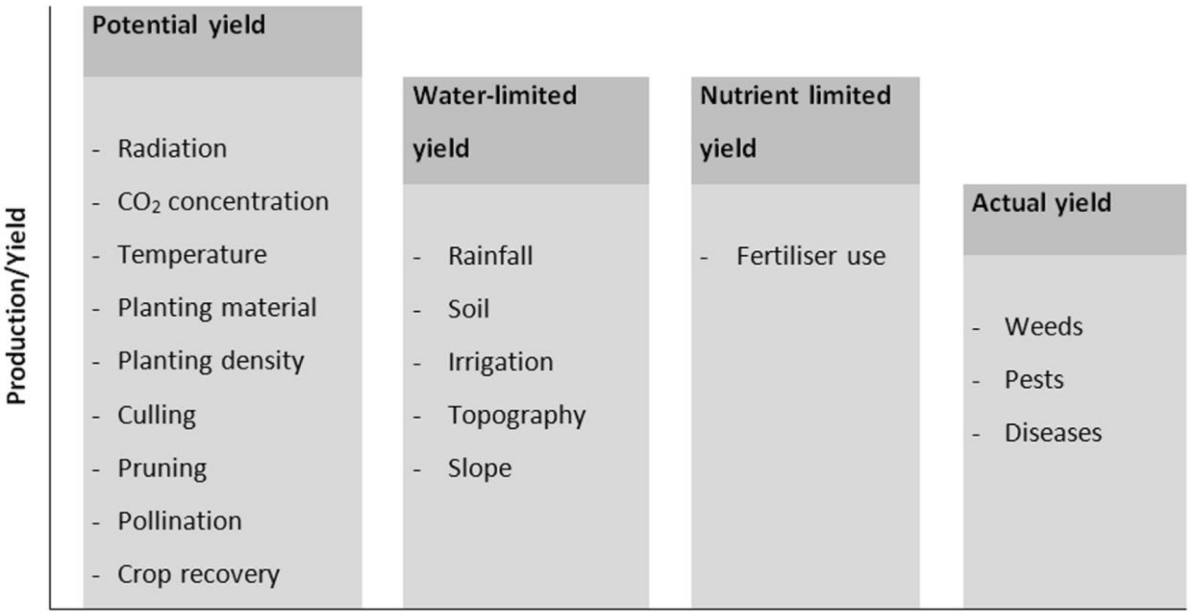


Figure 2.3 Different oil palm production levels and the contributing factors.

2.4.2 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 2.1). We discuss the different factors that determine the potential yield in further detail below.

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 2.1. A minimum of 15 MJ m^{-2} day^{-1} total solar radiation (equivalent to ~7.5 MJ m^{-2} 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 Van Kraalingen et al. (1989) indicated that each hour per day of bright sunshine results in 15–20 kg bunch dry matter production palm^{-1} 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 (van Kraalingen et al., 1989). Light saturation in oil palm leaves typically occurs at a photosynthetic photon flux density (PPFD) of 1100–1200 µmol m^{-2} s^{-1}, roughly equivalent to 250 W m^{-2} PAR (Dufrène et al., 1990). A light-saturated net assimilation rate of about 20 µmol CO_2 m^{-2} s^{-1} was measured at 1100 µmol m^{-2} 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 µmol CO_2 m^{-2} 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 likely to reduce yields significantly (Table 2.1). In Africa, dust from the Harmattan and smog cause periodic reductions in radiation.

CO_2 concentration

Under current circumstances the rate of photosynthesis in C3 crops such as oil palm is limited by the availability of CO_2. Yield increases of 10–30% in response to doubling atmospheric CO_2 concentrations have been observed in other C3 crops such as wheat (Kimball et al., 1993; Fuhrer, 2003), and may be expected in future in oil palm as it is well adapted to high-temperature environments (Dufrène and Saugier, 1993). Increases in photosynthetic rates in oil palm seedlings from 5 to 12 µmol m^{-2} s^{-1} have been observed in response to changes in atmospheric CO_2 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 (below). Mature palms are usually source-limited (Breure, 2003) making an actual yield response to rising CO_2 concentrations likely, if the temperature remains stable. No research has been carried out to date on the actual effect of available CO_2 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).

Temperature

The temperature range in the oil palm growing regions is shown in Table 2.1. 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; Paramananthan, 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 2.1). 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).

Planting material

Estimates of theoretical ceiling oil yields (with future planting materials under the best possible environmental and management conditions) range from 10.6 (Breure, 2003) and 14.0 (Henson, 1992) to 18.5 t oil ha^{-1} $year^{-1}$ (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 2.1). 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.

Table 2.1 Yield-determining factors in oil palm systems: potential yield (Yp).

<table>
<tr><th>Yield-determining factors</th><th>Range in oil-palm growing areas</th><th>Yield effects measured in case studies</th><th>Selected references</th></tr>
<tr><td>Radiation: solar radiation</td><td>• All regions: average 15 to 23 MJ total radiation m^{-2} day^{-1}
• Africa and parts of the Americas: < 10 MJ m^{-2} day^{-1} during the wet season</td><td>• Modelled increases of 1.7–2.1 t fruit bunches ha^{-1} year^{-1} per additional MJ m^{-2} day^{-1}
• Modelled 15–20% annual yield loss after reduction from 15 to 12 MJ total radiation m^{-2} day^{-1} for two months due to haze</td><td>Paramananthan et al., 2000
Henson, 2000
Goh, 2000
Caliman et al., 1998</td></tr>
<tr><td>Radiation: sunshine hours day^{-1}</td><td>• Asia: 5.3–6.9
• Americas: 2.2–7.7
• Africa: 3.6–6.3</td><td>• Productivity constraints if < 5.5 hrs day^{-1}
• One additional hr day^{-1} yields an additional 15–20 kg bunch DM palm^{-1} year^{-1} compared with productivity under cloudy conditions</td><td>Hartley, 1988: 100–101
van Kraalingen et al., 1989
Paramananthan, 2003</td></tr>
<tr><td>CO_2 concentration</td><td>• 1960: 317 ppm
• 1980: 339 ppm
• 2000: 370 ppm
• 2015: 399 ppm</td><td>• Modelled bunch DM production (t ha^{-1} year^{-1}) in site without water deficit:
<table><tr><th>CO_2 (ppm)</th><th>Temperature (°C)</th><th>Bunch DM</th></tr><tr><td>350</td><td>+0</td><td>11</td></tr><tr><td>550</td><td>+0</td><td>30</td></tr><tr><td>550</td><td>+2</td><td>18</td></tr><tr><td>550</td><td>+4</td><td>10</td></tr></table></td><td>Ibrahim et al., 2010
Henson, 2006
Tans and Keeling, 2015</td></tr>
<tr><td>Temperature</td><td>Lowest monthly minimum: 17.7 °C (Bahia, Brazil)

Highest monthly maximum: 34.6 °C (Aracataca, Colombia)</td><td>• Undefined strong yield reductions at minimum monthly average temperatures of less than 18–19°C
• Seedling growth inhibited at 15°C, seven times slower at 17.5°C and three times slower at 20°C than at 25°C
• Immature period in cold conditions up to 1 year longer</td><td>Hartley, 1988: 102–103, 110
Henry, 1958
Olivin, 1986</td></tr>
</table>

Planting material	• *Tenera* clones • *Tenera* semi-clones • DxP *tenera* seed • *Dura* seed • Seed of unknown origin	• *Tenera* clones: 15.7 t oil ha^{-1} year^{-1} at 7 YAP • *Tenera* semi-clones: 11.1 t oil ha^{-1} year^{-1} at 5 YAP • DxP *tenera* seed: 8.9 t oil ha^{-1} year^{-1} • *Dura* seed: ~ 35–50% reduced bunch oil content • Seed of unknown origin: reductions potentially very large depending on percentage *pisifera* in population (zero yield from *pisifera* palms) and potential yield of parent materials	Simon et al., 1998 Ng et al., 2003b Rajanaidu et al., 2005 Sharma, 2007
Planting density	• 110–156 palms ha^{-1} in favourable environments • 160–170 palms ha^{-1} in unfavourable soils	• Optimum fixed planting density: 140–160 palms ha^{-1}; optimum LAI: 5.5–6.0 • 1–2% reduction in cumulative plantation yield when density ± 10 palms from optimum • On deep peat: higher optimum densities (> 160 palms ha^{-1}) • Yield increase of 4 t fruit bunches ha^{-1} year^{-1} from 9–16 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	• Good: 20–30% of seedlings removed • Poor: incorrect or insufficient culling	• No culling: 20–30% abnormal seedlings producing 40–100% less yield than normal seedlings	Tam, 1973 Gillbanks, 2003
Pruning	• 50–60 leaves at 0–3 YAP • 40–50 leaves at 4–10 YAP • 32–40 leaves at > 10 YAP	• 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}, respectively • Under-pruning: direct but unquantified yield loss due to reduced harvesting efficiency	Hartley, 1988: 441–442 Henson, 2002 Corley and Hew, 1976

Table 2.1 (continued)

Yield-determining factors	Range in oil-palm growing areas	Yield effects measured in case studies	Selected references
	•	•	
Fruit set and pollination	• Pollinating weevil present in all regions • Average fruit set 70–80%	• 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, respectively • Quadratic 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	• Plantations: 7-day, 10-day or 14-day harvesting interval • Smallholders: usually 14 or 15-day harvesting interval, sometimes up to 30 days	• 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	• Varying from near complete recovery to less than 70% of fruit	• Reported yield losses of up to 5 t fruit bunches ha^{-1} due to poor crop recovery • Yearly losses under strict harvesting regime at 7-day interval: 200 kg fruit bunches ha^{-1} unharvested bunches and 65 kg ha^{-1} uncollected loose fruits • Incomplete collection of loose fruit: on average > 5% yield loss • ~30% less oil yield from unripe bunches	Fairhurst and Griffiths, 2014: Ch. 6 Donough et al., 2013 Corley, 2001 Wood, 1985

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 2.1). 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).

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 2.1) 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 2.1; 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 2.1).

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 2.1). All abnormal seedlings should be removed during the nursery phase or replaced within 12 months after planting (Jacquemard and Baudouin, 1998: 56; Gillbanks, 2003).

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 to 10 months after opening in palms of 3 and 10–12 YAP, respectively, after which activity decreases until the leaves senesce and die (Corley, 1976b; 1983). 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).

Pollination

A quadratic function describes the relationship between fruit set and bunch weight, with a maximum bunch weight at 90% fruit set, and a maximum oil to bunch ratio at 75% fruit set (Harun and Noor, 2002; Table 2.1). 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)

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 2.1). 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, 1999c; 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.

2.4.3 Water-limited yield and yield-limiting factors

The water-limited yield (Yw; Table 2.2) 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). Yw 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).

Rainfall

Oil palm transpires about 6 mm water day^{-1} under non-limiting conditions and requires sufficient rainfall throughout the year (Table 2.2). 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 2.3). 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 µmol CO_2 m^{-1} 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 2.2). 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).

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:

$$B = Res + R - Etp \qquad \textit{Equation 2.2}$$

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 I (excellent, such as young alluvial soils) to IV (unsuitable, such as very sandy or gravelly soils; Table 2.3). 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; Paramananthan, 2013; Table 2.2). 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 (Paramananthan, 2013).

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 (Paramananthan, 2003), but yield responses to soil conservation on slopes of 2–10° have been reported (Table 2.2). Water losses by run-off vary from zero to > 30%, with erosion and fertiliser loss occurring mostly from weeded circles and harvesting paths where soils are bare and become compacted (Banabas et al., 2008; Comte et al., 2012; Bah et al., 2014). 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).

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 (Carr, 2011; Abram et al., 2014; Table 2.2). Data on effects of drainage on productivity in waterlogged fields is scarce (Table 2.2). 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).

Table 2.2 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}) • Malaysia and Indonesia: 1700–4000 • Africa: 1200–3500 • Americas: 1600–3500 Dry months (less than 100 mm rain month^{-1}) • Malaysia and Indonesia: 0–3 • Africa: 3–6 • Americas: 0–5	• Yield reduced if rainfall < 2000 mm year^{-1} or > 3500 mm year^{-1} and/or < 100 mm month^{-1} • Yield reductions in relation to water deficit: ○ None if water deficit is less than threshold of 50–200 mm year^{-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} year^{-1} at water deficits of > 500 mm • See also: Table 2.3.	Dufrène et al., 1990 Hartley, 1988: 98–99 Paramananthan, 2003 Goh, 2000 Olivin, 1986
Irrigation	• 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	• 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): ○ 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) • SE Asia: ultisols, oxisols and histosols • Africa: oxisols, ultisols and mullisols • Americas: oxisols and ultisols	Most soil types are not constraining apart from: • Shallow soils (Malacca series and Baiayo family): < 30 t fruit bunches ha^{-1} $year^{-1}$ • 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} $year^{-1}$ when managed well	Goh et al., 1994 Gurmit et al., 1986 Paramananthan, 2013 Mutert et al., 1999 Paramananthan, 2000
Soil texture	• Sandy soils to heavy clay	• Large but unquantified yield losses in very sandy soils and in heavy clay soils	Paramananthan, 2003; 2013
Topography and slope	• Flat to hilly	• 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°	Paramananthan, 2003; 2013 Balasundram et al., 2006 Kee and Soh, 2002 Murtilaksono et al., 2011
Waterlogging	• Common in low-lying areas in all regions • Localised flooding or water logging for several days to months per year	• 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 2.3 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} $year^{-1}$)				
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

Table 2.4 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} • 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	• For N, P, K, and Mg: see Table 2.5 • 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, 1999c Rajaratnam, 1973a Cheong and Ng, 1977 Gurmit, 1988 Osman and Kueh, 1996 Ng, 2002

Table 2.5 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, 1973b 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 2.6 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 dystrudept)			
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} year^{-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			

2.4.4 Nutrient-limited yield and yield-limiting factors

The nutrient-limited yield (Yn; Table 2.4) 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 (Ng, 1977; Breure, 1982; Uexküll and Fairhurst, 1991; Goh et al., 2003). Oil palm requires particularly large quantities of potassium, as well as nitrogen, phosphorus, magnesium, and boron (Table 2.5). Fertilisation with copper and zinc is required on peat soils. In case of severe deficiencies, foliar symptoms become visible (Broeshart et al., 1957; Table 2.5). 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 (Foster and Prabowo, 2002; Tohiruddin et al., 2010b). 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 2.6 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 ha^{-1} $year^{-1}$ for N, P, and K, respectively, when comparing no fertiliser with average applications (Treatment 0–1; Table 2.6). When quantities of nutrients applied were increased from average to large quantities (Treatment 1–2; Table 2.6), NUE became negative in some cases, and maximum NUE were 13, 0, and 8 kg fruit bunches per kg nutrient ha^{-1} $year^{-1}$ for N, P, and K, respectively.

In none of the experiments in Table 2.6 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 (Webb, 2009; Tohiruddin et al., 2010a).

2.4.5 Actual yield and yield-reducing factors

The actual yield (Ya) 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 2.7 and are further discussed in the sections below.

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 (*Lamicodidae* spp.) in South-east 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 2.7). 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 this can kill the immature palms (Table 2.7).

Table 2.7 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	• 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)	• 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., 2014 Wood, 1977
Pests: Leaf-eating insects	• Common in all regions • In case of severe infestation complete defoliation of palm clusters can occur	• 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: *Oryctes*	• Common in immature plantations in all regions	• 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	• Common in all regions • In case of severe infestation populations reach > 300 individuals per hectare	• 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: *Ganoderma*	• Common in all regions, especially Southeast Asia • Potentially severe in Malaysia and Sumatra with up to 80% mortality at > 15 YAP	• 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 Flood et al., 2002 Virdiana et al., 2010
Diseases: Bud rot	• Common in South America with up to 100% mortality in severe outbreaks	• 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

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 2.7). In the immature phase, rats can eat through the bole of seedlings and destroy the growing point, causing palm death.

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 2.7). 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 *Phytophtora 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).

2.4.6 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).

2.5 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 2.8. 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 palm oil producing countries in the world in 2013 are shown in Table 2.9. 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 2.9 with the potential yields as estimated in Table 2.8, 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} $year^{-1}$ (Fairhurst and Griffiths, 2014). The estimated average production from smallholder plantations in Indonesia is only 13 t fruit bunches ha^{-1} $year^{-1}$ (FAO, 2013; Molenaar et al., 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} $year^{-1}$ (Jelsma et al., 2009). In Africa average actual yields are less than 8 t fruit bunches ha^{-1} $year^{-1}$ (Table 2.9).

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

Table 2.8 Potential yields over the plantation lifetime in six selected countries from Southeast Asia, Africa, and the Americas.

Country	Potential yield ($t\ ha^{-1}\ year^{-1}$)		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 2.9 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[a]	Annual production (Mt)		Yield (t ha^{-1} year^{-1})		OER[b] (%)	Data source
	(Mha)	FFB	CPO	FFB	CPO[c]		
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

[a] Area harvested excludes immature area.
[b] Oil extraction rate (OER) was calculated from the yield data ($ton\ CPO/ton\ FFB \times 100$).
[c] CPO yield was calculated by dividing production (Mton CPO) over harvested area (mHa).

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 2.9). 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; Marengo et al., 2009; Paeth 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 unquantified 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 (Koh et al., 2011; Miettinen et al., 2012). 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 CO_2 ha^{-1} $year^{-1}$ 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 Fertiliser Industry Association (Heffer, 2013) for Indonesia, Malaysia and Thailand are presented in Table 2.10. Applications are far less than optimal, ranging from 40 to 90% of recommended rates (Rankine and Fairhurst, 1999c). In Malaysian plantations, almost two times more P and K is applied than in Indonesian plantations, and almost three times more K is applied than in Thai plantations, 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 on fertiliser use in plantations for other countries are not available. In smallholder plantations in Indonesia (Lee et al., 2013; Molenaar et al., 2013; Woittiez et al., 2015) and Africa (Rafflegeau 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 (Rafflegeau 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.

Table 2.10 Fertiliser 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[a] (kg ha^{-1} $year^{-1}$)			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 area 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).

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 America 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).

2.6 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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CHAPTER 3

Fertiliser application practices and nutrient deficiencies in smallholder oil palm plantations in Indonesia

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Abstract

Oil palm has become an important source of revenue for smallholders in Indonesia, but productivity of smallholder plantations is generally poor. Nutrient limitations have been suggested as an important agronomic constraint to yield. Our research aimed to quantify fertiliser use, soil and tissue nutrient status, and palm growth and yield in a sample of independent smallholder plantations. We selected 49 plantations in Indonesia in two provinces with contrasting soils. For all plantations, we obtained self-reported fertiliser use and yield data, collected soil and tissue samples, and analysed vegetative growth. More than 170 kg N ha^{-1} $year^{-1}$ was applied in one site, and P was applied in excess of recommended quantities in both sites, but on average farmers applied less than 100 kg K ha^{-1} $year^{-1}$. Soils in the palm circle were poor in N, P and K in 29, 40 and 82% of the plantations, and deficiencies were measured in 57, 61 and 80% of the leaflet samples, respectively. We found statistically significant correlations between tissue nutrient concentrations and vegetative growth, but a large part of the variation in the data remained unaccounted for. Single leaf area was reduced in > 80% of the plantations. Average yields were estimated to be 50–70% of the water-limited yield. Our results demonstrate that widespread nutrient imbalances and deficiencies, especially potassium and phosphorus, occur in smallholder oil palm plantations, due to inadequate and unbalanced fertiliser application practices. These deficiencies may be an important underlying cause of the overall poor productivity, which threatens the economic and environmental sustainability of the smallholder sector.

3.1 Introduction

Oil palm (*Elaeis guineensis* Jacq.) has become increasingly popular as a source of revenue in rural Indonesia, providing smallholder farmers with the opportunity to increase their income and improve their livelihoods (Sheil et al., 2009; Budidarsono et al., 2012; Lee et al., 2013; Edwards, 2015). Initially, most smallholder plantations were closely linked to and technically supported by large-scale plantations, for example, in schemes where transmigrant farmers were allocated two-hectare oil palm plots planted by plantation companies (the so-called plasma schemes; Gatto et al., 2015). More recently, the number of independent smallholders has risen rapidly (Molenaar et al., 2013; Euler et al., 2016b). The production capacity of oil palm smallholders depends on both land ownership and land productivity. In a situation of land scarcity, improving productivity per area of land is a necessary strategy to increase harvested yields and income (Budidarsono et al., 2012). Average yields produced by Indonesian smallholders are much less than the achievable yields, indicating the existence of agronomic constraints (Molenaar et al., 2013; Euler et al., 2016a; Woittiez et al., 2017b). Poor yields can have strong negative effects on farmer income and interfere with Indonesia's commitment to increase palm oil outputs without further area expansion. In order to improve yields, the underlying causes of poor productivity need to be identified.

Several studies on the constraints to productivity of smallholder oil palm plantations in Indonesia have been carried out. In Jambi, Sumatra, Euler et al., 2016a) estimated the yield in smallholder plantations to be around 40% of the potential yield. Based on data collected through farmer surveys and modelling, fertiliser limitations, harvesting interval, and plant mortality were identified as key causes of the yield gap. Earlier, Lee et al. (2013) surveyed 313 households in 15 villages from three provinces in Sumatra. In this study, harvesting interval was found to be the main determinant of productivity, with irregular harvesting (once per month) correlating with poor yields (15 t fruit bunches ha^{-1} $year^{-1}$) and very regular harvesting (three times per month) correlating with good yields (24 t fruit bunches ha^{-1} $year^{-1}$). Results from a large-scale survey amongst 1069 households in six locations in Sumatra and Kalimantan (Molenaar et al., 2013) identified a number of key constraints, including insufficient fertiliser application, incorrect harvesting practices, non-hybrid varieties, poor (re)planting practices, and the overarching issue of lack of access to knowledge and finance. In all the previous investigations, inadequate (insufficient) or inappropriate (unbalanced) use of fertilisers appeared as a key constraint.

Current oil palm planting materials, under conditions of sufficient water and nutrients, can yield well over 35 t fruit bunches ha^{-1} $year^{-1}$, or 8 t oil ha^{-1} $year^{-1}$ (Mohd et al., 2014). In order to achieve such large yields, the application of N, P, K, Mg and B is required on most soils (Ng, 1977). A deficiency in any of these nutrients may lead to very large yield reductions (Woittiez et al., 2017b), but the nutrient requirements and yield penalties depend strongly on soil type (Goh, 2005) and planting material (Ollivier et al., 2017), among others. Company plantations routinely carry out randomised fertiliser trials to determine the nutrient applications required for optimal yields (for an overview of trial results from Sumatra, see Tohiruddin et al., 2006). In order to assess the palm nutrient status and provide fertiliser recommendations based on tissue sampling, a range of nutrient deficiency thresholds have been established (Foster, 2003). In Cameroon, soil and leaf sample analysis in smallholder oil palm plantations showed that deficiencies in especially N and K were common, causing large reductions in yield (Rafflegeau et al., 2010), but we could find no published reports on similar studies in Indonesia. Our study aimed to fill this gap. The objective was to increase our understanding of fertiliser use and nutrient deficiencies in independent smallholder plantations in Indonesia, and to assess the potential effects of nutrient limitations on palm growth and yield.

3.2 Materials and methods

3.2.1 Research setup

The research was carried out in two regions in Indonesia: Sintang regency, West-Kalimantan province on the island of Borneo, and Muaro Jambi regency, Jambi province on Sumatra. Both areas are expansion areas with large numbers of smallholders, and they were selected by a development NGO supporting independent smallholders based on their potential for combining nature conservation with sustainable agricultural development. In Sintang, two research areas were selected: Binjai Hilir village (fields located between S00.04152, E111.25298 and S00.09211, E111.30073), and Sungai Tebelian subdistrict (fields located between N00.14476, E111.23421 and N 00.11357, E111.29272). In Jambi, Ramin village (fields located between S01.48779, E103.78348 and S01.53911, E103.82259) was the only research area. Both sites were sampled in different years and seasons, and by different teams, and there were some differences in methods between sites. These differences are highlighted below, and the results from the sites are mostly reported separately in the results section.

3.2.2 Research area description

Sintang. Sintang is located in West Kalimantan, along the River Kapuas. The topography is flat to gently rolling. The soils are clay or sandy clay loam Ultisols, with some shallow peat pockets in the Sungai Tebelian area. The climate is humid tropical, with an average annual temperature of 26.9°C, an average maximum temperature of 32.5°C and minimum temperature of 22.9°C. The yearly precipitation is around 3,000 mm, with a rainy season from October to January and the driest month in August (~100 mm month^{-1}). In Binjai Hilir, an oil palm cooperative was active, which consisted of 2,410 households, divided over 7 villages. The total area under oil palm (including scheme and independent plantations) was 4,805 ha. Average yields in 2013 were 17–18 t fruit bunches ha^{-1} year^{-1}, with a peak season in November and December and a low season from February to June. Bondo Sepolo (Tebelian) cooperative consisted of a few thousand households, divided over 16 villages, with a total oil palm area of 5,579 ha planted around 2007. The average yield was 18 t ha^{-1} year^{-1}, with the peak season from October to January.

Jambi. Ramin village is located in sub-district Kumpeh Ulu of Muaro Jambi regency in Jambi province, about 40 km north-east of Jambi city. The topography is flat low-lying coastal plain. Soils in the village area are alluvial clay Entisols (34%) and deep fibric Histosols (66%), with most sample plantations located on the clay Entisols. The climate is humid tropical, with an average annual temperature of 27°C, an average maximum temperature of 31°C and minimum temperature of 22.5°C. The yearly precipitation is around 2,300 mm, with a rainy season from October to February and the driest months in June, July and August (~100 mm rainfall month^{-1}). In 2014, Ramin village covered 3,325 ha of agricultural land, of which 2,213 ha (67%) were used for oil palm cultivation. The village consisted of 397 households, of which 321 were involved in farming (2014 data obtained from the village office). Most oil palms were planted between 1999 and 2002. All oil palm farmers in Ramin were independent.

3.2.3 Farmer selection

In Sintang, 24 independent farmers from two areas (Binjai and Tebelian) with plantations planted in or before 2009 (mostly after 2003) were randomly selected from a list of independent oil palm farmers in Sintang, provided by the government-related organisation Fasda. If the selected farmer was not available at the time of the field visit, a next farmer was randomly drawn where possible or found by asking locally. The average plantation size of the sample in Sintang was 10.9 ha (s = 10.8). In Jambi, six farmers had been pre-selected to participate in a research project through discussion with a local informant. Soil and leaf sampling were regularly carried out in the fields of these six farmers. An additional 19 farmers were randomly selected for interviews and for soil and leaf sample collection. Plantations on deep peat were excluded from the sample, but shallow peat pockets were sometimes present in parts of the fields. The average plantation size in the sample from Jambi was 6.1 ha (s = 10.3).

3.2.4 Research activities

The research activities were carried out in November/December 2013 in Sintang, and in August 2015 in Jambi. The research consisted of two parts: an interview and a plantation visit. During the interview general farm characteristics (farmer origin; plantation size; division between scheme and independent fields; planting year), yields (harvest interval; best and poorest yields during the previous year; and duration of the extremes) and fertiliser use (type and quantity applied during the previous year) were discussed. The questions were based on recall unless the respondent kept records. After the interview, a plantation was selected for assessment and sampling. In Sintang, the oldest plantation closest to the house was selected. In Jambi, the closest plantation was selected. The selected plantations were mapped using a GPS device. In Sintang, three palms in the plantation were selected randomly for soil and leaf sampling. If the selected palm was sick or deemed unrepresentative, then a new palm was randomly selected. In Jambi, four palms were selected in the four corners of the field, three palms away from the edge. Leaf 17 was identified and excised (Chapman and Gray, 1949), and the length, petiole width and thickness, and number of leaflets of leaf 17 were measured or counted, as well as the length and breadth of the eight largest leaflets (four from the left and four from the right side). The trunk girth and the height of the trunk (at the base of leaf 41) were measured. For a sample of 5–20 loose fruits or harvested bunches (depending on availability), the number of *dura* fruits or bunches was scored.

3.2.5 Sample collection

The total sample size was 49 (24 from Sintang and 25 from Jambi) for both soil (circle and stack) and tissue (leaf and rachis). For the leaf samples, the middle ~20 cm piece of the eight largest leaflets of leaf 17 (four on the left and four on the right side of the rachis) were collected. In addition, a piece of rachis of approximately 20 cm in length was collected as rachis sample from the same point on the leaf. Soil samples were collected at a depth of 5–10 and 25–30 cm using a 100 cm^3 steel sampling ring in Sintang, or with an Edelman combination auger at 0–40 cm deep in Jambi. Two samples were collected around each sample palm: one at 50 cm from the trunk in the palm circle (representing around 20% of the plantation area) and one at 3 m from the trunk in the inter-row under the frond stack (representing around 12% of the plantation area; Fairhurst, 1996).

3.2.6 Sample processing and analysis

Soil samples were air dried in plastic trays or open plastic bags and ground. In Jambi, samples were sieved to < 2 mm after grinding to remove debris and aggregates and improve homogeneity. Leaflet and rachis samples were first air-dried and then oven-dried at ~50°C (Sintang) or 65°C (Jambi) for 48 h. After drying the samples were sent to a laboratory for analysis. Soil samples were analysed as follows: (i) water-extracted pH; (ii) total organic matter using a spectrophotometer at 600 nm; (iii) extractable P using the Bray II protocol; (iv) Al + H through KCl extraction and titration; (v) soil organic N through two-step Kjeldahl; (vi) soil extractable K using 1 M ammonium acetate extraction and flame photometry; (vii) soil extractable Mg and Ca using 1M ammonium acetate extraction and atomic absorption spectrometer (AAS) analysis; (viii) and soil texture by the Bouyoucos hydrometer method. For tissue samples, the following analyses were carried out: (i) leaf nitrogen through sulphuric acid digestion and semi-micro Kjeldahl distillation; (ii) leaf and rachis P through ashing followed by spectrophotometric analysis (vanadomolybdate method); (iii) leaf and rachis K using a flame photometer after ashing; (iv) leaf Ca and Mg (and Cu and Zn if required) by AAS after ashing; (v) leaf B using a colorimetric method after dry-ashing with CaO. Samples from Sintang were analysed at London Sumatra BLRS Analytical Laboratory in Medan, Sumatra. Samples from Jambi were analysed at Central Group CPS Laboratory in Pekanbaru, Sumatra.

3.2.7 Data analysis

Critical nutrient concentrations

The results from the tissue analysis were further analysed. First, the balance between the different nutrient concentrations was calculated for (i) leaf N and P, and (ii) leaf K, Mg and Ca. Leaf P concentrations are closely related with leaf N concentrations, and the critical deficiency threshold for P depends on the concentration of N (Ollagnier and Ochs, 1981). The critical P threshold was calculated using the following equation:

$$P = 0.0487 \times N + 0.039 \qquad \textit{Equation 3.1}$$

with P and N in %DM (Ollagnier and Ochs, 1981). Deficiency thresholds for leaf cations (K, Mg and Ca) are also closely related. The total leaf cation (TLC) concentration was calculated using the following equation:

$$TLC = \left(\frac{leaf\ K}{39.1 \div 1} + \frac{leaf\ Mh}{24.3 \div 2} + \frac{leaf\ Ca}{40.1 \div 2}\right) \times 1000$$ *Equation 3.2*

with TLC in cmol kg dry matter^{-1} and leaf K, Mg and Ca in % DM (Foster, 2003). The optimum values of leaf K and Mg were calculated relative to the TLC concentration by dividing the leaflet nutrient concentration in cmol kg^{-1} (for example: leaf K ÷ 39.1 × 1000) over the TLC concentration.

Principal component analysis

For vegetative growth parameters measured in the field (petiole cross-section, frond length, and average leaflet length and width) we ran a principal component analysis (PCA) on the correlation scale to explore and resolve the expected high multi-collinearity. Components above the inflection point in the scree plot, with an eigenvalue of > 1.0, were retained for further analysis, provided that the Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy scores were > 0.5 for all individual variables (Kaiser, 1974). A single vegetative growth component was extracted, and its values were calculated based on the factor scores and used for further analysis (from here on referred to as 'vegetative growth').

Regression model

The relationships between the nutrient concentrations and vegetative growth were explored using linear regression analysis. We fitted a single three-way interaction model

$$Yi = \alpha + \beta A + \gamma L + \tau N + \varepsilon i$$ *Equation 3.3*

where *Yi* is the vegetative growth component, as derived from the PCA; vector A contains the palm age (in years after planting) and the palm age squared; vector L contains the dummy variable for the two different research locations with contrasting soils; and vector N contains the tissue nutrient concentrations in the leaf (N, P, K, Mg and Ca) and rachis (P and K) with two two-way interactions (leaf N × leaf P; Ollagnier and Ochs, 1981; and leaf N × leaf K; Foster and Prabowo, 2002) and one three-way interaction (leaf K × leaf Mg × leaf Ca; Foster, 2003). All variables were centred before analysis, and coefficients were estimated using Ordinary Least Squares.

Potential and actual leaf area

To calculate the gap between observed palm growth and potential palm growth, we used leaf area as indicator for growth. We calculated the area of leaf 17 using the following equation:

$$l = 0.35 + 0.30 \times PCS \qquad \textit{Equation 3.4}$$

with l = area of leaf 17 and PCS = measured petiole cross-section in cm^2 (Gerritsma and Soebagyo, 1999). Potential leaf area was calculated based on the results from a cultivar times density experiment by Gerritsma and Soebagyo (1999). The least vigorous cultivar, at a standard density of 143 palms ha^{-1}, was selected as a benchmark, and the leaf area development was calculated using the following equation:

$$l = 10.80e^{-2.55e^{-0.40t}} \qquad \textit{Equation 3.5}$$

where l = single leaf area and t = years after planting (YAP).

All statistical analyses were run in SPSS. Significant results are shown with * for $P < 0.05$, ** for $P < 0.01$ and *** for $P < 0.001$.

3.3 Results

3.3.1 Fertiliser application practices

Overall, 100% of the farmers in Sintang and 92% of the farmers in Jambi applied mineral fertilisers in their plantation over the most recent year. The average total application across fertiliser types was 8.1 kg $palm^{-1}$ in Sintang, and 5.4 kg $palm^{-1}$ in Jambi (Table 3.1). Based on the reported fertiliser types and quantities used in the plantations, the yearly nutrient applications per palm and per hectare were calculated. On average, farmers in Sintang applied 178, 55, 102 and 7 kg ha^{-1} $year^{-1}$ of N, P, K and Mg, respectively, and farmers in Jambi applied 86, 29, 88 and 18 kg ha^{-1} year^{-1}. There were large variations among farmers in terms of nutrient amounts applied. One farmer in Jambi applied no chemical fertiliser whatsoever, and one farmer applied only some organic fertilisers.

Table 3.1 Fertiliser use per year in Sintang (in 2013) and Jambi (in 2013/14). For each site, the left column shows the percentage of farmers using a particular fertiliser or nutrient, and the right column shows the use in kg palm^{-1} year^{-1}. The use was calculated as the total use per site divided by the number of users, and therefore excludes farmers who do not use the fertiliser or nutrient. The fertiliser composition is shown as N–P_2O_5–K_2O–MgO unless otherwise indicated. The mineral content of P_2O_5, K_2O, and MgO is 44% P, 83% K, and 60% Mg, respectively. The total fertiliser application (top row) excludes organic fertilisers.

Fertiliser type	Composition	Use in Sintang (*n* = 24)		Use in Jambi (*n* = 25)	
		% of farmers	kg palm^{-1}	% of farmers	kg palm^{-1}
TOTAL		**100%**	**8.1**	**92%**	**5.4**
NPK fertiliser		**88%**	**5.1**	**80%**	**3.0**
NPK Ponska	15-15-15-0	67%	5.1	76%	2.4
Bungaraya/Mahkota	12-12-17-2	17%	2.7	12%	2.4
Mutiara	16-16-16-0.5	8%	4.6	12%	1.6
Pelangi	13-8-25-3	4%	2.3	0%	-
Kebunmas	12-6-22-3	4%	2.3	0%	-
Other	Unknown	4%	0.9	4%	1.5
N fertiliser		**46%**	**2.9**	**36%**	**1.8**
Urea	46-0-0-0	33%	2.7	32%	1.4
Sulphate of ammonium	21-0-0-0	21%	2.0	12%	1.8
P fertiliser		**46%**	**2.6**	**20%**	**1.3**
SP-36	0-36-0-0	46%	2.6	12%	1.5
Triple Super Phosphate	0-46-0-0	0%	-	8%	1.1
K fertiliser: KCl		**13%**	**1.6**	**24%**	**1.9**
KCl	0-0-60-0	13%	1.6	24%	1.9
Mg fertiliser		**33%**	**2.8**	**40%**	**3.1**
Dolomite	0-0-0-15	33%	2.6	40%	3.1
Kieserite	0-0-0-26	4%	1.3	0%	-
B fertiliser		**13%**	**0.02**	**8%**	**0.02**
Borax	11% B	13%	0.02	8%	0.02
Organic fertiliser		**21%**	**39**	**32%**	**4.0**
Empty bunches[a]	0.8-0.22-2.9-0.3	4%	22	0%	-
Other organic fertiliser	1.5-1.0-1.0[b]	17%	43	32%	4.0

[a] Composition of empty bunches returned from the mill in %DM (Gurmit et al., 2007).
[b] Approximate average composition of Petroganik fertiliser and fresh animal manure.

3.3.2 Soil nutrient status

Soil pH and nutrient concentrations in Sintang and Jambi are shown in Figure 3.1. The alluvial clays in Jambi were rich in minerals, especially Mg and Ca, and poor in organic matter, while the Ultisols in Sintang were highly weathered and nutrient-poor. In Sintang, and to a lesser extent in Jambi, P availability was higher in the circle, where the fertilisers were mostly applied. Both in Sintang and in Jambi soils were poor in K, but in Sintang these deficiencies were particularly severe (Figure 3.1). Soils in Sintang were also poor in Mg.

Soil nutrients in both areas were strongly correlated. In Jambi, the strongest significant correlations were found between Ca and Mg (Pearson's r = 0.796**); SOC and N (r = 0.685**); and pH and Mg (r = 0.652**) in the circle, and between SOC and N (r = 0.724**); pH and Mg (r = 0.693**); and Mg and Ca (r = 0.662**) under the stack. In Sintang, there were strongly significant correlations between SOC and K (r = 0.854**), N and K (r = 0.808**); and SOC and N (r = 0.785**) in the circle, and between SOC and N (r = 0.723**) under the stack. Application of Mg was significantly correlated with circle Ca in Jambi (r = 0.413*), and in Sintang Mg application was positively correlated with circle N (r = 0.626**) and K (r = 0.492*), and with N under the stack (r = 0.409*). No significant correlations were found between individual nutrient application rates and their corresponding soil concentrations.

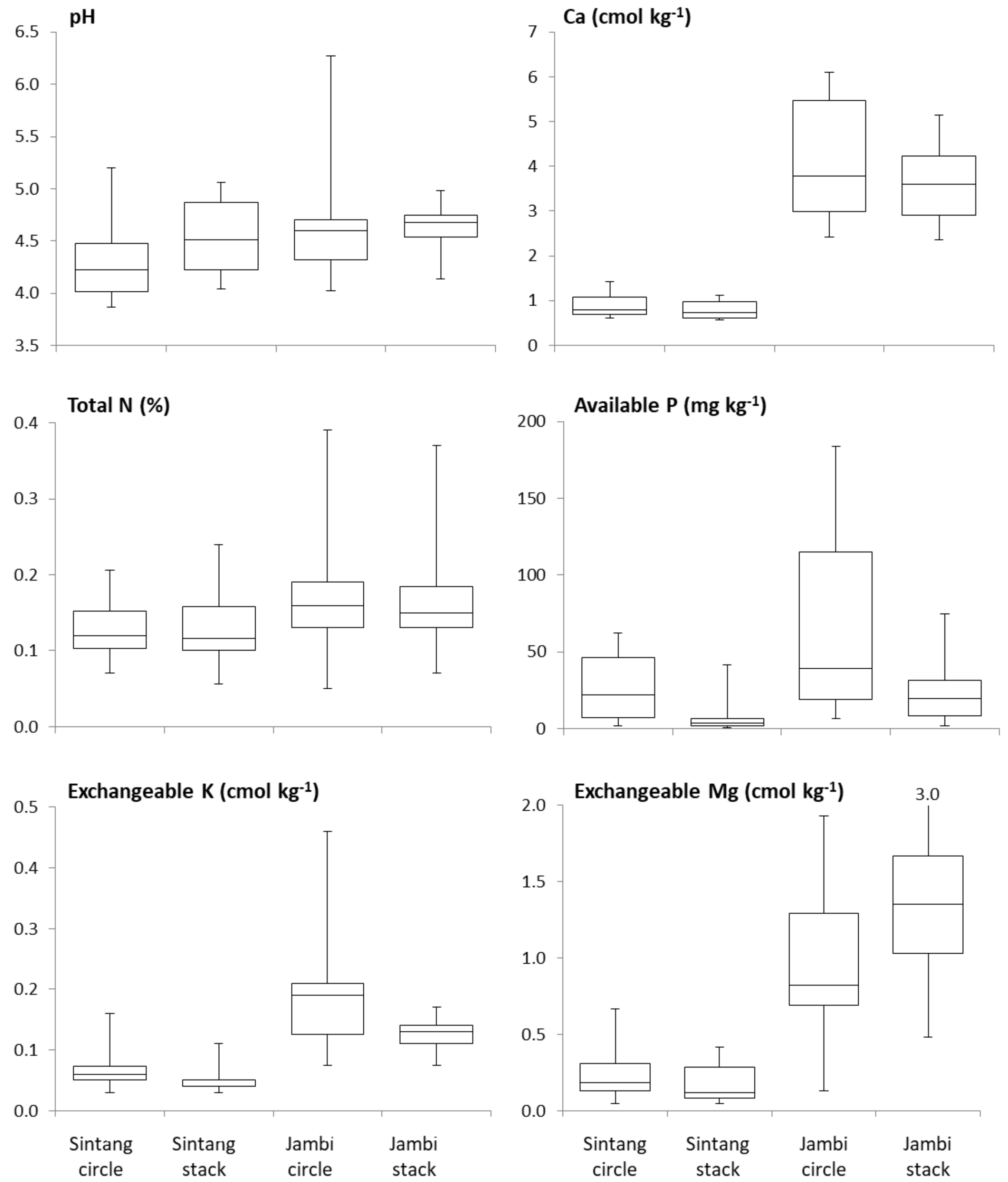

Figure 3.1 Soil nutrient concentrations in Sintang (*n* = 24), and Jambi (*n* = 25) in the circle and under the frond stack.

3.3.3 Tissue nutrient status

The critical leaflet N concentration depends on palm age and ranges from 2.65 %DM in palms < 9 YAP to 2.35 %DM in palms > 20 YAP (Ollagnier and Ochs, 1981). Average leaflet N concentrations were 2.33 %DM in Jambi and 2.66 %DM in Sintang (Figure 3.2). Average leaflet and rachis P concentrations were 0.146 and

0.064 %DM in Jambi, and 0.17 and 0.062 %DM in Sintang, respectively (Figure 3.2; Figure 3.3). For the whole sample, 16% of plantations were considered adequate in both N and P; 20 and 24% were specifically deficient in N and P, respectively; and the remaining 39% were deficient in both (Figure 3.2). Average K concentrations in the leaflets and the rachis were 0.59 and 0.46 %DM in Jambi, and 0.60 and 0.50 %DM in Sintang (Figure 3.3). Leaflet Mg was high in both areas (0.39 %DM in Jambi; 0.28 %DM in Sintang; Figure 3.3). The average TLC concentration was 86.2 cmol kg DM^{-1} (s = 15.1) in Jambi and 76.7 cmol kg DM^{-1} (s = 10.1) in Sintang. Leaf K and Mg relative to TLC are shown in Figure 3.4. While Mg relative to TLC was sufficient in all plantations in Jambi and 80% of the plantations in Sintang, for K less than 25% of the plantations in Jambi and 80% in Sintang were sufficient. For the complete sample, 18% of the plantations were adequate for both K and Mg; 71 and 2% were specifically deficient in K and Mg, respectively; and 8% were deficient in both. Soil Mg concentrations under the frond stack were significantly correlated with Mg concentrations in the leaf (r = 0.545**) and rachis (r = 0.527**) in Sintang.

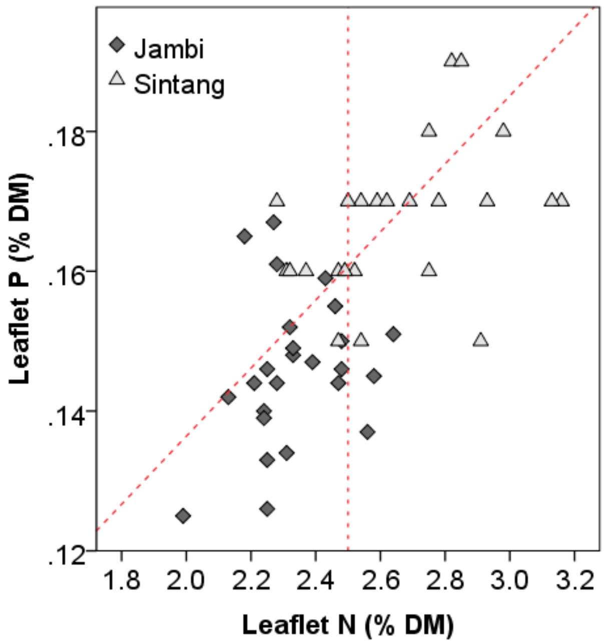

Figure 3.2 Leaflet N and P concentrations in Sintang and Jambi. The diagonal line shows the critical P concentration at various N concentrations; the vertical line shows the average critical N concentration (Ollagnier and Ochs, 1981).

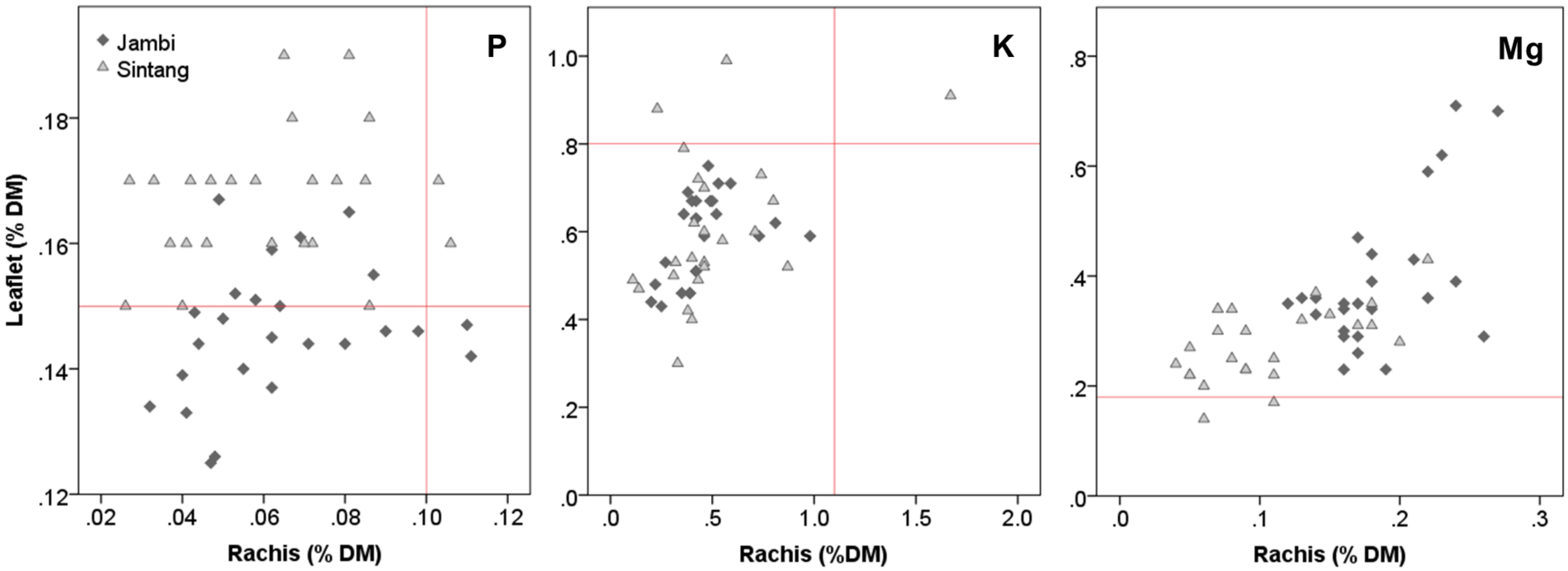

Figure 3.3 Rachis (x-axis) and leaflet (y-axis) concentrations of P, K and Mg in Sintang and Jambi. Lines show the fixed critical levels below which a yield response to nutrient application would be expected (Foster and Prabowo, 2006).

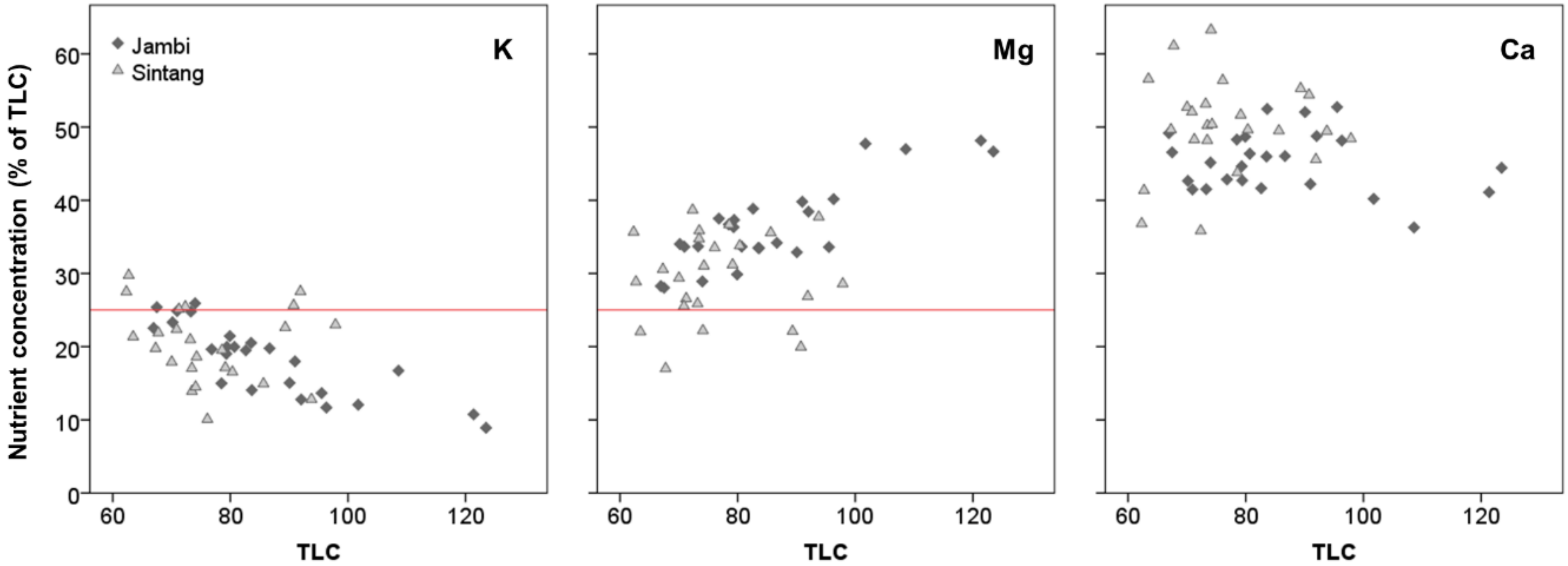

Figure 3.4 Concentrations of leaflet K, Mg and Ca as percentage of total leaf cation (TLC) concentration in Sintang and Jambi. The horizontal lines show the critical percentage for K and Mg below which a yield response to nutrient application would be expected (Foster, 2003).

3.3.4 Relationship between tissue nutrients and vegetative growth

Using PCA, we extracted a single vegetative growth component, after which we ran a regression analysis with the vegetative growth component as the dependent variable, and palm age, location, and tissue nutrient concentrations as the independent variables (Equation 3.3). The results from the regression analysis are shown in Supplementary Table S3.1. The full model explained 64% of the variation in vegetative growth, while 56% of the variation was explained by a reduced model, including location and squared palm age, only (data not shown). There was a highly significant positive effect of plantation age on yield, but plantation age squared had a significant negative effect in the full model. With regards to the tissue nutrients, we found a significant positive effect of rachis P and a significant negative effect of the leaf K–Mg–Ca interaction component, but not the individual leaf K, Mg and Ca components, on vegetative growth. None of other tissue nutrient effects was significant.

3.3.5 Leaf area development

Leaf area, as a function of palm age, is shown in Figure 3.5. The lines shows the modelled results following Gerritsma and Soebagyo (1999). In 42 out of the 49 plantations in our sample, the measured leaf area was less than the smallest modelled leaf area (Figure 3.5), with the remaining seven plantations showing a larger leaf area.

3.3.6 Yield

Estimated yearly yields in Sintang (n = 19) were 5–30 t fruit bunches ha^{-1}, with an average yield of 14 t fruit bunches ha^{-1} $year^{-1}$. Estimated yearly yields in Jambi were 21, 15, and 13 t fruit bunches ha^{-1} $year^{-1}$ on mineral soils (n = 15), mixed soils (n = 5), and peat soils (n = 12), respectively. Vegetative growth and yield were significantly positively correlated in Sintang (r = 0.728***) and in Jambi (r = 0.460*). There was no correlation between yield and palm age.

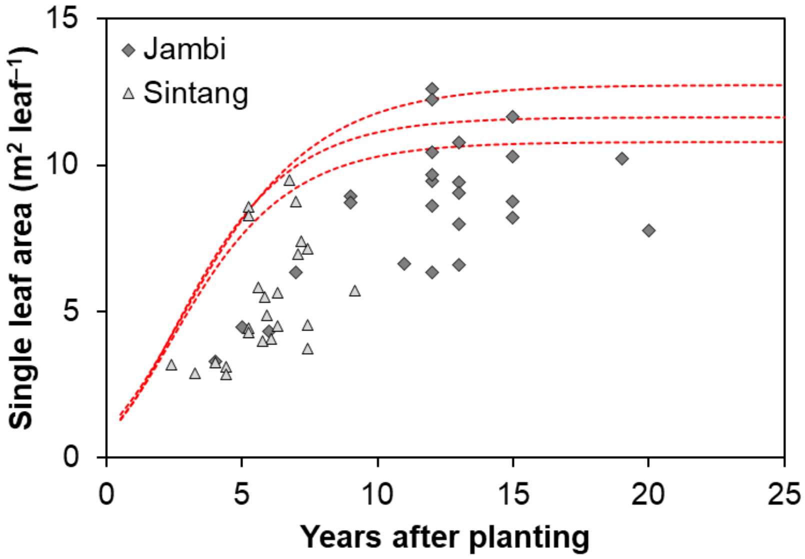

Figure 3.5 Leaf area in relation to years after planting in Sintang and Jambi. The curves show potential leaf area development of three cultivars reported by Gerritsma and Soebagyo (1999).

3.4 Discussion

Nutrient deficiencies in the smallholder plantations in our research areas were severe, especially in Jambi. The farmers strongly relied on NPK Ponska for the nutrition of their plantations but did not supplement with the necessary straight (single nutrient) fertilisers (especially K). The average N application in Sintang was within the recommended range (140–210 kg ha^{-1} year^{-1}; Rankine and Fairhurst, 1999c) and larger than the average N use in a sample of 21 plantation companies in Indonesia (141 kg ha^{-1} year^{-1}; van Noordwijk et al., 2017). In Jambi, the farmers applied less N than required; applications were about half those in Sintang. Average P applications were double the recommended rate (10–12 kg ha^{-1} year^{-1}; Rankine and Fairhurst, 1999) in Jambi, and four times the recommended rate in Sintang. Average K applications were only 50–60% of what is recommended (140–175 kg ha^{-1} year^{-1}; Rankine and Fairhurst, 1999c). The nutrient applications in our research areas were similar to those reported by Euler et al. (2016a), who conducted a survey among 236 smallholder farmers in Jambi, and concluded that only 15, 1 and 3% of farmers used straight K, Mg and B fertilisers. A study from Comte et al. (2015) in a 19.6 km^2 plasma area in Riau reports that farmers applied 40–75 kg ha^{-1} year^{-1} N, 17–27 kg P and 20–40 kg K, on average, which is somewhat less than what farmers used in our research areas.

In oil palm plantations, nutrients and organic matter accumulate in the top soil and decline with soil depth, and active roots are mostly found in the top 40 cm of the soil (Fairhurst, 1996). Throughout the plantation, different soil zones can be discerned; apart from the palm circle and the frond stack, there is usually a harvesting path (around 8% of the surface) and a 'remaining' area (around 60%) that can be either bare or covered with weeds (Fairhurst, 1996). In mature plantations the areas outside the circle are colonised by the palm roots (Foster and Dolmat, 1986) but do not receive large nutrient inputs from fertilisers or organic material. We collected samples only in the circle and under the frond stack, which probably means we overestimated the total soil nutrient pool when extrapolating to the other soil zones (Foster and Dolmat, 1986; Fairhurst, 1996). In Sintang, samples were collected at 5–10 and 25–30 cm depth, but not from the complete rooting zone. At these depths soils were poor in nutrients, especially under the frond stack. In the circle, N and P fertilisers were regularly applied, leading to increased soil acidification and increased nutrient concentrations. We observed strong correlations between SOC and soil nutrient concentrations, probably because the soils were inherently poor, and a relatively large part of the nutrients was supplied by the soil organic matter. Due to the young age of most plantations in Sintang and the lack of pruning, there was no difference in the SOC content between the circle and the frond stack (Haron et al., 1998). In Jambi, the complete rooting zone was sampled, showing that the soils were particularly rich in exchangeable Ca and Mg, which were strongly correlated. The correlations between soil pH, Mg and Ca can partly be explained by the regular application of Mg as dolomite ($CaMg(CO_3)_2$). The concentrations of P and K were much larger in the circle than under the frond stack, and the soil under the stack was poor in K.

A significant positive correlation between soil and tissue nutrient concentrations was found only for P (Sintang) and Mg (both areas), not for the other nutrients. This is in contrast with the strong correlations between soil and tissue K observed by Foster and Prabowo (2006). It is likely that rainfall conditions and the time elapsed since prior nutrient applications had a strong effect on soil nutrient concentrations and contributed to the large variability and poor correlations between soil and tissue nutrients observed in both areas.

The leaflet N concentration in Jambi was often deficient (Figure 3.2), which probably suppressed the mobilisation of P from the reserve tissue into the leaflets (Foster and Prabowo, 2006). The equation for calculating critical leaflet P concentrations (Equation 3.1) is valid in environments where N is non-limiting

(Ollagnier and Ochs, 1981). Alternatively, Rankine and Fairhurst (1999c) proposed fixed critical values to determine if tissues are deficient, and Foster and Prabowo (2006) argued that the rachis P concentration is a much more reliable measure than leaflet P. When looking at rachis P, only four plantations in our sample were above the critical concentration of 1.0 %DM proposed by Foster and Prabowo (2006; Figure 3.3). The poor tissue P status is remarkable considering the over-application of P fertilisers relative to standard recommendations. In Jambi, where soils were rich in P but clayey (leading to high P sorption) and acid, the results of the Bray 2 test used routinely for soil testing in laboratories in Indonesia may not have provided a useful estimate of the amount of P available to the palms (Foster and Prabowo, 2006). In Sintang, we found a significant correlation between soil and rachis P concentration, but rachis P deficiencies were common despite large applications of P. Successful infection of oil palm roots with mycorrhiza can greatly enhance the uptake of P (Blal et al., 1990) but we do not have data on the mycorrhizal infection in our research sites.

Tissue nutrient concentrations are more indicative of nutrient deficiencies than soil nutrient concentrations, and often there is little relationship between the two (Goh, 2005). In Jambi, leaf and rachis K concentrations were well below optimal in most of the plantations, and rachis K concentrations showed more severe deficiencies than leaflet concentrations (Foster and Prabowo, 2006; Figure 3.3). We found significant negative correlations between circle and tissue K (both rachis and leaflets), which was unexpected (Foster and Prabowo, 2006). We did not find significant correlations between tissue K and vegetative growth, although the positive effects of K on growth and yield have been shown in numerous randomised fertiliser trials (e.g. Ollagnier and Ochs, 1981; Tohiruddin et al., 2010a). We speculate that the tissue K concentrations may have been so poor that any potential positive effects on growth were obscured by the variability between and within plantations. The effects of leaf Mg and leaf Ca on vegetative growth were negative, on average, but these effects were not significant (with $P = 0.60$ for leaf Ca). The negative effects may be related to the antagonism between K on the one hand and Ca and Mg on the other (Ollagnier and Ochs, 1981; Foster, 2003). Due to this antagonism, the inclusion of the three-way interaction term in the model was important, but the lack of significant main effects implies that the significant negative effect of the K×Mg×Ca interaction term on vegetative growth needs to be interpreted with caution. The results may confirm the interdependence between the cations (Foster, 2003) as well as their important role in palm nutrition (Foster and Prabowo, 2006), but no definitive conclusions can be drawn. For all nutrients, the variability between plantations was large, and the sample size was relatively small. In addition, it was unclear when fertiliser had most recently been applied (as farmers did not keep records), which may have contributed to the large variability. In Sintang, particularly, the number of sampled palms per field was quite small, which decreased the reliability of the sampling results. Because of these issues, it is not possible to draw definitive conclusions about the relationship between nutrient deficiencies and vegetative growth based on the existing dataset. We can only conclude that nutrient deficiencies in the palm tissue were pervasive, and that vegetative growth was less than optimal in most plantations.

In order to estimate the yield performance of the smallholders in our sample, water-limited potential yields (Yw; Woittiez et al., 2017b) were estimated based on yields from best-performing fields in similar soil and climatic conditions: 30–35 t fruit bunches ha^{-1} $year^{-1}$ on mineral soils in Sumatra (Tohiruddin et al., 2006), and 23–25 t fruit bunches ha^{-1} $year^{-1}$ on deep peat soils, provided that the water table is properly managed (Othman et al., 2011). We conservatively estimated Yw at maturity to be 30 t fruit bunches ha^{-1} $year^{-1}$ on mineral soils, 22 t fruit bunches ha^{-1} $year^{-1}$ on deep peat soils, and 25 t fruit bunches ha^{-1} $year^{-1}$ on mixed soils, for palms of 7–18 YAP in Jambi (Euler et al., 2016a). In Sintang, Yw was estimated to increase linearly from 8 t fruit bunches ha^{-1} $year^{-1}$ at 3 YAP to 30 t fruit bunches ha^{-1} $year^{-1}$ at 7 YAP. Yields achieved by the respondents were mostly well below Yw, with only seven out of 51 farmers reporting yields at or above Yw. Average yields in Sintang and Jambi were 50–60% of Yw and 60–70% of Yw, respectively, taking into account the different soil types (data not shown). These numbers must be viewed with caution, as farmers did not keep yield records, and estimates may not have been accurate and were based on a single year.

Other issues apart from plant nutrition probably contributed to the poor yields in our research areas. In both areas, regular flooding of part of the plantations occurred during the rainy season (data not shown). Poor planting material was also a major problem, as we found *dura* (thick-shelled) palms in almost 50% of the plantations in Sintang, and in > 80% of the plantations in Jambi. While *dura* palms are equal to *tenera* (thin-shelled) in terms of fruit bunch yield (Corley and Lee, 1992), the concentration of N, P and K in *tenera* bunches is higher and therefore the removal of nutrients with *dura* bunches is significantly decreased compared with *tenera* (Prabowo and Foster, 2006). It is unclear to what extent this difference has affected the nutrient concentrations in our sample plantations.

3.5 Conclusions

Fertiliser application practices in the sampled plantations were often poorly aligned with crop needs, and the palms were particularly deficient in K, and, to a lesser extent, in P and N. The nutrient deficiencies, in turn, probably led to reduced vegetative growth, which was below optimal in 41 out of 49 plantations. Clear direct relationships between tissue nutrient status and vegetative growth could be identified only for rachis P, and a larger sample size is required. Yields were estimated to be 50–70% of the potential, indicating a large scope for intensification. The key challenge for the smallholders in our sample appears to be the application of nutrients in the right balance, which is important for both productivity and environment. If Indonesia is to achieve its goal of increasing the sustainability of the oil palm sector, then the widespread nutrient deficiencies that we observed need to be corrected. Farmers' knowledge and preferences, as well as fertiliser costs and availability, play a role in the farmers' management decisions. Improved nutrient management, in terms of fertiliser type, quantity and placement, could probably lead to large increases in yield, yet the prevalence of other constraints such as poor planting material may limit the profitability of investments in fertilisers. On-farm experiments in a wide range of conditions, and with regular sampling and accurate yield recording, are urgently required to come up with relevant and effective intervention strategies, and to provide oil palm smallholders with targeted recommendations for proper nutrient management.

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Supplementary materials

Table S3.1 Parameter estimates of the multiple linear regression model with vegetative growth as the dependent variable (Equation 3.3). Adjusted R^2 = 0.641; F = 6.860. All relevant tissue nutrient factors (as based on the literature) were included in the model.

Parameter	Coefficient	SE	Significance
Location (dummy; 0 = Sintang, 1 = Jambi)	0.717	0.372	**0.001**
Plantation age (years)	1.137	0.040	**0.000**
Plantation age (years) squared	-0.509	0.005	**0.000**
N leaflets	0.004	0.532	0.978
P leaflets	-0.047	9.371	0.743
K leaflets	0.062	0.853	0.599
Mg leaflets	-0.188	1.217	0.211
Ca leaflets	-0.236	0.863	0.060
P rachis	0.240	5.000	**0.040**
K rachis	-0.190	0.474	0.121
N leaflets × P leaflets	-0.146	22.505	0.136
N leaflets × K leaflets	0.179	2.548	0.126
K leaflets × Mg leaflets × Ca leaflets	-0.299	37.877	**0.027**

CHAPTER 4

Do wealthy farmers implement better agricultural practices?

An assessment of implementation of good agricultural practices among different types of independent oil palm smallholders in Riau, Indonesia

Jelsma, I., Woittiez, L.S., Ollivier, J., Dharmawan, A.H. (2019) Do wealthy farmers implement better agricultural practices? An assessment of implementation of Good Agricultural Practices among different types of independent oil palm smallholders in Riau, Indonesia. Agricultural Systems 179: 63-76.

Abstract

Palm oil has become a leading vegetable oil over the past 30 years. Smallholder farmers in Indonesia, the world's largest producer of palm oil with more than 12 million hectares, have massively engaged in oil palm (*Elaeis guineensis*) cultivation. In Sumatra, where more than 60% of Indonesian palm oil is cultivated, smallholders currently cover roughly 50% of the oil palm area. The rapid expansion of oil palm did not happen without controversy. In current efforts by the Indonesian government, NGOs and private sector to improve sector performance, smallholders are often characterised as the Achilles heel of the oil palm sector due to poor practices and low yields compared to companies. However, 'oil palm smallholders' is a container concept and there has been only limited research into smallholder diversity beyond the organised versus independent farmer dichotomy. This research delves into the implementation of good agricultural practices (GAP) among seven types of independent smallholders in Rokan Hulu Regency, Riau province. The research area consisted of a relative established agricultural area on mineral soils and a relative frontier, mostly on peat. Smallholder types ranged from small local farmers to large farmers, who usually reside in urban areas far from their plantation and regard oil palm cultivation as an investment opportunity. The underlying hypothesis is that larger farmers have more capital and therefore implement better agricultural practices than small farmers, who are more cash constrained. A wide range of methods was applied, including farmer surveys and farm audits, remote sensing, tissue analysis and photo interpretation by experts. These methods provided data on fertiliser use, nutrient conditions in oil palms, planting material, planting patterns, and other management practices in the plantations. Results show that yields are poor, implementation of GAP are limited and there is much room for improvement among all farmer types. Poor planting materials, square planting patterns, and limited nutrient applications were particularly prevalent. This implies that farmers across different typologies opt for a low-input low-output system. Under current conditions, initiatives such as improving access to finance or increasing availability of good planting material alone are not likely to significantly improve the productivity and sustainability of the smallholder oil palm sector.

4.1 Introduction

Palm oil has become the world's most produced and traded source of vegetable oil (USDA, 2016), in large part due to its unrivalled land to oil ratio. The largest palm oil producing country is Indonesia, which covers 54% of global palm oil production. Palm oil is a key foreign exchange earner for Indonesia, with export earnings up to 15.4 billion USD in 2015. It is of crucial importance to the country (DJP, 2017b). The sector provides direct employment for an estimated 4.3 million people and indirect employment for another 12 million (BPDPKS, 2017). Oil palm growers in Indonesia are classified into three categories: privately owned companies, state owned companies and smallholders. Companies usually manage several thousand hectares to feed their mill (Byerlee and Deininger, 2013) and cover an estimated 60% of the oil palm area in Indonesia. The remaining 40% of the oil palm area is cultivated by smallholder farmers, mainly in Sumatra and Kalimantan (DJP, 2017b).

The remarkable expansion of oil palm over the past four decades has been accompanied with controversy. The sector has been associated with deforestation (Abood et al., 2015; Gaveau et al., 2017) and biodiversity loss (Obidzinski, 2012; Sayer et al., 2012). Peat fires and associated smoke, which covered large parts of Indonesia, Malaysia and Singapore in 2015, are a major source of GHG emissions and are often linked to oil palm expansion (Gaveau et al., 2014b; Purnomo et al., 2017). The oil palm industry has also frequently been criticised for its negative social impacts on local communities (Colchester et al., 2006; Afrizal et al., 2013), unfair partnerships between local communities and companies (Gillespie, 2010; Cramb, 2013) and land grabbing (Gellert, 2015). These controversies have led to increased demands for sustainability and transparency in the oil palm sector, mainly due to customer demand in northern countries (Hidayat et al., 2015). Measures are being taken to improve the performance of the industry, notably through certification schemes.

The Roundtable on Sustainable Palm Oil (RSPO), a voluntary certification scheme initiated by major buyers and NGOs, is deemed to be one of the most stringent of numerous certification initiatives (Ivancic and Koh, 2016; Rival et al., 2016). It has pushed for better production standards by developing sustainability principles and criteria. Partially in reaction to this non-state actor initiative the Indonesian government launched the mandatory Indonesian Sustainable Palm Oil (ISPO) certificate in 2009. Currently the ISPO framework is being revised and strengthened in order to increase international recognition. In addition to these initiatives, the Indonesian Palm Oil Association (IPOA), the lobby of large scale oil palm producers, strongly advocates the implementation of good agricultural practices (GAP). Whilst debated in academia (Alcott, 2005; Villoria et al., 2013; Byerlee et al., 2014), these actors promote a narrative in which GAP leads to yield increases per hectare so that less land is required to fulfil global demand for palm oil. Thereby the environment is spared whilst farmers receive higher incomes. Corley (2009) suggested that the oil palm has a theoretical potential of 18 t oil ha^{-1} $year^{-1}$ and Mathews (2010) reported best yields for whole estates of 8 t oil ha^{-1} $year^{-1}$. Yet the average productivity in Indonesia in 2015 was only 3.6 t oil ha^{-1} $year^{-1}$, with smallholders producing on average 20% less than private companies (DJP, 2017b). While there is large scope for intensification throughout the sector, the smallholders currently are the weakest link in terms of productivity (Lee et al., 2013; Molenaar et al., 2013).

However, the smallholder segment of the sector is likely to continue to expand over the coming years (Euler et al., 2017) as it becomes more difficult for companies to open up large tracts of land because the most suitable lands are already occupied. Other factors which constrain company expansion through concessions include rising scrutiny towards the social and environmental performance of companies and related impacts on financing (van Gelder et al., 2017), and the oil palm moratorium which freezes the issuance of new permits for oil palm plantations (Busch et al., 2015). Also there is increased recognition of rights of indigenous populations (Forest People Program, 2013) and increased scrutiny from the anti-corruption agency and tax authorities (KPK, 2016). New technologies allow for easy tracing (and potentially sanctioning) of companies (see e.g. https://www.cifor.org/map/atlas/ for an overview of all oil palm concessions and mills in Borneo). The development of roads and mills by large scale oil palm companies has paved the way for smaller actors to access markets more effectively and to cultivate remaining patches of available land. This has happened particularly in Sumatra (62.5% of Indonesia's 11.3 million ha of oil palms in 2015), where the oil palm boom emerged through corporate expansion, but smallholders currently cover 48.8% of oil palm area (Bissonnette and De Koninck, 2017; DJP, 2017b). In other parts of Indonesia, mostly Kalimantan, large-scale expansion started later, and smallholders cover only 26% of the oil palm area (DJP, 2017b). Although it can be expected that the smallholder area and share will increase, smallholders are in a vulnerable position as they are often included in the value chain on disadvantageous terms. These include poor access to certified planting materials and technological know-how, and a poor bargaining position when selling bunches, leading to low prices and being last in line to sell fruit bunches when supplies are ample (Cramb and McCarthy, 2016; Hidayat, 2017). The RSPO acknowledges the weak position of smallholders and addresses it by working towards redeveloping the certification approach to better accommodate smallholders, and by prioritising smallholder implementation of GAP above certification itself (RSPO, 2017). Nevertheless, smallholders are prone to exclusion from value chains due to their large numbers, high costs associated with certification, and the current poor cultivation practices (Brandi et al., 2015).

The thin body of literature available on plantation practices of smallholders (see e.g. Lee et al., 2013; Euler et al., 2017) usually only differentiates between scheme and independent smallholders. Scheme smallholders cover roughly 40% of the smallholder area (Zen et al., 2015; Hidayat, 2017). They are characterised – despite there being a large diversity in these schemes with respect to support and management configurations (Gillespie, 2011) – by a partnership between farmers and companies, where the smallholder plantations are usually planted by the partner company and bunches are sold to the partner mill (Hidayat, 2017). Independent smallholder plantations on the other hand are usually developed autonomously, without resources from – or commitments to – oil palm companies (Hidayat et al., 2015). Scheme smallholders usually perform better than independent farmers as they are better integrated into large company plantation systems and hence often have yields close to corporate actors. Independent smallholder plantations, which cover about 2.8 M ha, are the least productive and it is among these farmers that promotion of GAP appears most important.

Good agricultural practices in oil palm have been defined based on extensive research in company plantations, research institutes and universities, and rely on basic agronomic principles (see Fairhurst and Härdter (2003) and Corley and Tinker (2016) for an overview). In short, GAP in plantations centre around soil and weed cover management, canopy management, harvesting, plant nutrition, and pest and disease management (Rankine and Fairhurst, 1999c). At planting, GAP include using high-quality planting materials, planting at the right distance and in the right pattern. Good field management includes maintenance of a weed cover with soft weeds (particularly *Nephrolepis* ferns, certain grasses, and legume cover plants), maintaining good plantation access, proper harvesting, and correct palm pruning. Appropriate fertiliser management is crucial for enhancing productivity and reducing negative impacts on the environment. In certain situations it can reduce input costs when fertilisers are used more efficiently (Goh et al., 2003; Soliman et al., 2016). Smallholders operate in different conditions than company plantations (such as having fresh fruit bunches, rather than oil, as their end product, and having more limitations in access to heavy equipment and inputs), but the same agronomic principles apply in smallholder fields.

In this article we explore the use of GAP by diverse groups of independent oil palm smallholders, including plantations which are on (or beyond) the blurry boundaries between family farms and large-scale plantations (McCarthy and Zen, 2016; Bissonnette and De Koninck, 2017). The farmer typology applied is based on the study of Jelsma et al. (2017a), which highlighted that independent smallholders are not a homogenous group. Our objective was to understand the use of GAP among different independent farmer types in Riau, to identify points of improvement, and to support the development of differentiated policies and approaches towards increased productivity. To achieve this, we employed a range of methods such as farmer surveys, field visits, tissue sampling, photo analysis and the analysis of satellite images. Whereas Jelsma et al. (2017a) focused on market linkages, social diversity and legal aspects, this article delves into the implementation of GAP given its centrality in current debates surrounding the sustainability of the smallholder oil palm sector. It further explores the hypothesis that larger farmers have more capital and therefore implement better agricultural practices than small farmers, who are usually more cash constrained.

4.2 Background

The research was conducted in Sumatra's Riau province, which is the province with the largest oil palm area in Indonesia (2.46 million ha). Approximately 28% of Riau's land area is planted with oil palm, of which 59% is owned by smallholders (DJP, 2015). About 33% of the palm oil processing capacity in Riau comes from independent mills (DIS-BUN Provinsi Riau, 2015), which do not own plantations and usually source from independent smallholders. This indicates the importance of the independent smallholder sector for the Riau oil palm industry. Within Riau our research focused on Rokan Hulu regency (Figure 4.1). With 39 mills – 17 without own plantations – and a total processing capacity of 1,605 t of fresh fruit bunches per hour, Rokan Hulu has the largest palm oil processing capacity in the province (DIS-BUN Provinsi Riau, 2015).

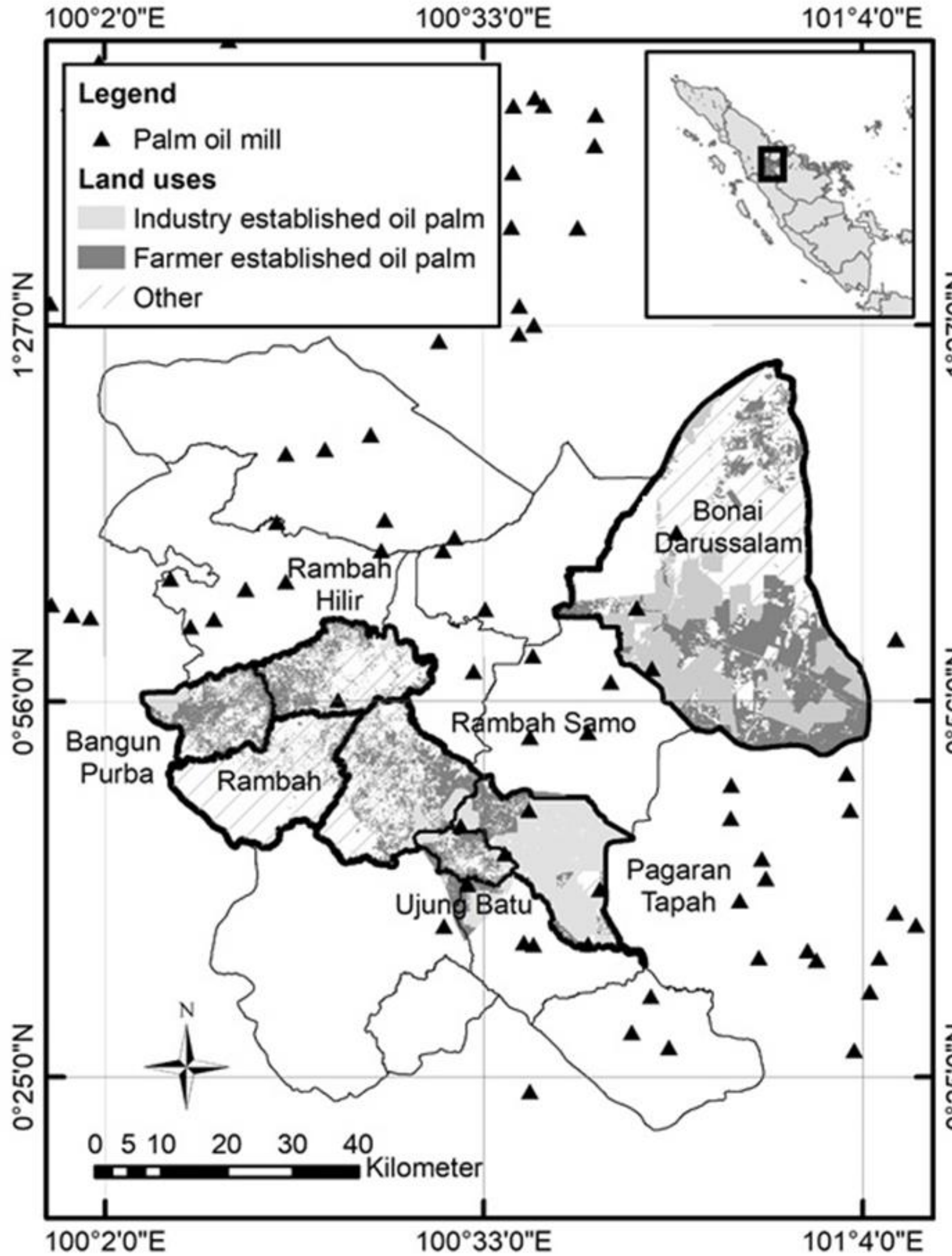

Figure 4.1 Overview of research area, oil palm plantations and mills in the area (source: CIFOR mill mapping and own data).

The research area consisted of two distinct areas in Rokan Hulu (Figure 4.1) which allowed us to capture a diversity of smallholders and landscapes. The first area was Bonai Darussalam (further referred to as BD, 0°52'-1°24' N, 100°39'-101°05' E) in the northeast, which is a single sub-district. Bonai Darussalam has a flat topography and largely consists of peat soils (Histosols). The area has experienced considerable deforestation after 2000 and has a low populations density. Peat fires associated with oil palm developments were common in BD. Most land officially falls under the forestry domain. Although this implies that de-jure the majority of land cannot be used for oil palm cultivation, de-facto much of the oil palm expansion in BD has taken place in the forestry domain. BD can be considered a relative frontier in the Riau context.

The other research area was Central Rokan Hulu (comprised of six sub-districts and further referred to as CRH, 0°36’-1°03’ N, 100°05’-100°45’ E). Central Rokan Hulu has a flat to slightly hilly topography in its oil palm growing regions and predominantly consists of mineral soils (mostly Acrisols). The area has been inhabited for a long time by indigenous populations and since the 1980s. It has seen a considerable influx of government sponsored and spontaneous migrants. Most land is classified for ‘other use’ (Areal Penggunaan Lain (APL)) and can be legally planted with palm oil. The forest domain largely covers the forested foothills of the Barisan mountains and includes a pulp and paper plantation. CRH has a population density of 151 inhabitants km^{-2} (BPS Rokan Hulu, 2015) and can be regarded as a relatively established agricultural area. Both areas have limited forests left (see Table 4.1 for details on research area).

Table 4.1 Research area characteristics. Sources: own research; MoA, 2011; CIFOR, 2014; MoF, 2014; BPS Rokan Hulu, 2015.

	Frontier (BD)		Established agricultural area (CRH)		Total (sampled sub-districts)	
Population density (people km^{-2})	29		151		95.1	
Land use	Area (ha)	Share	Area (ha)	Share	Area (ha)	Share
Deforested between 2000–2013	84,739	60.6%	6,222	3.8%	90,961	30.1%
Forest remaining in 2013	7,379	5.3%	16,743	10.3%	24,122	8.0%
Oil palm	75,275	54.2%	76,302	46.4%	151,577	50.0%
• Independent smallholder oil palm	39,252	28.2%	43,133	26.2%	82,385	27.2%
• Company developed oil palm	36,023	25.9%	33,169	20.2%	69,192	22.8%
Outside forest domain (APL)	51,399	37.0%	101,050	61.9%	152,449	50.1%
Forest domain	87,538	62.4%	64,367	37.5%	151,905	49.9%
Peatland (> 100 cm)	101,635	73.1%	0	0.0%	101,635	33.5%
Total area	138,949	45.8%	164,321	54.2%	303,270	100%

Table 4.2 Farm types and characteristics, and sample sizes.

	Cluster	**Small Local Farmers (SLF)**	**Medium Local Farmers (MLF)**	**Large Resident Farmers (LRF)**	**Small Migrant Farmers (SMF)**	**Medium Migrant Farmers (MMF)**	**Small & Medium Peat Farmers (SMPF)**	**Large Peat Investors (LPI)**
Farm size (ha)	Average plot size	1.1	2.9	52.3	1.4	3.4	4.2	179.2
	Average total area under oil palm	1.7	6.9	94.5	2.3	6.8	5.1	241.0
Primary place of residence	Within sub-district	100%	100%	67%	87%	76%	65%	18%
	Outside regency	0%	0%	15%	6%	8%	29%	78%
Origin	Within sub-district	100%	100%	29%	4%	2%	5%	2%
	Outside regency	0%	0%	67%	90%	89%	93%	95%
Ethnicity	Malay	62%	48%	22%	10%	7%	7%	3%
	Batak	21%	31%	41%	17%	24%	40%	54%
	Javanese	17%	20%	29%	72%	66%	52%	15%
	Sino-Indonesian	0%	0%	2%	0%	0%	0%	24%
	Other	0%	1%	6%	1%	3%	1%	3%
Soil type	Peat soil	0%	0%	0%	0%	0%	100%	100%
	Mineral soils	100%	100%	100%	100%	100%	0%	0%
Land classification	Outside Forest domain (APL)	74%	56%	59%	83%	74%	26%	26%
	Forest domain	28%	47%	43%	18%	27%	76%	86%
Location	Central Rokan Hulu	95%	96%	80%	87%	87%	0%	0%
	Bonai Darussalam	5%	4%	20%	13%	13%	100%	100%
Prevalence	Share of total farmer population [a]	19%	11%	6%	29%	20%	13%	2%
	Share of total research area (ha) [a]	7%	8%	18%	10%	14%	13%	31%
Farmer and farm surveys (231)		30	32	34	33	40	30	32
Valid paired surveys and photo interpretations (220)		29	31	33	31	39	29	28
Tissue samples (118)		13	10	19	15	14	23	24

[a] Sampling bias corrected; see Jelsma et al. (2017a) for more details.

The smallholder typology was developed by performing a Hierarchical Clustering Analysis (HCA) among 1,728 farmers and is described in more detail in Jelsma et al. (2017a). The variables used to develop the typology were inspired by the work of McCarthy et al. (2016) on rural differentiation through smallholder oil palm developments in Jambi, where they contrasted local and migrant smallholders and differentiated between farms of different sizes and resource endowments. Key determinants used in developing the typology were: 1) area of smallholder oil palm (proxy for wealth); 2) origin of farmers (locals or migrants); 3) residence (absentees or resident farmers); 4) peat or mineral soils; 5) land status (APL or state forest domain). The seven clusters derived in Jelsma et al. (2017a) were subsequently used in this analysis as well. Table 4.2 provides an excerpt from their study to characterise the different farmer types.

4.3 Methodology

4.3.1 Sampling

The sampling frame is based on spatial sampling using recent high-resolution Google Maps satellite imagery. From this imagery smallholder plantations were mapped. The research area was subsequently divided into 25 ha cells from which a random sample of 5% (287 cells containing 4451 ha of smallholder plantations) were visited. Small farmers were relatively prevalent in the established agricultural area whereas the frontier was dominated by large farmers. As especially the frontier area contains more large farmers who occupied several sampled cells, the number of farmer surveys is less than the number of cells visited. A total of 231 farmers were included in this study, with 30–40 farmers per farmer type (see Table 4.2 for details on sample sizes per farmer type). For all parameters that included expert photo assessments the sample size was reduced to 220, because for some plantations the photo sets were of insufficient quality to be assessed. For more details on sampling and tools applied see Jelsma et al. (2017a).

4.3.2 Surveys and plantation visits for assessing the implementation of good agricultural practices

Field work was conducted in May-June and August–September 2015. The survey instruments consisted of an in-depth farmer survey and a visual plantation inspection form for surveyors (see Supplementary Materials S4.1). Jelsma et al.

(2017a) focussed on developing the typology, and their article contains information on socio-legal and economic aspects such as share of income from oil palm, other sources of income, sources of capital for plantation development and type of land ownership documentation. The current article utilises the agricultural practices component of the survey and highlights aspects such as yields, fertiliser application rates, harvesting frequency and planting materials.

Plantation assessments (or 'audits') are common practice in company plantations (Fairhurst and Griffiths, 2014) and were also conducted for this study. Indicators of GAP were based on a diagnostic smallholder survey instrument develop by Aidenvironment (2013) and a smallholder oil palm handbook by Woittiez et al. (2015), which are both richly illustrated with photographic material and provide an extensive set of inspection criteria and guidelines on how to conduct smallholder plantation assessments. Sections from these documents were, with permission, translated into Bahasa Indonesia, used as training materials and shared with surveyors as reference material. For plant nutrition, we looked for the presence of common nutrient deficiency symptoms (particularly P, K, Mg and B) displayed in the foliage and the trunks; occurrence of these symptoms signals lack of GAP implementation. For soil and weed cover management, we looked for a continuous cover of legumes (usually *Mucuna bracteata*) or *Nephrolepis* ferns; absence of bare soils; signs of weeding (but not clear-weeding); and absence of woody weeds. For canopy management, surveyors looked at the retention of two to three fronds below the ripening bunches for palms up to four meters tall and one to two fronds for palms taller than four meters; the absence of dead leaves on the palm; and for the recycling of pruned fronds in stacks within the plantation. For harvesting, we checked for circle weeding practices; ease of access for harvesters in the plantation (based on whether harvesting paths were sufficiently clean and wide, without too many holes and generally accessible, e.g. no major waterlogging); and frequency of harvesting. For planting pattern and density, we looked for planting in triangles through satellite images (further explained in section 4.3.3). For planting material, we looked for the presence of thin-shelled *tenera* (DxP) fruits by cutting open a sample of 20 loose fruits per farmer; GAP would see an occurrence of more than 99% *tenera* fruits but for this research we used 95% as a cut of point, allowing one fruit to be *dura*. Black bunch counts (BBC) were performed among 20 trees as an alternative method for assessing yields (see section 4.3.4) to allow for triangulation with other tools for yield assessments such as farmer surveys and expert opinion. In addition to GAP indicators, we collected basic information about the plantation, such as age of oil palms and quality of the road to the plantation. Criteria for road quality were limited number of holes in the road and no indications of flooding of roads or damaged bridges or other clear obstacles that hinder fruit bunch transport or increase costs due to likely damage to vehicles, as described and illustrated in Aidenvironment (2013).

Tissue sampling was conducted in 118 farms to determine the nutrient content in the leaves and rachis and assess the nutritional condition of the plantation. A minimum of four non-randomly selected palms per plantation were compounded into one sample. Selection criteria for palms were location (at least two rows away from the road and preferably at least five palms away from other sampled palms) and absence of visual abnormalities. Sample collection was performed according to the protocol described in Woittiez et al. (2018b) and laboratory analyses were carried out by Central Plantations Services in Pekanbaru.

Due to budgetary constraints and high cost of laboratory testing, we were unable to sample all farms surveyed. Sub-sampling was conducted in a semi-stratified manner in which both CRH and BD sites were proportionally sampled in order to capture both landscapes and soil types. As database analysis or the typology development had not yet commenced during tissue collection it was impossible to proportionally sample farmer types. During sampling it appeared that especially small and medium farmers in the peatlands, which were expected to form separate categories, were only very limitedly captured. It was therefore decided to randomly increase the number of small and medium peat farmers and small farmers at the expense of large farmers, which in absolute numbers still received most tissue sampling (see Table 4.3). The eventual sample however effectively strikes a balance between geographic spread and covering all farmer types and presence in the landscape, with small and medium peat farmers forming one category and hence being slightly oversampled (see Table 4.2 and Table 4.3).

4.3.3 Photo interpretation of smallholder plantations by experts

In order to allow for expert assessment of plantations without requiring physical field visits, plantations were photographed during the field audit. On average plantations were captured in eight images which showed different aspects of the plantation floor (circle, stack, overview) and canopy, in different angles (see Supplementary Materials S4.2). Three experts audited the plantations based on the sets of photos, and their assessments were used to triangulate the results from the field visits and the survey. The experts estimated oil palm age, bunch weight and yield, and classified plantation condition as poor, reasonable, or good. Yield estimates were given in 5 t ha^{-1} year^{-1} intervals (0–5, 5–10, etc.), effectively creating a 'yields up to' average. Bunch weight estimates were also provided with 5 kg ripe bunch^{-1} intervals. Interval averages were subsequently used in calculations to account for lower values within these ranges and avoid overtly positive assessments. Plantation age was estimated in years. For maintenance, the third author separately assessed weeding practices and pruning.

The experts were an academic specialised in agronomic practices in smallholder oil palm plantations (second author of this article), a farmer from Rokan Hulu who is also a representative of the Serikat Petani Kelapa Sawit (SPKS, or Union of Oil Palm Smallholders, a national organisation representing independent smallholder farmers), and an experienced oil palm agronomist working at CIRAD (third author). All three experts have extensively visited smallholder oil palm plantations but did not visit smallholder plantations for this research, nor did they have information about farmers or plantations before completing farmer photo assessments.

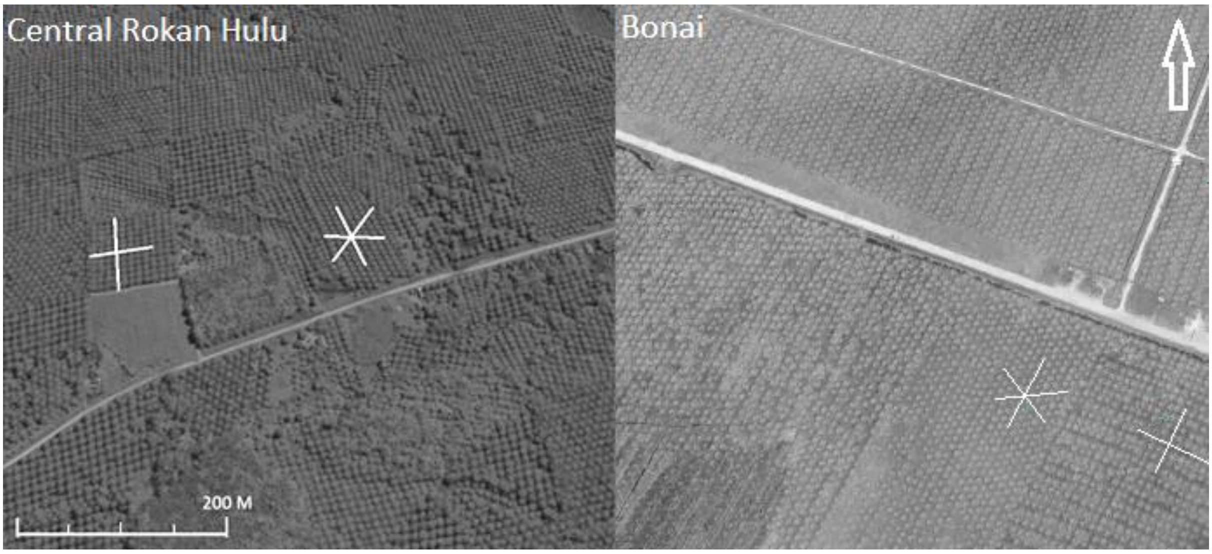

Figure 4.2 Example of satellite imagery of smallholder plantations in Central Rokan Hulu and Bonai. Note the differences in planting patterns between smallholders, demonstrating rectangular planting patterns and triangular patterns. The left picture illustrates typical example of a mosaic of smallholder plantations in Central Rokan Hulu. The right picture illustrates straight plantation patterns and a large smallholder in the north of the picture. Source: Google Earth, accessed on 16-12-2017.

Planting density and planting pattern (rectangular or triangular) were determined by tracing the palm row diagonals on high-resolution satellite imagery (Figure 4.2). Average distances between palm crowns were measured in meters using Google

Earth from either two or three diagonals depending on whether patterns were rectangular or triangular respectively. From this planting densities per hectare were calculated. Measured rows were preferably over 20 palms long, but less in small plantations.

4.3.4 Calculations

Seasonal patterns in yield were derived based on data from a nearby company plantation, which showed that the yields are highest in August and lowest in February (see Supplementary Materials S4.3a for company plantation yields throughout the year and S4.3b for climatic conditions). To account for these patterns when estimating yields, farmers were asked to estimate the yield per harvest in the peak and low season of last year. These yields were averaged, multiplied with the harvesting frequency, and divided by the land size. This approach is justified as yield records are mostly absent with farmers. Yields were benchmarked against a 20 t ha^{-1} $year^{-1}$ production curve deduced from Cramb and McCarthy (2016: p. 32) and presented as the share of the benchmark production curve at a given age.

Because farmer estimates are not always reliable, expert assessments and black bunch counts were used to provide additional yield estimates which allow for triangulation of results. Yields based on BBC were calculated by first taking the average BBC from 20 palms per plantation and multiplying this with the estimated average ripe bunch weight, to get the total bunch weight per palm. The ripe bunch weight could not be measured as ripe bunches are only available in the field in the short period between harvesting and transportation. For this reason, bunch weight estimates were obtained by averaging expert estimates from photos with surveyor estimates from field observations. Total bunch weights per palm were multiplied with three (assuming that bunches ripen in a four-month period) and with the planting density. Correction factors to compensate for date of surveying were developed based on average productivity curves from monthly yield data provided by three nearby companies (Supplementary Materials S4.3a). In order to benchmark yields against the production curve, survey yield estimates are associated with to survey oil palm age results and expert yield estimates are associated with expert age assessment. For the BBC yield benchmarking the average plantation age from survey and experts were used (Supplementary Materials S4.2).

In order to determine fertiliser practices, we calculated nutrient requirements and nutrient balances. Ng et al. (1999) indicate that for a mature plantation on tropical soils of poor fertility, the total demand for producing 20 t fruit bunches ha^{-1} $year^{-1}$ is 112.5 kg N, 14.0 kg P, 202.4 kg K, and 33.2 kg Mg, and for 30 t fruit bunches ha^{-1} $year^{-1}$ 145.5 kg N, 19.2 kg P, 247.5 kg K and 44.4 kg Mg. On peat soils, the quantities of nutrients removed in fruit bunches are similar, but the nutrient balance is different with more N and less K available in the soil (Goh, 2005). In order to compensate for this difference, the estimated N and K requirements on peat are set at 84.4 kg (25% less) and 303.6 kg (50% more), respectively, than the requirements at mineral soils (Ng et al., 1990). A nutrient balance was calculated for each plantation using the following equation:

$$B = (Fe + De) - ((Y \times c) + Tr + Ru + Er + Le)$$ *Equation 4.1*

with B = nutrient balance (kg ha^{-1}), Fe = input through fertilisers, De = deposition in rainwater, Y = reported yield, c = concentration of nutrient in the fruit bunches, Tr = nutrients taken up for trunk growth, Ru = loss through runoff, Er = loss through erosion, and Le = loss through leaching (Supplementary Materials S4.4).

SPSS version 19 was used to calculate differences among farmer type means, using either one-way Analysis of Variance (ANOVA; for scalar variables) or the Chi-Squared Test (for categorical variables). Appropriate post hoc tests such as Tukey and Games-Howell were conducted to calculate pairwise differences between farmer types. Matching letters in figures and tables indicate there are no significant differences between types of farmers according to post hoc tests. Where ANOVA revealed statistically significant differences, in some situations the post hoc tests could not indicate where those significant differences were located. This can be attributable to the sample size, a weak global effect, and differences between methods in how Type I errors are dealt with.

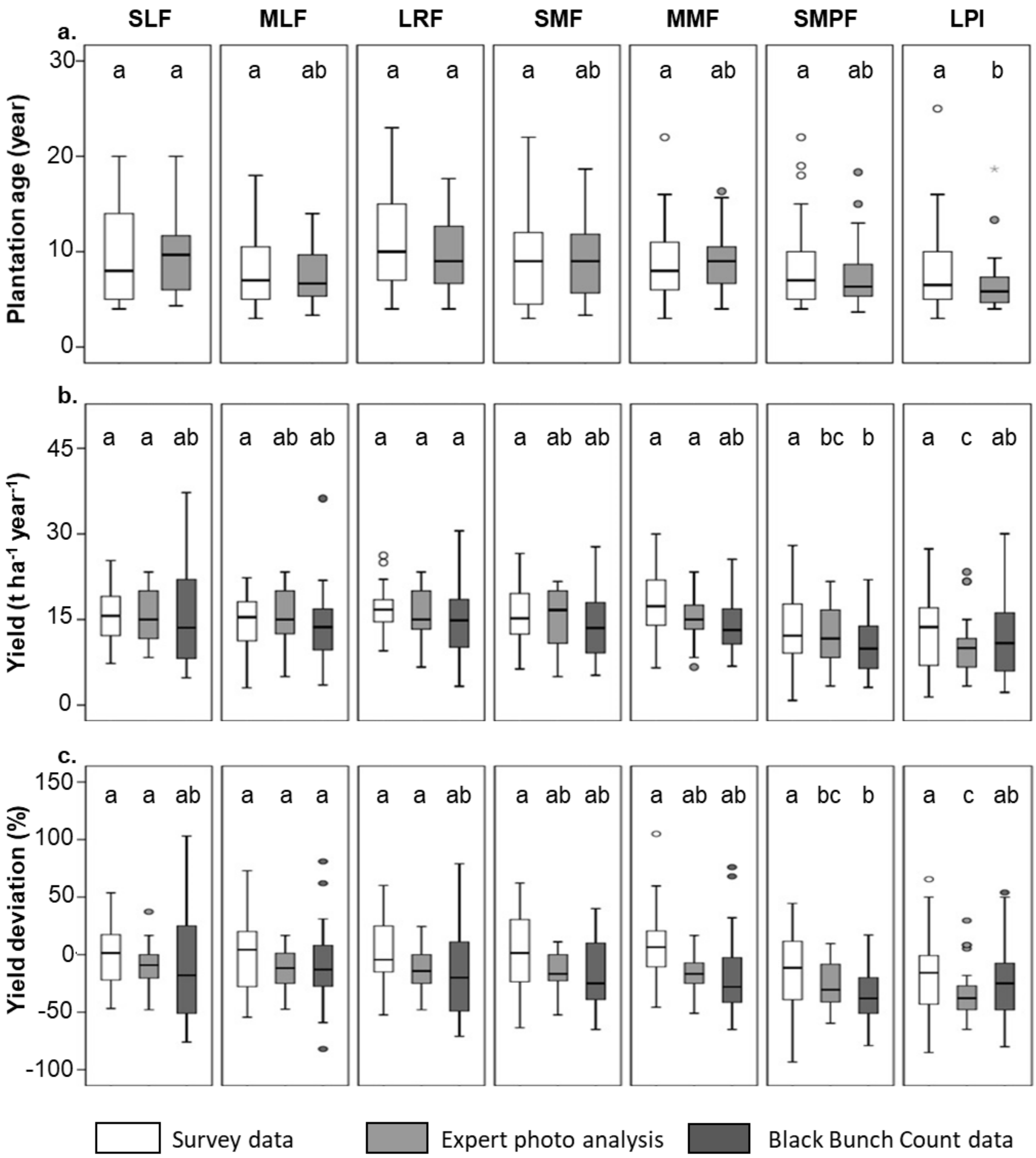

Figure 4.3 Age (a) and yield differences (actual yield (b) and deviation from reference production curve (c)) among farmer types using three different methods. SLF = Small Local Farmers, MLF = Medium Local Farmers, LRF = Large Resident Farmers, SMF = Small Migrant Farmers, MMF = Medium Migrant Farmers, SMPF = Small & Medium Peat Farmers, LPI = Large Peat Investors. Whiskers show the minimum and maximum values; the box shows the 1st and 3rd quartiles; the line shows the median. Values of > 1.5 interquartile range (IQR) are shown as circles, and > 3.0 IQR are shown as asterisks. Significance level $P < 0.05$. Pairwise significant differences are indicated per method only and not between methods.

4.4 Results

4.4.1 Age & yields

Yield is the ultimate product of three factors: genotype, management and environment (Tester and Langridge, 2010). In perennials yield depends on crop age, and therefore can be presented both in absolute terms and as deviation from a reference production curve (%). We used a reference production curve for a full 25-year production cycle, with a peak yield of 20 t ha^{-1} $year^{-1}$ as derived from Cramb and McCarthy (2016: 32).

Yield estimates from surveys, photo analysis by experts, and BBC provide a fairly uniform pattern (Figure 4.3). Limited differences were observed among farmer types, with the majority of significant differences observed between farmers on mineral soils and farmers on peat soils. All three yield assessment methods indicate farmers on peat generally have low yields.

4.4.2 Applications of fertilisers and nutrient balances

Smallholder fertiliser applications in general were limited, poorly balanced and variable between farmers and farmer types (Supplementary Materials S4.5). Nitrogen application rates were on average below the expected demand at 20 t fruit bunches ha^{-1} $year^{-1}$, with the exception of applications by migrant and large resident farmers (Figure 4.4). Average P applications appeared sufficient among most farmer types, but small local farmers and large peat investors applied too little on average to reach 20 t fruit bunches ha^{-1} $year^{-1}$. Average K applications were limited among all farmer types, with small local farmers applying only 32.1 kg ha^{-1} $year^{-1}$ on average. Less than 25% of farmers applied enough K to meet the demand for producing 20 t fruit bunches ha^{-1} $year^{-1}$. Average Mg applications were generally insufficient, especially among farmers on mineral soils. Small local farmers were most likely not to apply any fertilisers but differences between farmer types were not significant (Figure 4.4; Supplementary Materials S4.5).

Whereas Figure 4.4 highlights the nutrient requirement for producing 20 t fruit bunches ha^{-1} $year^{-1}$ and the actual nutrient applications of farmer types, Figure 4.5 provides a nutrient balance, using reported yields by farmers and the estimated offtake rates from Ng et al. (1999) to calculate the nutrient requirement.

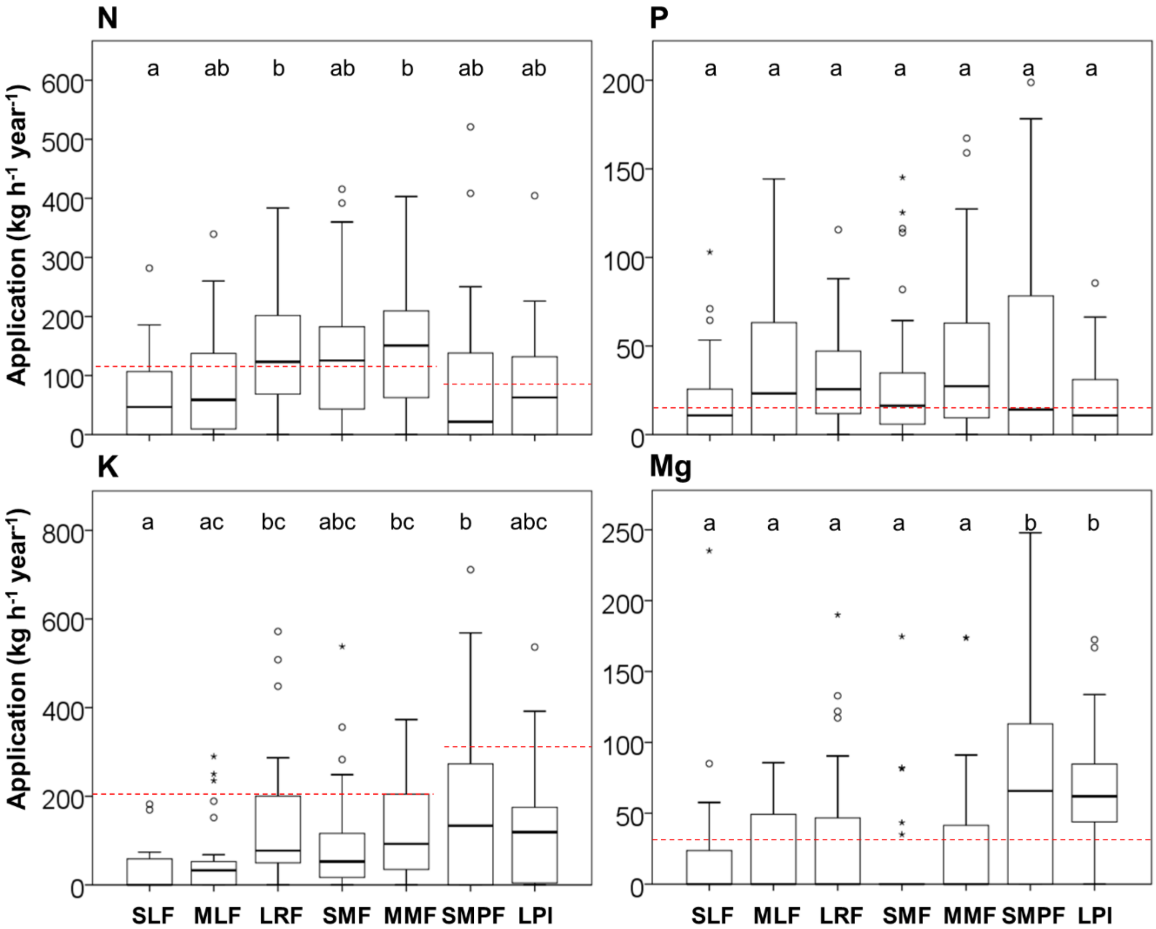

Figure 4.4 Nutrient application rates per farmer type. SLF = Small Local Farmers, MLF = Medium Local Farmers, LRF = Large Resident Farmers, SMF = Small Migrant Farmers, MMF = Medium Migrant Farmers, SMPF = Small & Medium Peat Farmers, LPI = Large Peat Investors. Whiskers show the minimum and maximum values; the box shows the 1st and 3rd quartile; the line shows the median. Values of > 1.5 interquartile range (IQR) are shown as circles, and > 3.0 IQR are shown as asterisks. Nutrient application outliers with values > 3.0 IQR in both the combined sample and in farmer groups were removed from further analysis. Dashed lines indicate requirements at 20 t fruit bunches ha^{-1} $year^{-1}$ for mineral soils (first five farmer types) and separately for peat soils (last two farmer types) where N and K requirements are different. Significance level $P < 0.05$.

The nutrient balances presented in Figure 4.5 indicate that especially small local farmers had negative N, P and K balances. Potassium shortages were common among all farmer types, and less than 75% of farmers applied enough K to sustain their estimated production levels. Peat farmers applied more Mg than farmers on mineral soils, mostly as dolomite which is a cheap fertiliser that farmers often believe to neutralise the acidic peat soils. However, the effectiveness of such a practice is probably limited, considering the high buffering capacity of peat soils (Bonneau et al., 1993).

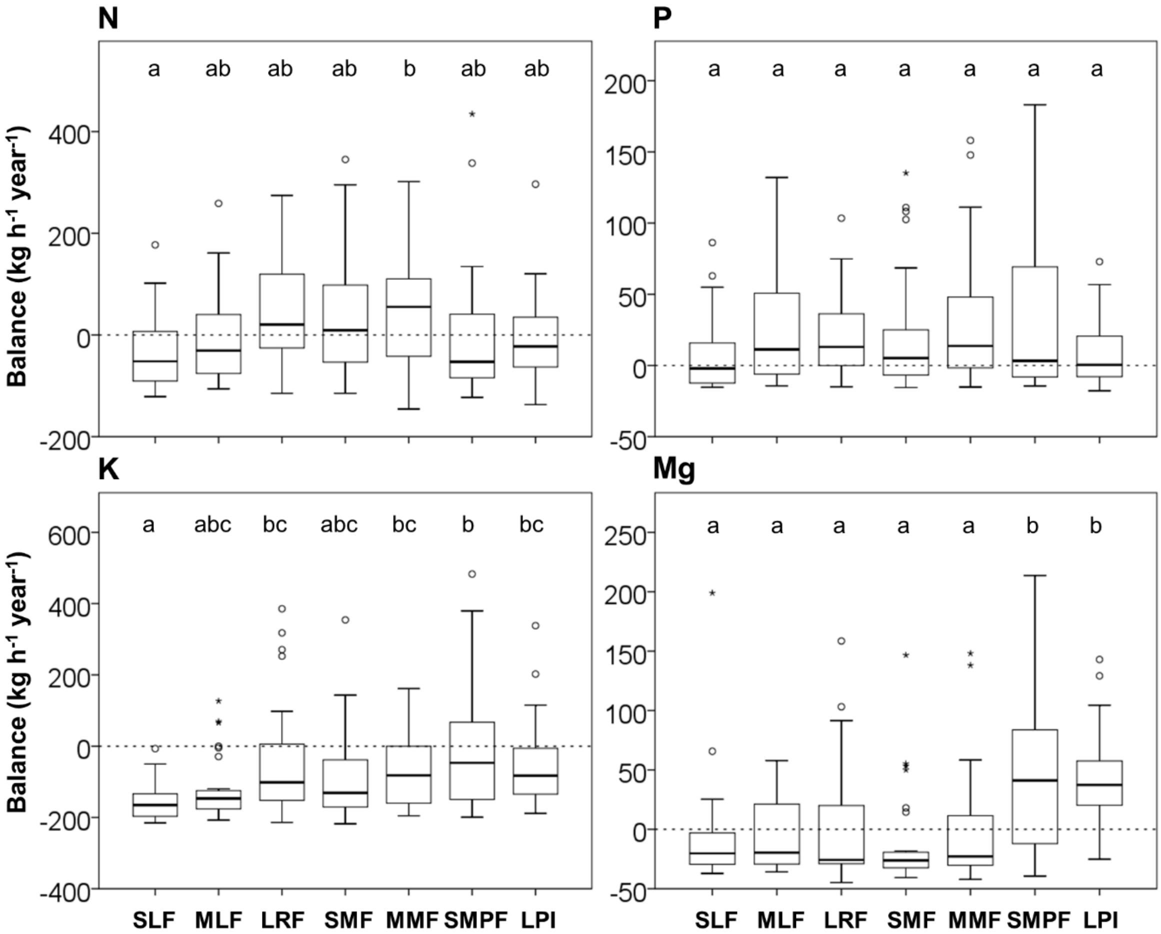

Figure 4.5 Nutrient balances based on yield data provided by farmers per farmer type. SLF = Small Local Farmers, MLF = Medium Local Farmers, LRF = Large Resident Farmers, SMF = Small Migrant Farmers, MMF = Medium Migrant Farmers, SMPF = Small & Medium Peat Farmers, LPI = Large Peat Investors. Whiskers show the minimum and maximum values; the box shows the 1st and 3rd quartile; the line shows the median. Values of > 1.5 interquartile range (IQR) are shown as circles, and > 3.0 IQR are shown as asterisks. Nutrient application outliers with values > 3.0 IQR in both the combined sample and in farmer groups were removed from further analysis. Significance level $P < 0.05$.

4.4.3 Leaf and rachis analysis

Leaf and rachis samples from 118 plantations were analysed to assess nutrient deficiencies (Table 4.3). Although there are some significant differences, our results indicate that the tissue concentrations of the different macro-nutrients (apart from Mg) were below the critical leaf and rachis concentrations on average for all sampled smallholder types, with especially K concentrations in leaf and rachis appearing very low. Peat farmers performed relatively well, and differences among farmers on mineral soils were minimal. Concentrations of micro-nutrients such as copper and boron were on average above critical values, except for copper in the plantations of large peat investors.

Table 4.3 Leaflet and rachis analysis and planting density per farmer type. SLF = Small Local Farmers, MLF = Medium Local Farmers, LRF = Large Resident Farmers, SMF = Small Migrant Farmers, MMF = Medium Migrant Farmers, SMPF = Small & Medium Peat Farmers, LPI = Large Peat Investors, DM = dry matter, *s* = standard deviation. Critical nutrient levels are from Fairhurst and Mutert (1999) for leaflets and from Foster and Prabowo (2006) for rachis. The critical values are for palms > 6 year after planting; they are slightly higher for younger oil palms.

		Critical value	SMF	MLF	LRF	SMF	MMF	SMPF	LPI	F Values (ANOVA)
Leaflet N	Mean	2.3	2.14^{a}	2.13^{a}	2.17^{a}	2.19^{a}	2.17^{a}	2.22^{a}	2.24^{a}	2.620*
(% DM)	*s*		*0.09*	*0.08*	*0.11*	*0.11*	*0.08*	*0.11*	*0.12*	(6, 111)
Leaflet P	Mean	0.14	0.13^{a}	0.14^{ab}	0.14^{ab}	0.13^{ab}	0.14^{ab}	0.15^{bc}	0.15^{c}	7.063**
(% DM)	*s*		*0.01*	*0.01*	*0.02*	*0.01*	*0.02*	*0.02*	*0.01*	(6, 111)
Leaflet K	Mean	0.75	0.71^{a}	0.60^{a}	0.66^{a}	0.63^{a}	0.66^{a}	0.71^{a}	0.79^{a}	1.864
(% DM)	*s*		*0.28*	*0.18*	*0.12*	*0.10*	*0.07*	*0.13*	*0.01*	(6, 111)
Leaflet Mg	Mean	0.20	0.26^{a}	0.37^{ab}	0.29^{a}	0.34^{ab}	0.33^{ab}	0.39^{b}	0.42^{b}	5.460**
(% DM)	*s*		*0.11*	*0.09*	*0.12*	*0.10*	*0.07*	*0.12*	*0.11*	(6, 111)
Leaflet B	Mean	8.0	10.3^{ab}	10.4^{ab}	12.2^{ab}	10.0^{a}	10.6^{ab}	13.4^{b}	13.0^{ab}	3.102**
(mg kg^{-1})	*s*		*1.7*	*2*	*3.5*	*1.5*	*2.2*	*6.8*	*3.1*	(6, 111)
Leaflet Cu	Mean	3.0	3.9^{a}	4.7^{a}	3.9^{a}	4.0^{a}	4.3^{a}	4.0^{a}	2.8^{b}	5.914**
(mg kg^{-1})	*s*		*1.1*	*1.1*	*0.8*	*1.0*	*1.1*	*1.2*	*0.7*	(6, 111)
Rachis P	Mean	0.09	0.07^{ab}	0.06^{a}	0.06^{a}	0.05^{a}	0.07^{a}	0.08^{ab}	0.13^{b}	5.673**
(% DM)	*s*		*0.07*	*0.03*	*0.03*	*0.02*	*0.03*	*0.05*	*0.07*	(6, 111)
Rachis K	Mean	1.1	0.63^{a}	0.57^{a}	0.58^{a}	0.57^{a}	0.65^{a}	0.61^{a}	0.89^{a}	1.833
(% DM)	*s*		*0.36*	*0.23*	*0.28*	*0.20*	*0.29*	*0.37*	*0.46*	(6, 111)
Density	Mean		143.2^{a}	136.6^{ab}	134.0^{b}	142.6^{ab}	140.2^{ab}	137.3^{ab}	135.9^{ab}	2.643*
(palms ha^{-1})	*s*		*14.9*	*11.6*	*13.1*	*11.1*	*12.5*	*12.5*	*9.9*	(6, 224)

4.4.4 Good agricultural practices in smallholder plantations

In company plantations the layout usually entails a harvesting path between every two rows of palms followed by a *pasir mati*, or row with pruned dead leaves. The leaves may be stacked in a row or in a U-shape around the palms, with the open end towards the harvesting paths. Neat rows or U-shapes facilitate easy access in the plantation, increase nutrient recycling and provide ground cover. Neat stacks were encountered more frequently in plantations on mineral soils than on peat soils, but differences between farmer types were not significant (χ^2 = 10.911, df = 6, P = 0.091; see Figure 4.6 for details on implementation of GAP). Significant differences among farmer types were observed regarding the presence of harvesting paths every second row (χ^2 = 13.317, df = 6, P = 0.038), with small local and medium local and medium migrant farmers less likely to have harvesting paths every second row compared to especially small-medium peat farmers and large resident farmers. Although some palms may be less accessible due to lack of structured paths, access for harvesting within the plantations was generally good and there were no significant differences among farmer types (χ^2 = 7.743, *df* = 6, *P* = 0.258). Farmers on mineral soils had slightly better access within their plantations compared to peat farmers (see Figure 4.6). This was mostly due to problems with waterlogging and excessive weed growth in plantations on peat.

Survey data indicated that bare soils, which are prone to erosion and fertiliser run-off, were absent in 80%–91% of the plots, without significant differences among farmer types (χ^2 = 3.369, *df* = 6, *P* = 0.761). This was in line with expert photo interpretations. Legume cover crops, which can fix nitrogen and suppress undesirable weeds such as *Imperata* and *Chromolaena*, were observed only in one farm (large resident farmer). Weeding was common practice among all smallholder types (χ^2 = 4.357, *df* = 6, *P* = 0.629). There were differences in weeding methods between farmer types: manual or mechanical weeding were preferred by especially small local farmers and to a lesser extent by the other farmer types on the mineral soils (χ^2 = 16.647, *df* = 6, *P* = 0.000), whilst peatland farmers were significantly more likely to implement chemical weeding (χ^2 = 26.327, *df* = 6, *P* = 0.000). Absence of woody shrubs was used as an indicator of good weeding practices, but most plantations did contain woody weeds (χ^2 = 8.996, *df* = 6, *P* = 0.174). Small local plantations were most commonly infested, with only 24% not having woody shrubs in their fields. In some large peat farms woody shrubs were difficult to spot as non-woody weeds covered everything. Circle weeding was common, and while small local farmers and large peat farmers were least likely to establish weeded circles, the differences among farmer types were not significant (χ^2 = 11.292, *df* = 6, *P* = 0.080). Similarly, there were no significant differences in pruning practices among farmer types (χ^2 = 5.825, *df* = 6, *P* = 0.443).

Regarding harvesting, we observed significant differences among farmer types, with large resident farmers and large peat farmers appearing more likely to adhere to harvesting cycles of 10 days or less compared with all other types (< 7%). Although more frequent harvesting cycles can be an indicator of high yields (e.g. Lee et al., 2013), we did not find significantly better yields among the larger farmer types. It may be that the harvesting frequencies from large farmers were inflated because of misinterpretations as larger farmers usually harvest more frequently due to their larger area, while in fact they are not harvesting the same palms more than once every two weeks. Excluding the large farmers, harvesting frequencies appeared very similar among remaining farmer types, with 97–100% indicating that they harvested every 14 days or twice per month.

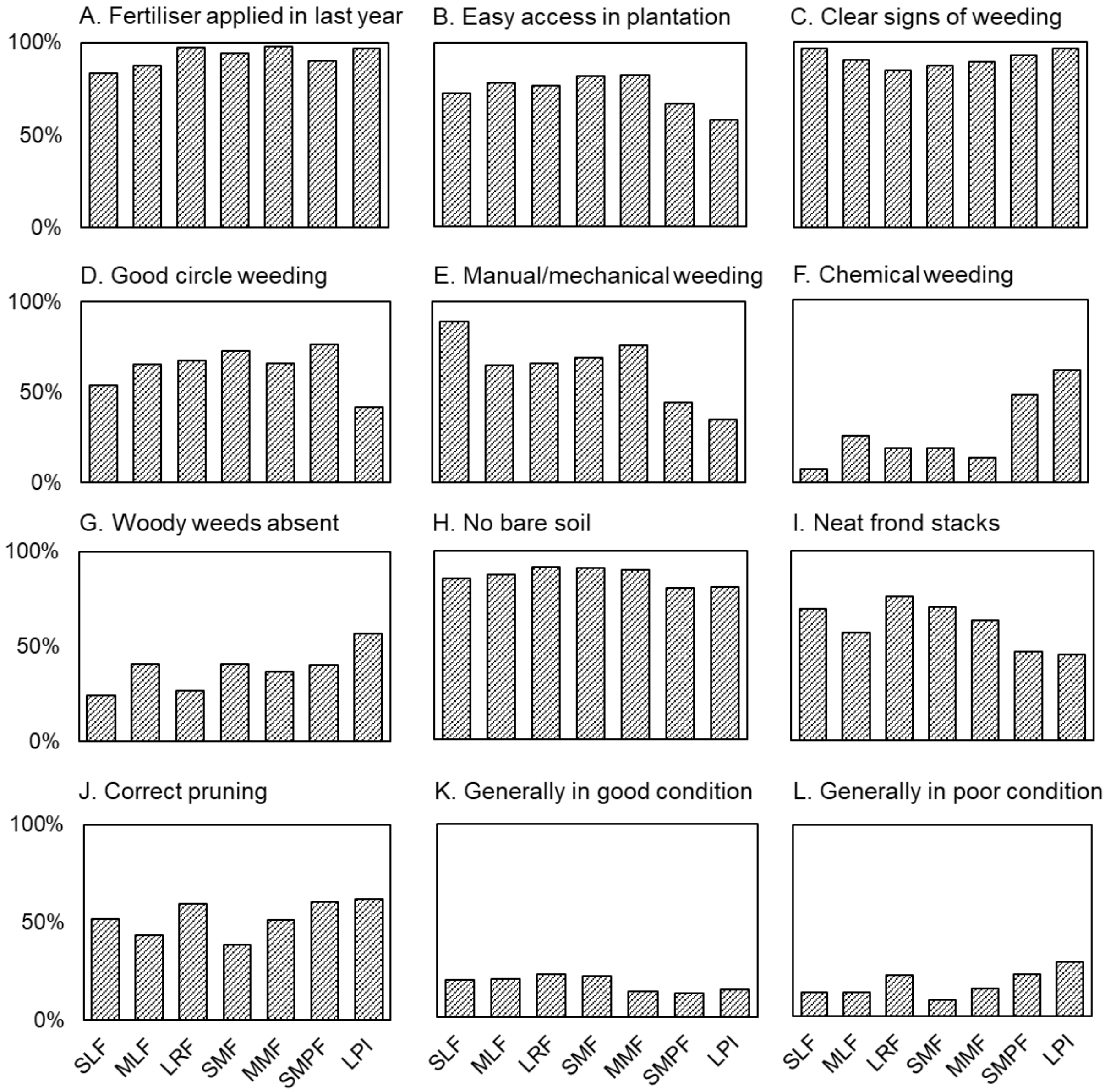

Figure 4.6 Share of farmers per farmer type that implement GAP. SLF = Small Local Farmers, MLF = Medium Local Farmers, LRF = Large Resident Farmers, SMF = Small Migrant Farmers, MMF = Medium Migrant Farmers, SMPF = Small & Medium Peat Farmers, LPI = Large Peat Investors. Y-axis indicates percentage of farmers, x-axis shows farmer types. Sub-figures 6K and 6L refer to expert photo assessments of management practices.

Overall plantation scores by experts indicated only limited differences in plantation condition between farmer types (Figure 4.6). When averaging the assessments of all three experts for all farmer types, 17% of plantations were assessed to be in poor condition, 65% in reasonable condition and 18% in good condition. Whereas large resident farmers had the highest share of plantations in good condition (22%), they also had the second highest score on plantations in poor condition (21%). Large peat investors were assessed worst with on average 29% of plantations being assessed as in poor condition. Wilcoxon Signed Ranks Tests indicate no significant differences among expert assessment and two of the three experts did not see significant differences amongst farmer types (χ^2 = 9.186, *df* = 12, *P* = 0.687 and χ^2 = 12.205, *df* = 12, *P* = 0.439 respectively). Only the farmer expert indicated significant differences between farmer types (χ^2 = 27.290, *df* = 12, *P* = 0.007), with conditions in large peat farmers plantations being assessed significantly poorer compared with other farmer types (Supplementary Materials S4.6).

There are conditions which are difficult and costly for individual farmers to correct once the plantation has been established. These conditions and differences amongst smallholder types are shown in Figure 4.7. With regards to topography, the sampled smallholder plantations were fairly similar: most were flat or slightly hilly, with only a few large resident farmers and medium migrant farmers partially operating on steeper slopes. Terraces or other soil conservation measures were not present in the few plantations on steep slopes. Figures 4.7D and 4.7F show that feeder roads (linking plantations to main roads) and main roads in the peatlands are of significantly poorer quality than the roads on mineral soils (χ^2 = 7.204, *df* = 6, *P* = 0.302 and χ^2 = 45.842, *df* = 6, *P* = 0.000 respectively).

There were significant differences in planting patterns between farmer types. The vast majority of large peat farmers implemented correct triangular patterns, compared with only 33.3% of the small local and small migrant farmers (χ^2 = 31.908, *df* = 6, *P* = 0.000). With 143.2 palms ha^{-1} on average, small local farmers tended to plant fairly densely and significantly denser than large resident farmers, who had the lowest average density with 134.0 palms ha^{-1} (Table 4.3). Although we observed some variation in planting densities within farmer types, average planting densities per farmer type were quite similar and in line with commonly recommended planting densities of 136–143 palms per hectare (Uexküll, 2003). Monocropping was standard practice among all smallholder farmer types (χ^2 =

4.381, *df* = 6, *P* = 0.625), but with some pineapple cultivation observed in peatlands and rubber and cocoa intercropping observed on mineral soils.

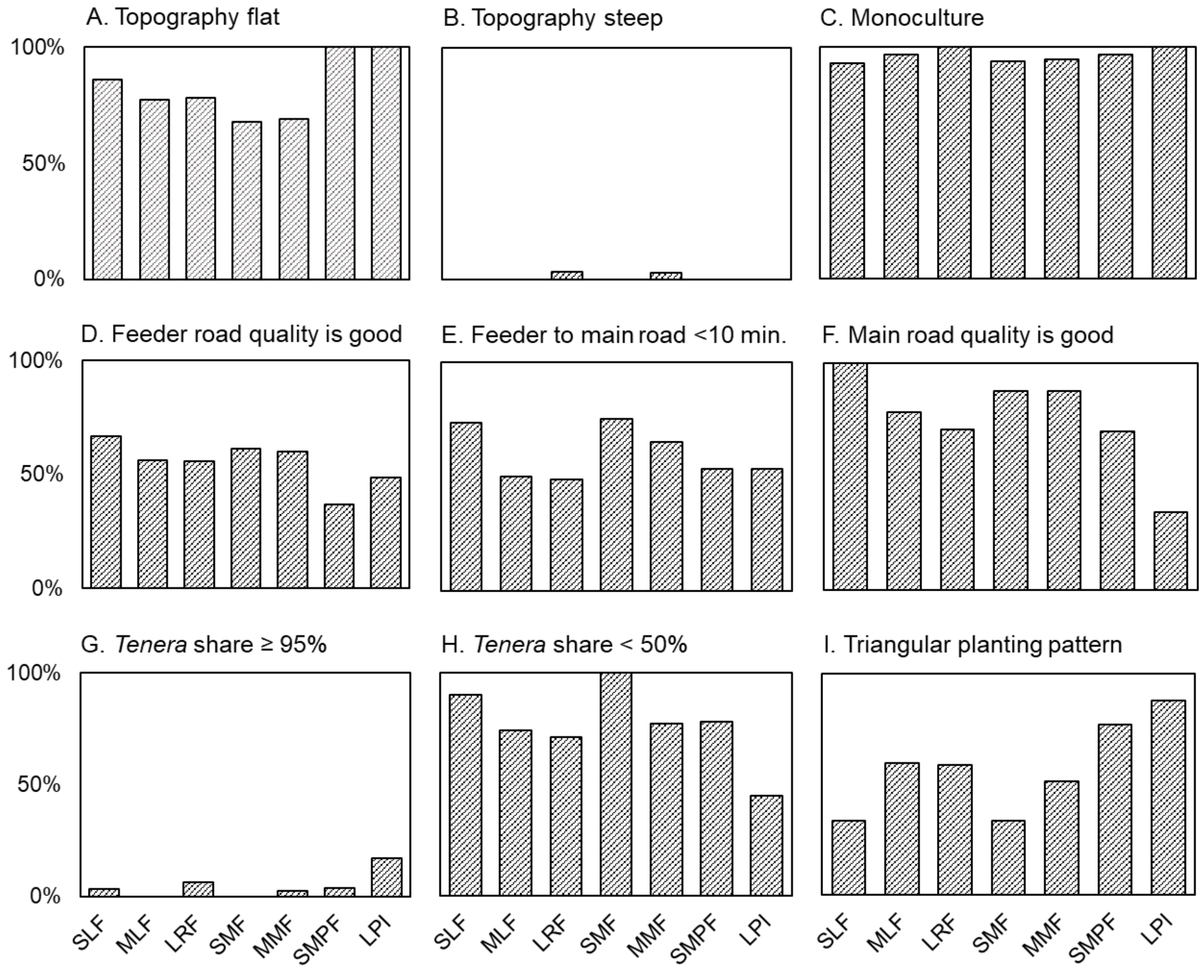

Figure 4.7 Semi-permanent plantation conditions among different farmer types. SLF = Small Local Farmers, MLF = Medium Local Farmers, LRF = Large Resident Farmers, SMF = Small Migrant Farmers, MMF = Medium Migrant Farmers, SMPF = Small & Medium Peat Farmers, LPI = Large Peat Investors. Y-axis indicates percentage of farmers, x-axis shows farmer types.

Planting material data highlights that *dura* palms were common among all farmer types. Most plantations had more than 50% *dura* palms on average. Smaller and medium farmers on several occasions mentioned *dura* fruits desirable as the large kernels are heavy and farmers are paid per kilo by the middlemen, rather than for fruit quality. However, on mineral soils (only) a linear regression model indicated that bunch numbers significantly increase with share of *tenera* in plantings (Supplementary Materials S4.7). The share of farms with > 95% *tenera* fruits was low among all farmer types but there were significant differences, with 17% of larger peat farmers and 7% of large resident farmers having > 95% *tenera*, while medium local or small migrant farmers never had > 95% *tenera* fruits (χ^2 = 14.025, *df* = 6, *P* = 0.029; Figure 4.7). A share of > 50% *dura* palms was common among especially small local and small migrant farmers and differences among farmer types were significant, with large farmers performing better (χ^2 = 28.283, *df* = 6, *P* = 0.000).

4.5 Discussion

Our results on fertiliser application practices, nutrient balances and tissue nutrient concentrations show that nutrient application rates among the various farmer types were limited, particularly for K. Potassium deficiencies were common in our sample and have been observed in samples from independent smallholder plantations in Jambi and West Kalimantan (Woittiez et al., 2018b). Active knowledge dissemination on the importance and necessity of balanced nutrition for good productivity in oil palm, combined with efforts to make the required fertilisers accessible to, and affordable for independent smallholders, are important measures to improve the nutritional status and productivity of smallholder plantations. Trainings on the specific nutrient requirements of plantations on peat would be an example of a targeted measure to increase efficient use of fertilisers. The application of empty bunches was uncommon among all smallholder types, indicating that there is space to improve nutrient cycling and reduce nutrient outflow from smallholder plantations. Besides educating farmers about the well documented advantages of empty bunch application (Comte et al., 2013; Woittiez et al., 2018a), improving linkages between mills and farmers and promoting the return of empty bunches to smallholders appears a worthwhile strategy to improve nutrient balances and soil management of smallholders. We found it striking that five of the seven farmers who did use empty bunches were large farmers, who have better direct access to mills compared to small and medium farmers who usually sell to middlemen and have no direct link with mills (Jelsma et al., 2017a). Whereas Soliman (2016) claims that fertiliser usage does not need to increase, based on N application only, results in this study show that N rates on average indeed appear enough for large resident and migrant farmers to produce 20 t fruit bunches ha^{-1} year^{-1}, but that in general quantities of nutrients provided are too limited to produce and sustain large yields.

Planting materials were often of substandard quality, limiting the potential for yield increases through the implementation of GAP. Besides limiting fruit bunch yield potential, *dura* bunches also contain around 30% less oil (Corley and Tinker, 2016), thereby reducing oil yields substantially. This partially explains low fruit bunch prices for farmers, as middlemen generally do not differentiate in prices for quality or variety of bunches delivered by individual farmers (Jelsma et al., 2017a). *Dura* palms were particularly prevalent in plantations of small local and small migrant farmers, often in combination with square planting patterns. These farmers often use uncertified planting materials, which are easily available as either loose fruits or via illicit seedling traders who are not hindered in their activities by the local authorities. Large farmers appear to have better access to official seedling producers and have more capital available for planting material. During discussions with leading seed producing companies in the 2018 annual GAPKI meeting, we were informed that efforts of companies to reach out to independent smallholders are limited to providing seeds at a reduced price. The crucial aspect of easy and local access, including administrative requirements and costs, remains a key obstacle for smallholders to purchasing certified planting materials. Only the Indonesian Oil Palm Research Institute regularly went to villages with three cars and sold seeds in Sumatra (Personal interviews, 1–3 November 2017). Industrial oil palm producers, banks and the Government of Indonesia, through the CPO fund (DJP, 2017a), do support replanting efforts for smallholders. We recommend carrying out awareness campaigns which demonstrate potential yield losses due to poor planting material and incorrect planting patterns, and which highlight the relatively limited costs of high-quality planting materials. We also recommend increasing the number of distribution centres with high-quality planting materials, banning non-certified seedling sellers, and possibly subsidising proper planting material. However, impacts on current farmers will be limited as palm stands are often young. Especially smaller and poorer farmers are unlikely to cut their young palms and accept an additional three years without income until their palms yield again. The negative effects of square planting patterns, which significantly reduce the growth and yield potential of the palms due to reduced availability of sunlight, can be reduced however by selective thinning (Uexküll et al., 2003) and rigorous pruning. Although there is support through the CPO fund, the chairman of the union of smallholder oil palm farmers has expressed its fear of 'plasmafication' of independent smallholders (SPKS, 2018), referring to being locked into undesirable relations with companies, banks and the bureaucracy; this is a key reason why the previous Revitalization policy, aimed at supporting smallholders with replanting, failed (Zen et al., 2016).

Good planting and nutrient application practices need to be accompanied by other GAP if intensification of the smallholder sector is to be achieved. Our results show that pruning, weeding, use of legume cover crops, and frond stacking practices are similar among all farmer types, and generally require improvement. Knowledge transfer to smallholders on good practices in oil palm cultivation has been limited in our research areas, with farmers receiving very little formal training, and with most knowledge coming from their input suppliers and their fellow farmers (Jelsma et al., 2017a; Woittiez et al., 2018a). Although the organisation of smallholders into cooperatives or groups is a key condition for RSPO or ISPO certification, and while there is evidence that organised oil palm smallholders can maintain high-input high output systems (Jelsma et al., 2017b), there are many barriers to improving practices. In Indonesia the extension services are weak, knowledge on GAP and certification is not widely available, and strong institutional structures through which knowledge can be readily distributed among smallholder farmers are rarely in place (Brandi et al., 2015; Hidayat, 2017). To add to this complexity, strategies need to be tailored to specific types of farmers in order to be effective. Ideally this would constitute easy access to quality information via local farmer training centres run by companies in collaboration with governments to support small and medium farmers, who mostly reside locally. Large peat investors might require a different approach as the scale of their activities is much larger and their environment poses different challenges. Yields in peat plantations were significantly less, which may be attributable to higher degrees of absenteeism, speculative investment decisions, difficulties in collecting fruit bunches due to flooding in the rainy season and other agro-ecological difficulties of peat soils relative to mineral soils for cultivating oil palm.

Although a straight comparison is difficult due to different methodologies, there are clear similarities in the types of farmers identified by McCarthy and Zen (2016) and the types used in our study. The 'prosperous farmers' identified by McCarthy and Zen (2016) appear similar to the large farmer types identified in Jelsma et al. (2017a) as they have considerable land holdings and considerable capital but still use poor planting materials, as they lack access to certified planting materials. The poor farmers mentioned by McCarthy are mainly local Melayu farmers who are '…trapped between their on-farm activities and work as labourers, with little time to invest in improving their plots', and indeed especially small local farmers appear to use least fertilisers or herbicides. Medium local and medium migrant farmers could be associated with progressive farmers mentioned by McCarthy and Zen (2016), as they have larger oil palm holdings compared to poor farmers, frequently have other jobs as e.g. civil servants and hardly work as labourers (Jelsma et al., 2017a). However, although McCarthy claims that prosperous farmers invest more in fertilisers and labour, and thus have relatively better yields than poor or progressive farmers, we did not find evidence for this. For this reason, we believe that improving enabling conditions for implementation of GAP is relevant for all farmer types.

The lack of technical and institutional support regarding the management of smallholder plantations needs to be placed in a broader framework of constraints hindering the implementation of GAP and yield intensification. Poorly developed and maintained infrastructure such as roads and waterworks hamper intensification. Among large peat farmers the lack of coordinated drainage systems was problematic. For the more remote farmers on (hilly) mineral soils the infrastructure was especially poor. These areas were relatively often occupied by larger farmers and during surveys and interviews, caretakers indicated that during the rainy season not all fruits were harvested due to poor accessibility of parts of their plantations. Besides flooding, the frequent occurrence of fire in peatlands increases the risks for farmers on loss of investments (Gaveau et al., 2014b; Purnomo et al., 2017). Such major risks do not provide a conducive environment for investments in GAP. Measures such as infrastructure development and fire prevention are relevant prerequisites for the implementation of GAP and for yield intensification.

Labour is known as a key constraint for intensive smallholder oil palm cultivation (Soliman et al., 2016) and appears to be a key reason why farmers prefer oil palm over rubber (Feintrenie et al., 2010a; Euler et al., 2017). A sufficiently large and well-trained labour force is a requirement for the implementation of GAP, labour issues are also a concern for companies, with rising labour costs being the 'silent killers' of profitability as productivity barely increased over the past 20 years (Liwang, 2017). Labour costs are relevant for smallholder oil palm farming as many of the surveyed farmers employed labourers as well (Jelsma et al., 2017a). As workers are paid at a piecemeal rate, their interest is in harvesting or pruning as many palms as possible in the shortest possible timeframe rather than in performing activities well. For this reason, the implementation of GAP would require considerable monitoring by farmers. Benefits associated with smallholder farming, such as ease of monitoring the fields and having a direct interest in production (Hayami, 2010; Hazell et al., 2010; Bissonnette and De Koninck, 2017), appear to be only of limited relevance for certain smallholder oil palm farmer types. This highlights the grey area between smallholders as family farmers and as company plantations (Bissonnette and De Koninck, 2017). The grey area was strongly observed in the peatlands, where managers of large farmers often complained about the limited number of workers (mostly migrants who were housed in barracks on the plantation). With peat farmers often residing outside the district (Jelsma et al., 2017a), labour and monitoring appear issues in the frontier, complicating the implementation of GAP.

We believe that further research is required to determine to what extent smallholder oil palm is cultivated for income from yields or for speculative purposes, as transforming 'empty lands' into oil palm plantations provides profits for many actors (e.g. Prabowo et al., 2017; Purnomo et al., 2017). Many plantations in the peatlands are located within the forestry domain and neither companies nor government are legally allowed to support farmers in these illegally obtained lands. Land documents of especially peat farmers and local farmers, and to a lesser extent migrant farmers, are often not fully recognised by the state (Jelsma et al., 2017a). This creates risks for the owners and reduces the interest in yield intensification measures, which take time before the investments pay off. Intensification is especially relevant when populations are increasing, and land is scarce, but this is not the case in large parts of the Indonesian outer islands. In Rokan Hulu logging and oil palm companies recently developed the infrastructure necessary to open new lands, and land is now more easily available than labour (Feintrenie et al., 2010a). Although for large companies opportunities for expansion are limited nowadays, there still are plenty of smaller 'empty' lands which appear to be grabbed by relatively small-scale investors (Susanti and Maryudi, 2016; Bissonnette and De Koninck, 2017). Whilst the goal of intensification for land saving appears worthwhile, a Jevons paradox lurks as intensification makes it more interesting to transform land into oil palm. Intensification programs therefore need to be accompanied with proper land use regulations, monitoring and enforcement, if the aim is to improve sustainability of the sector.

In this research, multiple methods were used to assess performance of the different types of smallholders. Uncertainties associated with surveys are that farmers often do not maintain farm records, and true plantation sizes are often slightly different compared to what smallholders mention. Yield estimates based on black bunch counts are prone to errors in field assessments (it is known ripe bunches were included, slightly inflating yields). These issues reduce the reliability of yield calculations. Nutrient balances and leaf and rachis analysis are common methods to assess nutrient conditions in company oil palm plantations. However, although the single critical values can provide indicators for the nutritional status of palms, in fact these thresholds are not static as nutrient concentrations vary with palm age, conditions and environment. Commonly used critical values are often developed in older planting materials and should therefore be taken as indicative only and interpreted together with yield and fertiliser application data and visual symptoms in the field (Fairhurst and Mutert, 1999; Corley and Tinker, 2016). However, as the main objective of this study was to compare performance of different types of smallholders and not to develop targeted fertiliser regimes, the values provided are sufficient to use as a benchmark. Photo interpretations allowed different experts to share their expertise and assess plantations but cannot replace field visits. The diversity of tools applied in this study proved sensitive enough to detect differences among a broad range of smallholder types and the landscapes in which they operate, and provide a fairly consistent overview of smallholder plantation conditions. Results indicate much space for improvements in independent smallholder practices and are in line with previous publications (Molenaar et al., 2013; Soliman et al., 2016; Woittiez et al., 2018a).

4.6 Conclusions

The independent smallholder oil palm sector can be portrayed as the Achilles heel for the oil palm sector's sustainability. Although our research included a wide variety of farmer types, differences between farmer types in the adoption of GAP were limited, and we observed poor yields among all independent smallholder types in this study. Our results suggest that the notion that larger, more capitalised farmers are significantly more likely to invest in GAP does not hold. The underlying reasons are plentiful. Small local and migrant farmers are locked in a system that is not amenable to investment and can have limited yield potential due to poor planting patterns and materials. Recent programs aimed at increasing access to finance for purchasing proper planting materials or fertilisers could increase yield potential with these groups. However, seeing that larger farmers for whom financial capital is comparatively accessible are not more likely to invest in GAP than smaller less capitalised farmers, it is uncertain that enhancing access to finance will lead to significant changes in practice. Farmer choices are informed by a complex amalgam of factors including, but not limited to, access to labour and knowledge, alternative crops and livelihoods, quality of infrastructure, fire threats, legal status of plantations, land markets, government policies and changes therein, market access and price uncertainty of the crop, and other risk assessments farmers make. While we acknowledge the limitations of our research (e.g. sample size, limited geographical coverage), our results show that under current conditions smallholders across the board prefer a low-input low-output strategy, for various reasons. This poses a significant challenge for initiatives such as ISPO, RSPO and other promotors of GAP, and could result in increased marginalisation of independent smallholders if sustainability thresholds are raised. In order to support further GAP implementation, we recommend future research to identify and quantify farmer aspirations and strategies as they relate to intensification, and to employ approaches that acknowledge farmers' diversity and the environments in which they operate. These approaches should also acknowledge that certain 'types of farmers', e.g. poorly performing peat farmers who operate in the forestry domain on recently deforested land, might have to be excluded from the value chain to improve sector sustainability. Linking performance to land reclassification and legalisation in peatlands might be a pathway to increase sector sustainability as well. Meanwhile, policy makers should increase efforts to make proper planting materials and knowledge on GAP available to smallholders, as a first requirement for intensification. Government bodies and NGOs should look for support from industry partners who have the technical expertise and who can be an important source of investment into the sub-sector. If sustainability of the sector is to be improved, it is imperative however to look beyond implementation of GAP, and there is a clear need to acknowledge the broader context in which farmers operate.

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Supplementary materials

S4.1a 20 palms field audit

Palm	Abnormal or missing	*Dura*	*Tenera*	Black Bunch Count	Deficiencies			
					P	K[a]	Mg	B
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								

[a] The data confirm frequent K deficiencies, but these data were not further used in the article.

Scoring system

- P deficiency: 2 = trunk strongly resembles bottle shape; 1 = bottle shape observed but limited; 0 = no bottle shape.
- K deficiency: 2 = strong leaf symptoms, 1 = some leaf symptoms, 0 = symptoms (almost) absent.
- Mg deficiency: 2= symptoms on > two leaves, 1 = symptoms on one leaf, 0 = symptoms absent.
- B deficienct: 2= symptoms on > two leaves, 1 = symptoms on one leaf, 0 = symptoms absent.

S4.1b Field audit form

Digital form using Samsung Tablets and ESRI software (see Jelsma et al. 2017a), with which photos could be added to the survey.

No.	Subject		Answer[a.]
1	Soil composition	Clay much	
		Clay some	
		Clay none	
		Sand much	
		Sand some	
		Sand none	
		Peat much	
		Peat some	
		Peat none	
2	Topography	Flat	
		Slightly hilly	
		Steep	
3	Water works	Clean canals	
		Dams present	
		Dams regularly present	
		Water table level good (30–70 cm below ground)	
		Water table level to high (less than 30 cm below ground	
		Water table level to low (more than 70 cm below ground)	
4	Feeder road quality	Quality good (not many holes and easily accessible, bridges well passable)	
5	Main road quality	Quality good (not many holes and easily accessible, bridges good enough)	
6	Distance feeder to main road	Less than 10 minutes by motorbike	
7	Harvesting path:	Present every two rows	
		Harvesting path 50 cm wide at least	
		Harvesting path easy access	
8	Clear signs of weeding		
9	Circle weeding good		
10	Loose fruits present in circles		
11	Woody shrubs present		
12	Other crops present in plantation		
13	Bare soils common in plantation		
14	Cover crops present		
15	Front stack size	Size small	
		Size medium	
		Size large	
16	Front stack in U shape or neat rows	Row	
		Shape U	
17	Pruning correct number of leaves	If you see frequent over-pruning or under-pruning in plantation (more than 30%) mark as not correctly pruned	

18	Front butts correctly pruned	If you see frequent over-pruning of front butts or under-pruning in plantation (more than 30%) mark as not correctly pruned	
19	Canopy cover	Cover closed	
		Canopy cover reasonably open	
		Canopy cover open	
20	Oil palms have similar age		
21	Estimate of palm age (years)		
22	Estimate of bunch weight (kg)		

[a.] 0 for no, 1 for yes unless indicated otherwise

S4.1c Farmer survey

Date:

Survei tanah dan Rumah tangga – Proyek LIFFE Options

Interview Information

Name interviewee	
Name respondent + no. tel.	
Name location sub-district in which plot is located	
Address plot owners (village)	
Cell no.	
Plantation no.	

1. Area and productivity

a. How many hectares of productive oil palms do you have at this location?

b. What is the productivity of your oil palms at this location?

	Volume (kg/harvest)	Frequency of harvesting
Low season		
High season		

c. How many hectares of oil palm do you own in total? (Include from other places as well)

2. Establishing the plantation

a. Did you plant or buy the plantation? (circle your answer)

b. What year did you buy/plant your plot? What was the price/ha?

c. From where did you obtain planting material?

I. Local agent without certificate
II. Local agent with certificate
III. Bought straight from an official oil palm seed company
IV. Don't know
V. 'Brondol' (took fruits from other oil palms and planted this)

d. If you did not buy Marihat or from another official producer, what is the reason for that?

I. No access to an official producer
II. No money to buy from an official producer
III. Other
IV. Not relevant

e. Are you involved in 'land sharing' in your plot? Yes/No

f. Are you involved in 'harvest sharing'? Yes/No

g. Please indicate who performed the following activities (but a V to indicate yes)

	Open land for starting the plantation	Develop infrastructure	Maintain infrastructure	Develop drainage system	Planting	Organise labour in the plantation	Selling of fruit bunches
Individually							
Collectively with family and/or friends							
Collectively with previously unknown people							
Government							
Contractor[a.]							
Don't know							

[a.] If by contractor indicate who paid the contractor

3. Fertiliser application

a. Fertiliser application

Indicate which fertilisers you have used in the past three years, when you used them, how much you applied and what your source is. Work from top to bottom and left to right

Fertiliser name	Last application (month and year)	How frequent per year	How much		Source of Fertiliser: (See Code A)
			Per oil palm	Per ha	
□ Urea					
□ SP36					
□ ZA					
□ Dolomite					
□ KCl					
□ NPK Phonska					
□ NPK Mutiara					
□ Pupuk NPK other:					
□ Triple Super Phosphate (TSP)					
□ Kieserite					
□ Borax/Boron					
□ Copper sulphate					
□ Zinc sulphate					
□ Empty Fruit Bunches					
□ Animal dung					

□ Other					

Code A 1. Individually at the marker/shop, 2. Oil palm company/mill, 3. Cooperative or group which is officially recognised and provides subsidised fertilisers, 4. Informal farmer groups, friends, shared purchase with other farmers, 5. Government. 6. Others (indicate)…………………..
7. Not relevant

b. Access to fertilisers:
   I. In your opinion do you provide enough fertilisers? Yes/No
   II. In your opinion do you provide fertilisers timely? Yes/No
   III. In your opinion is the quality of fertilisers good (not false)? Yes/No
   IV. From who do you receive information concerning fertiliser management (quality & quantity)? (choose from Code A)

4. Work in the plantation and sales of fresh fruit bunches

a. Types of activities performed by whom?

Activity	Direct household	Other family or friends	Outside labourers
Provide fertilisers			
Harvesting			
Pruning			
Weeding			
Organise daily activities (For large farmers only)			

b. To whom do you sell your fresh fruit bunches? (encircle correct one)

Small middleman (sells to large middleman)	Large middleman (sells straight to mill)	Straight to mill with Delivery Order	Other

c. What is the current price per kg of fruit bunches you receive? Rp. ………………

5. Social economic position

a. What are your other sources of income besides oil palm.

Civil servant	
Employee	
Labourer	
Other non-farming activities (e.g. shop keeper)	
Other farming	

b. Can you indicate how important oil palm is for your total income? (Check if yes)

0%	25%	50%	75%	100%

c. Did you migrate to this area? (Yes/No)

d. If yes, did you migrate for oil palm? (Check if yes)

No	
Yes, to become an oil palm employee/labourer	
Yes, to become an oil palm farmer	

e. Before you started this plantation, did you have experience in oil palm already? (Check for yes)

No	
Yes, as a labourer in a company	
Yes, as a non-labourer in a company	
Yes, as a farmer	

f. What did you do before you were an oil palm farmer? (Check for yes)

Cultivate another crop	
Government employee	
Private sector employee	
Worker in farm	
Business owner/entrepreneur	
Other…………………	

g. From where did you get the capital to start your plantation? (Check for yes)

Private capital	
Bank	
Social funds/assistance	
Other………………………	

h. What land ownership documents do you possess? (Check for yes)

Village level letter	
Sub-district level letter	
Certificate/ National level letter (BPN)	
Land lease from government (HGU, Hak Guna Usaha)	
No official land documentation	

S4.2 Two examples of photos from plantations, expert assessments, survey data and calculations of input to BBC yield assessments.

Photo examples from cell 64933: Large Peat Investor (LPI), waterlogged plantation. The plantation pictures indicate generally poor management (e.g. poor (circle) weeding and access within plantation, waterlogging). The picture left under shows hooked leaves, which is an indicator of boron deficiency.

		Age estimate	Yield estimate		Plantation condition	Bunch weight	
		Years	Category	kg ha^{-1} year^{-1}		Category	Translated to kg bunch^{-1}
Expert assessment	Academic	3.0	0	0	1	0	0
	Farmer	5.0	1	5000	1	1	3.0
	CIRAD	4.0	1	5000	1	1	3.0
	Combined	4.0	.67	3333	1	.67	2.0
Survey estimate		4.0		1415			3
BBC yield benchmark[a.]		4.0	Not relevant	Not relevant	Not relevant	Not relevant	2.5

[a.] Values used for BBC yield benchmark against production curve ((survey + average expert estimate) / 2)

Example of photos from cell 37836, a Small Migrant Farmer's plantation in Central Rokan Hulu, with generally proper management but high share of *dura* fruit producing palms.

		Age estimate	Yield estimate		Plantation condition	Bunch weight	
		Years	Category	kg ha^{-1} year^{-1}		Category	Translated to kg bunch^{-1}
Expert assessment	Academic	15	5	25000	3	4	17.5
	Farmer	10	4	20000	3	3	12.5
	CIRAD	10	4	20000	3	4	17.5
	Combined	11.7	4.3	21667	3	3.7	15.8
Survey estimate		9		17033			12
BBC yield benchmark[a.]		10.3	Not relevant	Not relevant	Not relevant	Not relevant	13.9

[a.] Values used for BBC yield benchmark against production curve ((survey + average expert estimate) / 2)

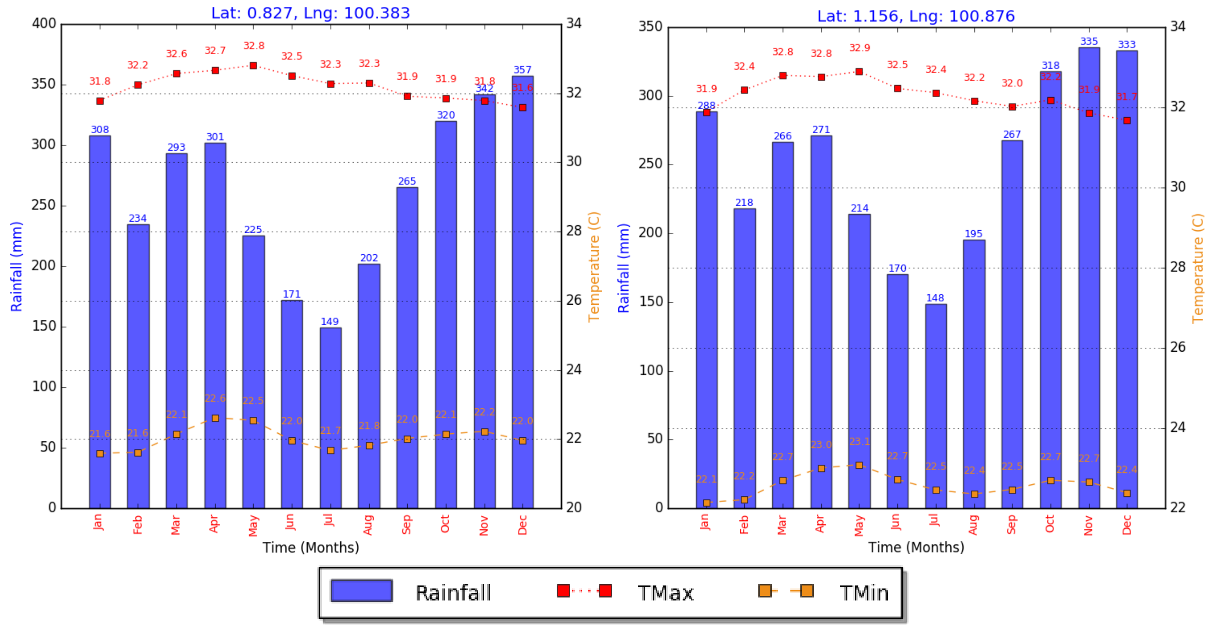
S4.3a Correction factors applied based on yields from nearby corporate plantations

	Percentage (%) of yearly yield											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PT. 1, 2014	8.4	5.3	6.4	7.1	7.0	6.5	8.9	10.7	10.1	12.0	10.0	7.8
PT. 1, 2015	7.6	5.4	6.3	6.4	6.7	6.6	7.9	14.3	11.4	10.4	8.6	8.3
PT. 2, 2013	7.5	6.7	6.4	7.4	6.6	6.8	9.6	9.9	10.0	9.6	9.6	9.9
PT. 2, 2015	8.0	6.4	8.5	7.4	7.5	7.8	9.4	12.7	10.5	8.6	6.9	6.3
PT. 3, 2014	5.9	6.2	6.6	6.9	6.3	7.2	9.8	10.0	10.2	10.0	10.3	10.5
Average PT.	7.5	6.0	6.8	7.1	6.8	7.0	9.1	11.5	10.4	10.1	9.1	8.6
Theoretical average	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Moving 4-month means	27	27	28	30	34	38	41	41	38	35	31	29
Correction factor	1.22	1.25	1.20	1.11	0.97	0.88	0.81	0.81	0.87	0.94	1.07	1.15

S4.3b Calculated weather conditions in research area for 2015

Source: http://gismap.ciat.cgiar.org/MarksimGCM/#, all models included, 99 replications, visited 22-10-2018.

Central Rokan Hulu | Bonai Darussalam



S4.4 Overview of nutrient values

Taken from Ng (1999) in Corley and Tinker (2016: 365) to calculate nutrient requirements ha^{-1} year^{-1}. Note: cover crops were not included as no values were available and only one farmer had cover crops. *Ye* = Yield estimate in t ha^{-1} year^{-1}, FFB = fresh fruit bunch.

			Static variables (kg ha^{-1} year^{-1})				Yield dependent variables (kg ha^{-1} year^{-1})			
			N	P	K	Mg	N	P	K	Mg
Nutrient Supply	Input through fertiliser application (Fe)		--	--	--	--				
	Input through rainfall deposition (De)		17	2.4	31.6	4.8				
Nutrient Demand	Trunk growth (Tr)		42	4.1	122	10.2				
		Shell		0.1			Ye×0.15		Ye×0.07	Ye×0.01
	FFB requirement (c)	Fibre					Ye×0.26	Ye×0.063	Ye×1.075	Ye×0.095
		FFB without shell/fibre					Ye×2.89	Ye×0.45	Ye×3.175	Ye+0.1
	Loss through run-off (Ru)		15	1	21.6	2.1				
	Loss through leaching (Le)		3.4	0.9	6.3	3.4				
	Loss through erosion (Er)		2.4	0	0	0.2				
Balance	Supply-demand		0	0	0	0				

S4.5 Overview of most common types of fertilisers and quantities applied by farmers in the past 12 months

Fertiliser application in kg ha^{-1} $year^{-1}$. For micronutrients such as boron and copper only whether they were applied is included. Fertilisers are ranked according to share of total farmers who apply the relevant fertiliser. TSP = triple super phosphate, ZA = sulphate of ammonium, SP-36 = double supe phosphate, RP = rock phosphate, POME = palm oil mill effluent, EFB = empty fruit bunches. Fertiliser application outliers with values > 3.0 IQR in both combined sample and farmer groups were removed from further analysis although farmers still are included in calculations on % of farmers applying fertilisers.

Fertiliser ($N-P_2O_5-K_2O-MgO$)		Small Local Farmers	Medium Local Farmers	Large Resident Farmers	Small Migrant Farmers	Medium Migrant Farmers	Small & Medium Peat Farmers	Large Peat Investors	Total sample
% farmers applying fertilisers		83.3%	87.5%	97.1%	93.9%	97.5%	90.0%	96.9%	92.6%
Urea (46-0-0-0)	% applying	40.0%	46.90%	**61.8%**	57.6%	60.0%	**26.7%**	43.8%	48.9%
	Mean (users)	209	255	292	349	362	427	268	309
	s (users)	105	112	187	226	162	235	194	184
	Mean (total)	84	119	181	201	217	114	117	151
	s (total)	122	150	181	243	219	223	185	201
Dolomite (0-0-0-15)	% applying	36.7%	43.8%	23.5%	**23.3%**	37.5%	66.7%	**81.3%**	43.7%
	Mean (users)	237	366	692	500	397	573	530	476
	s (users)	137	164	608	222	285	287	245	476
	Mean (total)	131	160	263	152	149	418	431	225
	s (total)	302	213	409	395	259	423	304	353
KCl (0-0-60-0)	% applying	**10.0%**	25.0%	55.9%	39.4%	47.5%	43.3%	**59.4%**	40.7%
	Mean (users)	215	243	371	333	361	502	314	355
	s (users)	123	134	315	282	177	293	179	244
	Mean (total)	22	61	207	121	172	218	186	144
	s (total)	73	124	299	239	219	316	207	234
NPK Ponska (15-15-15-0)	% applying	36.7%	50.0%	26.5%	**51.5%**	35.0%	23.3%	**21.9%**	35.1%
	Mean (users)	311	317	452	345	296	321	660	364
	s (users)	142	83	249	282	108	246	371	231
	Mean (total)	114	159	120	178	104	75	144	128
	s (total)	142	83	249	282	108	246	371	231

S4.5, continued

TSP	% applying	**13.3%**	**40.6%**	29.4%	30.3%	32.5%	30.0%	18.8%	28.1%
(0-46-0-0)	Mean (users)	192	237	236	346	293	502	203	296
	s (users)	132	131	152	250	170	277	125	203
	Mean (total)	26	96	69	105	95	151	38	83
	s (total)	79	144	135	209	168	276	95	171
ZA	% applying	**0.0%**	**0.0%**	11.8%	18.2%	**22.5%**	10.0%	12.5%	11.3%
(21-0-0-0)	Mean (users)	0	0	442.3	381	353	369	240	357
	s (users)	-	-	218.3	222	147	213	137	179
	Mean (total)	0	0	52	69	79	37	30	40
	s (total)	-	-	159	173	163	126	91	128
SP-36	% applying	6.7%	9.4%	**17.6%**	15.2%	22.5%	**0.0%**	3.1%	11.3%
(0-36-0-0)	Mean (users)	271	371	279	325	308	-	387	312
	s (users)	270	36	174	158	97	-	-	131
	Mean (total)	18	35	49	49	69	-	12	35
	s (total)	85	110	128	131	138	-	68	35
Kieserite	% applying	**0.0%**	**0.0%**	14.7%	3.0%	5.0%	10.0%	**15.6%**	6.9%
(0-0-0-26)	Mean (users)	**-**	**-**	362	284	218	350	228	300
	s (users)	-	-	244	-	79	127	105	163
	Mean (total)	-	-	53	8.6	11	35	57	23
	s (total)	-	-	156	49	50	112	174.9	102
NPK other	% applying	3.3%	3.1%	14.7%	0.0%	12.5%	3.3%	6.3%	6.5%
(15-15-15-0)	Mean (users)	177	308	649	-	204	163	276	364
	s (users)	-	-	426		79		14	314
	Mean (total)	5.9	9.6	96	0	26	5.4	17	24
	s (total)	-	-	277	0	73	30	68	119
Boron	% applying	0.0%	0.0%	11.8%	0.0%	5.0%	6.7%	12.5%	5.2%
Manure	% applying	6.7%	3.1%	2.9%	6.1%	7.5%	3.3%	0.0%	4.3%
(2-1-1-0)	Mean (users)	6775	12450	2288	17063	12144	15600	-	11445
	s (users)	460	-	-	7690	4730	-	-	5911
	Mean (total)	452	389	67	1034	911	520	-	495
	s (total)	1721	2201	392	`	3412	2848	-	2611

S4.5, continued									
Fertiliser ($N-P_2O_5-K_2O-MgO$)		Small Local Farmers	Medium Local Farmers	Large Resident Farmers	Small Migrant Farmers	Medium Migrant Farmers	Small & Medium Peat Farmers	Large Peat Investors	Total sample
EFB (10-1-2.4-0.2)	% applying	0.0%	0.0%	8.8%	0.0%	2.5%	3.3%	6.3%	3.0%
	Mean (users)	-	-	8950	-	10930	19200	4490	9423
	s (users)	-	-	2948	-	-	-	2701	5352
	Mean (total)	-	-	790	-	273	640	281	286
	s (total)	-	-	2677	-	1728	3505	1206	1835
Copper	% applying	0.0%	0.0%	0.0%	0.0%	0.0%	3.3%	9.4%	1.7%
Ash (1-2-33-4)	% applying	0.0%	0.0%	2.9%	0.0%	0.0%	10.0%	0.0%	1.7%
	Mean (users)	-	-	137	-	-	1691.3	-	1303
Solid/POME (0-0.1-1.1-0.2)	% applying	3.3%	0.0%	5.9%	0.0%	0.0%	0.0%	0.0%	1.3%
	Mean (users)	6450	-	6200.0	-	-	-	-	6283.3
	Mean (total)	215		182					27
RP (0-15-0-0)	% applying	0.0%	0.0%	0.0%	0.0%	2.5%	3.3%	3.1%	1.3%
	Mean (users)	-	-	-	-	147	277	256	227
	Mean (total)					3.7	9.2	8.0	1.0
N		30	32	34	33	40	30	32	231

S4.6 Expert assessment of plantation condition

All experts were asked to assess all available photos of plantations and provide their opinion on the level of implementation of good agricultural practices in their plantation. *Too little* indicates a clearly neglected plantation with the plantation subsequently being in poor condition, *reasonable* implies a plantation which clearly is managed but practices appear not yet optimal, whilst *good* implies the plantation appears well managed and good agricultural practices appear standard. Results are shown in the tables below.

		Small Local farmers	Medium Local farmers	Large resident farmers	Small immigrant farmers	Medium immigrant farmers	Small & medium peat farmers	Large peat investors
Academic	too little	5	7	8	2	7	7	2
	reasonable	19	18	17	23	29	18	20
	good	5	7	8	6	3	4	6
Farmer	too little	4	2	8	3	7	7	15
	reasonable	18	21	16	19	23	17	9
	good	7	9	9	9	9	5	4
CIRAD Expert	too little	2	3	5	3	3	5	7
	reasonable	22	26	23	23	32	22	19
	good	5	3	5	5	4	2	2

		Small Local farmers	Medium Local farmers	Large resident farmers	Small immigrant farmers	Medium immigrant farmers	Small & medium peat farmers	Large peat investors
Academic	too little	17.2%	21.9%	24.2%	6.5%	17.9%	24.1%	7.1%
	reasonable	65.5%	56.3%	51.5%	74.2%	74.4%	62.1%	71.4%
	good	17.2%	21.9%	24.2%	19.4%	7.7%	13.8%	21.4%
Farmer	too little	13.8%	6.3%	24.2%	9.7%	17.9%	24.1%	53.6%
	reasonable	62.1%	65.6%	48.5%	61.3%	59.0%	58.6%	32.1%
	good	24.1%	28.1%	27.3%	29.0%	23.1%	17.2%	14.3%
CIRAD Expert	too little	6.9%	9.4%	15.2%	9.7%	7.7%	17.2%	25.0%
	reasonable	75.9%	81.3%	69.7%	74.2%	82.1%	75.9%	67.9%
	good	17.2%	9.4%	15.2%	16.1%	10.3%	6.9%	7.1%

Wilcoxon Signed Ranks Tests indicate no significant differences among expert assessments

Test Statistics

	Academic vs. CIRAD	Farmer vs. CIRAD	Farmer vs. Academic
Z	-.346[a]	-.956[a]	-.480[a]
Asymp. Sig. (2-tailed)	.729	.339	.631

[a] Based on negative ranks

S4.7 Regression analysis on bunch number, age and share of *tenera* fruits in plantations

Model Summary

Peat	Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
No	1	.384[a]	.147	.136	1.15528
Yes	1	.329[a]	.108	.075	1.44356

[a] Predictors: constant, *tenera* share, age

ANOVA[b]

Peat	Model		Sum of Squares	df	Mean Square	F	Sig.
No	1	Regression	35.683	2	17.842	13.368	.000[a]
		Residual	206.872	155	1.335		
		Total	242.556	157			
Yes	1	Regression	13.432	2	6.716	3.223	.048[a]
		Residual	110.445	53	2.084		
		Total	123.877	55			

[a] Predictors: constant, *tenera* share, age
[b] Dependent variable: bunch number (corrected)

Coefficients[a]

			Unstandardised Coefficients		Standardised Coefficients		
Peat	Model		B	Std. Error	Beta	t	Sig.
No	1	Constant	3.586	.248		14.446	.000
		Age	-.092	.022	-.308	-4.141	.000
		Tenera share	1.042	.361	.214	2.884	.004
Yes	1	Constant	3.879	.490		7.915	.000
		Age	-.097	.045	-.282	-2.165	.035
		Tenera share	.696	.612	.148	1.137	.261

[a] Dependent Variable: bunch number (corrected)

CHAPTER 5

Nutritional imbalance in smallholder oil palm plantations in Indonesia

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Abstract

In Indonesia more than 40% of the area under oil palm is owned by smallholders. The productivity in smallholder plantations is usually less than in large plantations, and limited fertiliser applications may be one of the key reasons. We investigated the use of fertilisers by > 300 smallholder farmers in Sumatra and Kalimantan, some of whom were involved in training programmes aimed at yield improvement. In our sample, the total applications of N were largest (166 kg ha^{-1} $year^{-1}$), followed by K (122 kg ha^{-1} $year^{-1}$) and P (56 kg ha^{-1} $year^{-1}$). The applications of K were insufficient to compensate for the off-take with a production of 20 t fruit bunches ha^{-1} $year^{-1}$, while N applications were excessive. On average, farmers applied 1130 kg fertiliser ha^{-1} $year^{-1}$, and relied strongly on subsidised fertilisers, especially NPK Ponska (66%) and urea (39%). The average costs for fertiliser application were USD 225 ha^{-1} $year^{-1}$. Trained farmers applied significantly more P in one research area, but for the other nutrients and research areas, there was no significant difference between trained and untrained farmers. Plantation sise and nutrient application were weakly correlated in some areas, but not in the sample as a whole. Previously reported nutrient application rates were mostly less than our findings indicated, suggesting that actual nutrient limitations may be more severe. To overcome nutrient limitations and enhance nutrient use efficiency, we recommend that fertilisers are used in the correct balance; a ground cover vegetation is maintained to protect against erosion; and the application of empty fruit bunches is encouraged.

5.1 Introduction

Oil palm (*Elaeis guineensis* Jacq.) is a highly efficient producer of vegetable oil, with an estimated potential production of well over 10 t oil ha^{-1} $year^{-1}$ (Corley, 2009a). Indonesia is the world's largest palm oil producer, with a cultivated area of 11.8 million hectares in 2017 (USDA, 2017) equivalent to about 11% of the combined land area of Sumatra and Kalimantan. Oil palm expansion in Indonesia and Malaysia has been associated with tropical deforestation (Abood et al., 2015; Gaveau et al., 2016), and expansion of plantations into peat forests has caused large emissions of CO_2 (Murdiyarso et al., 2010). If oil palm is to continue its role as the main global source of vegetable oil, then rapid and uncontrolled expansion need to be replaced with intensification and controlled expansion into degraded areas (Corley, 2009a; Smit et al., 2013; Afriyanti et al., 2016).

In terms of poverty reduction in rural Indonesia, oil palm has played an important and mostly positive role (Gatto et al., 2015). Currently over 40% of the Indonesian oil palm area is managed by smallholder farmers (Molenaar et al., 2013), many of whom depend on oil palm as their primary source of income (Euler et al., 2017). Indonesian smallholder farmers are usually classified as plasma farmers (also called scheme or tied; i.e. fields were planted as a company scheme and bunches are sold to the company mill); independent farmers (i.e. fields were planted independently by smallholder farmers, and bunches can usually be sold to any mill); and mixed farmers (or tied+, i.e. farmers who own both plasma and independent fields; Vermeulen and Goad, 2006). Most smallholder farmers manage their plantations individually, and yields are generally around 3–4 t oil ha^{-1} $year^{-1}$, which is less than in large plantations (Molenaar et al., 2013). The underlying agronomic factors causing this yield gap have been investigated in multiple studies and include poor planting material (Papenfus, 2002), delayed replanting (Koczberski and Curry, 2003), infrequent harvesting (Lee et al., 2013; Euler et al., 2016a), limited fertiliser use (Papenfus, 2002; Koczberski and Curry, 2003; Euler et al., 2016a), or a combination of the above (Molenaar et al., 2010; 2013). If smallholder yields are to be improved, then the implementation of good agricultural practices (GAP) is required. The Roundtable on Sustainable Palm Oil (RSPO) considers GAP, including good management of soil fertility, to be one of the key pillars of sustainability (RSPO, 2013). To date, the number of RSPO-certified smallholder farmers in Indonesia remains very small, but there is a strong drive to increase this (RSPO, 2017). The Indonesian Sustainable Palm Oil (ISPO) certification, which was introduced in 2011 and which has been mandatory since 2014 (Rival et al., 2016) is reinforcing the attention for GAP. The implementation of GAP is particularly important in smallholder plantations to create added value (in the form of yield increase) to pay for the expensive certification process (Rietberg and Slingerland, 2016) and to facilitate the inclusion of smallholder farmers in the certified supply chain.

Good fertiliser management is a key aspect of GAP; the excessive use of fertilisers is financially unattractive and damaging for the environment (van Noordwijk and Cadisch, 2002), while insufficient fertiliser use leads to yield limitations and nutrient mining. In mature oil palm plantations, the application of N, P, K, and Mg as fertiliser is usually required, as most soils cannot supply sufficient nutrients to meet palm demand (Goh, 2005). Ng et al. (1999) propose that on tropical soils of poor fertility, the total demand of a mature plantation producing 20 t fruit bunches per year is 129.5 kg N, 16.4 kg P, 236 kg K, and 38 kg Mg per hectare. Some of these nutrients are supplied in the rainfall, so the total input requirement to sustain the yield of 20 t fruit bunches is 112.5 kg N, 14.0 kg P, 204.4 kg K and 33.2 kg Mg per hectare per year (Ng et al., 1999). From these inputs, 10–20% are lost through leaching and run-off (Ng et al., 1999), especially during periods of high rainfall (Banabas et al., 2008; Comte et al., 2015) and after large nutrient applications (Comte et al., 2015). From the nutrients taken up by the oil palm, 30–50% are allocated to the palm trunk (Ng et al., 1999; Corley, 2009b). These nutrients are mostly no longer available to the palm for other purposes and are considered as being removed from the balance, although palms are able to re-mobilise some nutrients from the trunk when concentrations in the reserve tissue are sufficiently high (Foster and Prabowo, 2006). Nutrients allocated to the oil palm leaves and male inflorescences are recycled within the plantation after pruning and harvesting, and do not affect the nutrient balance. Nutrients allocated to the bunches are removed from the plantation at harvesting (Corley, 2009b; Donough et al., 2016) and are considered as being removed from the balance. The share of total nutrients in the balance that are removed in 20 t of bunches are 51, 64, 37, and 58% for N, P, K and Mg, respectively. The nutrient content of crude palm oil (CPO) is negligible: 44 g N, 18 g P, < 10 g K, and 3 g Mg per t CPO (Donough et al., 2016). This means that most of the nutrients remain behind in the empty bunches and in the mill waste streams, which can be recycled in the plantation to meet part of the palm nutrient demand (Ng et al., 1999; Chiew and Rahman, 2002; Comte et al., 2013). To maximise yields, nutrients must be applied in the correct balance (Janssen et al., 1990; Goh et al., 2009). Some guidelines for fertiliser applications in mature plantations on different soil types have been proposed (Goh, 2005), based on randomised fertiliser trials combined with regular tissue sampling (Webb, 2009).

It is clear from previous studies that fertiliser applications by smallholder farmers in Indonesia are not optimal for producing good yields, but we lack an in-depth analysis of nutrient use by smallholders. In addition, the drivers and constraints underlying farmers' choices of fertilisers are poorly understood, but strongly affect the success of training interventions on fertiliser use. We investigated the use of fertilisers in smallholder oil palm plantations in Indonesia by reviewing the literature and conducting a survey with > 300 farmers in three provinces in Indonesia. We also assessed the effect of different training interventions on farmers' fertiliser use. Based on the findings from the review and the survey, we discuss the opportunities for improving nutrient management in smallholder plantations, and we formulate targeted recommendations to improve fertiliser management and increase plantation profitability and sustainability.

5.2 Methods

Between March and August 2016, we conducted surveys with 309 smallholder farmers in three provinces in Sumatra (Riau and Jambi) and Kalimantan (West Kalimantan). In each of the selected areas, local or international non-governmental organisation (NGOs) were actively providing training on GAP to some of the farmers. Important elements of GAP that were trained in all areas were harvesting (regular and at correct ripeness); weeding (circle and path weeding; selective weeding); pruning (removal and retention of the correct number of leaves) and balanced fertiliser application that meets the palm nutrient demand.

5.2.1 Research areas

Kumpeh (Jambi province; Kumpeh district; Ramin village) is a transmigration and former plasma area that was mostly planted in 2002 and was abandoned by the company around 2008, after which the farmers became independent. There was an active cooperative in the first years that no longer functions. Farmers in Ramin had good access to several mills to sell their fruit bunches. They mostly sold through traders, who were also from the village. In Ramin, six farmers were trained for 3 years (starting in 2014) and they were hosting an experimental demonstration plot (organised by Wageningen University and Netherlands Development Organisation (SNV)) at the time of the research. In the demonstration plots, good management practices were implemented. The sample composition is shown in Table 5.1. For the trained farmers, the survey investigated the practices in the fields outside the
demonstration plot.

Tanjung Jabung Barat (Jambi province; Tanjung Jabung Barat (TJB) district; Sungai Rotan village) is an area of local independent oil palm farmers. All farmers sell their bunches through traders. A farmer group with 86 voluntary members was initiated by Yayasan Setara Jambi in 2013, to prepare for RSPO certification. Five selected farmer group members received a 1-day GAP training by agronomists from the plantation company Asian Agri, in a classroom setting. The trained farmers then provided training to the other farmers in the group, and one Asian Agri agronomist remained available to answer the farmers' questions. Setara Jambi provided additional training on making a farmer group and RSPO certification. The sample composition is shown in Table 5.1. All trained farmers were members of the farmer group, and all selected farmers were in the direct network of six intensively trained local leaders.

Table 5.1 Number of trained and untrained farmers included at each of the research areas.

Region	# trained farmers	# untrained farmers	Total sample size
Kumpeh	6	56	62
Tanjung Jabung Barat (TJB)	53	12	65
Siak	11	39	50
Sintang	6	60	66
Sekadau	6	60	66
Total	82	227	309

Siak (Riau province; Siak district; Dosan, Teluk Mesjid, Benayah, and Sungai Limau villages) is a semi-independent smallholder area established mostly on peat soils. All villages, apart from Dosan, had functional cooperatives at the time of the survey. Bunches were sold through these cooperatives. In 2009, a three-day training was provided by a British oil palm specialist together with Wageningen University, World Wide Fund for Nature (WWF) and the Indonesian environmental NGO Elang. During the training, mornings were spent in the classroom, while afternoons were used to establish a good practices demonstration plot. Most active participation was from Dosan farmers, and there was also some attendance from Teluk Mesjid. Standard Operating Procedures were drafted in Dosan village after the training. The sample farmers were selected through key informant suggestions, from four different villages (to achieve spatial separation). Nine trained farmers from Dosan and two trained farmers from Teluk Mesjid were selected; the remaining 39 farmers were untrained (Table 5.1).

Sintang (West-Kalimantan province; Sintang regency; Sungai Tebelian district; Mrarai village) is an area with farmers from mixed transmigration and local (Dayak) origin. Farmers mostly own both plasma and independent fields. Plasma farmers sell their bunches through a cooperative; independent farmers sometimes use traders or mix their independent bunches with plasma loads. All bunches are sold to a company mill that processes only smallholder bunches. The mill is regularly overloaded. Trained farmers were all members of an independent farmers' cooperative, which traded directly with the mill. The independent farmer cooperative was initiated and supported by WWF since 2012. Six farmers with both plasma and independent fields were trained for three years (starting in 2014) and they were hosting an experimental demonstration plot (organised by Wageningen University and SNV) at the time of the research. In the demonstration plots, good management practices were implemented. The sample composition is shown in Table 5.1. For the trained farmers, the survey discussed the practices in the fields outside the demonstration plot.

Sekadau (West-Kalimantan province; Sekadau Hilir district; Gonis Rabu, Gonis Tekam, Empring, and Segori villages) is a mixed area with plasma and independent fields. Most farmers sell their bunches through the plasma cooperatives. A training project was set up by an international and a local NGO (World Education) and the local Credit Union Keling Kumang, supported by Solidaridad and Stichting Doen. In the project, a Training of Trainers approach was implemented through Farmer Field Schools, with a first round of classes in 2012 and 2013. The GAP trainings were either for mature or for immature plantations. Each course consisted of 13 classes divided over 13 weeks. Trainers were NGO staff who were previously trained by plantation agronomists, as preparation for the project. In addition to GAP trainings, financial literacy trainings were also provided. For the sample, six farmers trained in the first round of Farmer Field Schools, and 60 untrained farmers in the direct network of the trained farmers were selected (Table 5.1).

5.2.2 Surveys

The surveys served multiple purposes: to assess the current management practices of smallholder farmers; to assess the impact of trainings on farmer practices; and to assess the spread of knowledge through informal networks. To facilitate the second and third objectives, the farmers participating in the survey were selected non-randomly. In all areas apart from Siak, a group of six farmers who had participated in the trainings were selected through the training providers and interviewed. Each of these farmers was asked to name 10 farmers in their network, and these farmers were also interviewed, following the snowball sampling procedure (Goodman, 1961). In Siak, farmers were non-randomly selected from four different villages through local enquiries, without a fixed sampling structure but aiming at maximum geographic spread (i.e. avoiding neighbours and close relatives). We asked selected farmers about their plantation management, particularly harvesting, weeding, and fertiliser application. We also asked whether they had recently changed their practices, and if so, why. Finally, we asked open questions about the information flows, focusing on which farming-related topics were regularly discussed (e.g. yield), with whom these topics were discussed (e.g. family members), and the reasons for discussion (e.g. to compare own situation with others). After the surveys the answers were grouped and coded to facilitate further analysis.

5.2.3 Literature review

Because our sample was influenced by training, we compared our results with data from the literature. We searched grey (Google Scholar) and peer-reviewed (Web of Science) literature for reports on (nutrient) management practices in oil palm smallholder plantations in Indonesia, and we selected publications which reported fertiliser application rates per hectare. The selected publications are described in Table 5.2. Soliman et al. (2016) and Lee et al. (2013) considered only N; the other studies took at least N, P and K into account.

5.2.4 Statistical analysis

Outliers in nutrient applications were identified as points that were beyond the three times interquartile range (indicated with an asterisk in the box plots) and were removed before analysis. Plantation area and nutrient use data were not normally distributed and were analysed using non-parametric tests. Overall differences between areas in terms of nutrient application and costs were analysed using the Kruskal–Wallis test of independent medians, with pairwise comparison and Bonferroni correction. The differences between specific areas and the effect of training on nutrient use were analysed using the Mann–Whitney U test to compare group medians. Correlation between plantation area and nutrient application was calculated using the Spearman rank correlation test. Differences were considered significant when $P < 0.05$. Analyses were conducted using SPSS.

Table 5.2 Overview of the case studies included in the literature review.

Source	Location	Sample size	Description
Comte et al., 2015	Riau	~ 2000 ha	Plasma (3 groups)
Euler et al., 2016a	Jambi	173 households	Plasma & independent
Harsono et al., 2012	Central Kalimantan	~ 10000 ha	Plasma
	West Kalimantan	~ 12000 ha	Independent
	Riau	~ 7500 ha	Plasma
	North Sumatra	~ 6500 ha	Independent
Lee et al., 2013 (Ch 4)	Sumatra	44 households	Plasma
	Sumatra	27 households	Independent
Lifianthi and Husin, 2012	South-Sumatra, dryland	30 households	Plasma
	South-Sumatra, peatland	30 households	Plasma
Soliman et al., 2016	Sumatra	170 households	Plasma & independent

5.3 Results

5.3.1 Nutrient application surveys

Nutrient application rates in each research area are shown in Figure 5.1. Most farmers applied substantial amounts of fertiliser. In all areas but Siak, the average applications for each research area were greater than 300 kg of nutrient per hectare, which was equivalent to at least 1000 kg of fertiliser per hectare. Across all research areas, the average applications of N were largest (166 kg ha^{-1} $year^{-1}$), followed by K (122 kg) and P (56 kg). Compared with the required input rates (112.5 kg N, 14.0 kg P, and 204.4 kg K per hectare, to sustain a yield of 20 t fruit bunches; Ng et al., 1999), the average applications of N and P were more than required in all areas apart from Siak, but K applications were only 45–70% of the required input rates. There were large variations in the quantities of nutrients applied among farmers. The research areas were significantly different in terms of median N ($P < 0.001$), P ($P < 0.001$) and K application rates ($P < 0.05$; Figure 5.1). Overall, 15% of the farmers applied no N; 20% applied no P; and 18% applied no K fertilisers. Excessive nutrient applications (defined here as more than 1.5 times the offtake rates for N and K) were observed in 25% of the cases for N, 72% of the cases for P, and 5% of the cases for K, excluding outliers.

5.3.2 Nutrient application rates reported in the literature

The largest N applications (around 240 kg ha^{-1} $year^{-1}$; Figure 5.2) were reported by Lifianthi and Husin (2012) in South-Sumatra and were about twice as much as the nutrient offtake. Harsono et al. (2012) reported N applications which were more than six times less, and which were around 60% of the calculated offtake. Similar N applications were reported by Comte et al. (2015). A somewhat smaller range was observed in the application of P, but maximum applications (114 kg ha^{-1}; Harsono et al. 2012) were over 10 times more than the calculated offtake. For K, the maximum application rate (144 kg ha^{-1}; Lifianthi and Husin 2012) was well below the calculated offtake rate, and the smallest applications (21 kg ha^{-1}; Comte et al. 2015) were almost ten times less (Figure 5.2).

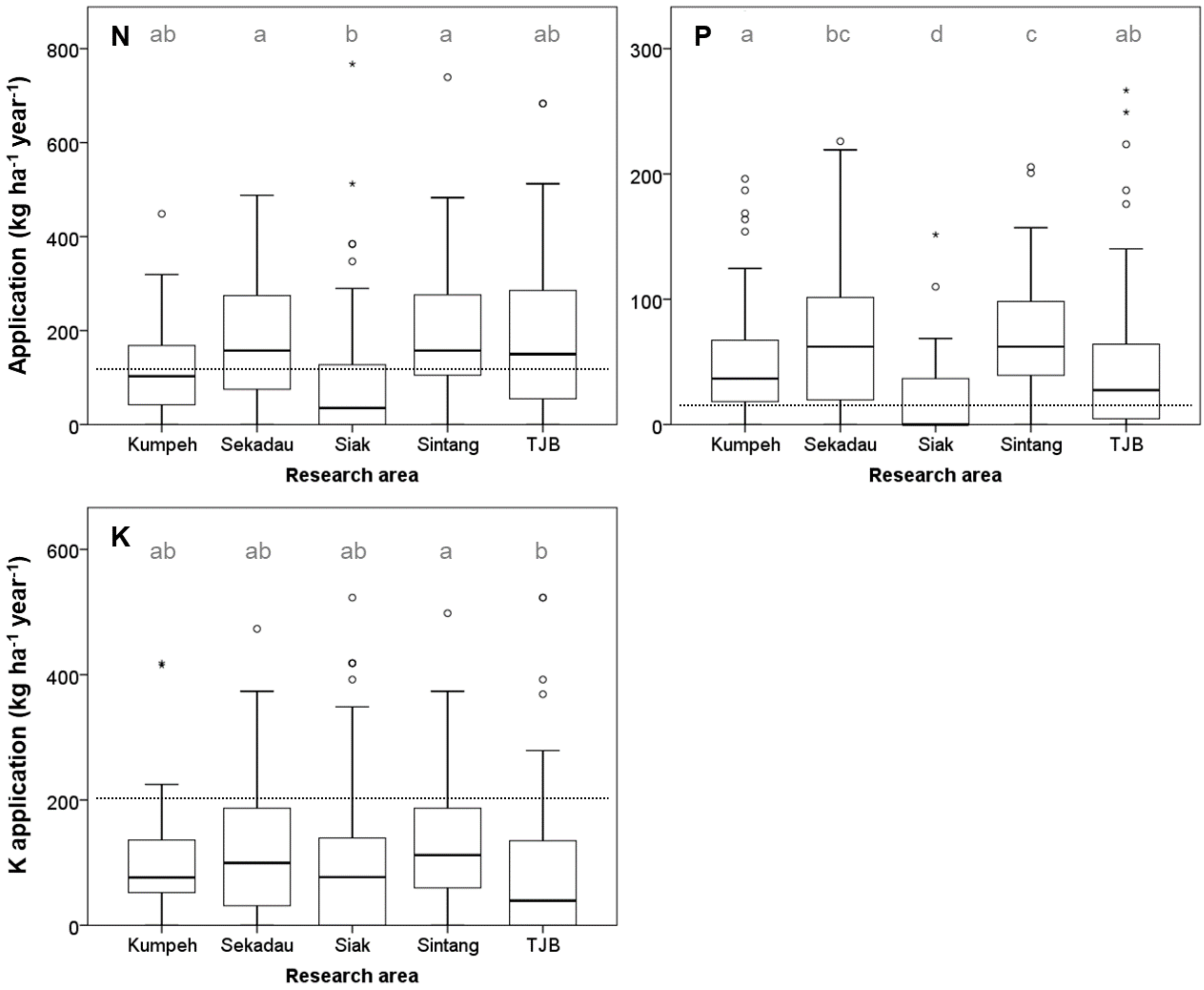

Figure 5.1 Application rates of elemental N, P and K in the five research areas. Significant differences between research areas ($P < 0.05$) are indicated with letters. Whiskers show the minimum and maximum values; the box shows the 1st and 3rd quartile; the line shows the median. Values of > 1.5 inter-quartile range (IQR; not considered outliers in the analysis) are shown as circles, and > 3.0 IQR (considered as true outliers) are shown as asterisks. The dashed line shows the approximate nutrient removal rate at 20 t fruit bunches ha^{-1} $year^{-1}$ (Ng et al., 1999). Outliers with values > 800 kg N ha^{-1}; > 300 kg P ha^{-1}, and > 700 kg K ha^{-1} were excluded from the graphs.

5.3.3 Types of fertilisers used, and costs

On average, farmers applied 1130 kg fertilisers ha^{-1} $year^{-1}$, of which almost half was the subsidised fertiliser NPK Ponska (Table 5.3). NPK Ponska was applied by 66% of the farmers, and contains 15% N, 15% P_2O_5 (equivalent to 6.5% P) and 15% K_2O (equivalent to 12.5% K). NPK Pelangi has the same composition and was applied by 9% of the farmers. The NPK fertilisers were supplemented with urea (46% N), dolomite ($CaMg(CO_3)_2$; around 15% Mg), KCl (50% K) and SP-36 (16% P). Less than 1% of the farmers used organic fertilisers such as manure or empty fruit bunches (0.32% N, 0.04% P, 0.96% K, 0.07% Mg per fresh weight; water content 60–65%; Gurmit et al., 1990).

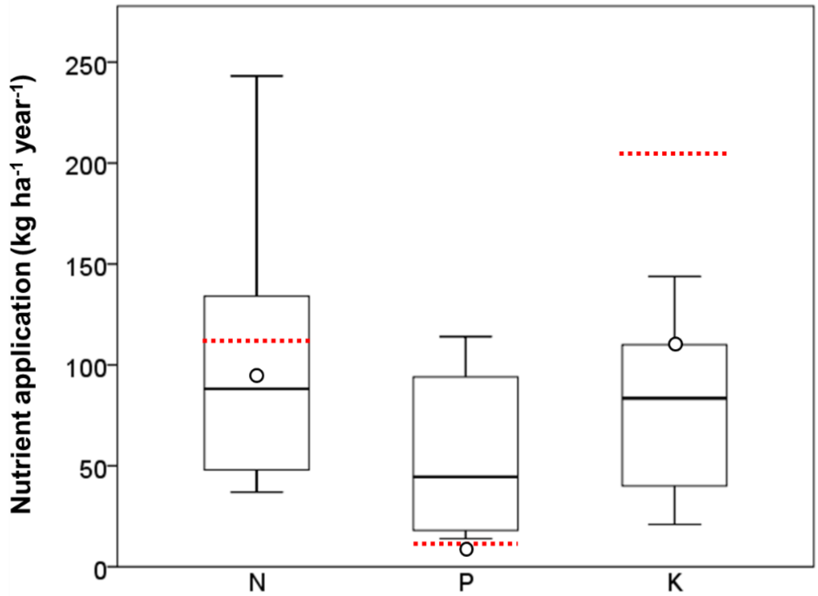

Figure 5.2 Nutrient applications (elemental N, P and K) in smallholder oil palm plantations from eleven case studies presented in six published papers that were found through the literature review (Table 5.2). Whiskers show the minimum and maximum values; the box shows the 1st and 3rd quartile; the line shows the median. The dashed lines show the nutrient removal at a production of 20 t fruit bunches ha^{-1} $year^{-1}$ (Ng et al., 1999), and the circles show the average nutrient application in large plantations in Indonesia in 2010 (Heffer, 2013).

In total, farmers spent around 225 USD per hectare per year on fertilisers, mostly on NPK Ponska, KCl, urea, and SP-36 (Figure 5.3 and Table 5.3). There were no significant differences among the research areas in terms of fertiliser expenditure ($P > 0.05$). NPK Ponska, urea, SP-36, NPK Pelangi, and ZA are subsidised. It appears that the fertiliser subsidies strongly influenced farmers' choices (Table 5.3). Because KCl is not subsidised, the average costs of its use were larger than for urea and dolomite, although the average application was less. Dolomite is not subsidised but is very cheap and was used by farmers as the main source of magnesium. In addition, it appeared from the interviews that farmers also use dolomite to 'improve the soil' and to reduce soil acidity (data not shown).

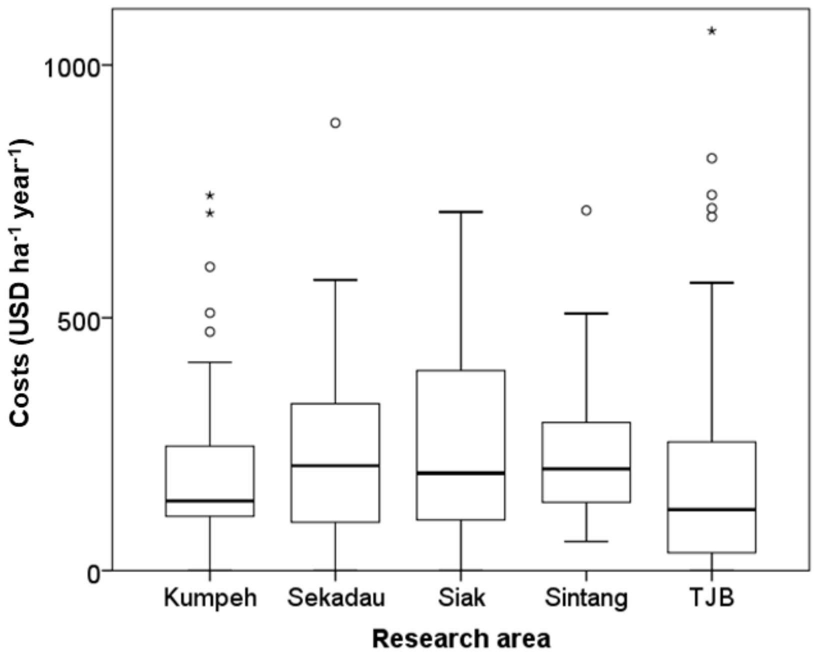

Figure 5.3 Costs of fertilisers applied by smallholder farmers in the research areas. Whiskers show the minimum and maximum values; the box shows the 1st and 3rd quartile; the line shows the median. Values of > 1.5 inter-quartile range (IQR; not considered outliers in the analysis) are shown as circles, and > 3.0 IQR (considered as true outliers) are shown as asterisks. Outliers with values > USD 1050 were excluded from the graph.

Table 5.3 Nine most common fertilisers used by smallholder farmers (n = 309) in the research areas. The column Composition' refers to the ratio $N:P_2O_5:K_2O:MgO$. The column n shows the number of valid responses. The column 'Use (%)' indicates the percentage of farmers who apply that fertiliser. The application rate shows the application among users only, while the mean application and its standard deviation were calculated over the entire sample of users and non-users. The costs were also calculated over the entire sample. Fertiliser composition and prices were obtained through discussions with farmers and fertiliser dealers.

Fertiliser brand	Composition	Price (USD t^{-1})	n	Use (%)	Application (kg ha^{-1} $year^{-1}$)			Costs (USD ha^{-1} $year^{-1}$)	
					Rate	Mean	s	Mean	s
NPK Ponska	15-15-15-0	192	294	66	692	457	550	88	105
Urea	46-0-0-0	150	299	39	456	178	314	27	47
Dolomite	0-0-0-20	33	287	25	535	123	432	4	14
KCl	0-0-60-0	325	299	21	510	107	325	35	106
SP-36	0-36-0-0	167	301	21	452	95	241	16	40
NPK Pelangi	15-15-15-0	192	303	9	756	68	243	13	47
TSP	0-46-0-0	304	300	7	400	28	125	9	38
ZA	21-0-0-0	117	302	4	450	18	119	2	14
RP	0-20-0-0	88	302	1	1000	10	137	1	12

5.3.4 Effect of training and farm size

In all areas, more trained than untrained farmers indicated that they changed the types of fertilisers that they applied in recent years; 40–100% of trained farmers and 30–75% of untrained farmers said they changed their practices. For the quantities of N and K applied, there was no significant difference between trained and untrained farmers in any of the research areas, nor for the sample as a whole (Figure 5.4). For P, the application rates of trained farmers in Siak was significantly greater than those of untrained farmers ($P < 0.05$), but there was no significant difference over the entire sample. Farmers with larger plantation areas were significantly more likely to receive trainings than farmers with smaller areas ($P < 0.001$ for the whole sample; $P < 0.05$ in Jambi and Sintang; not significant for the other areas; data not shown). N application rate was significantly positively correlated with plantation size in Sintang (*rho* = 0.285; $P < 0.05$), and P and K application rates were significantly positively correlated with plantation size in TJB (P: *rho* = 0.309; $P < 0.05$; K: *rho* = 0.282; $P < 0.05$). In the other areas, and over the sample as a whole, the application rates of N, P and K were not significantly correlated with plantation size (Figure 5.5).

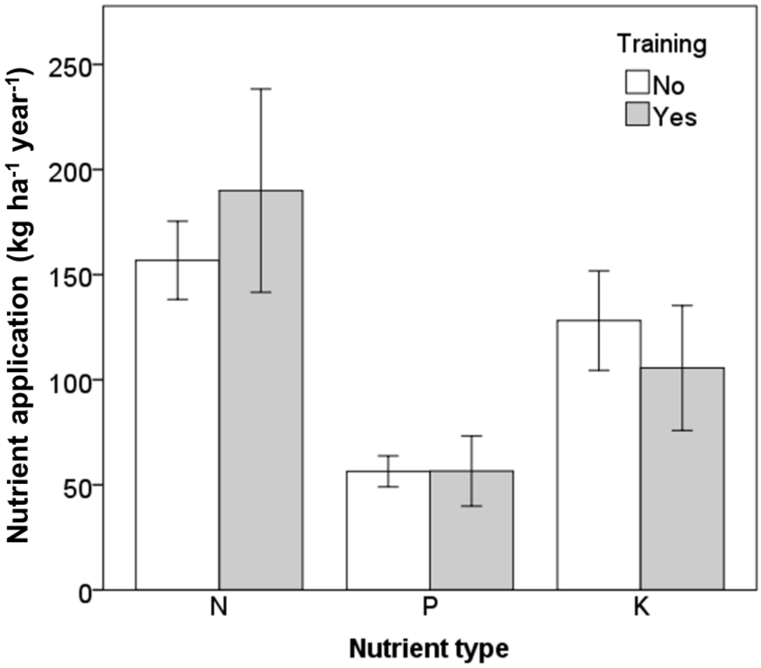

Figure 5.4 Nutrient application in relation to training for elemental N, P and K. Outliers with application rates of > 1000 kg ha^{-1} year^{-1} (two for N and two for K) were excluded from the graph. There were no significant differences in nutrient application between trained and untrained groups in any of the research sites.

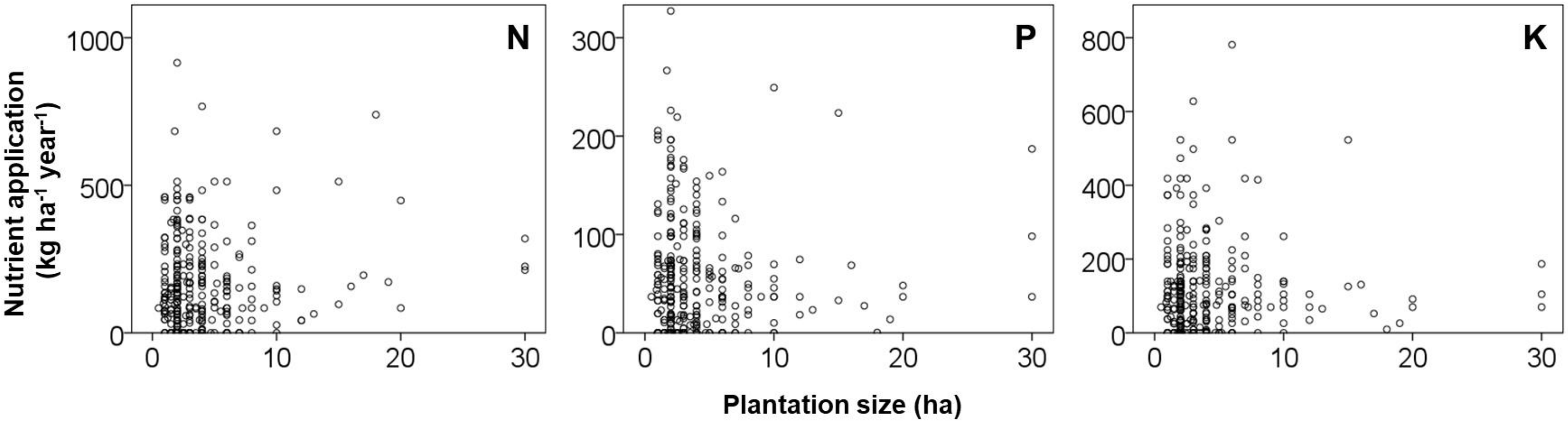

Figure 5.5 Nutrient application as a function of plantation size. No significant correlation was observed.

5.3.5 Networks and information sharing

The sampling of the farmers focused specifically on the spread of information through farmer networks. The farmers were asked with whom they shared information about farming, and what they discussed. Farmers mostly shared information with family members and friends (Figure 5.6a) and the most important topic they discussed was fertiliser application (Figure 5.6b). Less than 15% of farmers indicated that they did not discuss their farming practices with anyone. When asked why they applied limited amounts of fertiliser, farmers mostly cited fertiliser and cash availability as the key constraints. The availability of subsidised fertilisers for farmers who were not part of a cooperative or farmer group was particularly problematic. The farmers indicated that cooperatives and traders sometimes provided loans for fertilisers. None of the interviewed farmers indicated that they borrowed money from a bank for the purpose of buying fertilisers.

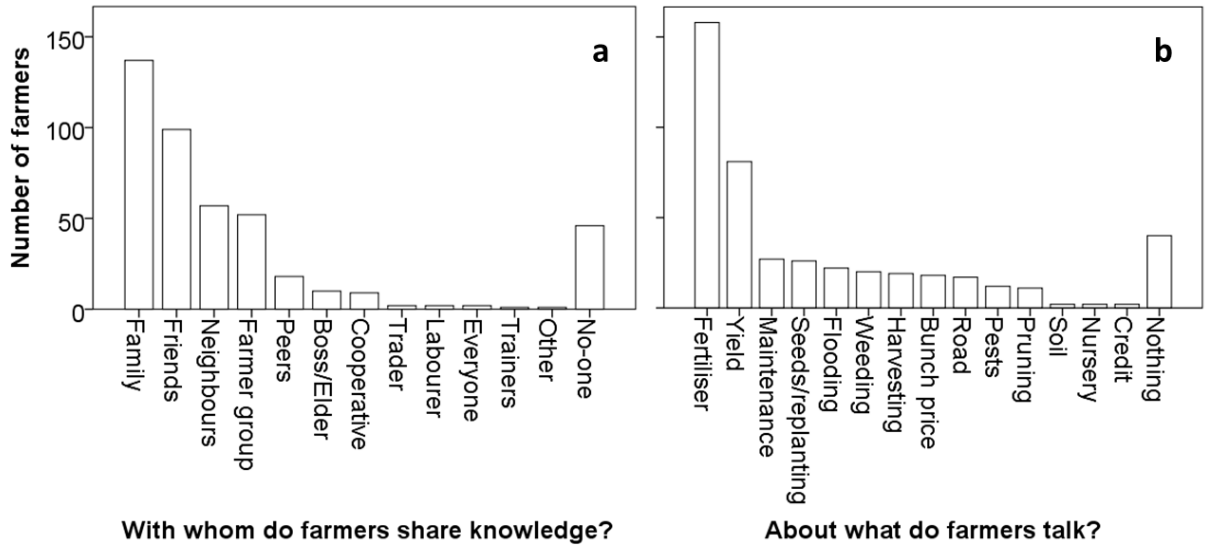

Figure 5.6 Knowledge sharing networks in the research areas (a) and the topics that were discussed (b). The total counts add up to > 309 because farmers could indicate multiple discussion partners and multiple topics of discussion.

5.4 Discussion

The results from the survey and the literature provide important insights into the practices of the farmers in our sample and in Indonesia. From both the literature and the survey it appeared that the K applications were the most limited in smallholder plantations compared with large plantations and with palm demand. While the average applications in our sample were well below the offtake rate at 20 t fruit bunches ha^{-1} $year^{-1}$, the applications in Sintang were still larger than any of the K applications found in literature, and the K applications in the other areas were also large compared with most results from literature (Figure 5.2). Although the N applications from the survey fell within the range observed in literature, they were larger than the average, with none falling below the average applications in Indonesia. Only for P were the applications estimated from the survey similar to the applications described in literature. There may be several reasons why the survey results for N and K were higher than those reported in literature. First, and most obviously, the training in the research area may have influenced farmers' decisions concerning fertiliser applications. When questioned about self-reported changes in fertiliser applications in recent years, more trained than untrained farmers indicated that they changed their practices in all the research areas (data not shown), and a Wilcoxon signed rank test showed that this difference was statistically significant ($Z = -2.023$, $P < 0.05$). However, no significant differences were observed between trained and untrained farmers with regards to N, P and K applications in any of the research areas, which suggests that the reported changes in practice did not result in increased applications of N, P and K. In conclusion, the training effect on nutrient application does not adequately explain the higher N and K applications reported in our survey.

As an alternative explanation, our sample may have been biased towards better-performing farmers. This selection bias has been well documented (e.g. Feder et al., 2004) but may go both ways (Larsen and Lilleør, 2014). It is likely that the choice of project areas was biased towards those that were relatively accessible and populated with farmers who were somewhat organised and willing to participate. Our data suggest that the choice of project participants was also biased toward farmers with larger farms, but no effect on nutrient application was observed. This indicates that constraints or enablers such as road quality, access to mills and markets, and farmer organisation may have a stronger effect on fertiliser use than plantation size and agronomic knowledge (Molenaar et al., 2010).

A fairly consistent picture of fertiliser use by smallholder farmers emerges from the results of our survey and from literature across different oil palm growing areas of Indonesia. Most farmers applied substantial amounts of fertilisers in their fields, especially N and K. The differences among farmers and research areas were large, with some farmers applying no fertiliser whatsoever, and others applying excessive amounts, especially of N. Soliman et al. (2016) concluded that smallholder farmers 'on average, could reduce their [...] fertiliser use by 65% and maintain the same yield'. Our results show that this conclusion is not tenable, as it is based only on the rates of N applied. If farmers reduced their overall fertiliser use by 65%, the additional shortages of K would probably lead to large reductions in yield. Rather than promoting an overall reduction in fertiliser use, we would suggest that the application of nutrients in the right balance deserves further attention. Palm age and soil type have a particularly strong influence on the nutrient needs of the palms. In most soils, the K requirement exceeds the N requirement (Foster, 2003; Tohiruddin et al., 2006). Excessive N application may exacerbate K deficiency (Broschat, 2009) and reduce yields. The case of phosphorus is complicated, as a large share of the P applied is usually fixed in the soil and will not be available to the palm (Foster and Prabowo, 2006). Although the total palm demand for P may be small, the application of substantial amounts of P fertiliser (1–2 kg rock phosphate per palm per year) is usually recommended to achieve good yields (Goh, 2005). Large oil palm plantations make use of tissue sampling combined with randomised fertiliser trials to determine the optimum nutrient application in the plantation (Goh, 2005). If tissue sampling is not feasible in smallholder plantations, then fertiliser recommendations need to be based on existing information about soil type and fertiliser requirements; visual deficiency symptoms; and suggestions from nearby plantations (Webb et al., 2011). A properly evaluated basic fertiliser recommendation scheme for the most common soil types would be of great benefit to the smallholder farmers.

Most farmers in the sample heavily relied on subsidised fertilisers, especially urea and NPK Ponska. In order to access official supplies of subsidised fertilisers, farmers must be member of a farmer group and apply for the fertilisers collectively (Daemeter Consulting, 2013). In practice, a large share of the fertilisers ends up on the market, where they are sold at an inflated price (Daemeter Consulting, 2013). The large price difference between subsidised fertilisers and other fertilisers (particularly KCl) is probably one of the main reasons why farmers tend to over-apply N and under-apply K (Molenaar et al., 2013). The economic rationale of investing in non-subsidised K fertilisers require further investigation, especially when returns on investment are constrained by low crude palm oil (CPO) prices and insecure relationships with mills, or responses to fertilisers are limited because of poor harvest quality, poor planting material, sub-optimal growing conditions (Cock et al., 2016) and increased climatic risks due to climate change

(Paterson et al., 2017). Fake fertilisers are an additional risk, with fertilisers being replaced with cheaper materials, such as ground bricks in case of MOP (Daemeter Consulting, 2013). In a small set of 10 fertiliser samples collected randomly in Sintang, Riau and Jambi, we found three fake fertilisers which contained little or no nutrients (data not shown). When farmers work together as a group, they may decide to test the fertilisers they purchase, but for individual farmers this is neither feasible nor affordable. We noted that many farmers were unaware of simple tests such as dissolving fertilisers in water. In addition to fake fertilisers, we found some very dubious products claiming fertiliser properties, such as bacterial and hormonal solutions. At least 10 farmers reported to use these products. One product sold as 'hormonal fertiliser' in Jambi provides a good illustration: it contains four different plant hormones, and according to the instructions it needs to be injected into the palm trunk every 3 months at a volume of 2 ml per palm, dissolved in 10 ml water. With a price of 120,000 Rp per litre, the expenditure per hectare per year is over 80 USD for the input only, without considering the additional labour costs. It is worrying to see farmers invest in these types of products, but to restrict their use of mineral fertilisers such as MOP because they are considered too expensive.

Fertiliser application practices can be optimised to increase nutrient capture and use. From multiple field observations, we concluded that farmers usually applied all fertilisers in a narrow band around the palms. Most fertilisers were applied only once per year, rather than in multiple splits; and farmers often mixed fertilisers manually (data not shown). While available studies do not show any effect of fertiliser placement on oil palm yield (Goh et al., 2003; 2009), the even spreading of fertilisers on the largest possible soil area is considered sensible in mature plantations (Goh et al., 2003). In mature plantations the areas outside the circle are colonised by the palm roots (Foster and Dolmat, 1986) and the application of fertilisers (particularly P, K and Mg) on top of decomposing fronds, rather than on the dry and bare soil in the palm circle close to the trunk has been recommended to improve fertiliser infiltration and reduce leaching and run-off (Maene et al., 1979; Foster and Dolmat, 1986; Goh et al., 2003). The application of soluble fertilisers in at least two splits is common practice to reduce the risk of nutrient losses, especially on coarse soils (Goh et al., 2003). The manual mixing of straight fertilisers is obviously not recommended. Farmers use this as a labour-saving option and are not aware of the poor fertiliser distribution that may result.

The efficiency of nutrient use depends among others on plantation maintenance, especially weeding. In total, over 44% of the farmers in the research sites indicated that they clear-weeded their plantations, usually by the application of paraquat (60%) or glyphosate (35%). Clear-weeding leads to high vulnerability to soil erosion and fertiliser run-off, especially P. Improved weeding practices (i.e. the establishment of weeded circles and harvesting paths and the maintenance of a dense ground cover vegetation outside these areas; Rankine and Fairhurst, 1999c) can probably improve nutrient retention and infiltration. To catch nutrients, fronds may be stacked in boxes or lines along the contour. Most farmers (75%) stacked dead fronds in a row, and 22% stacked the fronds in a box shape around the palms (data not shown). Frond stacking in boxes or along the contour line does not require additional inputs of materials and labour and can contribute to improved soil quality and increased nutrient use efficiency. It must be kept in mind that harvesters cut most of the fronds but are paid per tonne of harvested bunches. Monetary incentives could be a useful tool to improve stacking practices.

The return of empty fruit bunches or empty bunch-based compost to farmers' fields is one of the most promising options to improve both palm nutrition and soil quality and fertility, without requiring large additional investments in fertilisers and without potential negative environmental impacts of excessive chemical fertiliser use (Chiew and Shimada, 2013; Bessou et al., 2017). Empty bunches are a waste product of the milling process, and every five t fresh fruit bunches produce around one t empty bunches. The positive effects of empty bunch applications on soil quality are well documented, and include strong increases in organic matter content, water holding capacity and water infiltration, and nutrient content (Chan et al., 1993; Comte et al., 2013). Empty bunches can be applied in several ways: directly as a mulch; incinerated to produce bunch ash; or mixed with palm oil mill effluent (POME) and composted for 2–4 months. The empty bunches are very rich in K (Donough et al., 2016), and an application of 25–40 t ha^{-1} as mulch can meet the K demand of a high-yielding plantation for one year. Nutrients applied as organic fertiliser are less likely to leach into stream water than nutrients applied as mineral fertilisers (Comte et al., 2015). In peat soils, bunch ash can provide large quantities of K and alleviate soil acidity. Despite these benefits, empty bunches are often not available to, or used by, smallholder farmers (Molenaar et al., 2010), for several reasons. We observed that smallholder farmers often were unaware of the benefits of applying empty bunches, or they were afraid of pest problems. Farmers may also be discouraged by high transport and labour costs involved with spreading the empty bunches in the plantation, although anecdotal evidence from

Jambi and Sintang suggested that the costs per kilo of K from empty bunches were generally smaller than from mineral fertiliser, even when including transport and labour costs. We also encountered anecdotal evidence of empty bunch loads going to waste at the mill, either because of poor distribution infrastructure or due to lack of demand (cf. Maitah et al., 2016). On the other hand, the availability of empty bunches for smallholder farmers may be an issue when stocks are bought up by plantation companies. To increase the use of empty bunches by smallholder farmers, awareness building through training and demonstrations should be combined with ensuring farmer access to empty bunches at the mill. If plantation companies are allowed to buy up empty bunches at the expense of smallholder farmers, then there is a de facto stream of nutrients (especially K) from resource-constrained smallholder plantations to company plantations. Leading trading and plantation companies (especially RSPO members) should commit themselves to ensuring that their mills implement fair and proper distribution of empty bunches to smallholder farmers.

5.5 Conclusions

Our study shows that smallholder farmers in Indonesia use much more fertiliser than is often assumed—but often of the wrong types. Increased applications of K fertiliser, combined with sufficient (but not excessive) applications of N and P, are required to meet the palm nutrient demand. Subsidised fertilisers do not provide the correct nutrient balance, and therefore it is essential that farmers either use suitable blends or supplement with straight fertilisers, especially K. Providing training on good agricultural practices to farmers does not appear to be sufficient to improve fertiliser application practices. In order to support good management of plant nutrition, farmers need to be connected with a reliable fertiliser dealer, purchase fertilisers collectively as a farmer group, or be provided with good-quality fertilisers by the mill they deliver to. For timely purchase of suitable fertilisers, farmers need access to credit through banks, cooperatives, or traders. The use of mobile devices and apps can help farmers to implement proper yield recording, which is necessary to support decision-making with regards to fertiliser applications. Regular application of empty fruit bunches in the plantation is important, in addition to correct application of mineral fertilisers. The implementation of low-cost practices such as proper management of the ground cover vegetation and stacking of the pruned fronds are beneficial for preventing soil erosion and improving soil quality. Good trainings and extension materials (such as posters and movies) dealing with the basics of soil science, plant physiology and plant nutrition should be made available for those farmers who are interested in becoming more knowledgeable. Supporting farmers to implement a more balanced approach to management of the mineral nutrition of oil palm offers the benefits of increased production, less risk of negative environmental impacts and higher profits.

Acknowledgements

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CHAPTER 6

People, palms, and productivity: Testing better management practices in Indonesian smallholder oil palm plantations

Lotte S. Woittiez, Maja Slingerland, Meine van Noordwijk, Abner Silalahi, Ken E. Giller (In preparation). People, palms and productivity: Testing better management practices in Indonesian smallholder oil palm plantations.

Key messages

- Mature palms responded to increased fertiliser application by more vigorous vegetative growth and an increased bunch weight, but not by increased yield.
- Modest applications of N, P, and B were sufficient to correct tissue nutrient deficiencies, but K and Mg concentrations were not always sufficient.
- Drought appeared to over-ride the effect of improved management on yield (if any); the same was probably true for flooding.
- The increased costs of the recommended fertiliser applications outweighed the benefits, leading to a negative financial result.
- Key bottlenecks in farmer plantations were drought and flooding; for the experiments, yield recording and keeping good controls were very challenging.

Abstract

More than 40% of the total palm oil volume produced by Indonesia comes from smallholder plantations. For large plantations, guidelines are available on so-called 'best management practices', which should give superior yields at acceptable costs when followed carefully. We tested a subset of such practices in a sample of smallholder plantations, aiming to increase yields and profitability. We implemented improved practices (weeding, pruning, harvesting, and fertiliser application) in 14 smallholder plantations of 13–15 years old in Jambi province (Sumatra) and in West-Kalimantan province (Kalimantan), for a duration of three to three-and-a-half years. During this period, we collected yield records and did measurements and laboratory analyses of palm leaves. Contrary to our expectations, yields did not increase after three years, although the size of the bunches and the size of the palm leaves did increase significantly over time. The tissue nutrient concentrations also increased significantly, although after three years the potassium concentrations in the rachis were still below the critical value. Because of the limited yield increase and the additional costs for fertiliser inputs, the net profit of implementing better management practices was negative and 'business as usual' was financially justified. Some practices, such as harvesting at 10-day intervals and the weeding of circles and paths, were received positively by those farmers who could implement them autonomously, and were applied beyond the experiment. Specific conditions during the experiment (the El Niño event in

2015, and flooding in Jambi in 2017) have likely contributed to the lack of yield response.

6.1 Introduction

Palm oil is currently the most important vegetable oil in the world, with an annual production of around 70 million metric tonnes in 2017 (USDA, 2018). The oil palm (*Elaeis guineensis* Jacq.) is a highly efficient crop, with potential production well over 10 t oil ha^{-1} $year^{-1}$ (Corley, 2009a). Indonesia is the world's largest palm oil producer, with a cultivated area of 11.8 million hectares in 2017 (USDA-FAS, 2018) equivalent to about 11% of the combined land area of Sumatra and Kalimantan. Currently over 40% of the Indonesian oil palm area is managed by smallholder farmers (Molenaar et al., 2013), many of whom depend on oil palm as their primary source of income (Euler et al., 2017). Indonesian smallholders are usually classified as plasma farmers (also called scheme or tied; i.e. fields were planted as a company scheme and bunches are sold to the company mill); independent farmers (i.e. fields were planted independently by smallholder farmers, and bunches can usually be sold to any mill); and mixed farmers (or tied+, i.e. farmers who own both plasma and independent fields; Vermeulen and Goad, 2006). Most smallholder farmers manage their plantations individually, and yields are generally around 3–4 t oil ha^{-1} $year^{-1}$, which is less than in large plantations (Molenaar et al., 2013). Oil palm expansion in Indonesia and Malaysia has been associated with tropical deforestation and biodiversity loss (Abood et al., 2015), and expansion of plantations into peat forests has caused large emissions of CO_2 (Murdiyarso et al., 2010). If oil palm is to continue its role as the main global source of vegetable oil, then rapid and uncontrolled expansion need to be replaced with intensification and controlled expansion into areas of degraded land (Smit et al., 2013).

Yield gap analysis in oil palm has been described in detail in Woittiez et al. (2017b) and a short summary will be provided here. Yield gap analysis (van Ittersum et al., 2013) typically recognises four reference levels: the potential yield (Yp), the water (Yw) and nutrient (Yn) limited yields, and the actual yield (Ya). Yp is the maximum yield that the best available variety of a crop can achieve in a given environment (irradiation, temperature, CO_2 concentration), and is the benchmark for irrigated crops. In rain-fed crops (such as oil palm in Indonesia) the Yw is the benchmark, which accounts for limitations in water availability (based on rainfall and soil-specific factors). Both Yp and Yw are often calculated using simulation models (van

Ittersum et al., 2013). Farmer yields generally appear to plateau at 75–85% of Yw/Yp, and the benchmark of '80% of Yw/Yp' has been introduced as the yield that can be achieved in practice (van Ittersum and Rabbinge, 1997; Cassman, 1999). Finally, Ya is the average or actual yield of a crop in a certain environment, and the difference between Ya and Yw/Yp is the 'yield gap', while the difference between Ya and 80% of Yw/Yp is the 'exploitable yield gap' (van Ittersum et al., 2013).

Perennial crops such as oil palm have certain unique features that make yield gap analysis less straightforward than it is for annuals (Woittiez et al., 2017b). The long lifespan of plantations (around 25 years) means that the 'latest planting material' does not reflect the average genetic potential of the population in the field. In addition, sub-optimal conditions during the establishment phase strongly affect yields later on, resulting in 'cumulative' yield reductions over time. Good agricultural practices (GAP) in nursery, immature, and mature oil palm plantations are well described (Rankine and Fairhurst, 1999a; 1999b; 1999c; Fairhurst and Härdter, 2003), and can result in excellent yields of over seven t oil ha^{-1} $year^{-1}$ in commercial plantations when implemented rigorously (Woittiez et al., 2017b). Good agricultural practices for plantation establishment involve the selection of the site and planting material; nursery management; field preparation; and planting. Good management in the immature phase ensures that the palms become productive 30 to 36 months after planting. In the mature phase, good management usually focuses on harvesting, weeding, pruning, nutrient management, and control of pests and diseases. Regular and correct harvesting is a key determinant of oil palm productivity (Ng and Southworth, 1973). While harvesting probably does not affect the actual bunch production of the palms, the implementation of more rigorous harvesting standards can result in a rapid increase in the volume and quality of the plantation harvest (Donough et al., 2009). Weeding and pruning may not have a direct positive influence on yield (Woittiez et al., 2017b) but are important to facilitate efficient harvesting, protect the soil, and recycle nutrients. The yield response of oil palm to fertilisers is well investigated and has been reviewed by Goh et al. (2003) and Goh (2005). Fertiliser experiments are usually established on young mature or immature palms, but Warriar and Piggott (1973) and Sidhu et al. (2009) convincingly demonstrated that neglected mature palms (which received no fertilisers for four years) can be brought back into full productivity when fertiliser applications are resumed. Pest and disease problems in Indonesian oil palm plantations are usually limited (apart from rats, which can reduce oil yields by 5%; Wood and Liau, 1984) but serious infection with the fungus *Ganoderma* can be a reason for early replanting.

In smallholder oil palm production, the same agronomic principles apply, but smallholders face a range of unique constraints and challenges (Martin et al., 2015; Euler et al., 2016a; Woittiez et al., 2018a). Smallholders have less investment capacity and less access to knowledge and inputs (Molenaar et al., 2010). They have less options in selecting favourable soil conditions and must accept site quality as is, with limited opportunities to modify drainage or correct specific soil constraints. For this reason, aiming for 'best practices' is not necessarily fitting for smallholders, and recommendations from large-scale companies for improving yields cannot be assumed to work for smallholder farmers as well. We define better (rather than 'best') management practices as practices that increase yield or the environmental performance or both, without aiming for (or claiming) the absolute best.

Studies on the management of smallholder plantations (Molenaar et al., 2010; Molenaar et al., 2013; Euler et al., 2016a; Hutabarat et al., 2018; Woittiez et al., 2018a) generally point to limited implementation of good agricultural practices in smallholder fields. This can be attributed, at least partly, to the costs farmers face when trying to increase yields, due to high input prices, labour costs, uncertain farm-gate prices for their products, challenges in obtaining credit for investments and lack of reliable information on crop responses to be expected. The common notion that yield gaps as such imply 'efficiency gaps' is not empirically supported (van Noordwijk and Brussaard, 2014). Nevertheless, yields of ~5.5 t oil ha^{-1} over the productive plantation lifetime have been reported with several groups of well-organised plasma smallholders (Jelsma et al., 2017b). Thus, smallholders can produce similar yields as large plantations, provided that the establishment phase was well managed, and farmers work together.

The current poor productivity in smallholder plantations means that more land is required to meet the demand for palm oil (Khatun et al., 2017). Improving yields in smallholder plantations can be achieved through two pathways: rehabilitation (improving yield in existing stands) and renovation (replanting). In practice, replanting is a large investment, and improving yields in existing stands through the implementation of better management practices is the more likely approach to be taken up in plantations below the 'critical age' of 25 years after planting. Knowledge on the yield effects and the costs and benefits of better practices in smallholder oil palm plantations is limited. Here, we report a study on the implementation of better practices in 14 smallholder plantations in Sumatra and

Kalimantan, in Indonesia. We address the following questions: 1) What yields can be achieved in mature smallholder oil palm plantations after implementing better practices? 2) How do yields change over time in response to better practices? And 3) What are the costs, benefits and risks of intensification? Our objectives are to improve our understanding of the response of mature smallholder oil palms plantations to better practices, to assess the costs and benefits, and to provide recommendations on the opportunities and the risks of different agronomic practices.

6.2 Materials and methods

6.2.1 Research areas

The research was conducted in 14 farmers' oil palm plantations in two contrasting regions in Indonesia: Sintang regency, West-Kalimantan province on the island of Borneo (referred to as 'Sintang'), and Muaro Jambi regency, Jambi province on Sumatra (referred to as 'Jambi'). In both areas our partner organisation, the Netherlands Development Organisation (SNV), was already active and was able to provide support on the ground. In Jambi, the experiments were in Ramin village (1°30'9.94"S, 103°48'41.09"E), and started in April 2014. The experiments in Sintang started in September 2014 and were in Mrarai village in Sungai Tebelian subdistrict (0° 6'56.37"S, 111°27'13.52"E).

Jambi. Ramin village is located in sub-district Kumpeh Ulu of Muaro Jambi regency in Jambi province, about 40 km northeast of Jambi city. The area is flat and is situated on a low-lying coastal plain. Soils in the village area are alluvial clay Entisols (34%) and deep fibric Histosols (66%), with all sample plantations located on the clay Entisols (Table 6.1). The climate is humid tropical, with an average annual temperature of 27˚C, an average maximum temperature of 31˚C and minimum temperature of 22.5˚C. The yearly precipitation is around 2300 mm, with a rainy season from October to February and the driest months in June, July and August (~100 mm rainfall per month; Figure 6.1). In 2014, Ramin village covered 3325 ha of agricultural land, of which 2213 ha (67%) were used for oil palm cultivation. A large part of the area prone to flooding, but the situation improved after the drainage canals were cleaned in 2014. The village consisted of 397 households, of which 321 were involved in farming (2014 data obtained from the village office). Most oil palms were planted between 1999 and 2002. All oil palm farmers in Ramin were independent (i.e. without an obligation to sell to a specific mill to repay existing debts) at the time of the research.

Sintang. Mrarai is located in West Kalimantan, close to the River Kapuas, with flat to gently rolling topography. The soils are clay or sandy clay loam Ultisols, with some shallow peat pockets (Table 6.1). The climate is humid tropical, with an average annual temperature of 26.9˚C, an average maximum temperature of 32.5˚C and minimum temperature of 22.9˚C. The yearly precipitation is around 3000 mm, with a rainy season from October to January and the driest month in August (~100 mm $month^{-1}$; Figure 6.1). Two cooperatives (one for plasma and one for independent farmers) were active in the area at the time of the research. The plasma cooperative consisted of a few thousand households, divided over 16 villages, with a total oil palm area of 5579 ha planted around 1999. The average yield was 18 t fruit bunches ha^{-1} $year^{-1}$, with the peak season from October to January. The independent cooperative was created with support from WWF Indonesia in 2013, and consisted of 235 farmers, most of whom also owned plasma fields.

Table 6.1 Soil and biophysical properties of the BMP and the REF plots in the 14 sample plantations. Plantations S2, S3 and S5 (S6, S7 and S8) contained peat pockets which are shown on separate lines (S2P, S3P, and S5P) because the soil properties were very different.

Code	Soil properties								Remarks
	Texture	SOC[a] (%)	pH[b]	N[b] (%)	P[b] (ppm)	Ca[b]	Mg[b] $(cmol_{(+)}\ kg^{-1})$	K[b]	
Jambi									
J1	Clay	3.8	4.2	0.14	9.0	1.70	0.75	0.08	2017: Flooding in REF plot
J2	Clay	4.9	4.5	0.20	33.8	2.94	1.05	0.11	
J3	Clay	3.1	4.6	0.14	7.0	1.75	0.85	0.09	Full legume cover crop
J5	Clay	3.8	4.2	0.15	24.7	1.70	0.49	0.11	2017: Flooding in REF plot
J6	Clay	4.3	4.3	0.17	12.0	3.00	1.10	0.09	
J4[c]	Clay	3.5	4.6	0.14	28.9	3.34	0.90	0.18	
Sintang									
S1	Silt loam	4.6	4.8	0.06	26.9	0.61	0.05	0.19	Palm density BMP too high
S4	Sandy loam	4.5	4.9	0.09	11.5	0.42	0.09	0.10	
S6	Clay loam	5.4	4.4	0.13	94.7	0.45	0.05	0.23	Sloping
S7	Clay loam	4.6	4.9	0.10	73.7	0.65	0.09	0.20	Sloping; eroded
S8	Loam	3.8	4.8	0.08	25.2	0.29	0.05	0.14	Sloping
S3[c]	Clay loam	7.4	4.9	0.10	43.4	1.17	0.20	0.05	
S3P[c]	Peat	22.6	4.1	0.82	174.4	6.32	0.57	0.28	Front + back of field (0.9 ha)
S5[c]	Sandy loam	5.2	4.9	0.06	12.2	1.41	0.13	0.12	
S5P[c]	Peat	20.5	4.1	0.92	73.4	2.83	0.28	0.32	Centre of field (0.9 ha)
S2[d]	Loam	7.3	4.9	0.14	66.2	1.11	0.10	0.18	Sloping
S2P[d]	Peat	21.8	4.2	0.76	228.9	3.13	0.27	0.35	Centre of field (0.8 ha)

[a] Average between circle and interrow at 0 to 40 cm depth.
[b] Circle at 0–40 cm depth.
[c] Removed from yield and cost-benefit analyses.
[d] Removed from the sample: data incomplete and management not carried out correctly.

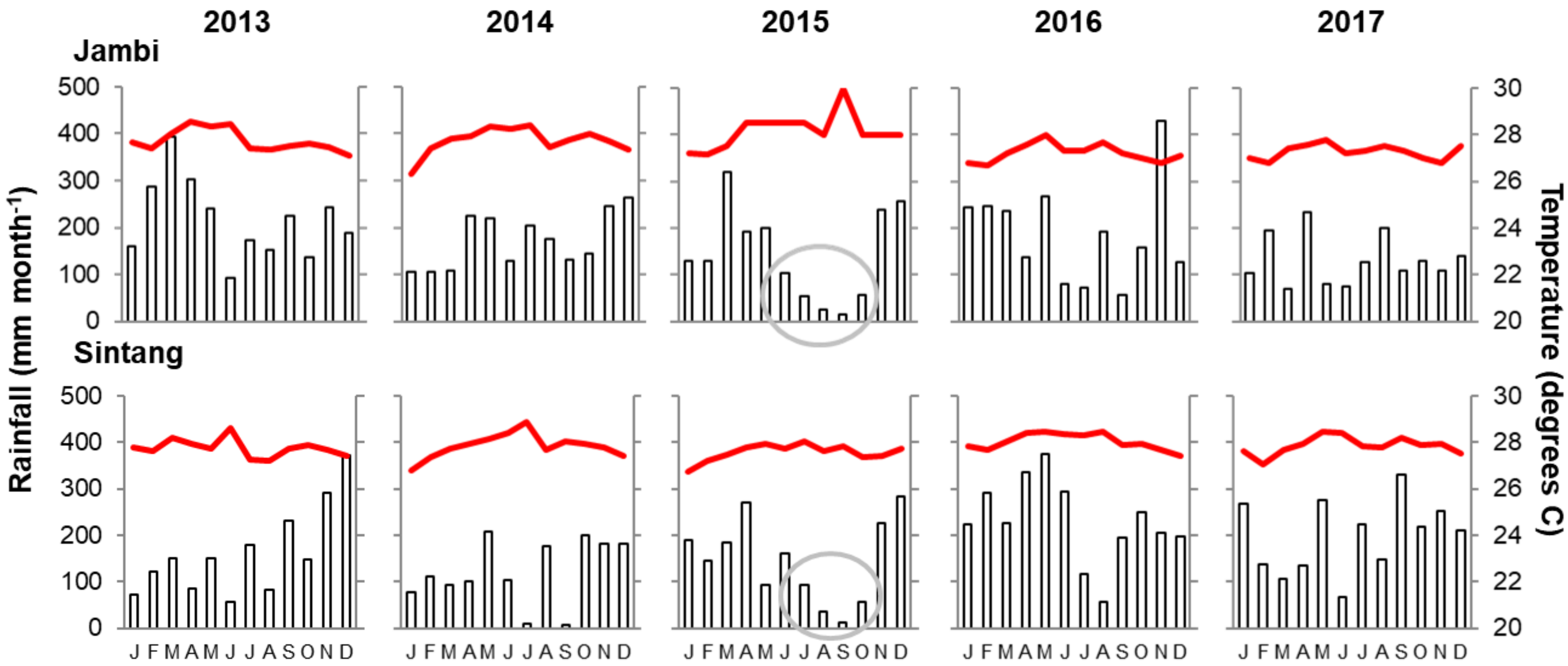

Figure 6.1 Rainfall (bars) and temperature (line) in Jambi (top row) and Sintang (bottom row). The El Niño event in 2015 is indicated with a grey circle.

6.2.2 Farmer selection

In both areas, farmer selection was facilitated by the Netherlands Development Organisation (SNV) as the experiments were part of larger projects focused on oil palm production. In Jambi, a local informant introduced the researchers to several potential areas, and the final choice for Ramin village was made based on biophysical characteristics (mainly correct palm age and limited contamination of the planting material with *dura* palms). In Ramin, a local leader was identified, and the project idea was discussed with him. He then identified suitable candidates to host experimental plots. The candidates were assessed by the researchers based on a) the size and biophysical properties (especially flooding risk and absence of large shade trees in the plantation) of their plantation, and b) the candidate's willingness and capacity to participate in an intensive long-term experiment. The selected sample consisted of six farmers, who were all (extended) family or close friends of the local leader. The average size of their plantations was 19 ha, which was significantly larger than the average plantation size of other farmers in the village (4.1 ha). In Sintang, SNV connected the researchers with the head of the independent cooperative, and a similar process as in Jambi was followed. To ensure homogeneity in terms of palm age and planting materials, all selected plantations in Sintang were plasma plantations, but the farmers also owned independent fields and were part of the independent cooperative. Eight plantations of two hectares each were selected, of which three were managed by one farmer (but owned by others). The main biophysical selection criteria was soil type (three plantations had peat pockets; the others were on mineral soils). Maximum distance from the cooperative office was set at 30 minutes by car. There were only five suitable plantations on mineral soils, which were all selected.

6.2.3 Experimental set-up

Each two-hectare plantation was divided into three parts: a BMP plot (where better management practices were introduced); a REF plot (the reference or control, where farmers were encouraged to continue with their management as usual); and two rows of palms between the plots to separate them, which were managed as the REF plots and were not sampled. To fulfil their function as a demonstration, the BMP plots were always the ones next to the road. If both plots were next to the road, then the BMP plot was allocated randomly. The plots were mapped with a GPS, and the number of productive palms was counted.

6.2.4 Soil and tissue sample collection

In all mineral plots, six sample palms per plot (referred to as LSU; Leaf Sampling Units) were selected based on a grid system, representing the four corners of the plot, and two palms in the middle. In the peat plots, four palms per soil type per plot were selected. Unhealthy, immature, and shaded palms, and palms within two rows from the plot border were excluded. Leaf 17 was identified and excised (Chapman and Gray, 1949), and the length, petiole width and thickness, and number of leaflets of leaf 17 were measured or counted, as well as the length and breadth of the eight largest leaflets (four from the left and four from the right side of the rachis). The trunk girth and the height of the trunk (at the base of leaf 41) were measured. The middle ~20 cm piece of the eight largest leaflets of leaf 17 were collected as leaf samples. In addition, a piece of rachis of approximately 20 cm in length was sampled from the same point on the leaf. Vegetative measurements and tissue sampling were repeated yearly. Samples were collected between 8.30 am and 4.30 pm. Where possible, sampling directly after heavy rainfall was avoided. In two plantations in Sintang (S4 and S6) the tissue samples from the individual palms were analysed separately (apart from the sample at the start of the experiment), and samples were collected at a 4-month interval. The newest fully opened frond (Leaf 1) was marked and the number of newly initiated leaves was counted at each measurement round. Soil sampling was carried out once, at the start of the project. Soil samples were collected with an Edelman combination auger at 0–40 cm deep. Two samples were collected around each sample palm: one at 50 cm from the trunk in the palm circle (representing around 20% of the plantation area) and one at 3 m from the trunk in the inter-row under the frond stack (representing around 12% of the plantation area; Fairhurst, 1996).

Table 6.2 Better management practices (BMPs) implemented in the smallholder fields.

Category	Activity	Method	Frequency
Weeding	Establishing weeded circles	Manual/mechanical/chemical	3 rounds/year
	Establishing harvesting paths	Manual/mechanical/chemical	3 rounds/year
	Removing woody weeds	Manual/mechanical/chemical	2 rounds/year
	Cutting inter-row weeds to knee height	Manual/mechanical	2 rounds/year
Pruning	Pruning to 40 leaves per palm	Manual	2 rounds/year
	Stacking fronds in U-box	Manual	At pruning/harvesting
Harvesting	Harvesting when bunches are fully ripe (at least 1 loose fruit)	Manual	Every 10 days
	Collecting bunches separately at roadside	Manual/with motorbike	At harvesting
	Collecting all loose fruits	Manual	At harvesting
	Counting bunches and recording bunch quality	Manual	At harvesting
	Recording yield per plot	Manual	At harvesting
Other	Making footbridges over canals	Manual	At project start

Table 6.3 Nutrient applications in the BMP plots in Jambi and Sintang. EFB = empty fruit bunches.

Nutrient	Amount (kg palm^{-1} year^{-1})				Applied as	Remarks
	2014 [a]	2015	2016	2017		
Jambi						
N	0.8	0.9	0.9	0.9	Urea	Two splits
P	0.6	0.2	0.2	0.2	Rock phosphate	One split
K	1.2	1.5	1.5	1.5	KCl	Two splits
B	0.03	0.03	0.03	0.03	Fertiliser borate	One split
Sintang						
N	0.5	1.2	3.2	1.2	Urea; EFB (2016)	Two splits
P	0	0.6	0.4	0.2	Rock phosphate; EFB (2016)	One split
K	0.7	1.3	6.7	1.3	Korn Kali B; EFB (2016)	Two splits
Mg	0.1	0.2	0.5	0.2	Korn Kali B; kieserite; EFB (2016)	Two splits
B	0.02	0.03	0.01	0.03	Korn Kali B; EFB (2016)	Two splits
Cu	0	0.05	0	0	$CuSO_4$ (2015)	One split, on peat
Zn	0	0.08	0	0	$ZnSO_4$ (2015)	One split, on peat

[a] In Sintang the experiments started in the end of 2014, so only one round of Korn Kali B and urea was applied in that year.

6.2.5 Soil sample processing and analysis

Soil samples were air dried in plastic trays or open plastic bags and then ground and sieved with a 2 mm sieve. The < 2 mm soil fraction was analysed as follows: pH in water; extractable P using the Bray II protocol; Al + H through 1M KCl extraction followed by titration; soil extractable K using 1 M ammonium acetate extraction followed by flame photometry; soil extractable Mg and Ca using 1 M ammonium acetate extraction followed by atomic absorption spectrometry (AAS); and soil texture by the Bouyoucos hydrometer method. Samples were ground further to < 0.5 mm for the analysis of soil organic N through Kjeldahl digestion and distillation followed by titration; and of total organic matter through the Walkley-Black chromic acid wet oxidation method. All samples were analysed at Central Group CPS Laboratory in Pekanbaru, Sumatra.

6.2.6 Tissue sample processing and analysis

Before drying, the midrib of the leaflets was removed, and the remainder was cut into 0.5 cm strips. Rachis samples were shredded using a machete. Leaflet and rachis samples were first air-dried and then oven-dried at ~70°C for 48 hours. After drying the leaflets were coarsely ground in a coffee grinder and subsamples were sent to the laboratory for analysis. In the laboratory, the samples were ground finely and passed through a 0.5 mm sieve. Then the following analyses were carried out: leaf nitrogen through Kjeldahl digestion and semi-micro Kjeldahl distillation; leaf and rachis P through dry ashing followed by spectrometric analysis (vanadomolybdate method); leaf and rachis K using flame emission photometry after dry ashing; leaf Ca and Mg by atomic absorption spectroscopy after ashing; and leaf B using spectrometry after dry-ashing and uptake in H_2SO_4. Samples were analysed at Central Group CPS Laboratory in Pekanbaru, Sumatra.

6.2.7 Training; management; yield recording

At the start of the project, all participating farmers were trained in better management practices, both in a classroom and in the field. The better management practices that were implemented are listed in Table 6.2. Before the first round of fertiliser application, farmers were asked to establish weeded circles, harvesting paths, and frond stacks, and to carry out pruning. Management practices were scored during annual field audits on a scale from 1 (poor) to 3 (good). Based on the results from soil and leaf testing, a fertiliser application plan was drawn up (Table 6.3). Fertilisers were purchased directly from distributors in

Jambi and Sintang and were applied by the farmers and the researchers together. Rock phosphate was broadcast everywhere apart from the harvesting path; KCl (in Jambi) and Korn Kali B (in Sintang) were applied over the frond stack; and urea and borate (in Jambi) were applied in the palm circle. Fertiliser applications were repeated every six months (urea, Korn Kali B) or yearly (rock phosphate, borate). Empty fruit bunches (EFB), copper and zinc were applied only once. Although farmers were requested to continue their previous nutrient application practices in the control plots, the application practices changed quite strongly during the project. At least five farmers reported that they started to apply more fertilisers after learning from the programme. On the other hand, three farmers stopped applying fertilisers altogether for one or more years, to save money for plantation expansion (one farmer) or for family matters (two farmers). Farmer S4 began with a very under-fertilised plot and he resumed fertiliser application in the control plot at the start of the project.

Production was recorded at every harvest by a local project assistant. The harvesters were instructed by the farmers to separate the bunches from the BMP and the REF plots, and for each plot the number of bunches was counted, and the total weight was recorded. The bunch weight was calculated by dividing the total weight over the bunch number. In Sintang, the bunch number recordings were unreliable, especially during the first year. For this reason, the individual bunch weights in a single harvest were measured separately every year for each plot. Also in Sintang, the size of the plots in three fields (S6, S7 and S8) changed in March 2015, because we decided to exclude the peat pockets from the plots.

6.2.8 Statistical analysis

One plantation (IRO in Sintang) was ignored in the data analysis because the data was incomplete and management practices in the BMP plot were not implemented to a sufficient standard. The results from RAT and IYA in Sintang were excluded from the yield analysis because plantation sizes were not clear, and SAN in Jambi was also excluded because yield records showed abnormal numbers (bunch weights > 35 kg). This resulted in a total of 5 plots in each of the areas for yield and cost-benefit calculations. For other calculations, six fields in Jambi and seven in Sintang were included. The palms on peat were excluded from the tissue nutrient concentrations and the vegetative growth calculations; these include only data from the four palms on mineral soil. Before analysis, normality of the data was tested using the K-S test. Non-normal data was transformed through log-transformation. All statistical analyses were performed in SPSS.

Tissue nutrient concentrations were analysed at plot level (n = 26) and vegetative growth parameters were collected and analysed for individual palms (n ~ 148, depending on the number of missing values). To test for differences between BMP and REF plots in each year, we ran a mixed model with Restricted Maximum Likelihood Estimation of fixed effect size and with *Treatment* (BMP or REF), *Year* (2014 to 2017), and *Area* (Jambi or Sintang) as fixed factors. For the random effects we used a random intercept (*Field*) and a random slope (*Field* nested in *Treatment*) with an autoregressive (AR1) covariance structure. Pairwise comparisons were based on estimated marginal means with Bonferroni adjustment for multiple pairwise comparisons.

Missing yield values (less than 10% of the total number of values) were filled in using the average of the two yield records before and the two yield records after the gap. Yields were calculated by dividing the monthly production over the plot size. Four outliers for bunch weight (> 3 × Inter Quartile Range) were removed before statistical analysis. Yield and bunch weight differences between the BMP and the REF plot were calculated using a mixed model with Restricted Maximum Likelihood Estimation of fixed effect size and an autoregressive (AR1) covariance structure, with *Treatment(Field)* as the nested random factor, *Month*, *Treatment* and *Location* as the fixed factors, and a random intercept for *Field*.

Data on costs of labour and inputs were not systematically collected except for fertiliser costs. For this reason only fertiliser costs were included in the cost-benefit analysis.

6.3 Results

6.3.1 Farmer practices

Farmer practices in terms of fertiliser application are shown in Figure 6.2. In Jambi, average nutrient application rates decreased strongly during the project, while in Sintang the application rates remained stable. Average applications in Sintang were much larger than in Jambi, which is in line with trends observed in a baseline study among more than 60 farmers in each of the areas (Woittiez et al., 2018a).

While less nutrients were generally applied in REF plots than in the BMP plots in Jambi, the median applications in Sintang were mostly similar to the BMP median. At the start of the project, circle weeding, weed composition and leaf number (pruning) scored 1.6 (poor to acceptable; some circles present); 1.4 (poor to acceptable; many noxious and woody weeds), and 2.3 (acceptable to good), respectively, with no differences between the BMP and the REF plots. At the end of the project, circle weeding, weed composition and leaf number scored 2.8, 2.3 and 2.8 in the BMP plots, and 2.1, 2.2 and 2.9 in the REF plots, indicating that better weeding was implemented, especially in the BMP plots.

6.3.2 Tissue nutrient concentrations

The results from the leaflet nutrient analyses are shown in Figure 6.3 (see Supplementary Figure S6.1 for results from individual palms measured every four months in fields S4 and S6). At the start of the project, the average tissue nutrient concentrations for N, P and K (but not Mg and B) were below the critical values, and fertiliser applications were expected to increase tissue concentrations. During the project the concentrations of N, P, K and B in the palm tissue increased significantly (Figure 6.3).

For the concentrations of N, P and Mg in the leaflets and of P in the rachis there was a significant positive effect of year ($P < 0.001$) but not of the treatment (Figure 6.3; Figure 6.4). There was no effect of year or treatment on leaflet K, but a highly significant positive effect of both treatment ($P < 0.001$) and year ($P < 0.01$) on rachis K (Figure 6.3; Figure 6.4). In Jambi, rachis K values were significantly larger than in Sintang ($P < 0.01$). Three years after the start of the experiment, average rachis K values remained below the critical line, but leaflet concentrations relative to the total leaf cation concentration (Foster, 2003) were above or close to critical values in Jambi from 2015 onwards. This indicates that K availability in Sintang may still be a yield-limiting factor, while the K applications in Jambi were approaching the optimum. Leaflet B concentrations responded rapidly to increased B fertiliser application, and both treatment and year had a highly significant positive effect ($P < 0.001$).

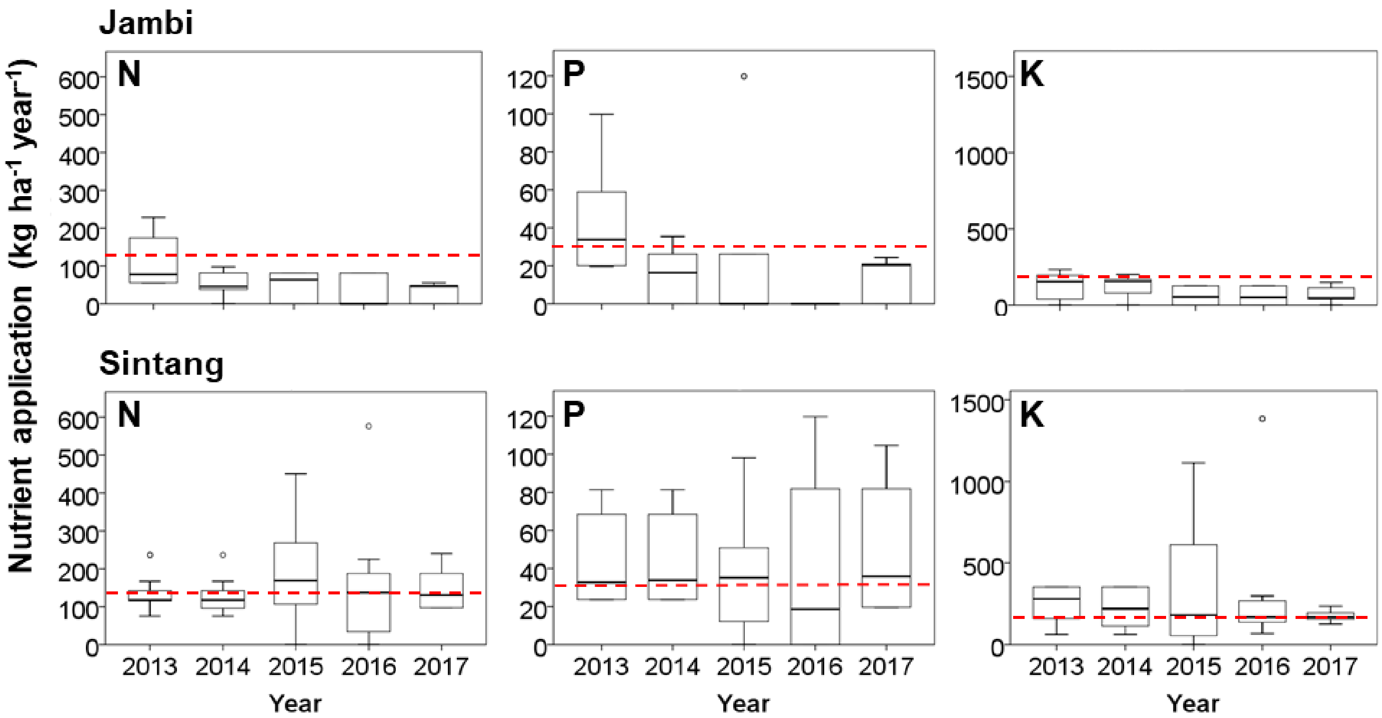

Figure 6.2 Nutrient application practices in the REF plots for N, P and K in Jambi (top row) and Sintang (bottom row). The dashed line shows the median applications in the BMP plots in 2015–2017. The median application for the BMP plots in Sintang in 2016 was excluded from the calculation because the nutrients were applied as empty bunches and quantities were excessive.

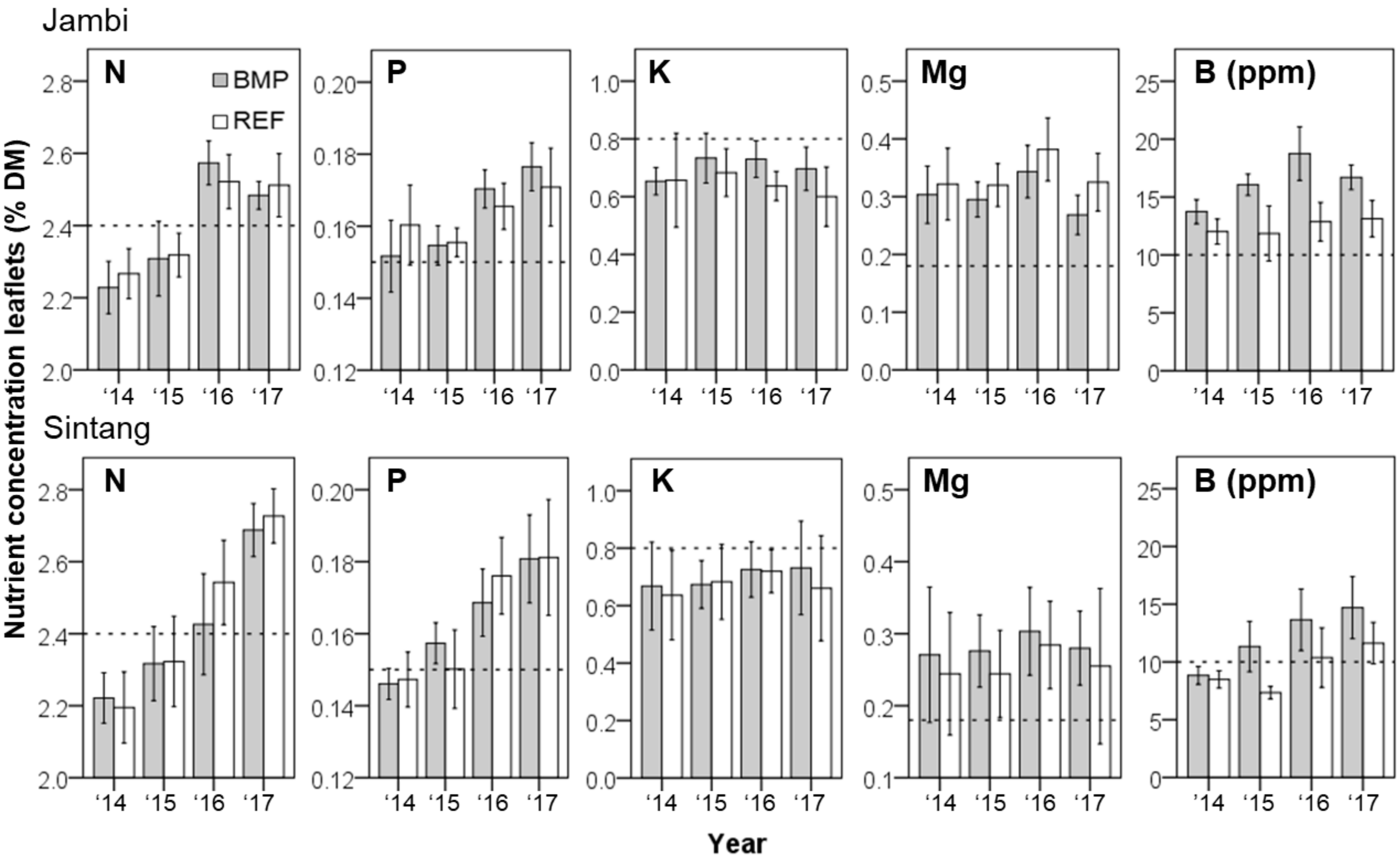

Figure 6.3 Mean leaflet nutrient concentrations in Jambi (*n* = 6; top row) and Sintang (*n* = 7, bottom row). The error bars show the 95% confidence interval of the observed mean, and dotted lines show the critical nutrient concentrations adapted from Rankine and Fairhurst, (1999c) and the Bah Lias Research Station Annual Reports (unpublished).

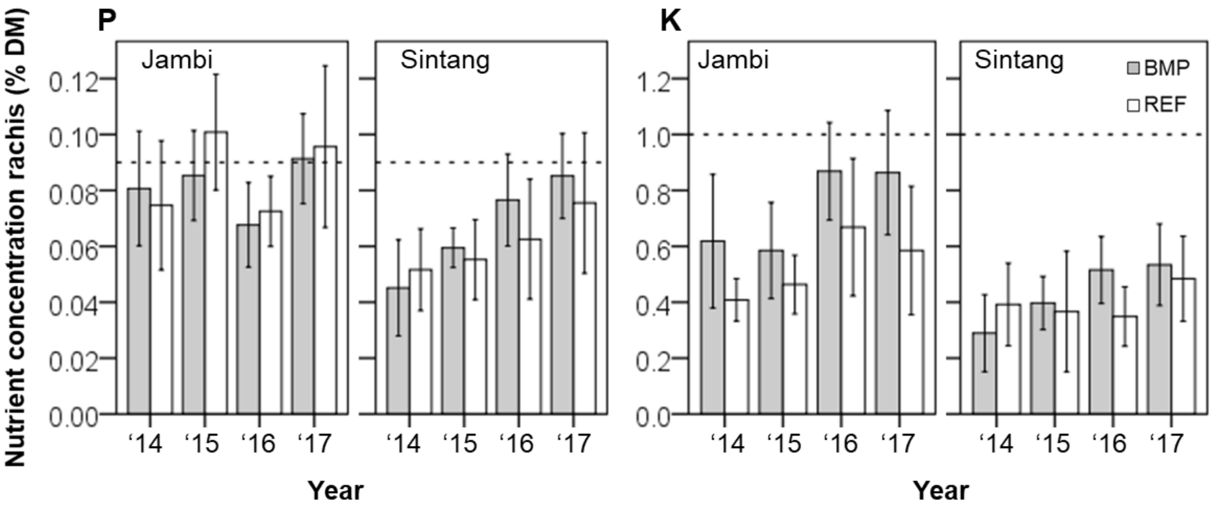

Figure 6.4 Mean rachis nutrient concentrations for P and K in Jambi (n = 6) and Sintang (n = 7). The error bars show the 95% confidence interval of the observed mean, and dotted lines show the critical nutrient concentrations adapted from (Foster and Prabowo, 2006).

6.3.3 Vegetative growth

Several palm vegetative growth parameters were measured at each sampling round (Figure 6.5; see Supplementary Figure S6.2 for results from individual palms measured every four months in fields S4 and S6). As all the palms in the sample plantations were more than ten years old, no significant increase in leaf size due to palm aging was expected, but palm height was expected to increase gradually. All vegetative growth parameters were normally distributed apart from petiole cross-section (PCS; D(104) = 0.092, P < 0.05), which was log-transformed to resolve skewness. All vegetative growth components were strongly correlated (P < 0.01) apart from leaflet length and leaflet breadth.

On average, there was a significant positive effect of BMP on petiole cross section, palm height, leaflet length (P < 0.05) and leaflet breadth (P < 0.01) from 2015 onwards. The effect was even more pronounced in 2017. Frond length did not show a significant response to the BMP treatment but increased strongly between 2014 and 2016 (P < 0.01; Figure 6.5). On average changes were more pronounced in Jambi than in Sintang. In 2014 and 2015 there were no significant differences between the BMP and the REF plots for any of the vegetative parameters.

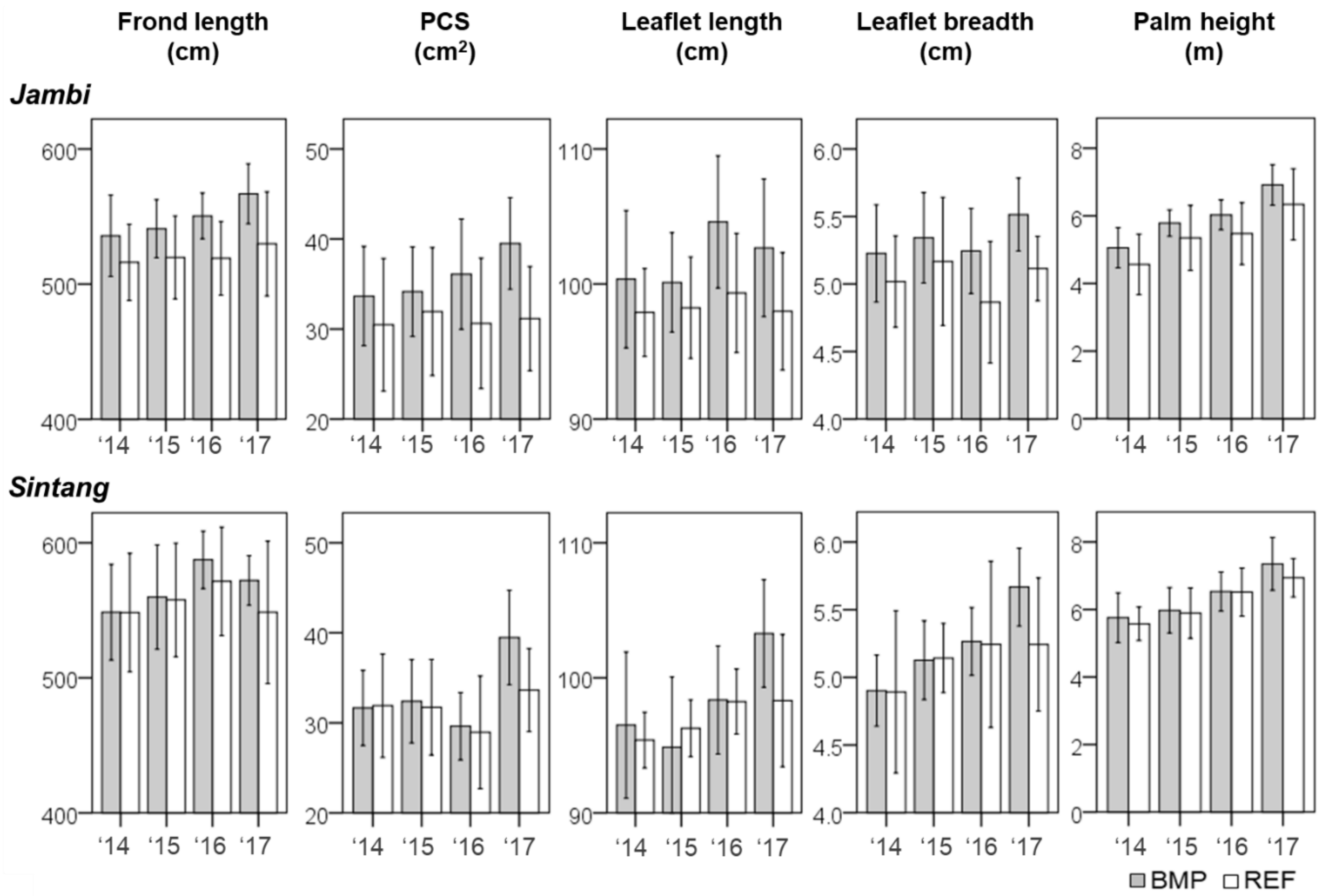

Figure 6.5 Vegetative growth parameters measured for palms in Jambi (*n* = 6; top row) and Sintang (*n* = 7, bottom row), showing from left to right: frond length, petiole cross-section (PCS), leaflet length, leaflet breadth, and palm height. Error bars show the 95% confidence intervals of the observed means.

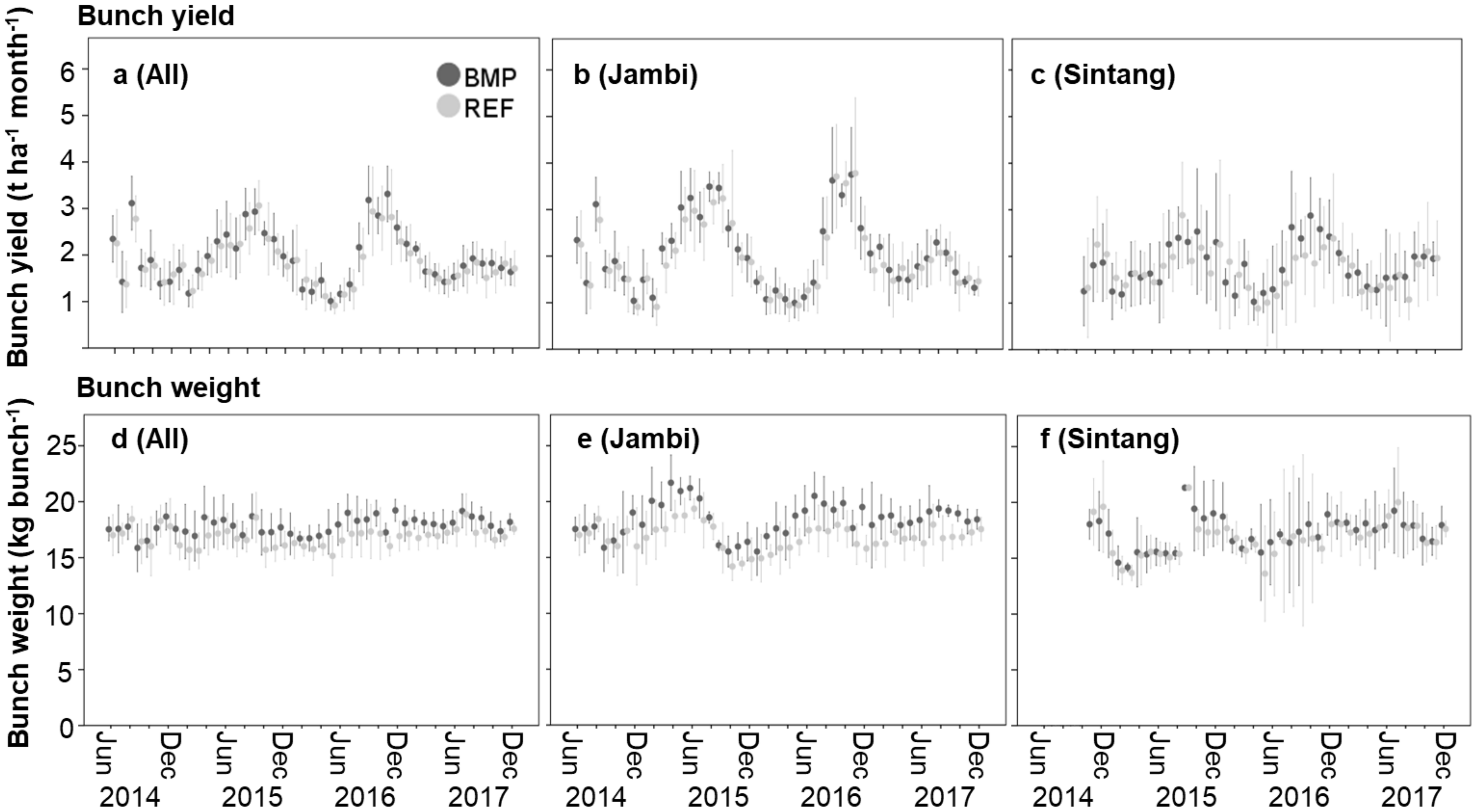

Figure 6.6 Mean yields (top) and bunch weights (bottom) in all plantations (left, *n* = 10) and plantations in Jambi (middle, *n* = 5) and Sintang (right, *n* = 5). Error bars show the 95% confidence intervals of the observed means.

6.3.4 Bunch weight and yield

No significant differences in yield between the BMP and REF plots were observed (mean difference in monthly yield 94.4 kg; *SE* = 75.75; *P* = 0.246; Figure 6.6 a-c). A separate analysis was carried out to test if there was a significant BMP response observed in the poorer yielding half of the plantations (J3, J5, J6; S4, S8) but this was not the case either (data not shown). A clear trend of increasing yield was observed in field S4 (Supplementary Figure S6.3) but statistical analysis could not be performed (*n* = 1). In short, from the data it cannot be concluded that the implemented better management practices resulted in yields different from the reference plots.

A trend of increasing yields in both the BMP and the reference plots was observed in Jambi in the first half of 2015, but the yields collapsed under the influence of El Niño towards the end of 2015 (Figure 6.1; Figure 6.6; Figure S6.3). In 2016 peak yields in Jambi were beyond the yields measured in 2015 but increases in the BMP plots and REF plots were the same. On average, yields in 2016 in Jambi decreased compared with yields in 2015, due to the very poor yields in the first half of the year (Figure 6.6; Figure 6.7). This phenomenon was observed throughout Indonesia and was attributed to drought associated with a strong El Niño event, as well as to the heavy rainfall and lack of sunlight in early 2016 (Figure 6.1). BMP effects appeared to be more pronounced in the peak seasons and were reduced in the trough seasons, particularly in Sintang, with average peak yields in October 2015 and November 2016 being 30% higher in the BMP than in the control plots. Also in Sintang, the trend of yield decline in 2016 due to the adverse weather was pronounced in the REF plots, but absent in the BMP plots, but these results were not significant. In 2017, yields in Jambi did not peak, which may indicate severe after-effects of the El Niño weather event.

Average bunch weights showed a clear and highly significant response to the BMP treatment (mean difference between BMP and REF 1.14 kg; *SE* 0.296, $P < 0.01$; Figure 6.6 d–f). In Jambi, bunch weight in the BMP plots increased significantly after an initial 6-month period, with a maximum average bunch weight of 21 kg in April 2015. Bunch weight collapsed in the second half of 2015, probably due to the El Niño drought. From November 2015 onwards, bunch weight in the BMP plots in Jambi was consistently larger than in the REF plots. Reliable yield recordings started in September 2015 in Sintang. Bunch weight in the BMP plots was consistently larger until April 2017, but the difference was small. The maximum average bunch weight in Sintang was 20 kg in September 2015.

The average yearly yields over all plots and in both research areas are shown in Figure 6.7. There were no significant differences in yield between the BMP and the REF plots in any of the years. Yields changed significantly between 2015 and 2016 but not between 2016 and 2017. Average yields in Jambi were significantly larger than in Sintang ($P < 0.05$). In 2015 average yields were around 22 t ha^{-1} year^{-1} in Sintang and 27 t ha^{-1} year^{-1} in Jambi, which is far more than the estimated national average for smallholders (Molenaar et al., 2013). In 2016, one year after the El Niño drought, yields in Jambi showed a strong decline, while yields in Sintang remained stable in the BMP plots but declined in the REF plots. In 2017, average yields were around 21 t ha^{-1} year^{-1} in Jambi and 20 t ha^{-1} year^{-1} in Sintang; this was still more than the smallholder average and more than the reported yields in Jambi in 2014 (from three fields; 17–19 t ha^{-1} year^{-1}) but significantly less in 2015. Field S4 in Sintang was an exception as it showed a clearly increasing trend in bunch weight, bunch number, and yield over the years, which occurred in both the BMP and the REF plots (Figure S6.3). There was no significant difference between BMP and REF yields in either of the locations, although the BMP plots consistently out-yielded the REF plots by a margin of about 1.2 t ha^{-1} year^{-1}. This margin can be explained by the increase bunch weight of 1.14 kg bunch^{-1} in the BMP plots, and a similar number of bunches in both plots.

6.3.5 Costs and benefits

The quality of the data on maintenance costs (particularly weeding and pruning) was insufficient to provide exact numbers on the differences between the treatments. Our available data suggest that restricting weeding to the circle and path zone saved both herbicide costs and labour costs compared with clean weeding of the entire field; the estimated herbicide saving was around one litre per hectare, while the labour demand was about half a day per hectare instead of one day for clear weeding. On average, farmers used 3–6 L ha^{-1} year^{-1} of herbicides, representing a cost of Rp 200,000 to Rp 400,000 (equivalent to 16–33 USD). The manual cutting of weeds to knee height and the selective removal of woody weeds, either manually or through the spot application of chemicals, were costly practices due to high labour requirements. Average labour costs were around 100.000 Rp man-day^{-1} in the research areas, and farmers spent 5–10 man-days ha^{-1} year^{-1} on pruning and weeding activities.

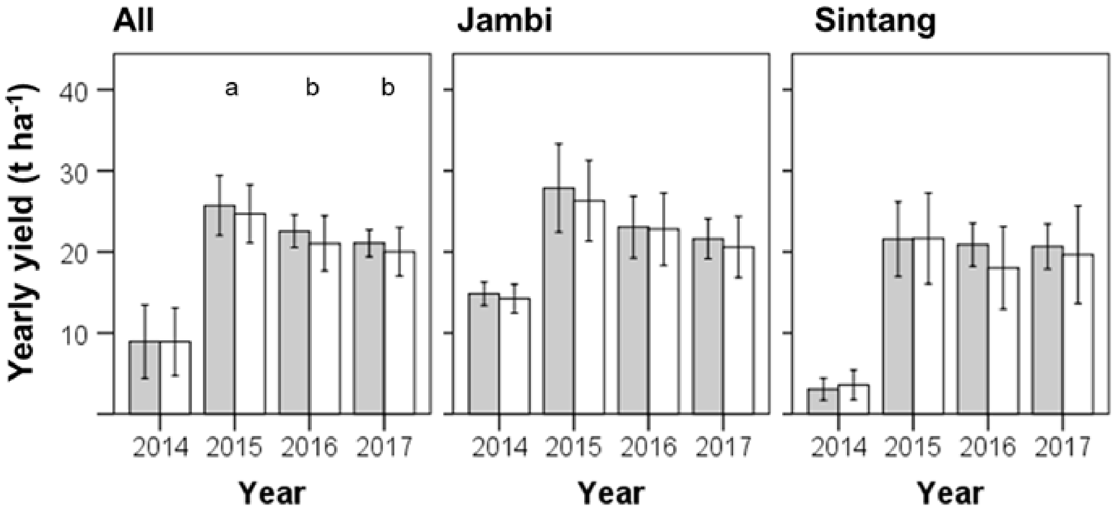

Figure 6.7 Yearly yields in all plantations (left, *n* = 10), Jambi (middle, *n* = 5) and Sintang (right, *n* = 5). Yields from 2014 only show the data from the months after the start of the project: from June onwards in Jambi, and from November onwards in Sintang. Error bars show the 95% confidence interval. Letter codes show significant differences (mixed model analysis with Bonferroni adjustment for multiple pairwise comparisons; $P < 0.01$) between the years 2015, 2016 and 2017.

We used fertiliser prices and changes in yield to calculate the profitability of the BMP plots compared with the control plots (Table 6.4). Although the yields in the BMP plots were consistently larger than in the control plots, the costs for fertilisers increased more than the returns in yield. This led to decreases in profit in Jambi, but in Sintang the margins in 2016 and 2017 were positive, partly due to large investments in fertilisers in the REF plots (Figure 6.2). The price of fertilisers and the price that farmers received for their product strongly determined the profitability of fertiliser applications. For example, farmers in Sintang did not (overall) apply less fertilisers in the REF than in the BMP plots, but they used cheaper, subsidised fertilisers, and received the same bunch price, so the profits in the REF plots were larger.

Table 6.4 Costs and benefits of fertiliser application in the BMP plots, in million Rp per hectare per year. Profits were calculated using an average fruit bunch price of 1200 Rp kg^{-1}. One million Rp is equivalent to around 70 US dollars. The column 'yield change' shows the increase in yield in the BMP plots compared with the control plots; benefits are the yield change times the fruit bunch price; costs are the difference in fertiliser expenses in the BMP versus the control plot; and change in profit is the difference between the benefits and the costs.

Location	Year	Yield change	Change in benefits	Change in costs	Change in profit
		(kg ha^{-1} year^{-1})	(million Rp ha^{-1} year^{-1})		
Jambi	2015	2151	2.58	2.96	–0.38
	2016	152	0.18	2.77	–2.59
	2017	1117	1.34	2.98	–1.64
	Average	1140	1.37	2.90	–1.54
Sintang	2015	–94	-0.11	4.44	–4.55
	2016	2861	3.43	1.72	1.72
	2017	1005	1.21	0.70	0.51
	Average	1257	1.51	2.29	–0.78
Combined	2015	1028	1.23	3.70	–2.47
	2016	1506	1.81	2.24	–0.44
	2017	1061	1.27	1.84	–0.57
	Average	1198	1.44	2.60	–1.16

6.4 Discussion

In this research we addressed the following questions: 1) What yields can be achieved in mature smallholder oil palm plantations after implementing better practices? 2) How do yields change over time in response to better practices? And 3) What are the costs, benefits and risks of intensification? We set out to learn along with farmers, who were supported in trying several changes in their management practices. In experiments with perennial crops under smallholder conditions the concept of 'controls' needs to be adapted to farmers and their approach to learning: if a treatment seems to 'work', farmers are tempted to apply it on their whole farm. Williams et al. (2001) documented such challenges with on-farm experiments with rubber in Jambi (Indonesia) and we faced a similar situation. We had to consider what farmers actually implemented, rather than to assume homogeneous BMP and control treatments.

In both locations several farmers produced excellent yields of around 30 t ha^{-1} year^{-1}, but we observed no statistically significant difference in yield between the BMP and the control plots in any year, although the BMP plots consistently out-yielded the control plots with 1.2 t ha^{-1} $year^{-1}$, on average (Table 6.4). The lack of a statistically significant response was observed despite a clear and significant increase in bunch weight (Figure 6.6), vegetative growth (Figure 6.5), and, to a lesser extent, tissue nutrient concentrations (Figure 6.3; Figure 6.4), particularly of K and B. Due to the increased costs, particularly for fertilisers, the financial benefits from the BMP plots were less than from the REF plots. There may be several explanations for the absence of a significant yield response, which are discussed below.

We expected that implementation of better management practices would lead to substantial yield increases. Vegetative vigour and bunch weight increased substantially and significantly (Figure 6.5), as anticipated, but bunch number and yield did not (Figure 6.6; Figure 6.7). In one well-described but small (n = 2) earlier study on the rehabilitation of nutrient-deficient oil palm plots, Sidhu et al. (2004) demonstrated that within three years, yields from un-fertilised plots could be restored to the same yield as fully fertilised plots by resuming nutrient applications. Griffiths and Fairhurst (2003) achieved large yield gains in a rehabilitation project in a company plantation, with large investments in drainage and soil conservation, but with fertiliser applications similar to our own. In field S4 in Sintang, we observed a steady increase in yield in response to resumed fertiliser applications, especially during the first two years of the project (Figure S6.3). Yield in oil palm is determined by three factors: bunch number and bunch weight (to determine bunch yield) and oil content (to determine oil yield; Sparnaaij, 1960). Of these three factors, bunch number is most responsive to stresses (Corley, 1976a). Bunch number is regulated through the sex ratio (Sparnaaij, 1960) and can be reduced through the abortion of female inflorescences or, in extreme cases, of bunches (Corley, 1976a). There is a time lag of 20–30 months between sex determination and bunch ripeness (Corley et al., 1995), so the response of bunch number to a treatment or stress is expected to develop after this lag period. Bunch weight responds within a few months to changes in availability of assimilates (Corley and Breure, 1992) but the effect on yield is smaller.

In Jambi the yields in 2015 were very high, which was probably the consequence of the greatly improved drainage in 2014, in combination with improved harvesting and fertiliser application practices, of which the positive effects are well-documented (Ollagnier and Ochs, 1981; Tohiruddin et al., 2010a; Lee et al., 2013). The El Niño event occurred when the palms were extremely productive, with average fruit bunch yields of over 3.5 t ha^{-1} $month^{-1}$, requiring maximum quantities of assimilates. We observed an immediate reduction in bunch weight and yield during the El Niño drought, which points at acute assimilate shortages in the palms. These shortages may have led to bunch and inflorescence abortion and to a massive shift in sex determination towards male inflorescences, which would explain the absence of a production peak in 2017, two years after the event. The palms in Jambi may have been very sensitive to drought precisely because they were at peak productivity. As Cornaire et al. (1994) noted, an effective way to deal with drought is by removing developing bunches to increase reserves, but the palms in Jambi were in the opposite situation. Caliman et al. (1998) also suggested that highly productive palms are more sensitive to drought and are more likely to experience severe effects than poorly producing palms.

In 2016, the poor yield in Jambi resulted from a very long 'low' season which was probably exacerbated by the heavy rains between January and June. Waterlogging and a lack of radiation may have depressed yields during this period. The water table in the rainy season was very high throughout the research area in Jambi apart from 2014–2015, even though the BMP plots and large parts of the REF plots were located on slightly elevated land. The REF plots were more prone to flooding (as they were partly located in a lower-lying strip of land), and in 2017 drainage had deteriorated to such an extent that patches of three REF plantations were flooded for three months, which hampered harvesting, and which may have affected growth and productivity as well. Our yield data suggest that climatic factors can override fertiliser responses, which has implications for farmers who must consider the economic risks of investing in fertilisers and other aspects of BMP.

In Sintang, the peak yield in 2015 was less pronounced than in Jambi, and the effect of the El Niño event on yield was less strong, particularly in the BMP plots (Figure 6.6; Figure 6.7). In 2016, the yield in the BMP plots was the same as in 2015 but yields in the REF plots appeared to decrease, although the difference was not significant. Three out of five fields in Sintang were well-managed at the start of the project and average nutrient applications in REF plots were large. The responses in tissue nutrient concentrations, vegetative growth, and bunch weight in Sintang were mostly absent (with the notable exception of field S4; Figure S6.3), so the absence of a significant yield response during the project is in line with these observations.

The increased leaf size and bunch weight observed in Jambi appear to contrast with the lack of a statistically significant yield increase in the BMP plots, but there are plausible explanations. In an effectively closed-canopy situation, such as a mature oil palm plantation, increases in leaf size do not necessarily increase total light capture or yield. Oil palms prioritise vegetative growth over generative growth (Corley et al., 1971) and there is strong inter-palm competition for sunlight in mature plantations planted at recommended densities (Uexküll et al., 2003). Breure (1977) showed that increased fertiliser applications had a significantly positive effect on leaf area and on bunch weight irrespective of palm density, but that there was a significant negative density × fertiliser effect on yield. The experiment of Sidhu et al. (2004) was planted at more or less the same density as our fields but the palms were younger and much smaller at the start of the experiment. Still, in year six of the experiment of Sidhu and colleagues the average frond length (600 cm) exceeded the average frond length in the final year of our experiment (Figure 6.5), but yields were very large. It would be worthwhile to investigate if selective thinning is an essential step for increasing yields in older plantations where the LAI is already high (Uexküll et al., 2003; Teuscher et al., 2016).

Harvesting probably affected yield, but there was no differentiation between the treatments. Before the start of the project, the farmers in both areas harvested once per 14 or 15 days, while the optimum harvesting interval is 10 days or less (Corley, 2001). In Jambi in particular, the participants rigorously followed the recommended 10-day harvesting round in the period 2014–2016 (both in the BMP and in the control plots) but stopped doing so in 2017 because of personal circumstances of the lead farmer, who was also the trader. Increased harvesting frequency has been proposed as a strong driver of increased bunch yield (Donough et al., 2010; Lee et al., 2013) and improved oil content and quality (Corley, 2001; Donough, 2003), leading to improved bunch prices (Hutabarat et al., 2018). The combination of better harvesting practices and better drainage could explain a large part of the excellent 2015 yields in Jambi, and the return to a 15-day harvesting interval combined with flooding in 2017 may explain why yields were reduced in that year. In Sintang, harvesting was irregular and increasing the harvesting frequency was not on option as the mill did not accept bunches at a 10-day interval, so a strong effect of harvesting on yield was not expected.

Although we are confident in the yields we reported, especially in Jambi, recording oil palm yields is difficult in smallholder settings due to the way harvesting is organised (Jelsma et al., 2017a). The farmers were dependent on the cooperative (Sintang) or local traders (Jambi) to arrange the harvesting and transport of their bunches; few harvested themselves. Farmers in Sintang particularly had little control over the harvesting practices and over the timing of harvesting. Harvesters were paid Rp 100,000 to Rp 150,000 per tonne of harvested bunches (depending on year, palm age and field maintenance), and there appeared to be a shortage of harvesting labour. The harvesting teams changed regularly, so training them was not feasible. The subdivision of the fields into BMP and REF plots was not relevant for the harvesters and the separation of the bunches was not always carried out correctly. In addition, the farmers were not always informed when the harvesting took place, and neither was the local project assistant, so not all yields could be recorded. The problems with yield recording were particularly severe for the fields containing peat pockets (S2, S3 and S5). These pockets were excluded from the yield recording several months after the start of the project, but although the palms were re-marked, the harvesters were confused. As a result, the peat pockets were sometimes included and sometimes excluded in the records, and for this reason the yield data had to be discarded. For future research in smallholder plantations we recommend that the whole field or block is the experimental unit unless a very good and independent yield recording system can be put in place.

Most farmers implemented circle and path weeding in the BMP plots, and either clear weeding or circle and path weeding in the control plots (data not shown). There are no reliable studies which show convincingly that weeding practices have a significant impact on oil palm yield (Woittiez et al., 2017b). An indirect but important benefit of good weeding (especially the establishment of paths and circles) and pruning is that these practices facilitate quick and complete harvesting, which had major impact on yield in a smallholder GAP project in Ghana (IPNI, 2015; Rhebergen et al., 2018). At least one farmer stated that the harvesting costs per tonne in the well-weeded and well-pruned BMP plots were less, because harvesters adapt the price to the effort required for harvesting. Regular pruning facilitates the recycling of nutrients in the plantation. Other pruning related practices implemented in the BMP plots (but also in most control plots by the farmers) were to stack the fronds in a U-shape around the trees, and to spread fertilisers over the stack. The infiltration of water into the soil is better under the frond stack than in other parts of the plantation (Fairhurst, 1996) and on slopes the strategical placement of fronds can limit soil erosion and water and fertiliser run-off (Paramananthan, 2013), but the exact effects of frond and fertiliser placement on yield could not be quantified in our experiments.

Unlike harvesting, weeding, and pruning, fertiliser application practices in the BMP plots were controlled by the project. Clear differences between BMP and REF plots existed in terms of quantities and fertiliser types applied in Jambi, and in terms of fertiliser types applied in Sintang (Table 6.3). At the start of the project, the concentrations of N, P and K in the leaflets and rachis were mostly below the critical concentrations (Ollagnier and Ochs, 1981; Foster and Prabowo, 2006) in both research areas, suggesting that deficiencies were prevalent. The N, P and B concentrations in the leaflets were increased to well above the individual critical values within one or two years after the project start (Figure 6.3; Figure S6.1), indicating that applications of these nutrients were sufficient to meet the demand and correct existing deficiencies. The K concentrations changed more slowly, and average concentrations never reached the critical threshold (Figure 6.3). The limited increase in leaflet K concentrations in Jambi may be explained by the observations of Dubos et al. (2017), who noted that in some soils with high Ca^{2+} concentrations the application of KCl can actually reduce the leaflet K concentration while increasing yield. The leaflet K concentration in relation to Total Leaf Cations (K^{+}, Mg^{2+} and Ca^{2+}; Foster, 2003) is considered a better indicator of sufficiency than individual critical values. It was on average sufficient (> 31.3) in the BMP plots in Jambi from 2015 onwards (data not shown), while in Sintang it improved from very deficient (22.7) to nearly sufficient (28.6; Foster, 2003). These results are noteworthy, because the rachis values in both areas indicated a severe deficiency throughout the project (Figure 6.4). Palms in the experiment of Sidhu et al. (2009) reached rachis K values of > 1.0% in year 3, but in Sintang the average K concentrations in the rachis did not exceed 0.6 at the end of the project, which indicates a severe deficiency (Foster and Prabowo, 2006). Concentrations in Jambi were higher, but also remained below the deficiency line. At the same time, the Mg concentration in Sintang went from low (26.1) in 2014 to deficient (24.1) in 2017, which was probably due to the antagonistic effect of K on Mg availability in the soil (Daliparthy et al., 1994). Although Mg fertilisers were applied in Sintang, these were not sufficient to prevent induced Mg deficiency. Even in Jambi, where native soil Mg concentrations were very high, the tissue Mg concentrations relative to Total Leaf Cations fell from 32.5 (sufficient) in 2014 to 27.2 (low) in 2017. This suggests that Mg fertilisers in Jambi will be required in future, if the K applications as proposed in the BMP are continued. Boron fertiliser was applied in relatively large quantities, which resulted in a spike in tissue B concentrations (Figure 6.3). It is likely that B applications could be strongly reduced without negative effects on yield, as the relationships between B fertilisation and yield are not well established (Corrado et al., 1992).

Despite the responses in vegetative growth and bunch weight that we observed, the costs of the additional nutrient applications far outweighed the benefits, even without considering the additional labour investments for fertiliser application. These results are in line with the findings of Hutabarat et al. (2018), who studied a group of RSPO-certified independent smallholders and observed that the implementation of better management practices similar to ours, in combination with RSPO certification, led to a small increase in yield but a decrease in farm income, due to the great increase in costs. It is likely that fertiliser application and other BMPs will have a stronger effect on yield in plantations which are more nutrient-constrained and have poorer starting yields. Foster and Mohammed (1988) noted that even within the same soil series and with similar management practices, yield responses to fertilisers can differ significantly due to factors such as palm age, planting density, slope, drainage, and rainfall. Our results confirm that these factors deserve full attention and need to be addressed before or together with nutrient management if the latter is to be successful. Using subsidised fertilisers at rates as recommended in the BMP may be profitable if yields are maintained and bunch prices are sufficiently high.

In terms of weeding, there appear to be few trade-offs: good practices save costs for input and labour, and result in improved harvesting efficiency (IPNI, 2015). Pruning is a costly practice due to the large labour investment, and with harvesters paid per tonne, not per hour, the returns on investment are not very clear. More regular harvesting is likely to have strong financial benefits, and these benefits were recognised by the participating farmers. Unfortunately, farmers are often dependent on other parties for their harvesting, and harvesting is very labour intensive, so the benefits may not be so easy to reap.

6.5 Conclusions

We addressed three questions: 1) What yields can be achieved in mature smallholder oil palm plantations after implementing better practices? 2) How do yields change over time in response to better practices? And 3) What are the costs, benefits and risks of intensification? The best yields that were achieved exceeded 30 t fruit bunches ha^{-1} $year^{-1}$, but this yield peak was achieved one year after the start of the project (in 2015) and yields dropped to around 21 t fruit bunches ha^{-1} $year^{-1}$ in the years after. The BMP treatment resulted in significantly larger palms and bigger bunches, but not in significantly better yields, and the financial results were negative. The yield response was strongly affected by the 2015 El Niño event, and probably by drainage and planting density.

Through our long-term engagement with the farmers we have been able to identify several practices (the 10-day harvesting interval; circle and path weeding; selective removal of woody weeds; frond stacking in a U-shape; fertiliser application over the frond stack; application of K fertiliser) that were enthusiastically implemented by a number of farmers, and sometimes by the majority, both in the BMP and in the control plots. These practices had in common that they were financially attractive (such as circle and path weeding), demonstrated clear benefits (the 10-day harvesting interval resulting in better prices at the mill in Jambi) or had visible effects in the field (palm roots growing into frond stacks; leaves turning green after the application of K). On the other hand, practices that were expensive and did not have clear effects (such as regular pruning) were not so readily implemented.

Our results emphasise the difficulties of finding and implementing intensification options that are both sustainable and profitable, and that have a substantial impact on yield. To find such options, on-farm experimentation and data collection are essential. Trying out better management practices in farmers' fields helps to improve our understanding of the processes that underlie productivity in oil palm plantations while fully engaging with the farmers. This is necessary for achieving rehabilitation on a larger scale, with approaches that are environmentally and financially sustainable and that fit within farmers' realities and preferences.

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Supplementary materials

Figure S6.1 Tissue nutrient concentrations (leaflet N, P, K and Mg; and rachis P and K) in field S4 and field S6. Individual palm samples were collected every four months, starting in November 2014 (Round 1) and ending in February 2018 (Round 10; three months delayed due to organisational issues). For leaflet K and leaflet Mg, the concentration relative to Total Leaf Cation (TLC) is presented instead of the absolute concentration. Whiskers show the minimum and maximum values; the box shows the 1st and 3rd quartile; the line shows the median. Outliers are marked with a circle (1.5–3.0 × Inter Quartile Range) or a square (> 3.0 × Inter Quartile Range). The dashed line shows the critical nutrient value. Stars show Bonferroni-corrected significant differences between the BMP and REF treatments at $P < 0.05$.

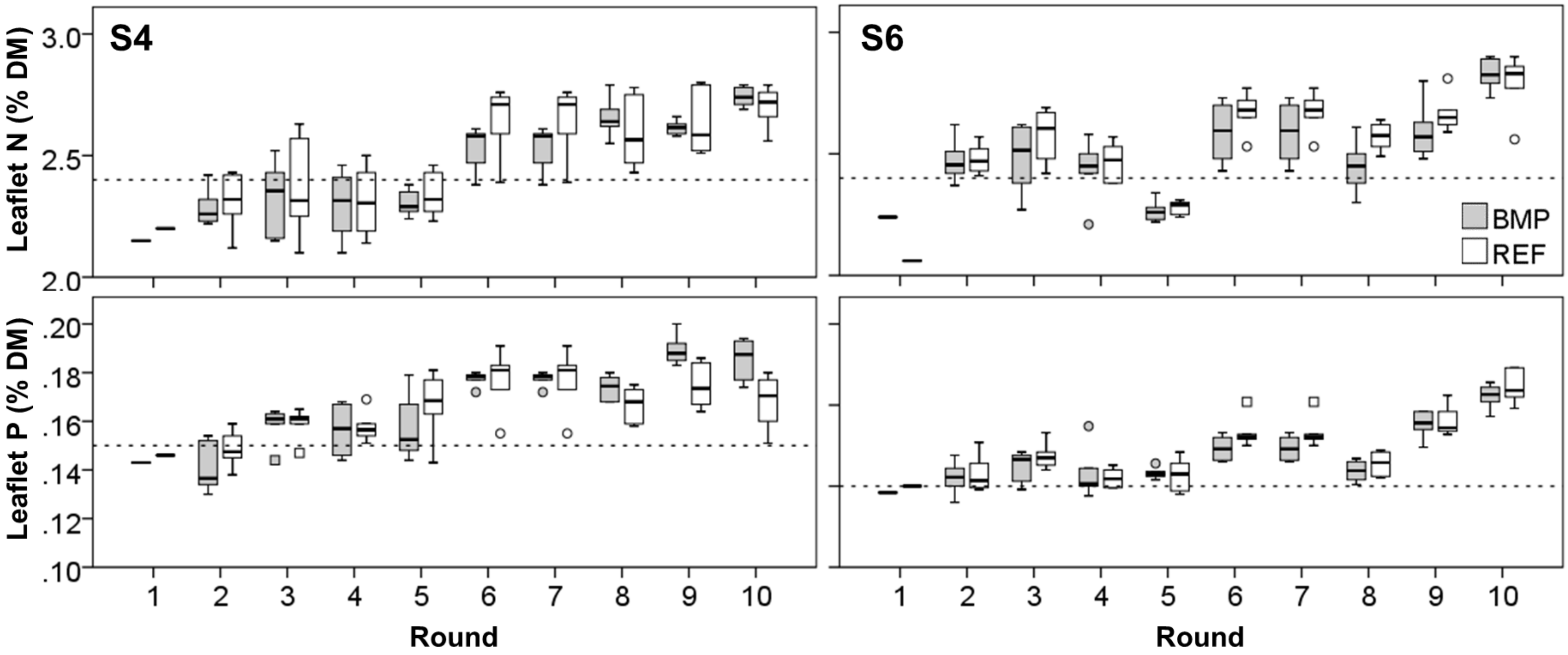
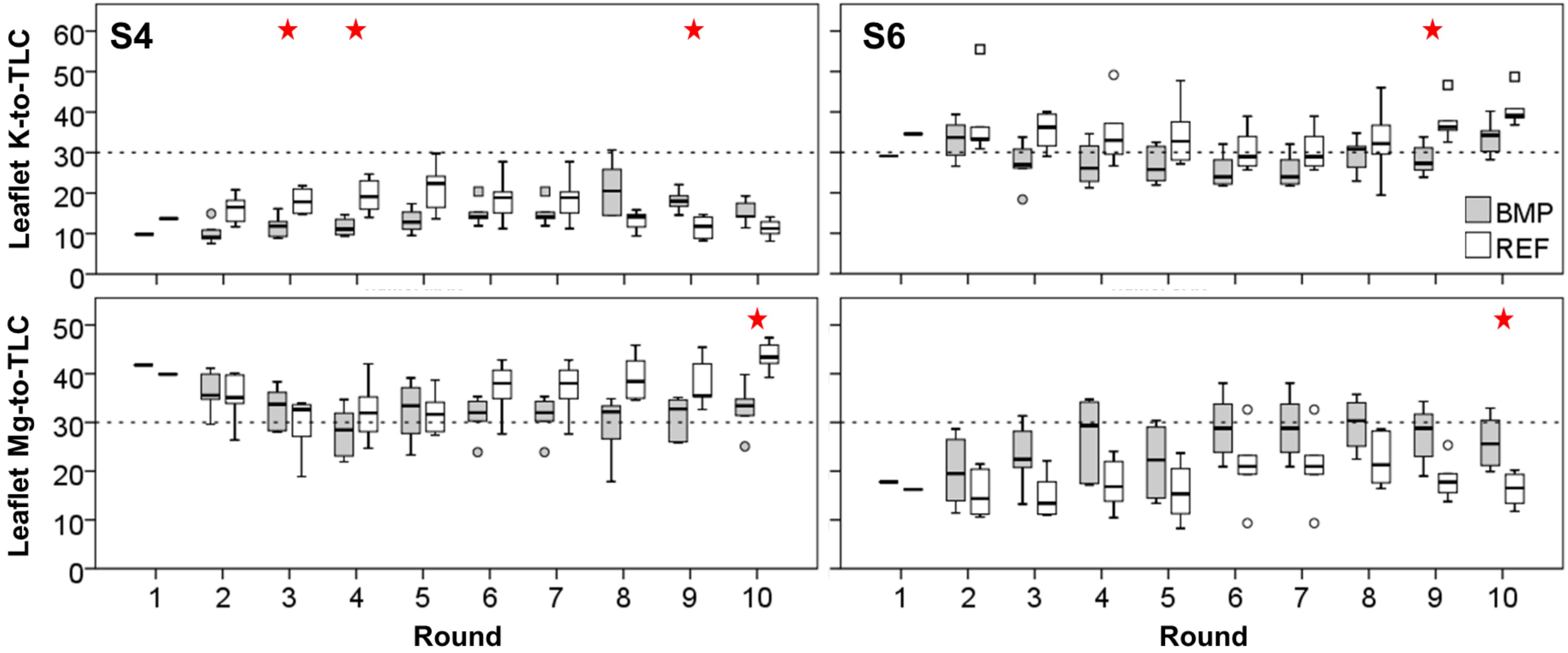


Figure S6.1, continued



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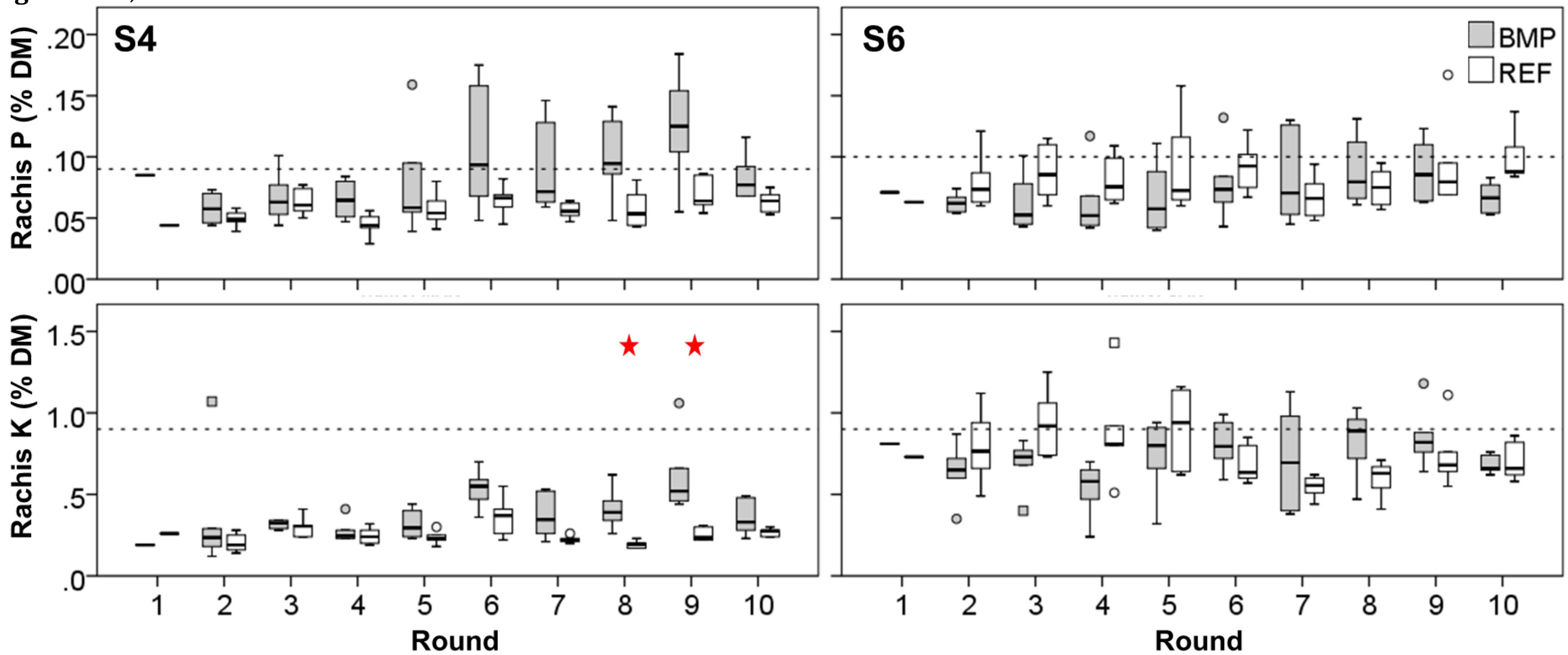


Figure S6.2 Frond length and petiole cross-section (PCS) in field S4 and S6.
Vegetative measurements were done every four months, starting in November 2014 (Round 1) and ending in February 2018 (Round 10; three months delayed due to organisational issues). PCS = petiole cross-section. Whiskers show the minimum and maximum values; the box shows the 1st and 3rd quartile; the line shows the median. Outliers are marked with a circle (1.5–3.0 × Inter Quartile Range) or a square (> 3.0 × Inter Quartile Range). Stars show Bonferroni-corrected significant differences between the BMP and REF treatments at $P < 0.05$.

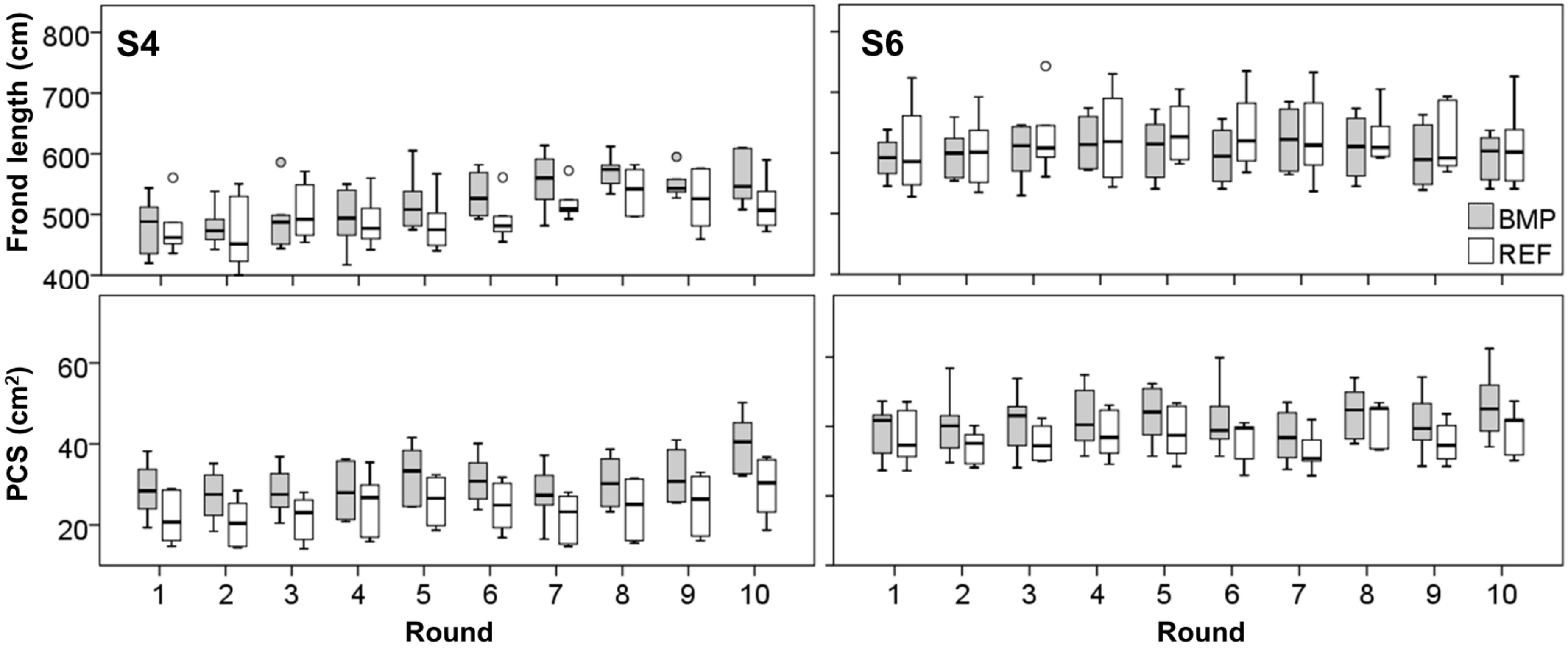
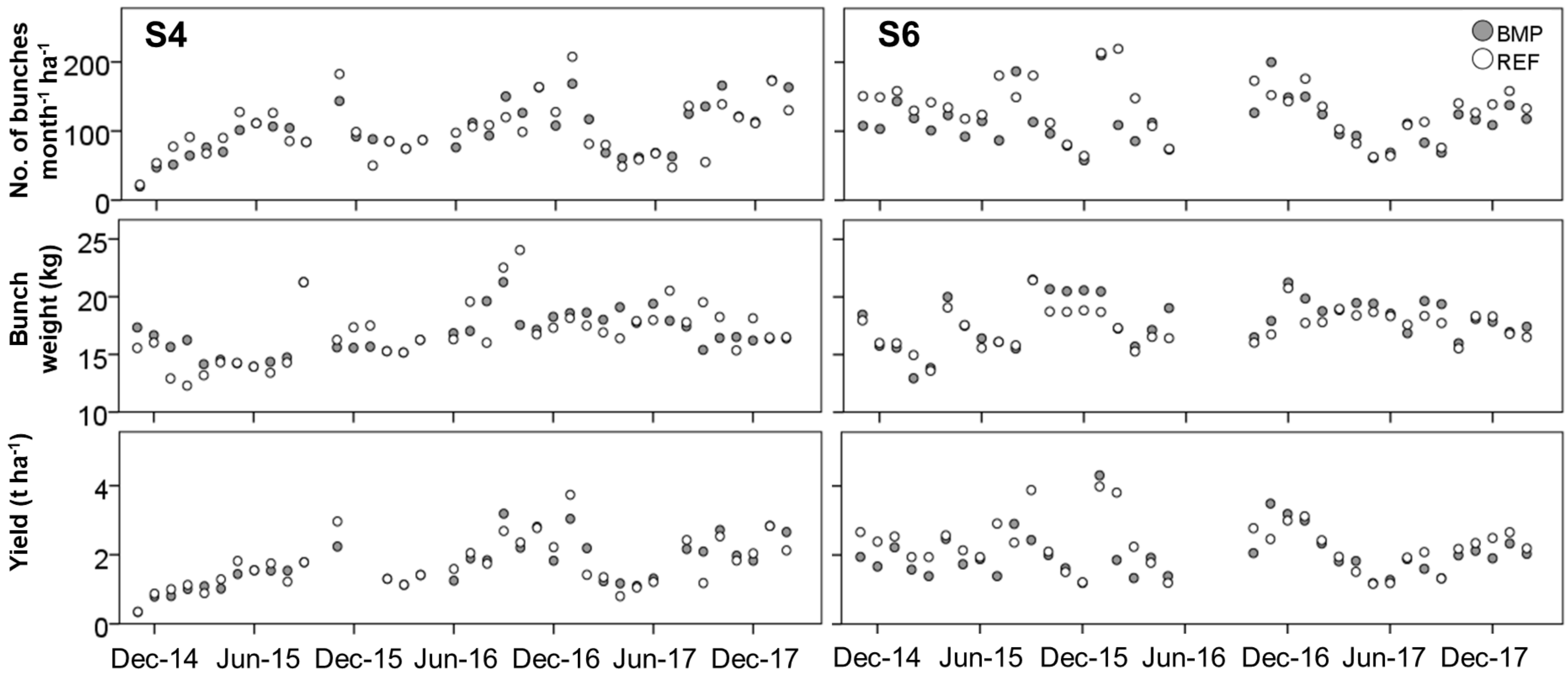


Figure S6.3 Monthly number of bunches, bunch weight and yield in field S4 and S6.
Data on bunch number and total bunch yield were collected every two weeks. Bunch weight was calculated by dividing total yield over number of bunches. There were some gaps in the yield records (shown as missing data points). The seasonal variation and the increasing trend in bunch number, bunch weight and yield in field S4 are clearly visible.



CHAPTER 7

General discussion

7.1 Introduction

In Indonesia alone, an estimated two million smallholders depend on palm oil production as their major source of income. These smallholders contribute 30–35% of the total palm oil production in Indonesia (InPOP, 2015; INOBU, 2016), but their yields are poor. In this thesis I investigated the agronomic practices of Indonesian oil palm smallholders, and I tested several better management practices that may contribute to better productivity in a sustainable way. In this General Discussion I integrate the results from the five research chapters, reflect critically on these results, and discuss the insights and recommendations that appear from my findings. The chapter is structured around the four research questions and hypotheses that were formulated in the introduction. These research questions were:

1. What are the causes of yield gaps in oil palm plantations, and how large are their effects on yield?
2. How prevalent are nutrient deficiencies in Indonesian smallholder oil palm plantations, and what are their effects on yield?
3. What yield-determining, yield-limiting, and yield-reducing factors can explain the large yield gap in Indonesian smallholder oil palm plantations?
4. What is the scope for sustainable intensification in mature Indonesian smallholder oil palm plantations?

In response to the research questions, I formulated the following four hypotheses:

1. The causes of yield gaps in oil palm plantations can be classified as yield-determining, yield-limiting, and yield-reducing factors, and their actual effects on yield vary greatly depending on the local biophysical and socio-economic conditions.
2. Nutrient deficiencies are present in most smallholder plantations and have a strong yield-limiting effect.
3. The yield gap is mostly explained by poor planting material, poor drainage, infrequent harvesting, and poor nutrient management, but the factors vary depending on the local biophysical and socio-economic conditions.
4. There is large scope for sustainable intensification in mature smallholder plantations through the implementation of better management practices, which will result in economic and environmental benefits.

From 2013 to 2017, I reviewed the literature and carried out intensive field work in Indonesia, and this resulted in five research chapters. In section 7.2, I summarise the key findings of the different chapters in relation to the research questions, and in section 7.3 I discuss the limitations of my research approach and the effects of these limitations on the key findings. In sections 7.4 to 7.7, I discuss each of the four research questions individually. After answering the research question and accepting or rejecting the hypothesis, I critically assess how my results support my answers to the questions, how these results relate with what is found in literature, how potential discrepancies can be explained, what the possible directions for future research are, and what the contributions of my findings are to the general knowledge. In section 7.8, I identify the constraints to sustainable intensification in smallholder plantations, and I discuss the options for addressing these constraints. Finally, in section 7.9, I present some personal reflections and concluding remarks.

7.2 Summary of the key findings

In the literature review (Chapter 2) I quantified the contribution of a large range of production factors to the yield gap in oil palm plantation systems. I concluded that closing this yield gap to 80% of the water-limited yield would provide as much additional palm oil as the cultivation of 4–6 Mha of new plantations. I also found that yield responses to important environmental and management factors like waterlogging, drainage, micronutrient fertilisers, and biotic stresses are poorly quantified and require further investigation. From the review, it consistently appeared that yield gaps in smallholder plantations are particularly large, and in Chapter 3 I investigated further the causes of these large yield gaps in communities in Jambi and West-Kalimantan. During my research I observed a very large prevalence of nutrient deficiencies in smallholder fields, particularly for potassium (K; deficiencies in > 80% of the fields) but also for nitrogen (N) and phosphorus (P; both > 60% deficient). I also observed that many of the farmers had planted inferior planting materials, and a similar pattern appeared among farmers in Riau, as described in Chapter 4. The research in Riau was mostly carried out by Idsert Jelsma, and he previously developed a useful classification system of the different smallholder 'types' into seven groups. Based on the data collected by Jelsma from 231 smallholder plantations, we analysed the use of good agricultural practices, and to our surprise we concluded that there were no clear differences in management between the different farmer types, which ranged from small local farmers to commercial plantations of hundreds of hectares owned by Jakarta-based businessmen. Less surprisingly, we observed that farmers in peat areas produced poorer yields than their peers on mineral soils. As in the plantations described in Chapter 3, K deficiencies and the use of inferior planting material were particularly common, and yield gaps were quite large. To dig deeper into the nutrient use of smallholders in Indonesia, I developed a survey which was administered to more than 300 farmers in Jambi, Riau and West-Kalimantan (Chapter 5). From the results of this survey I concluded that the majority of the farmers used fertilisers, and that fertiliser users spent an average of 225 USD per hectare per year on fertiliser inputs. But fertiliser applications were not well balanced, with the 'cheaper' nutrients (N and P) applied in large quantities (sometimes in excess) and the 'expensive' nutrients (K) applied in small quantities. To test if better nutrition would lead to better yields, I did a three-year experiment with 14 farmers who established a 'demonstration plot' where a set of better management practices (BMPs) were implemented, and a control plot (Chapter 6). After three years, the palms in the BMP plots had significantly larger leaves and produced heavier bunches, but the improvements in yield were small and not statistically significant. In the discussion of Chapter 6, I propose that environmental constraints (particularly the 2015 El Niño event and waterlogging in Jambi) had an over-ruling effect on yield. I also concluded that improving smallholder yields in mature oil palm plantations is not easy, particularly when starting yields are already good, and that a direct and substantial yield response to improved agricultural practices should not be taken for granted.

7.3 Limitations of the research

In this section I discuss briefly the limitations of my research approach. I focus on five limitations that I identified: sample selection, the reliability of survey data, common errors with tissue sampling, problems with 'farmer controls', and difficulties with collecting yield data from smallholder plantations.

7.3.1 Sample selection

The sampling for Chapter 4 was exemplary, as it was based on impartial criteria using satellite images (Jelsma et al., 2017a). Sample selection for Chapter 3 and 5 was done through a mix of random sampling (from lists of farmers) and 'snowball sampling' when lists or farmers were not available. Although this method is commonly used and accepted, it risks the exclusion of less-visible groups of farmers (Heckathorn, 1997). I think that farmers are likely to refer researchers (particularly white, foreign researchers) to their relatives or friends, because the visit of such a researcher is a bit of a treat, as the numerous selfies with farmers and families that I star on can attest. This may have led to the exclusion of poor, less connected households, and I think that my sample was biased towards the better-off farmers. If this was the case, then the identified yield gaps may be even larger, and I may have formed an overly positive image of the wealth and potential of the average smallholder. One farmer in Jambi burst into tears both times I visited her; she was desperately poor, and I do not think she had many opportunities to improve her yields at all. I may have overlooked other farmers in a similar situation, for whom oil palm cultivation is not a way out of poverty (McCarthy, 2010). The presence of such farmers would explain better why one of my students observed that land tenure in Jambi became more unequal over the years, with a few farmers accumulating land and many others selling theirs (van Reemst, 2015). For the experimental work (Chapter 6) the sampling was non-random and problematic. Key problems were the peat pockets in three plantations in Sintang, the different sample size in the two locations, and the small yield gaps in some of the plantations. The sample was also 'not representative', but that was a conscious decision, as we wanted to work with farmers who had the means to implement the proposed better management practices. The small yield gaps may be one of the main reasons why the yields did not increase significantly. I think that the experimental results from Chapter 6 cannot be extrapolated to the less resource endowed and less productive farmers, and to the independent farmers who planted their fields without company support.

7.3.2 Reliability of survey data

The data for Chapter 3, 4 and 5 was collected partly or fully (Chapter 5) through surveys. Data collection based on farmers' recall is easy and quickly done but it is probably not very reliable. I noticed that farmers were often not well aware of their yield and of the size of their plantations, although they could often give the number of palms they had planted. For yields, I asked farmers for their best and their worst yield and made an average out of this number, but this is an approximation at best. The lack of reliable yield data to support the yield gap story is a major limitation, which is inherent to working with smallholders who do not keep records. Field audits, either physical or based on photographs, can be used to triangulate survey results (Chapter 4). Someone who has experience with oil palm cultivation should be able to observe the most important management practices after a short field inspection, although estimating exact yields or nutrient inputs is not really possible. Field audits were not part of the data collection for Chapter 5, and the estimated quantities of nutrients applied should be interpreted with caution, although I think the general trend is reliable and consistent with other studies.

7.3.3 Issues with tissue sampling

Tissue sampling is considered the 'gold standard' for detecting nutrient limitations in oil palm, because in well-managed randomised fertiliser trials clear correlations have been observed between tissue concentrations of some nutrients and yield response to fertilisers (Warriar and Piggott, 1973; Foster and Prabowo, 2002; Foster and Prabowo, 2006; Sidhu et al., 2009). Although the leaf sampling technique has been in use for a long time (Chapman and Gray, 1949), there are some technical difficulties. The nitrogen concentrations measured in Riau (Chapter 5) were below the normal range and should be viewed with caution. Nitrogen is the nutrient that is most easily lost during sample drying and processing, so I suspect that the values reflect errors during processing and analysis, rather than true concentrations of N. In Chapter 6 I noted that nutrient concentrations in individual palms were extremely variable, with up to a factor three difference between palms with the highest and palms with the lowest tissue concentrations in a single field (Figure S6.1). I think this reflects true differences among palms (the differences were somewhat consistent over time), but part of the variation probably also arose during sample processing and analysis. I often sampled both in the morning and afternoon, in the wet and the dry season, and sometimes within three months after fertiliser application. All these factors will have affected the results, and I think the error margins are large. Homogenising samples before sub-sampling was very challenging (particularly for rachis samples, which can only be ground with a specialised grinder and which were sent to the laboratory un-ground). Finding a reliable laboratory was also difficult, although I think I found one in the second year of the project. Figure 7.1 shows the relationships between duplicate samples. Although there is a significant positive correlation between concentrations measured in duplicates, the variability is large. I do not think that this variability affects the conclusions of my thesis, because the results from the tissue sampling are supported with other data. I do think that sampling only in the morning, in the dry season, and not within three (or even four) months after fertiliser application would give more reliable results, but in practice this is very challenging outside company plantations.

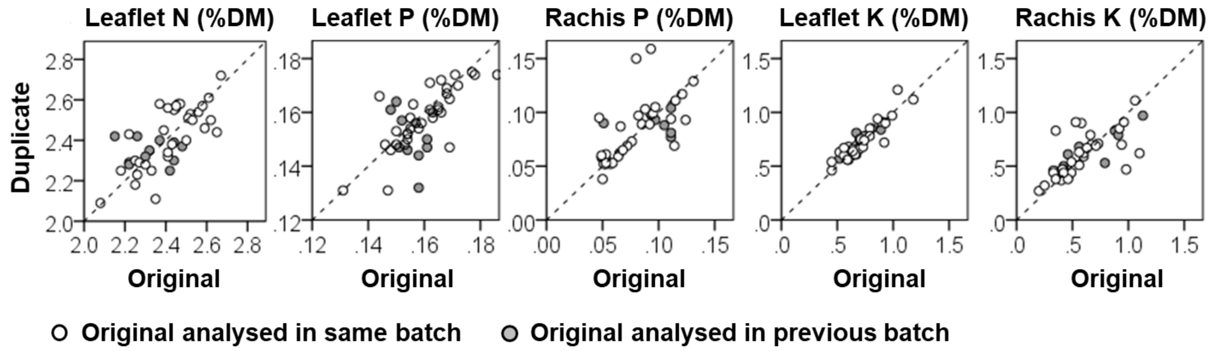


Figure 7.1 Results of duplicate sample analyses in reference to a 1:1 line. The samples were collected and analysed for the experimental work reported in Chapter 6. Duplicates were either analysed in the same batch (white dots) or in later batches (grey dots) to assess the stability of results over different rounds of analysis.

7.3.4 Using farmer-managed control plots

I think the problem with using farmer-managed control plots is well illustrated by the following anecdote. Half a year or so after the start of the project, one of the farmers in Jambi told me with great enthusiasm that she had observed how the leaves in her BMP plot had turned from yellow to green due to the potassium fertilisers, and that she had applied a large quantity of potassium fertiliser in the control field because it seemed to work so well. I know that at least half of the farmers copied one or several better management practices in their control fields, and this could be an important reason why no significant yield increase was observed. Because of this limitation, I cannot say with confidence the proposed better management practices do not work. It might have been better for the experiment to prescribe certain practices for the control plots, but I would not consider this a fair option as farmers are dependent on their plantations for their income and should have the autonomy to manage their field as they see fit.

7.3.5 Reliability of yield data

Finally, the collection of yield data through surveys and in the experiments was problematic, even though in the experiments we hired local staff to keep the records. One key problem was the division of single harvesting units (kavlings) into different plots. This led to much confusion, especially when some of the plots were re-drawn in the fields with peat plots, and in the end these fields needed to be excluded from the yield calculations. In retrospect it would have been easier, both for implementation and for yield recording, to apply BMP and control treatments in separate fields. Such a setup would not have the advantage of paired plots, and a larger sample size (in terms of area) would be required, but I think the benefits in terms of management and data collection outweigh the disadvantages. I also think that establishing experiments in plantations where yield recording systems are in place (from a cooperative or a company) would have been a better idea, but the problem with the different sub-plots would have remained.

7.3.6 Conclusions

I identified several important limitations in my study, most of which had to do with the difficulties of doing thorough scientific research in the messy reality of farmers' fields. I have argued that these limitations do not invalidate my conclusions, but I do not think that the results from the experimental work can be extrapolated to the entire smallholder population. This is an important limitation to keep in mind.

7.4 Causes of yield gaps in oil palm plantations

In Chapter 2, I reviewed a large body of scientific and grey literature with the aim of quantifying the factors underlying yield gaps in oil palm. The review provides a state-of-the-art overview of what is known (and not known) about yield gaps in oil palm plantations. To avoid repeating myself, I will limit the discussion to a short reflection on the hypothesis, and to a few recommendations on possible directions for future research.

I investigated the following research question: *What are the causes of yield gaps in oil palm plantations, and how large are their effects on yield?* My hypothesis was that *the causes of yield gaps in oil palm plantations can be classified as yield-determining, yield-limiting, and yield-reducing factors, and their actual effects on yield vary greatly depending on the local biophysical and socio-economic conditions.* In the literature review, I proposed that the yield-determining factors are radiation, CO_2 concentration, temperature, planting material, culling, planting density, pruning, pollination, and crop recovery (harvesting); the yield-limiting factors are rainfall, irrigation, soil, waterlogging, topography, slope, and nutrition; and the yield-reducing factors are weeds, pests, and diseases. As I hypothesised, the reported yield effects of these factors varied widely depending on local conditions, and quantifying these yield effects was often challenging, particularly for yield-limiting and yield-reducing factors.

As the frequency of El Niño events is expected to double with a 1.5 °C increase in global temperature (Wang et al., 2017), drought is likely to become a more important issue in areas that normally have adequate rainfall. It is important that we improve our understanding of the basic mechanisms that underlie the highly dynamic response of oil palm to climatic stresses, particularly drought and lack of irradiation. Company records of the 2015–2017 period could provide a good basis to study and model the effects of the El Niño event on bunch weight and yield, but available data are scarce. Cornaire et al. (1994) suggest that the effect of drought can be mitigated by the removal of developing bunches to increase carbohydrate reserves, and I think this suggestion deserves further testing. El Niño prediction systems can accurately forecast the occurrence of future events (the next is predicted to occur in 2019; IRI, 2018), and a simple bunch removal and bunch count study at individual palm level could be set up to test the recommendations of Cornaire and to experiment with other coping strategies, such as irrigation, soil conservation, and adapted nutrient management.

Waterlogging is another yield-limiting factor that is poorly understood. Waterlogging reduces the ability of the roots to respire and take up nutrients, and for this reason the carbohydrate availability in waterlogged palms is reduced. Considering that oil palm stores its carbohydrate reserves in the trunk (Legros et al., 2009c) it would be interesting to carry out research in areas which are waterlogged for prolonged periods and in newly drained areas, to assess the changes in trunk reserves, the vegetative growth, and the numbers of inflorescences and bunches that are produced.

The yield-limiting effects of nutrient deficiencies (particularly N, P, K and Mg) have received much attention in literature (Goh et al., 2003; Goh, 2005), but the effects of boron deficiencies on yield are not well understood. This is a serious gap, considering that the application of boron is generally recommended. Some small-scale fertiliser trials in representative locations could help to fill this gap. Another point of interest is the interaction between potassium nutrition and stomatal regulation. A research project by an MSc student under my supervision provided evidence that oil palm stomata close during mid-day, even when soil water is sufficient to meet the transpiration needs of the palm (Putranto, 2018), in line with the findings of Smith (1989). Putranto hypothesised that increased potassium nutrition may lead to a better responsiveness of the stomata to vapour pressure deficit. He could not confirm his hypotheses because there were many confounding factors, but his data suggested that K-deficient palms may close their stomata earlier in the day, while K-sufficient palms close their stomata more gradually, but more completely during the warmest and driest part of the day. This research needs to be continued, preferably in a young mature randomised fertiliser trial located in an area with a pronounced dry season, to determine what the exact effect of K is on stomatal conductance.

7.5 Nutrient deficiencies and their effects on yield

In the previous section, I looked at the causes of yield gaps in oil palm plantations in general, including company and smallholder plantations from all palm oil producing countries. In the remaining sections, I will focus on smallholder oil palm plantations in Indonesia. First, I will try to answer the following question: *How prevalent are nutrient deficiencies in Indonesian smallholder oil palm plantations, and what are their effects on yield?* I hypothesised that *nutrient deficiencies occur in most smallholder plantations and have a strong yield-limiting effect.* Based on my data, I think this hypothesis can partially be accepted. We found clear evidence of insufficient and unbalanced fertiliser applications (Figure 7.2) and we saw deficiency symptoms in many plantations. We also found tissue nutrient deficiencies for N, P and K in 57, 61 and 80%, respectively, of the plantations in Sintang and Jambi (Chapter 3) and in 95, 67 and 75% of the plantations in Riau (Figure 7.3). We recorded poor yields (based on farmer estimates), but there were many confounding factors (waterlogging, poor planting materials, poor harvesting), so the actual effect of nutrient deficiencies on yield could not be determined. I conclude that the first part of the hypothesis can be confirmed, but the second part remains open for further testing.

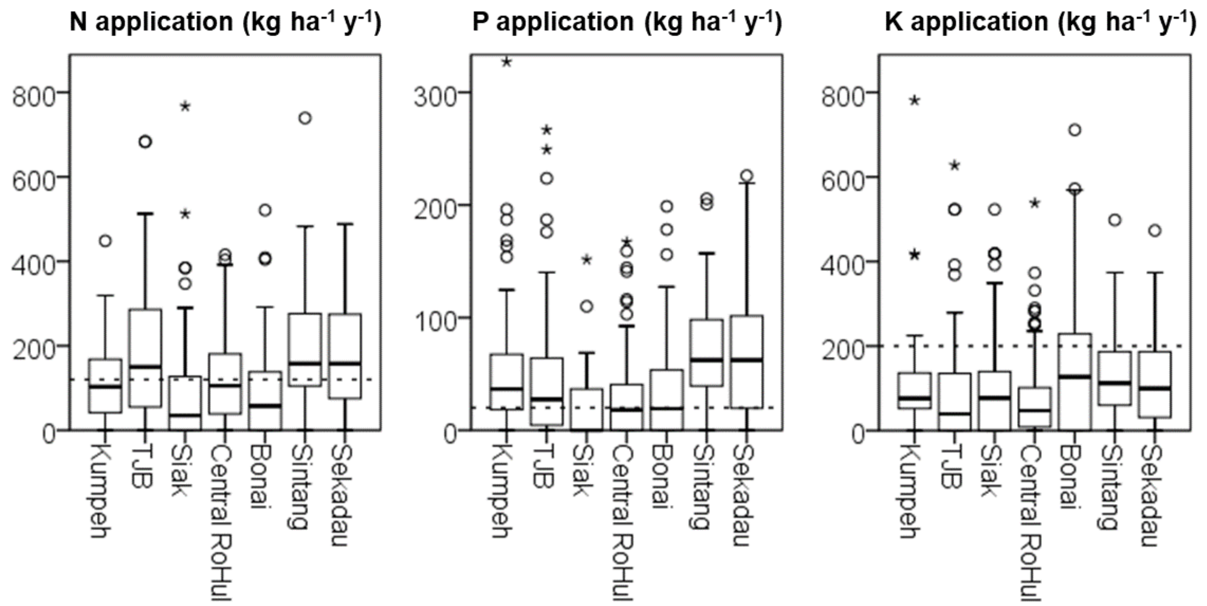


Figure 7.2 Nutrient applications in Jambi (Kumpeh (*n* = 60) and TJB (*n* = 63)), Riau (Siak (*n* = 48), Central Rokan Hulu (*n* = 146), and Bonai (*n* = 78)) and West-Kalimantan (Sintang (*n* = 66) and Sekadau (*n* = 66)). Whiskers show the minimum and maximum values; the box shows the 1st and 3rd quartile; the line shows the median; dots and asterisks show the outliers. Dotted lines show the nutrient offtake at a productivity of 20 t fruit bunches ha^{-1} $year^{-1}$ (Ng et al., 1999).

The qualitative and quantitative diagnosis of severe nutrient deficiencies in most smallholder plantations, particularly for K, and to a lesser extent for P and N, is a novel output of my thesis. I think the supporting evidence is strong, as it is based on three indicators: reported fertiliser applications, visual nutrient deficiencies, and tissue nutrient concentrations. The reported fertiliser applications by smallholders (Chapter 3–5) suggested that deficiencies would be present for all nutrients (in plantations where farmers applied little or no fertilisers) or for specific nutrients (in plantations where farmers applied only cheap or available nutrients). On average, the nutrient applications reported by farmers in our sample were larger than those reported in literature (Comte et al., 2015; Euler et al., 2016a; Harsono et al., 2012; Lee, 2013; Lifianthi and Husin, 2012; Soliman et al., 2016; Chapter 5; Figure 7.2), which suggests that deficiencies may be even more prevalent than our data suggest. The conclusion that nutrient applications were often insufficient is supported by the clear visual nutrient deficiency symptoms that I observed in the plantations that I visited and audited (in real life or through photographs; Chapter 4). Most commonly I observed K and B deficiency symptoms, while P and Mg deficiency symptoms were less common. Although there is no clear-cut relationship between visual leaf (or trunk) deficiency symptoms and tissue nutrient concentrations (Corley and Tinker, 2016: 351), visual symptoms usually show up when deficiencies are quite severe. So, while the absence of visual symptoms does not mean that nutrition is optimal, the presence of clear symptoms is a good indication that there are deficiencies (Fairhurst et al., 2005). This indication was confirmed by the nutrient concentrations in leaf and rachis samples that were collected from around 170 plantations in Jambi, West-Kalimantan, and Riau (Figure 7.3). These samples showed wide-spread nutrient deficiencies, particularly for K but also for P and N (but as previously mentioned, the nitrogen concentrations in Riau must be viewed with caution). The tissue nutrient concentrations, visual nutrient deficiency symptoms, and nutrient applications all point to the same conclusion: nutrient deficiencies in smallholder oil palm plantations are very common and quite severe, particularly for K, and for a lesser extent for P and N.

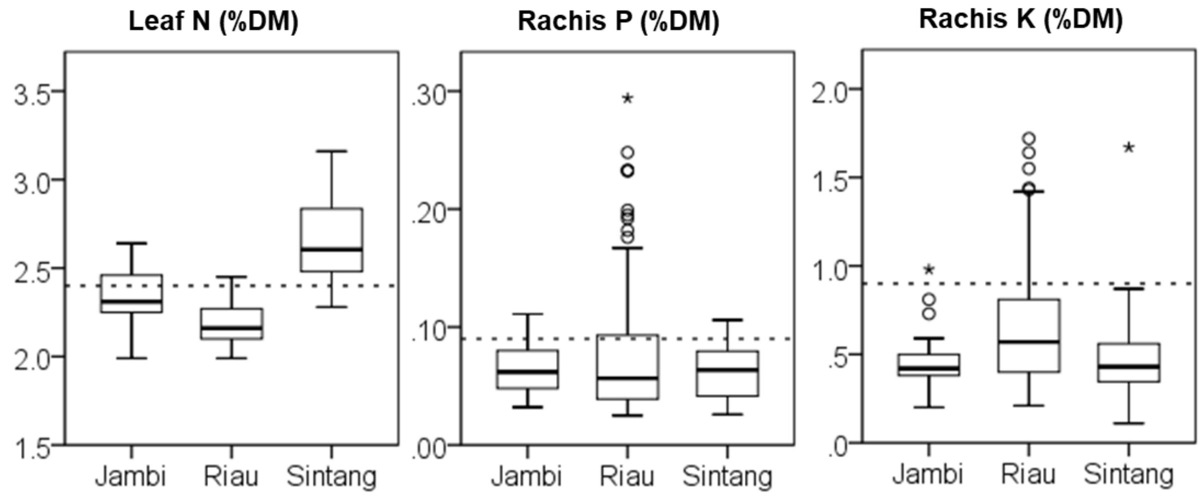


Figure 7.3 Leaflet (N) and rachis (P, K) concentrations in Jambi (n = 25), Riau (n = 118), and Sintang (n = 24). Whiskers show the minimum and maximum values; the box shows the 1st and 3rd quartile; the line shows the median; dots and asterisks show the outliers. The dotted line shows the critical line; if the concentration falls below this line, then a yield response to nutrient application is likely to occur.

Whether the nutrient deficiencies also limit smallholder yields, as my own study and the large surveys conducted by Molenaar et al. (2013) suggest, cannot be confirmed by my research work, but there is a large body of literature that describes the effects of nutrients on productivity in oil palm. A selection of the literature is presented in Chapter 2, but I think the actual effects of K and P deficiency on productivity require further discussion. I am no longer convinced that the application of K fertilisers will have a large effect on yields in most smallholder fields. The often-cited data from Foster and Prabowo (2006) show that there is a yield response of 3 t fruit bunches ha^{-1} $year^{-1}$ to the application of K fertilisers when rachis K concentrations fall below 1.3% DM, but this response occurs in plantations that are otherwise perfectly managed, and the response does not change between 0.9 and 1.3% DM. In our sample, only ~10% of the plantations had rachis concentrations above 1.3% DM, while more than 85% had rachis K concentrations below 1.1% DM. Over the 'medium' range of rachis K concentrations the yield response changes very slowly, varying between 6 and 3 t fruit bunches ha^{-1} $year^{-1}$ at 0.5% and 1.3% DM, respectively. This raises the question whether increasing potassium concentrations from 0.5 to 0.9% DM will give a sufficient return on investment to make it worthwhile. As Tinker and Smilde (1963) note, the large applications of K recommended in Southeast Asia may actually allow for quite some luxury uptake of K. For rachis concentrations below 0.5%, the expected yield responses quickly increase (Foster and Prabowo, 2006), so plantations with very poor rachis concentrations are more likely to benefit from additional K fertilisers. For rachis P, the situation is very similar, with responses of 4 and 2 t fruit bunches ha^{-1} $year^{-1}$ at concentrations of 0.055% and 0.08% DM, respectively. But as P is a cheap fertiliser, and soils are generally very poor in P, the application of ample quantities of P is more likely to be profitable. For K fertilisers, the returns on investment in farmers' plantations need to be determined through additional experiments.

7.6 Other causes of yield gaps in smallholder plantations

In this section, I address the following question: *What yield-determining, yield-limiting, and yield-reducing factors can explain the large yield gap in Indonesian smallholder oil palm plantations?* I hypothesised that *the yield gap is mostly explained by poor planting material, poor drainage, infrequent harvesting, and poor nutrient management, but the factors vary depending on the local biophysical and socio-economic conditions.* My results partly confirm this hypothesis. All the factors mentioned were identified in smallholder fields, but their prevalence varied. Poor planting material was a typical issue for independent smallholders but is not likely to be a problem for scheme smallholders; poor drainage occurred in most areas but depended very much on the topography and soil type; infrequent harvesting was the norm; and poor nutrient management was discussed in the previous section. Additional issues that appeared from Chapter 3–6 were sub-optimal planting density, poor culling (leading to large variability and the presence of unproductive palms), soil erosion, and rat damage. Again, I would expect that wrong density and poor culling are typically problems that occur in independent plantations, and I only observed soil erosion on slopes. I observed rat damage in all plantations that I audited, so I think it is another key contributor to the yield gap. An overview of the key issues is shown in Figure 7.4. Below, I will discuss the different factors in more detail.

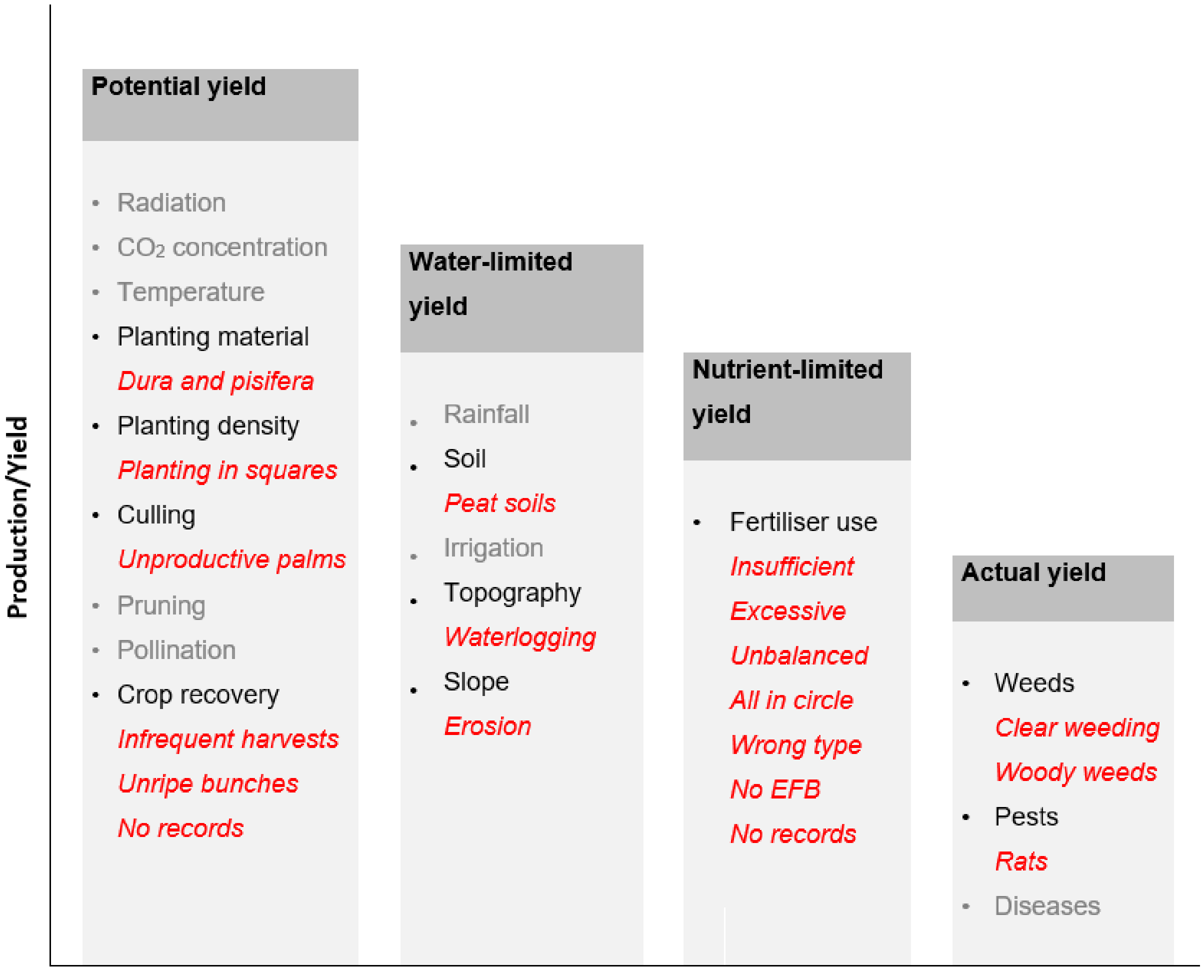


Figure 7.4 The main yield-determining, yield-limiting and yield-reducing factors in smallholder oil palm plantations in Indonesia. Important factors are shown in black; other factors are shown in grey; common problems in smallholder fields are show in red italics.

7.6.1 Yield-determining factors

I will not discuss the yield-determining factors related with the environment, because oil palm smallholders in Jambi, Sintang and Riau operate in a near-optimal climate for oil palm cultivation, which should allow for the potential production of at least 40–48 t fruit bunches ha^{-1} (Hoffmann et al., 2014). I will also not discuss pollination, because this is unlikely to have a strong effect on smallholder yields in most years (Wood, 1985), and I will not discuss pruning because severe under or over pruning were not observed often. With regards to planting material, I found *dura* palms in nearly 50% of the smallholder plantations in Sintang (Chapter 3) and 80% of the plantations in Jambi (Chapter 3). In Riau, most of the plantations had more than 50% *dura* palms in their population (Chapter 4). Seeds taken from plantations will give inferior yields due to the presence of 25% sterile *pisifera* palms in the next generation, but the potential yield of *dura* palms and second generation *tenera* palms is not well known. In terms of fresh fruit bunch production, *dura* palms may not produce less than *tenera* palms (Corley and Lee, 1992), and many smallholders reported that they prefer *dura* palms because the bunches are so large. Inbreeding depression is known to occur in selfed *dura* populations (Gascon et al., 1969), but the yield depression effects of sibling crosses appear to be limited (Luyindula et al., 2005), so second generation *tenera* palms may have the same productivity as their parents. The yield potential could be studied for the sake of interest, but in practice the planting of seeds from the plantation is risky for farmers because *dura* bunches may fetch a poor price or be refused, and it has a negative effect on oil productivity per hectare. I think prevention is more urgent than studying the exact effects on yield.

In addition to *dura* palms, I found much anecdotal evidence of abnormal and unproductive palms within plantations. These were sometimes *pisifera* palms (recognisable by their large size and the half-developed, aborted bunches) and sometimes they were just runts or deformed palms. Abnormal palms should be culled during the nursery phase (Tam, 1973), but farmers expressed unwillingness to throw away abnormal seedlings or cut down abnormal palms. The presence of unproductive palms has large yield-depressing effects, because these palms (particularly the *pisifera* palms) use large amounts of sunlight, nutrients and water, while reducing the number of productive palms per hectare. The optimal planting density in oil palm has been well established (Chapter 2), but in Riau (Chapter 4) and incidentally in Jambi (data not shown) we observed plantings at higher density or in square patterns, instead of the optimal triangular ones. The planting in square patterns results in more overlapping fronds and more open spots, and the yield penalties could be very severe, as oil palm responds strongly to competition for light (Corley, 1973a; Uexküll et al., 2003). Planting in squares is probably less problematic on peat soils (Gurmit et al., 1986), because the vegetative growth of the palms is much less vigorous.

Issues with harvesting, particularly long harvesting intervals (14 or 15 days instead of 10 days), harvesting of unripe bunches, incomplete harvesting, and incomplete collection of bunches and loose fruits, were universal in the different smallholder areas (Chapter 3–6). The negative effects of poor harvesting on yields and profits are likely to be very substantial (Chapter 2; Corley, 2001; Donough et al., 2010). I propose in Chapter 2 that the yield loss due to infrequent harvesting is 5–20%, but with additional reductions in price for unripe bunches, I speculate that the losses in profits in smallholder plantations could be over 30%. This is in line with the findings of Lee et al. (2013), who observed that farmers who harvested three times per month had 60% more yield than farmers who harvested once per month. There were many confounding factors, but harvesting frequency was an even better predictor for yield than type of management (scheme or independent), which emphasises its importance.

7.6.2 Yield-limiting factors: water-limited yield

Sintang, Jambi and Riau normally have optimal rainfall quantities and patterns which allow for production close to the potential yield (Chapter 2). A notable exception was during the El Niño events in 1998–1999 and 2015–2016, when rainfall was decreased until it fell well below the required quantities for oil palm production. In the 1998–1999 season the yield loss in Malaysia was 12–15% (Oettli et al., 2018), and my yield records from Chapter 6 show a yield decrease of a similar order of magnitude between 2015 and 2016. Climate change is likely to cause increased incidence of droughts, and to widen the gap between potential and water-limited yield.

Waterlogging was a more common problem than drought; I observed pockets of peat or freshwater swamp in 14 out of 25 plantations in Sintang (Chapter 3, data not shown) and the area in Jambi was subject to regular flooding, both in the peat swamps (60% of the village area) and in the remainder, with the exception of some plantations on slightly higher land. In Riau, about a quarter of the plantations was located on peat, and in these plantations the productivity was 15–30% less than in plantations on mineral soils (Chapter 4). The numbers are in line with results from Molenaar et al. (2013) who found that ~40% of the farmers in their sample had either their entire plantation or pockets within the plantation on peat or other less suitable soils, or in swampy areas. As I mentioned previously, the yield penalties of waterlogging are poorly understood, despite the prevalence of the issue. Quantifying the effect of waterlogging and drainage on yield would be particularly beneficial for smallholder rehabilitation efforts because the establishment of drainage canals is laborious and expensive and is unlikely to be done unless the expected returns on investment are understood and are considerable.

In Sintang, and in some parts of Jambi and Riau, I observed that soils on slopes without soil conservation were quite eroded. I also have anecdotal evidence from two plantations within my experiments (Chapter 6) where palms on the side of slopes were more nutrient deficient (particularly for Mg) than palms at the bottom of the slopes; this is in line with the findings of Balasundram et al. (2006).

Overall, yield-limiting factors related to water appear to play a very large role in smallholder oil palm plantations, and the gap between potential and water-limited yield is probably substantial, even though the Indonesian climate normally provides ideal rainfall conditions for oil palm cultivation.

7.6.3 Yield-reducing factors

The effect of yield-reducing factors in smallholder plantations is probably small compared with the effects of the yield-limiting and yield-defining factors, except for rat damage to bunches, which was observed in most of the plantations. Rat damage gives an estimated yield loss of 5% (Wood and Liau, 1984), and I think this loss is fully incurred in most smallholder fields. Financial losses are probably larger if damaged bunches fetch a poor price at the mill. On peat soils, there was anecdotal evidence of termite damage. I saw little evidence of infestation with leaf-eating pests (data not shown) and some incidental signs of infestation with *Oryctes rhinoceros*, especially in immature plantations. I did not see any clear signs of diseases (particularly *Ganoderma boninense*) in the smallholder plantations that I assessed. Woody weeds in smallholder plantations were very common, but their yield-reducing effects are not well quantified (Chapter 2).

7.6.4 Conclusions

In smallholder plantations, the potential yield is often reduced due to poor planting and harvesting practices, and the gap between the potential, water-limited, nutrient limited, and actual yield is large. In the next section, I will discuss the different yield-improving practices that may be implemented to increase the productivity and profitability of smallholder plantations.

7.7 Options for sustainable intensification in smallholder plantations

In the previous sections, I discussed the causes of yield gaps in oil palm plantations, with a focus on nutrient deficiencies in smallholder fields. The fourth and last research question relates to the possibilities for closing yield gaps. It reads: *What are the options for sustainable intensification in mature Indonesian smallholder plantations?* As an answer, I hypothesised that *There is large scope for sustainable intensification in mature smallholder plantations through the implementation of better management practices, which will result in economic and environmental benefits.* After testing the better harvesting, weeding, pruning, and fertiliser application in 14 smallholder fields (Chapter 6) I cannot confirm that better management practices give economic benefits because the implemented practices did not lead to significantly better yields or increased profits in my sample. I did observe that a weed cover was re-established on previously bare soils in clear-weeded plantations; that fertilisers were applied over frond stacks while they previously were concentrated in the weeded circles; and that excessive N applications were reduced. Based on these observations, I propose that there is scope for improving the environmental performance of smallholder plantations through the use of better management practices.

In Chapter 6 and in section 7.3 I argued that the absence of a significant yield response in my experimental plots shows that better management practices do not lead to universal yield increases in every set of conditions. To explore the options for using better management practices to increase yields in the Indonesian smallholder sector, I discuss the different better management practices that are available, their potential to increase yields, and the conditions required to implement them successfully, on the basis of my findings from Chapter 2–6. I also propose additional options for improving yields or land use, and I prioritise the practices that are likely to have the strongest impact.

7.7.1 Increasing the potential yield

To increase the potential yield in smallholder plantations, I propose four main interventions: using improved planting materials, planting at the correct density, removing unproductive palms, and improving harvesting practices (Figure 7.4). Of these four interventions, the first two need to be addressed at re-planting, while the latter two can be implemented during the plantation lifetime.

The reduction of the potential yield caused by poor planting material is difficult to address during the plantation lifetime, because early replanting is costly and labour-intensive. It only becomes worthwhile if the expected bunch price after replanting is much better than the price before replanting, and if the overall price is high (Ismail and Mamat, 2002). Re-planting becomes more urgent when the density is too high or too low (due to palm loss) or when palms were planted in squares. There are many economic constraints to replanting, which I discuss below. Selective thinning (the removal of sterile or poorly producing palms) could be an effective way increase the availability of light, water and nutrients for the productive palms in the plantation (Uexküll et al., 2003). The scope is illustrated by an example from Chapter 6; in a sample of 12 palms in field S6, the total black bunch production over three years varied from 16 to 45 bunches per palm (data not shown), even though the sample palms did not include any runts. It would be of interest to study in more detail the variability between palms in smallholder fields, and to test the effects on yield of selective removal of un-productive palms. Planting at high density conflicts with the possibilities for intercropping in the immature period. Intercropping provides income during the unproductive phase. It is usually considered poor practice by plantation companies, but I have not found convincing evidence in literature that demonstrates the negative impact of intercropping on immature palms or on future palm yields. I propose that intercropping may do little harm as long as palm fronds are not removed or shortened, and manure or fertilisers are applied to meet the additional nutrient demands of the intercrop. Intercropping can reduce weeding costs, as observed by Nchanji et al. (2016) in smallholder plantations in Cameroon. During my field visits I have seen many immature plantations that were completely overgrown with weeds, and this is likely to have a negative impact on palm growth (Samedani et al., 2014). An intercrop could serve as an incentive for farmers to manage their immature palms better. In addition, intercropping has a positive effect on biodiversity (Ashraf et al., 2018). I think there is an urgent need for agronomically sound experiments with different intercropping species and management practices, to establish best practices for optimising the yields of the intercrop without incurring large losses in palm yields later on. For longer-term intercrops (into the mature phase) the double-row avenue system was developed by the Malaysian Palm Oil Board (Suboh et al., 2009). This system requires further investigation before I would recommend it as a suitable option for smallholders. Finally, to maximise the effectiveness of any approach to increase productivity, good harvesting is key. Good harvesting practices are very simple to understand

and implement but need to be enabled by harvesters, traders, cooperatives, and mills.

7.7.2 Increasing the water-limited yield

To increase the water-limited yield, I propose three main interventions: drainage, soil conservation, and water retention in peat soils (Figure 7.4).

Waterlogged plantations have three problems: many palms will not survive the immature phase (Abram et al., 2014), the remainder will not produce many bunches, and the bunches that are produced are difficult to harvest. If waterlogged areas are drained before replanting, then the yield gains are likely to be large. If drainage occurs after planting, then the missing palms will decrease the potential yield, but the surviving palms might recover rapidly as they have a large plasticity (Warriar and Piggott, 1973; Sidhu et al., 2009; Chapter 6). It may also be that in very waterlogged areas the roots of the palms are so poorly developed that the yields remain poor, in which case replanting is required. Not all waterlogged areas are drainable, and for small patches drainage is probably not worthwhile because of the large labour investments required (Rankine and Fairhurst, 1999a). Steep slopes are not suitable for oil palm cultivation, because they are vulnerable to erosion unless they are terraced. On less steep slopes, the planting of a legume cover crop and the stacking of palm fronds in the windrow can help to protect the soil against erosion (Afandi et al., 2017). These practices are easy to implement; I have anecdotal evidence from Jambi where legume cover crops grew along the roadside but rarely in plantations, because farmers found them too invasive and tried to keep them out. Other options for soil conservation, such as digging silt pits and applying empty fruit bunches (Moradi et al., 2015), are labour-intensive but easy to implement. For plantations on peat soils, the yield limitations due to waterlogging or drought are particularly large. Excessive peat drainage also leads to large greenhouse gas emissions. The farmers in Jambi observed that they could not retain the water in their plantations on peat because a nearby company drained the peat dome on which the farmers were located. In a future with more frequent El Niño events, water management in peat areas will probably have an even larger influence on yields. Low-tech solutions like the building of small dams (Jelsma, 2011) can improve water retention, and the yield impact of such solutions deserves further investigation. Larger-scale projects to test the impact of collective water management in peat areas are also required, especially because water retention in peat provides a double benefit for profitability and environment.

7.7.3 Overcoming nutrient limitations

In the smallholder handbook (Woittiez et al., 2016) I propose a 'basic' fertiliser package that should work in many plantations, and I recommend that farmers determine the soil type in their plantation and look for foliar deficiency symptoms in their area to identify the nutrients that may be limiting under the local conditions. When I tested the 'basic' package in 14 plantations (Chapter 6) I did not manage to increase yields, although the tissue nutrient concentrations increased significantly. Considering the climatic and market risks that smallholders face, I would propose that the 'basic' fertiliser recommendations could be downscaled for independent smallholders who fall in the 13–15 t fruit bunches ha^{-1} $year^{-1}$ yield range (Molenaar et al., 2013). The use of NPK Ponska (15-15-15) may be a good starting point, if it is applied in sufficient quantities, on the frond stack, and in at least two splits. Supplementation with dolomite might be beneficial (Tohiruddin et al., 2006), but I should note that the palms in the best-performing plantation in Sintang were magnesium deficient. Large investments in K and B are risky and might not pay off, but it is necessary to test this in farmers' fields. Other useful sources of nutrients are animal manure and empty fruit bunches, which are relatively cheap and have many beneficial effects on yield and soil quality (Chiew and Rahman, 2002).

There are many farmers who already apply substantial amount of nutrients and achieve yields that are well above 15 t fruit bunches ha^{-1} $year^{-1}$ (Chapter 3, 4, 6). For these farmers, increasing the nutrient limited yield will be more challenging, as I noticed in my experimental fields. I propose that it is necessary to increase the potential yield (through selective thinning and good harvesting) and resolve the water-related limitations (through drainage and soil conservation) before investing in increased nutrient applications. It would be particularly useful if a simple fertiliser recommendation system for smallholders could be developed, similar to the Foster system (Foster et al., 1985a; Foster et al., 1985b), but based on only a few plantation and soil properties. Routine leaf sampling is unlikely to be feasible for smallholders, but the one-time collection of soil samples for determining basic soil properties (texture, SOM content, pH, CEC, total N, available P, extractable K, Mg, Ca) is cheap and easy. In addition, it is essential that farmers start recording their yields and input use, so that the effects of nutrient applications on yield can be assessed accurately. Much more experimentation in farmers' fields is urgently required to test the extent to which nutrient-limited yields can be improved.

7.7.4 Increasing the actual yield

The yield gains of improved weed management may not be large, but smarter weeding practices could reduce herbicide use and labour needs while improving the protection of the soil and creating a habitat for beneficial insects. The weed *Asystasia gangetica*, for example, is common in plantations that are regularly clear-weeded; it is also a fodder with a high protein content (Yeoh and Wong, 1993) and a host plant for the natural enemies of leaf-eating pests (Kamarudin and Wahid, 2010). The introduction of livestock in the plantation increases the productivity per unit of land (Gabdo and Ismail, 2013) and has benefits for weed control and manure production (Devendra and Thomas, 2002; Figure 7.5). In Indonesia, there is a large demand for cattle (Agus and Mastuti Widi, 2018) and a more modest demand for sheep (Udo and Budisatria, 2011) and goats (Putra and Agunga, 2014). I think there is great potential for further integration of livestock in oil palm production systems. The other important yield-reducing factor, rats, is much more difficult to address. The different control options have their problems: baiting is ineffective in single plantations, damaging for predators, and risky if livestock roam freely in the plantation, while natural control through owls or snakes is only partially effective (Wood and Chung, 2003), difficult to implement when predator populations are not yet present, and potentially in conflict with other interests like safety (Lenin, 2015) and wildlife trade (Shine et al., 1999). I did not meet many farmers who were actively trying to manage their rat populations, and I do not think this problem will be solved soon.

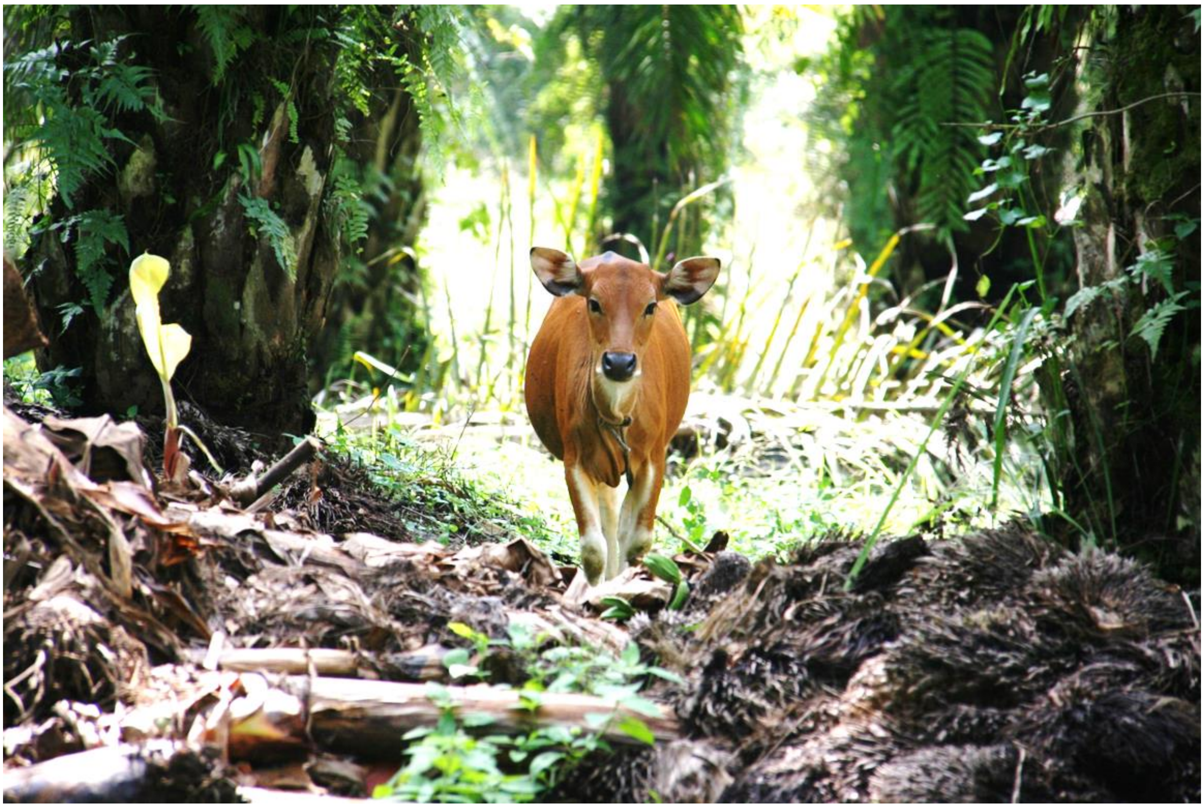


Figure 7.5 Cow in a smallholder plantation in Jambi.

7.8 Underlying constraints to sustainable intensification

In the previous sections, I discussed the biophysical constraints to yield in smallholder plantations, and the management practices which can be implemented to overcome these constraints. The implementation of such management practices requires secure land tenure (Feder et al., 1985; Kubitza et al., 2018b; Chapter 4) and access to knowledge, inputs, equipment, labour, finance, and markets (Feder et al., 1985; Cassman, 1999; Vermeulen and Goad, 2006; Rist et al., 2010; Molenaar et al., 2010). In terms of land tenure and access, large differences are expected to exist between scheme (supported) and independent (un-supported) smallholders (Barlow et al., 2003; Vermeulen and Goad, 2006; Molenaar et al., 2010). In the best-case scenario, scheme plantations will have the strong advantage of a land certificate (after the loan for (re)planting has been paid off; Rist et al., 2010), access to good planting materials, correct planting densities, good drainage, year-round road access, and regular transport of bunches to a mill. In addition, scheme smallholders may have access to inputs and agronomic advice through the company, and a fair bunch price may be guaranteed. For these reasons the yield gap in scheme plantations is smaller than in independent plantations (Molenaar et al., 2013). In Sintang, farmers produced up to 24 t ha^{-1} $year^{-1}$ in their scheme fields before the start of the project (Chapter 6), which is comparable to the yield of good company plantations. But the variability between scheme smallholders is likely to be large; some may be associated with a poorly performing company from which they hardly benefit, and in such plantations the yield gap may still be substantial (Molenaar et al., 2010).

Independent smallholders often do not have a secure land title (Jelsma et al., 2017a; Kubitza et al., 2018b) and cannot benefit from a company for access to production resources. For this reason, the constraints to intensification in independent plantations are particularly large (Vermeulen and Goad, 2006; Molenaar et al., 2013; Euler et al., 2016a). In addition, independent smallholder farmers often balance multiple livelihood activities (Vermeulen and Goad, 2006; Euler et al., 2017), which means that scarce resources such as labour and inputs need to be divided between different activities. These constraints affect the ability and willingness of farmers to invest in better management practices in their oil palm plantations. Overcoming such constraints on a small scale is certainly possible (Jelsma et al., 2017b; Hutabarat et al., 2018) but the real challenge is to achieve a sector-wide yield improvement in millions of smallholder plantations (Brandi et al., 2015). Below, I reflect on the different issues that constrain the implementation of better oil palm management practices on a larger scale, with a focus on the Indonesian farmers (although many of these issues will be relevant in other countries as well). First, I discuss the lack of access to production resources, and the role that farmer groups or cooperatives, finance, and the 'jurisdictional approach' may play in addressing these issues. After that, I discuss the issue of knowledge limitations, and the need and possibilities to improve smallholders' knowledge and skills. Thirdly, I touch briefly upon the issue of labour. Finally, I address the potential problems with the lack of fit of the 'intensification' narrative in smallholders' socio-cultural realities. I do not address the issue of land rights, because this is beyond my expertise, and the importance of secure tenure for making investments has been discussed elsewhere (Besley, 1995; Mercer, 2004; Kubitza et al., 2018b). I conclude this section by proposing several options for achieving successful intensification in smallholder production systems at a larger scale.

7.8.1 Lack of access

A lack of access to inputs, finance, knowledge, and labour is the most commonly-cited reason for poor productivity in smallholder plantations (Vermeulen and

Goad, 2006; Rist et al., 2010; Molenaar et al., 2010; Euler et al., 2016a; Chapter 5). In my research areas, the access issues that were mentioned most frequently related to knowledge, subsidised fertilisers, finance, labour, and markets for selling fresh fruit bunches. Free and fair access requires collaboration between farmers and other actors in the supply chain, including traders, mills, banks, and agro-dealers. It also requires that shortages, particularly of certified seeds and subsidised fertilisers, are resolved by government agencies or private companies. The program of IOPRI, which sells certified seeds to farmers from the back of a car and on local stations, is a step in that direction (IOPRI, 2018). Farmer groups can play an important role in gaining access to subsidised fertilisers, to markets (through collective selling to the mill), and to knowledge by providing technical support to members, and collaboration can lead to excellent productivity and profitability in smallholder plantations (Jelsma et al., 2017b). Farmer group formation is also a prerequisite for RSPO certification and can facilitate access to finance (Bronkhorst et al., 2017; Johnston et al., 2018). But the formation and maintenance of well-functioning groups is challenging, as groups are vulnerable to disagreement and mis-management (Jelsma et al., 2017b; Glasbergen, 2018). Jelsma et al. (2017b) emphasise that the creation of successful groups is possible but requires time, effort, and the right approach. I think that intensification efforts need to strike a careful balance between supporting collaboration and group formation on the one hand and strengthening the capacity and resilience of individual farmers on the other.

7.8.2 Lack of knowledge on how to grow oil palm

During my work in the field, I observed that there was a large variation in the knowledge and skills of the oil palm farmers. Some farmers were very knowledgeable about oil palm cultivation (often due to a background as a plantation company worker) but many others were not aware of even the basic concepts of plant production and plantation management. For example, farmers were often not aware of the differences between *dura* and *tenera*; contact and systemic herbicides; and ripe and unripe bunches (Chapter 5). These gaps in knowledge can be addressed through training, but I concluded in Chapter 5 that the trainings as implemented in the research areas that I visited did not lead to any significant improvements in management practices. Even the RSPO certification process, which usually involves intensive training, and which comes with a host of guidelines for good agricultural practices, does not necessarily result in yield improvements (Rietberg, 2016). Similarly, my own intensive training program with the 14 farmers participating in my experiments did not lead to a full implementation of good practices, and one particularly poor practice (the ineffective injection of expensive plant hormones into the palm trunk) spread while my experiments were ongoing. As Wijaya et al. (2018) note, the assumption that poor productivity can be resolved through training alone neglects the other underlying issues, and I think this is very much the case in oil palm systems. On the other hand, if farmers do not know the difference between ripe and unripe bunches, or between *dura* and *tenera*, then good agricultural practices become like a set of rules to follow, devoid of logic or insight into why they should work, and difficult to adapt to non-standard conditions. I propose that a basic level of knowledge is required to allow farmers to make informed decisions, but that knowledge alone does not automatically lead to decision-making towards sustainable intensification, because other issues limit the implementation or the effectiveness of good practices.

7.8.3 Labour issues

The RSPO supposes that in smallholder plantations the family provides most of labour (RSPO, 2018c), but the reality is more complex. McCarthy (2010) notes that poor or landless farmers often work in others' plantations, and that there is much demand for such labourers. In my own research, I found that for harvesting, nearly half of the respondents depended on hired labourers or on farmer groups (Woittiez et al., 2017a). When external labour was involved, it was more difficult for the farmers to implement the recommended better management practices, because labourers were not trained and were not necessarily interested in following the recommendations. At times labour was scarce and expensive, particularly in Sintang, but labourers are also vulnerable, and they can easily be marginalised (McCarthy, 2010). I think labour relations need to be better understood and to be considered as an important factor for successful intensification, because the availability and commitment of labourers is key for the implementation of better management practices.

7.8.4 Lack of fit of the 'intensification' narrative

While interacting with farmers, I noticed that the intensification narrative does not always fit with farmers' perceptions of what is important. One reason is that in many oil palm production areas, land for plantation expansion is still readily available, either close by or in neighbouring districts or provinces (Susanti, 2016).

New land can be converted from another crop, bought from community members (van Reemst, 2015), or bought from local authorities (Enrici and Hubacek, 2016; Jelsma et al., 2017a). The studies by Feintrenie et al. (2010b) and Jelsma et al. (2017a), among others, illustrate that smallholders generally do not have a conservationist attitude, and that many will opt to convert forest into oil palm if the opportunity presents itself. Where land for expansion is available and affordable, intensification is not a necessity, and the motivation to invest in better management is likely to be limited, unless other incentives (such as a price premium; Saadun et al., 2018) are in place. Intensification depends on increased investments in terms of capital (herbicides, fertilisers) and labour (harvesting, weeding) and increased resource use efficiency, and these in turn require a general interest in making investments, being efficient, and increasing profits from the side of the plantation owner. In each community that I visited I encountered farmers who were committed to increasing the yield and profit from their plantations, but these were usually a minority and could be classified as 'early adopters' of technology (Diederen et al., 2002). It is easy to take for granted that most plantation owners would aspire to achieve better yields and larger profits, but for farmers making a profit may be just one objective among many (Curry and Koczberski, 2012). If agronomic practices require a very profit-oriented attitude that does not fit with farmers' preferences, then providing training and addressing access issues will not lead to the large-scale uptake of these practices (Feder et al., 1985). This problem can be overcome by taking better care in presenting options that fit with farmers' preferences, but this is not always feasible. An alternative approach would be to look for suitable incentives to enhance uptake (such as a price premium), or to make certain practices mandatory through the involvement of governments and the private sector. I propose that the implementation of practices that are expected to have a positive effect on productivity and the environment, such as selective weeding (as opposed to clear weeding), soil conservation on slopes, the planting of good quality materials (after ensuring their availability), regular harvesting, the prevention of nutrient over-application (particularly N; Soliman et al., 2016; Chapter 3; Chapter 5) and record keeping, need to be supported through incentives and enforced through regulations. This requires involvement and capacity building of local governments, as well as the involvement of traders, mills, and retailers (Nesadurai, 2018). The jurisdictional approach (Pirard et al., 2015; Paoli et al., 2016; Hill and Higman, 2017) takes a large step in this direction. Traceability can be another important tool for enforcing regulations, with the Palm Oil Innovation Group (POIG) demanding full traceability, down to field level, for all its members (POIG, 2016) to guarantee deforestation-free palm oil. Clearly, any practice that is enforced needs to be enabled and supported, otherwise regulations may easily lead to the exclusion of smallholders from the supply chain (Brandi, 2017).

7.8.5 Conclusions

The lack of access to resources, lack of knowledge, lack of fit of the intensification approach, and lack of incentives are strong barriers against the implementation of better management practices in smallholder plantations. There are solutions, such as group formation, training, and regulations, but these are time-consuming and difficult to implement. Clearly, there is no easy way out when it comes to transforming the smallholder sector. To speed up the intensification process, I think it is essential that government agencies, NGOs and researchers become more committed to collecting and sharing data, both quantitative and qualitative. In this way, each programme or intervention will contribute to a collective learning process, as I hope my own research has done. Honest reporting and critical reflection may help to tackle some of the complicated challenges of sustainable intensification in smallholder oil palm plantations.

7.9 Personal reflections and concluding thoughts

We live in a world of climate change, an ever-growing population, plastic pollution, rising inequality, monopolies, greedy global elites, herbicide-resistant superweeds, Donald Trump and Geert Wilders and Jair Bolsonaro, corruption, short-term thinking, taxes paid by the poor not the rich, hedge funds, and corporations that earn more than small nations. Meanwhile, we edge closer every day towards the limits of the earth. As we enter the tipping zone it may turn out that Malthus, not Boserup, has the final word. We stand by and watch the disaster unfold. The ruling free-market paradigm with its constant drive towards growth and its externalisation of all negative side effects (for human health and dignity, and for nature and planet Earth) offers no answers and cannot provide us with a viable future. Palm oil production fits within this paradigm. It is dominated by huge corporations that make gigantic profits, and it is rife with forest destruction, exploitative labour conditions, land grabbing and bribery. Transforming the sector to make sustainable palm oil the norm, which is the mission of the RSPO, is a daunting challenge indeed.

Smallholder palm oil production is not free from problems like inequality, environmental damage and poor labour conditions. But at its best, it offers small oil palm entrepreneurs the dignity and equality that the Sustainable Development Goals and the RSPO aspire to. Well-managed oil palm plantations can also capture and store carbon, harbour biodiversity, and maintain soil quality, while producing large quantities of vegetable oil from a limited area of land. Oil palm cultivation can be good for people, planet, and profit, but the sector needs to evolve, and smallholders must play a central role. In this thesis, I showed that there are large yield gaps in smallholder oil palm production systems. These gaps are related to nutrients, planting material, planting practices, soils, and harvesting, among other factors. Climate extremes such as the El Niño event in 2015 also have a strong negative impact on yield. Closing yield gaps is challenging, because many interventions have not been tested in the field, and because over-riding constraints such as drought, waterlogging, poor establishment and poor harvesting frequency limit the effectiveness of the interventions. There is large variability among smallholder farmers in terms of yield, plantation size, management, and socio-economic conditions, and the poorer farmers should not be left behind. To improve yields and facilitate inclusion in the sustainable palm oil supply chain, smallholders need access to resources (particularly certified seed and fertilisers), increased collaboration, support from mills, a basic level of knowledge, and proper incentives and regulations.

A real transformation of the palm oil sector is unlikely to happen unless the RSPO's mission to 'transform the sector and make sustainable palm oil the norm' is reinforced by supporting policies and interventions from governments of producing and consuming countries. If the RSPO-supporting countries want to maintain or expand their influence on the sector, then banning palm oil is the worst possible approach. The IUCN report on oil palm and biodiversity, published in June (Meijaard et al., 2018), concludes that: *'A ban on palm oil, as for example called for by some, could have overall negative biodiversity impacts, if, for example, demand for vegetable oil was then satisfied by conversion of biodiverse ecosystems for cultivation of alternatives more land-hungry than oil palm, such as soy. Similarly, yield increases in palm oil could mean that the same amount of oil is produced on less land, thus benefiting biodiversity, but it could also make palm oil even more competitive compared to other crops, increasing palm oil expansion at the expense of other lower yield crops. This would demand stricter control on expansion than currently seems possible. The palm oil debate is not simple'*. It is unfortunate that the palm oil debate often lacks such nuance and is held on very simplistic terms, with little consideration for the complexity of the real world. The deniers of oil palm-driven deforestation resemble the Iraqi general 'Baghdad Bob', who broadcast press conferences in which he denied that the American invasion was happening. Meanwhile the American tanks could be seen behind his back, rolling through the streets and heralding the destruction of the country and years of humanitarian disaster. In the era of fake news, the denial of reality, be it about military invasion, climate change or environmental destruction, is particularly worrying. The anti-palm-oil lobby can be equally out of touch with the real world, particularly when it ignores the role of the logging and pulp and paper industries in deforestation, and when it denies the benefits of palm oil production for smallholders. Smallholders are conveniently depicted as 'victims' of the oil palm boom to support the call for a palm oil ban, but the scientific evidence supports my own experience to the contrary: many smallholders are beneficiaries of the boom. The results from my thesis suggest that there is much scope for improving the productivity and the sustainability of Indonesian smallholder plantations. It is not an easy task, but as Nicholas Sparks said: 'Nothing that's worthwhile is ever easy.' The real challenge for the future is not to replace palm oil with other oils, but to create a truly sustainable palm oil industry. In this industry the smallholders, with productive and sustainably managed plantations and fully integrated in the supply chain, have a central role to play.

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Summary

With an annual production of around 70 million metric tonnes in 2017, palm oil is the most-used vegetable oil in the world. It is an ingredient of biscuits, soap, ice cream, instant noodles, chocolate, shampoo, and a wide range of other supermarket products. Palm oil is produced from the fruit of the oil palm (*Elaeis guineensis* Jacq.). Oil palm expansion in Indonesia and Malaysia has been associated with tropical deforestation and biodiversity loss, and expansion of plantations into peat forests has caused large emissions of CO_2. The production system can become more sustainable if the rapid and uncontrolled expansion that happened in the past (and is still ongoing) is replaced with sustainable intensification in existing plantations, and with controlled expansion into areas of degraded land. A well-managed oil palm plantation can produce more than 10 t oil ha^{-1} $year^{-1}$.

Indonesia is the world's largest palm oil producer, with a cultivated area of 11.8 million hectares in 2017, equivalent to about 11% of the combined land area of Sumatra and Kalimantan. Currently over 40% of the Indonesian oil palm area is managed by smallholder farmers, many of whom depend on oil palm as their primary source of income. The Indonesian smallholder plantations are very diverse, ranging from one-hectare fields near the homestead to 50-hectare plantations complete with a field manager and a team of workers. The yields in smallholder plantations are generally around 3–4 t oil ha^{-1} $year^{-1}$, which means that a large yield gap exists. Sustainable intensification in smallholder plantations is generally expected to have benefits for profitability and for the environment.

The objective of this thesis was to investigate the agronomic practices of Indonesian oil palm smallholders, with a focus on fertiliser application, and to propose and test better management practices that can contribute to sustainable intensification. The thesis is structured around four main research questions:

1. What are the causes of yield gaps in oil palm plantations, and how large are their effects on yield?
2. To what extent are nutrient deficiencies prevalent in Indonesian smallholder oil palm plantations, and what are their effects on yield?
3. What yield-determining, yield-limiting, and yield-reducing factors can explain the large yield gap in Indonesian smallholder oil palm plantations?

4. What is the scope for sustainable intensification in mature Indonesian smallholder oil palm plantations?

The research questions are accompanied by four hypotheses:

1. The effects of yield-determining, yield-limiting, and yield-reducing factors, on yield of oil palm in plantations vary greatly depending on the local biophysical and socio-economic conditions.
2. Nutrient deficiencies are prevalent in smallholder plantations and have a strong yield-limiting effect.
3. Yield gaps are mostly explained by poor planting material, poor drainage, infrequent harvesting, and poor nutrient management, but the factors vary depending on the local biophysical and socio-economic conditions.
4. There is large scope for sustainable intensification in mature smallholder plantations through the implementation of better management practices, which will result in economic and environmental benefits.

In the literature review (Chapter 2) 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 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 year^{-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.

Chapter 3 quantifies fertiliser use, soil and tissue nutrient status, and palm growth and yield in a sample of independent smallholder plantations. We selected 49 plantations in Indonesia in two provinces with contrasting soils. For all plantations, we obtained self-reported fertiliser use and yield data, collected soil and tissue samples, and analysed vegetative growth. More than 170 kg N ha^{-1} $year^{-1}$ was applied in one site, and P was applied in excess of recommended quantities in both sites, but on average farmers applied less than 100 kg K ha^{-1} $year^{-1}$. Soils in the palm circle were poor in N, P and K in 29, 40 and 82% of the plantations, respectively and deficiencies were measured in 57, 61 and 80% of the leaflet samples. We found statistically significant correlations between tissue nutrient concentrations and vegetative growth, but a large part of the variation in the data remained unaccounted for. Single leaf area was reduced in > 80% of the plantations. Average yields were estimated to be 50–70% of the water-limited yield. Our results demonstrate that widespread nutrient imbalances and deficiencies, especially K and P, occur in smallholder oil palm plantations, due to inadequate and unbalanced fertiliser application practices. These deficiencies may be an important underlying cause of the overall poor productivity, which threatens the economic and environmental sustainability of the smallholder sector.

Chapter 4 delves into the implementation of good agricultural practices (GAP) among seven types of independent smallholders in Rokan Hulu Regency, Riau province. The research area consisted of a relative established agricultural area on mineral soils and a relative frontier, mostly on peat. Smallholder types ranged from small local farmers to large farmers who usually reside in urban areas far from their plantation and regard oil palm cultivation as an investment opportunity. The underlying hypothesis was that larger farmers have more capital and therefore implement better agricultural practices than small farmers, who are more cash constrained. A wide range of methods was applied, including farmer and farm surveys, remote sensing, tissue analysis and photo interpretation by experts. These methods provided data on fertiliser use, nutrient conditions in oil palms, planting material, planting patterns, and other management practices in the plantations. Results show that yields are poor, implementation of GAP are limited and there is much room for improvement among all farmer types. Poor planting materials, square planting patterns, and limited nutrient applications were particularly prevalent. This implies that different types of farmers opt for a low-input low-output system. Under current conditions, initiatives such as improving access to finance or availability of good planting material alone are not likely to significantly improve the productivity and sustainability of the smallholder oil palm sector.

Chapter 5 investigated the use of fertilisers by > 300 smallholder farmers in Sumatra and Kalimantan, some of whom were involved in training programmes aimed at yield improvement. In our sample, the total applications of N were largest (166 kg ha^{-1} $year^{-1}$), followed by K (122 kg ha^{-1} $year^{-1}$) and P (56 kg ha^{-1} $year^{-1}$). The applications of K were insufficient to compensate for the off-take with a production of 20 t fruit bunches ha^{-1} $year^{-1}$, while N applications were excessive. On average, farmers applied 1130 kg fertiliser ha^{-1} $year^{-1}$, and relied strongly on subsidised fertilisers, especially NPK Ponska (66%) and urea (39%). The average costs for fertiliser application were USD 225 ha^{-1} $year^{-1}$. Trained farmers applied significantly more P in one research area, but for the other nutrients and research areas, there was no significant difference between trained and untrained farmers. Plantation size and nutrient application were weakly correlated in some areas, but not in the sample as a whole. Previously reported nutrient application rates were mostly less than our findings indicated, suggesting that actual nutrient limitations may be more severe. To overcome nutrient limitations and enhance nutrient use efficiency, we recommend that fertilisers are used in the correct balance; a ground cover vegetation is maintained to protect against erosion; and the application of empty fruit bunches is encouraged.

In Chapter 6 we tested a set of better management practices in a sample of smallholder plantations, aiming to rehabilitate plantations and boost yields. We implemented good practices (weeding, pruning, harvesting, and fertiliser application) in 14 smallholder plantations of 13–15 years old in Jambi province (Sumatra) and in West-Kalimantan province (Kalimantan), for a duration of three to three-and-a-half years. During this period, we collected yield records and did measurements and laboratory analyses of palm leaves. Contrary to our expectations, yields did not increase after three years, although the size of the bunches and the size of the palm leaves increased significantly over time. The tissue nutrient concentrations also increased significantly, although after three years the potassium concentrations in the rachis were still below the critical value. Because of the negligible yield increase and the additional costs for fertiliser inputs, the net profit of implementing better management practices was less than the profit from 'business as usual'. Despite these disappointing results, some practices, such as harvesting at 10-day intervals and the weeding of circles and paths, were received positively by those farmers who could implement them

autonomously. We hypothesise that several factors, such as the implementation of BMP practices in the control fields, good starting yields, the El Niño event in 2015, flooding in Jambi in 2017, conservative fertiliser applications, and increased competition for sunlight between palms may have resulted in the lack of a significant yield response to the treatment.

The results from the research chapters, as discussed in Chapter 7, show that there are large yield gaps in smallholder oil palm production systems. These gaps are related to nutrients, planting material, planting practices, soils, and harvesting, among other factors. Climate extremes such as the El Niño event in 2015 also have a strong negative impact on yield. Closing yield gaps is challenging, because many interventions have not been tested in the field, and because over-riding constraints such as drought, waterlogging, poor establishment and poor harvesting frequency limit the effectiveness of the interventions. There is large variability among smallholder farmers in terms of yield, plantation size, management, and socio-economic conditions. To improve yields and facilitate inclusion in the sustainable palm oil supply chain, smallholders need access to resources (particularly certified seed and fertilisers), increased collaboration, support from mills, a basic level of knowledge, and proper incentives and regulations.

In conclusion, there is much scope for improving the productivity and the sustainability of Indonesian smallholder plantations, but it is not an easy process. The challenge for the future is to create a truly sustainable palm oil industry. In this industry the smallholders, with productive and sustainably managed plantations and fully integrated in the supply chain, have a central role to play.

Ringkasan

Minyak sawit merupakan minyak nabati yang paling banyak digunakan di dunia sebagai bahan untuk biskuit, sabun, es krim, mie instrant, coklat, shampoo dan berbagai produk yang diperdagangkan di pasar modern. Rata-rata produksi kelapa sawit pada tahun 2017 sekitar 70 juta ton. Minyak sawit dihasilkan dari buah kelapa sawit (*Elaeis guineensis* Jacq.). Perluasan kebun kelapa sawit di Indonesia dan Malaysia berasosiasi dengan deforestasi dan hilangnya keanekaragaman hayati. Perluasan kebun kelapa sawit di lahan gambut telah menyebabkan emisi CO_2 yang tinggi. Sistem produksi minyak sawit akan berkelanjutan jika perluasan secara masif kebun kelapa sawit, baik yang telah terjadi maupun yang sedang berlangsung digantikan dengan mempraktekkan intensifikasi secara berkelanjutan, dan perluasan kebun sawit hanya dilakukan pada lahan terdegradasi. Kebun kelapa sawit yang dikelola dengan baik dapat menghasilkan lebih dari 10 ton minyak ha^{-1} $tahun^{-1}$.

Indonesia merupakan negara penghasil minyak sawit terbesar di dunia, dengan luas kebun 11.8 juta ha pada tahun 2017, atau setara dengan 11% dari total luas Pulau Sumatra dan Kalimantan. Saat ini lebih dari 40% dari perkebunan kelapa sawit di Indonesia merupakan kebun yang dikelolah oleh petani skala kecil yang sebagian besar menggantungkan kepada kelapa sawit sebagai sumber pendapatan utama. Luasan perkebunan kelapa sawit rakyat sangat beragam, berkisar antar 1 ha yang berada di lahan pekarangan sekitar rumah, hingga 50 ha lengkap dengan pengelola kebun dan tenaga kerja. Produksi minyak sawit dari perkebunan kelapa sawit rakyat sekitar 3–4 ton minyak ha^{-1} $tahun^{-1}$, atau terdapat kesenjangan produksi (*yield gap*) yang besar jika dibandingkan dengan produksi dari perkebunan skala besar. Intensifikasi yang berkelanjutan diperlukan perkebunan kelapa sawit rakyat untuk memperoleh keuntungan baik secara ekonomi maupun lingkungan.

Tujuan dari penelitian ini adalah untuk mengkaji praktek budidaya perkebunan kelapa sawit rakyat di Indonesia, dengan fokus pada penerapan penggunaan pupuk dan pengelolaan kebun yang lebih baik (*better management practices*) yang merupakan bagian dari intensifiksai berkelanjutan. Penelitian ini disusun dengan empat pertanyaan penelitian:

1. Faktor apa yang menyebabkan adanya kesenjangan produksi di perkebunan kelapa sawit rakyat, dan seberapa besar faktor ini mempengaruhi produksi?
2. Sejauh mana kekurangan unsur hara mempengaruhi produksi perkebunan kelapa sawit rakyat?
3. Faktor penentu produksi, pembatas produksi, dan penyebab penurunan produksi yang mana yang dapat menjelaskan adanya kesenjangan produksi pada perkebunan kelapa sawit rakyat?
4. Adakah ruang untuk intensifikasi berkelanjutan dalam perkebunan kelapa sawit rakyat yang sudah berproduksi?

Empat hipotesis yang menyertai empat pertanyaan penelitian adalah:

1. Pengaruh faktor penentu produksi, pembatas produksi, dan penyebab penurunan produksi perkebunan kelapa sawit rakyat sangat bervariasi tergantung pada kondisi biofisik dan sosial ekonomi setempat.
2. Kekurangan unsur hara di perkebunan kelapa sawit rakyat merupakan hal yang umum terjadi dan merupakan faktor utama pembatas produksi.
3. Kesenjangan produksi dapat dikaitkan dengan kualitas bibit rendah, drainase buruk, panen yang jarang, dan penyediaan unsur hara yang buruk, tetapi faktor-faktor tersebut bervariasi tergantung pada kondisi biofisik dan sosial ekonomi setempat.
4. Terdapat ruang yang luas terkait intensifikasi berkelanjutan di perkebunan kelapa sawit rakyat yang sudah berproduksi melalui penerapan praktik pengelolaan kebun yang lebih baik, yang akan memberikan manfaat ekonomi dan lingkungan.

Dalam kajian pustaka (Bab 2) kami menyajikan ikhtisar mengenai faktor penentu produksi, pembatas produksi, dan penyebab penurunan produksi; pengaruh dari faktor-faktor tersebut terhadap produksi telah diukur atau dihitung menggunakan pemodelan komputer dalam suatu kajian; demikian pula hal mendasar terkait mekanisme fisiologi tanaman. Kami membedakan tingkat produksi menjadi empat, yaitu: produksi potensial, produksi dalam kondisi kekurangan air, produksi dalam kondisi kekurangan unsur hara, dan produksi aktual. Produksi potensial dalam satu daur hidup ditentukan oleh besarnya radiasi aktif fotosintesis (*photosynthetically active radiation*/PAR), suhu, konsentrasi CO_2 dalam atmosfir dan kualitas bibit, dengan asumsi proses pembukaan kebun, populasi tanaman kelapa sawit berkisar antara 120–150 batang per hektar, pengelelolaan tajuk berkisar antara 30–60 pelepah per batang tergantung dari umur kelapa sawit, penyerbukan, dan pemanenan dalam kondisi optimum. Produksi pada kondisi kekurangan air sebesar > 400 mm tahun^{-1} adalah sekitar sepertiga dari produksi potensial, tergantung pada faktor-faktor lain seperti suhu, kecepatan angin, tekstur tanah, dan kedalaman tanah. Produksi pada kondisi kekurangan unsur hara terutama N dan P sekitar setengah dari produksi potensial. Produksi aktual dipengaruhi oleh faktor penurun produksi seperti vegetasi penutup tanah yang tidak sesuai, hama dan penyakit yang bisa mendekati nol jika terjadi serangan hebat. Petani skala kecil menghadapi beberapa permasalahan seperti benih palsu dan aplikasi dosis pupuk yang kurang. Menutup kesenjangan produksi di perkebunan yang ada dapat meningkatkan produksi global sekitar 15–20 Mt minyak sawit tahun^{-1}, sehingga dapat membatasi perluasan kebun kelapa sawit pada skala global. Untuk meningkatkan produksi kebun kelapa sawit yang ada saat ini dan dimasa mendatang secara berkelanjutan, semua faktor produksi yang telah disebutkan perlu difahami dan ditangani.

Bab 3 mengkaji dosis penggunaan pupuk, kandungan unsur hara dalam tanah dan jaringan tanaman, pertumbuhan dan produksi kelapa sawit pada kebun kelapa sawit rakyat yang dipilih sebagai contoh. Kami memilih 49 kebun kelapa sawit di Indonesia di dua propinsi yang berbeda jenis tanahnya. Pada semua kebun contoh, kami memperoleh data penggunaan pupuk dan produksi, mengumpulkan contoh tanah dan jaringan tanaman, serta menganalisis pertumbuhan vegetatif. Di salah satu lokasi, penggunaan pupuk N lebih dari 170 kg N ha^{-1} tahun^{-1}, sedangkan di lokasi lain pupuk P diaplikasikan lebih dari jumlah yang direkomendasikan, namun rata-rata petani menerapkan kurang dari 100 kg K ha^{-1} tahun^{-1}. Kandungan hara N, P dan K tanah di sekitar batang sawit berkisar 29, 40 dan 82% dari perkebunan skala besar, dan kandungan N, P dan K daun masing-masing 57, 61 dan 80% dari perkebunan skala besar. Kami menemukan korelasi antara konsentrasi kandungan hara daun dan pertumbuhan vegetatif, tetapi variasi dalam data masih cukup besar. Luas daun sekitar > 80% lebih rendah dari perkebunan skala besar. Rerata produksi diperkirakan 50 - 70% dari produksi pada kondisi kekurangan air. Hasil kami menunjukkan bahwa ketidakseimbangan dan kekurangan unsur hara yang meluas, terutama K dan P, terjadi di perkebunan kelapa sawit rakyat, karena praktik aplikasi pupuk yang tidak memadai dan tidak seimbang. Kekurangan-kekurangan ini merupakan penyebab mendasar dari produktivitas yang rendah, yang mengancam keberlanjutan ekonomi dan lingkungan dari sektor perkebunan kelapa sawit rakyat.

Bab 4 membahas tentang penerapan praktik pertanian yang baik (*good agricultural practices*/GAP) di tujuh kebun kelapa sawit rakyat di Kabupaten

Rokan Hulu, Provinsi Riau. Wilayah kajian merupakan lahan pertanian di tanah mineral yang relatif mapan dan berbatasan dengan lahan gambut. Perkebunan kelapa sawit rakyat bervariasi, mulai dari petani kecil hingga petani besar yang umumnya tinggal di daerah perkotaan, jauh dari perkebunan mereka dan menganggap budidaya kelapa sawit sebagai peluang investasi. Hipotesis yang mendasar adalah petani dengan lahan lebih luas dan memiliki modal lebih banyak mampu menerapkan praktik pertanian yang lebih baik dibandingkan petani dengan luas lahan dan modal lebih kecil. Berbagai metode telah diterapkan, termasuk survei petani dan pertanian, penginderaan jauh, analisis daun dan interpretasi foto. Metode-metode ini menyediakan data tentang dosis penggunaan pupuk, status hara dalam kelapa sawit, kualitas bibit, pola tanam, dan praktik pengelolaan kebun lainnya. Hasilnya menunjukkan bahwa hasil panen rendah, penerapan GAP terbatas dan ada banyak ruang untuk memperbaiki. Kualitas bibit yang rendah, pola tanam persegi, dan aplikasi hara yang terbatas merupakan hal yang banyak dijumpai. Hal ini mengindikasikan bahwa pada semua lokasi, petani memilih sistem dengan input-output rendah. Dalam kondisi saat ini, hanya meningkatkan akses ke modal atau tersedianya kualitas bibit yang baik tidak akan secara nyata meningkatkan produktivitas dan keberlanjutan sektor perkebunan kelapa sawit rakyat.

Bab 5 mengkaji penggunaan pupuk oleh lebih dari 300 petani di Sumatra dan Kalimantan, beberapa diantaranya terlibat dalam program pelatihan yang bertujuan untuk meningkatkan produksi. Dari 300 petani, aplikasi pupuk terbesar adalah pupuk N (166 kg ha^{-1} $tahun^{-1}$), diikuti oleh pupuk K (122 kg ha^{-1} $tahun^{-1}$) dan pupuk P (56 kg ha^{-1} $tahun^{-1}$). Aplikasi pupuk K tidak cukup untuk mengimbangi produksi sebesar 20 ton tandan buah ha^{-1} $tahun^{-1}$, sedangkan aplikasi pupuk N berlebihan. Rata-rata, petani menggunakan 1130 kg pupuk ha^{-1} $tahun^{-1}$, dan sangat bergantung pada pupuk bersubsidi, terutama NPK Ponska (66%) dan urea (39%). Biaya rata-rata untuk aplikasi pupuk adalah USD 225 ha^{-1} $tahun^{-1}$. Di beberapa lokasi kajian, petani yang terlatih menggunakan pupuk P lebih banyak, di beberapa lokasi kajian yang lain, tidak ada perbedaan penggunaan pupuk yang signifikan antara petani yang terlatih dan yang tidak terlatih. Di beberapa lokasi (tidak keseluruhan lokasi), ada korelasi (namun lemah) antara luasan kebun dan dosis pupuk. Dosis pupuk yang dilaporkan sebelumnya sebagian besar kurang dari hasil temuan kami, hal ini menunjukkan bahwa kekurangan unsur hara yang sebenarnya mungkin lebih parah. Untuk mengatasi keterbatasan unsur hara dan meningkatkan efisiensi penggunaan pupuk, kami menyarankan agar pupuk digunakan secara seimbang; vegetasi penutup tanah dipertahankan untuk melindungi dari erosi; dan penerapan tandan buah kosong.

Pada Bab 6 kami menguji serangkaian praktek pengelolaan yang lebih baik (*better management practices/BMP*) di beberapa perkebunan kelapa sawit rakyat, yang bertujuan untuk merehabilitasi perkebunan dan meningkatkan produksi. Kami menerapkan praktik pengelolaan yang baik (penyiangan, pemangkasan, pemanenan, dan aplikasi pupuk) di 14 perkebunan rakyat berumur antara 13-15 tahun di Provinsi Jambi (Sumatra) dan di Provinsi Kalimantan Barat (Kalimantan), selama 3 – 3.5 tahun. Selama periode ini, kami mencatat produksi, mengukur dan melakukan analisis daun kelapa sawit di laboratorium. Hasil pengukuran produksi tidak seperti yang kami harapkan, produksi tandan buah tidak meningkat setelah tiga tahun, meskipun ukuran tandan dan ukuran daun kelapa sawit meningkat secara nyata dari waktu ke waktu. Konsentrasi unsur hara pada daun juga meningkat secara nyata, meskipun setelah tiga tahun konsentrasi kalium dalam rachis masih di bawah ambang kritis. Peningkatan produksi dengan penerapan praktik pengelolaan yang lebih baik tidak sebanding dengan biaya tambahan penggunaan pupuk, dengan kata lain keuntungan bersih dari penerapan praktik pengelolaan yang lebih baik kurang dari keuntungan tanpa penerapan praktik pengelolaan yang lebih baik. Terlepas dari hasil yang mengecewakan ini, beberapa praktik pengelolaan, seperti panen dengan interval 10 hari dan penyiangan di sekitar batang kelapa sawit, dapat diterima secara positif oleh para petani dan dapat menerapkannya secara mandiri. Hipotesa kami, beberapa faktor seperti produksi awal yang baik, peristiwa El Niño pada 2015, banjir di Jambi pada 2017, aplikasi pupuk konservatif, dan meningkatnya persaingan untuk mendapatkan sinar matahari di antara kelapa sawit merupakan beberapa faktor yang mempengaruhi tidak adanya perbedaan yang nyata antara yang menerapkan BMP dengan yang tanpa menerapkan BMP.

Hasil dari Bab 2 – 6 yang dibahas dalam Bab 7, menunjukkan bahwa ada kesenjangan produksi yang besar dalam sistem produksi kelapa sawit dari pekebunan kelapa sawit rakyat. Kesenjangan ini terkait dengan unsur hara, kualitas bibit, praktik penanaman, tanah, dan pemanenan, serta faktor-faktor lainnya. Iklim ekstrem seperti peristiwa El Nino pada 2015 juga memiliki dampak negatif yang kuat pada produksi. Menekan kesenjangan produksi merupakan tantangan tersendiri, karena banyak intervensi yang belum diuji di lapangan, dan karena kendala-kendala lain seperti kekeringan, banjir, pembukaan kebun dan dan frekuensi panen yang buruk membatasi efektivitas intervensi. Terdapat variabilitas perkebunan kelapa sawit rakyat yang tinggi, dalam hal produksi kelapa sawit, luas perkebunan, pengelolaan kebun, dan kondisi sosial ekonomi. Untuk meningkatkan produksi minyak sawit berkelanjutan, petani kecil membutuhkan akses ke sumber daya (khususnya benih dan pupuk bersertifikat), peningkatan kolaborasi, dukungan dari pabrik, tingkat pengetahuan dasar, dan insentif serta peraturan yang tepat.

Dapat kami simpulkan, ada banyak ruang untuk meningkatkan produktivitas dan keberlanjutan perkebunan kelapa sawit rakyat di Indonesia, namun hal ini bukan merupakan proses yang mudah. Tantangan di masa mendatang adalah menciptakan industri minyak sawit yang berkelanjutan. Dalam industri ini, petani kecil dengan perkebunan yang produktif dan dikelola secara berkelanjutan dan terintegrasi dengan rantai pasokan (*supply chain*), memiliki peran utama.

Samenvatting

Met een productie van ongeveer 70 miljoen ton in 2017 is palmolie de meest gebruikte plantaardige olie ter wereld. Het is een ingrediënt van koekjes, zeep, ijs, instantnoedels, chocolade, shampoo en een breed scala aan andere supermarktproducten. Palmolie wordt geproduceerd uit de vrucht van de oliepalm (*Elaeis guineensis* Jacq.). De expansie van oliepalmen in Indonesië en Maleisië is in verband gebracht met tropische ontbossing en verlies van biodiversiteit, en uitbreiding van plantages in veenbossen heeft grote CO_2-emissies veroorzaakt. Het productiesysteem kan duurzamer worden als de snelle en ongecontroleerde expansie die zich in het verleden heeft voorgedaan (en die nog steeds aan de gang is) wordt vervangen door duurzame intensivering in bestaande plantages en gecontroleerde uitbreiding naar gedegradeerd land. Een goed beheerde oliepalmplantage kan meer dan tien ton olie per hectare per jaar produceren.

Indonesië is 's werelds grootste palmolieproducent, met een gecultiveerd areaal van 11,8 miljoen hectare in 2017, wat overeenkomt met ongeveer 11% van het gecombineerde landoppervlak van Sumatra en Kalimantan. Momenteel wordt meer dan 40% van het oliepalmgebied in Indonesië beheerd door kleine boeren. Velen van hen zijn afhankelijk van oliepalm als primaire bron van inkomsten. De Indonesische kleinschalige plantages zijn zeer divers, variërend van velden van één hectare in de buurt van de woning tot plantages van 50 hectare, compleet met een manager en een team van werknemers. De opbrengsten in kleinschalige plantages zijn in het algemeen ongeveer drie tot vier ton olie per hectare per jaar, wat betekent dat er een grote opbrengstkloof bestaat. Duurzame intensivering in kleinschalige plantages zal naar verwachting in het algemeen voordelen hebben voor de winstgevendheid en voor het milieu.

Het doel van dit proefschrift was om de landbouwpraktijken in Indonesische oliepalmplantages te onderzoeken, met een focus op bemesting, en om betere landbouwmethoden die kunnen bijdragen aan duurzame intensivering te vinden en te testen. De scriptie is opgebouwd rond vier hoofdonderzoeksvragen:

1. Wat zijn de oorzaken van de opbrengstkloof in oliepalmplantages en hoe groot zijn de effecten van deze oorzaken op de opbrengst?
2. In hoeverre zijn tekorten aan voedingsstoffen prevalent in Indonesische kleinschalige oliepalmplantages en wat zijn hun effecten op de opbrengst?

3. Welke opbrengstbepalende, opbrengstbeperkende en opbrengstreducerende factoren kunnen de grote opbrengstkloof in Indonesische kleinschalige oliepalmplantages verklaren?
4. Wat zijn de mogelijkheden voor duurzame intensivering in Indonesische kleinschalige oliepalmplantages?

De onderzoeksvragen gaan vergezeld van vier hypothesen:

1. De effecten van opbrengstbepalende, -beperkende en -reducerende factoren op de opbrengst van oliepalmplantages variëren sterk en zijn afhankelijk van de lokale biofysische en sociaaleconomische omstandigheden.
2. Tekorten aan voedingsstoffen komen veel voor in plantages van kleine boeren en hebben een sterk opbrengstbeperkend effect.
3. Opbrengstkloven worden meestal verklaard door slecht plantmateriaal, slechte drainage, onregelmatig oogsten en slechte bemesting, maar de factoren variëren afhankelijk van de lokale biofysische en sociaaleconomische omstandigheden.
4. Er is veel ruimte voor duurzame intensivering in kleinschalige plantages door de implementatie van verbeterde landbouwpraktijken, die zullen resulteren in economische en ecologische voordelen.

In de literatuurstudie (hoofdstuk 2) presenteren we een overzicht van de beschikbare gegevens over opbrengstbepalende, -beperkende en -reducerende factoren in oliepalmen; de effecten van deze factoren op de opbrengst, zoals gemeten in casestudies, of berekend met behulp van computermodellen; en de onderliggende plantfysiologische mechanismen. We onderscheiden vier productieniveaus: de potentiële productie, de watergelimiteerde productie, de nutriënten-gelimiteerde productie, en de werkelijke productie. De potentiële productie over de levensduur van een plantage wordt bepaald door inkomende fotosynthetisch actieve straling (PAR), temperatuur, atmosferische CO_2-concentratie en plantmateriaal, uitgaande van optimale plantpatronen, plantdichtheid (120–150 palmen per hectare), snoeibeleid (tot 30–60 bladeren per palm, afhankelijk van de palmleeftijd), bestuiving en oogstbeleid. De watergelimiteerde opbrengst in omgevingen met een watertekort van meer dan 400 mm per jaar kan minder zijn dan een derde van de potentiële opbrengst, afhankelijk van aanvullende factoren zoals temperatuur, windsnelheid, bodemtextuur en bodemdiepte. De nutriënten-gelimiteerde productie kan minder dan 50% van de potentiële opbrengst zijn wanneer niet bemest wordt met stikstof of kalium. De werkelijke opbrengsten worden beïnvloed door reducerende factoren, zoals onkruid, plagen en ziekten, en kunnen in ernstige situaties in de buurt van nul zijn. Kleine boeren hebben te maken met specifieke beperkingen, zoals het gebruik van niet-gecertifieerd plantmateriaal en onvoldoende bemesting. Het dichten van de opbrengstkloof in bestaande plantages zou de wereldwijde productie met 15 tot 20 megaton olie per jaar kunnen verhogen, wat de noodzaak voor verdere uitbreiding van het areaal op wereldwijde schaal zou beperken. Om de opbrengsten van bestaande en toekomstige plantages op een duurzame manier te verhogen, moeten alle belangrijke productiefactoren bekend zijn en worden geoptimaliseerd.

Hoofdstuk 3 kwantificeert het gebruik van meststoffen, de voedingsstatus van bodems en bladeren, palmgroei en opbrengst in een steekproef van onafhankelijke kleinschalige plantages. We selecteerden 49 plantages in Indonesië in twee provincies met contrasterende bodems. Voor alle plantages hebben we zelfgerapporteerde meststofgebruiks- en opbrengstgegevens verzameld, bodem- en bladmonsters geanalyseerd, en vegetatieve groei gemeten. Op één locatie werd gemiddeld meer dan 170 kg stikstof (N) per hectare per jaar gebruikt en op beide locaties werd fosfaat (P) gebruikt boven de aanbevolen hoeveelheden, maar gemiddeld gebruikten boeren minder dan 100 kg kalium (K) per hectare per jaar. Bodems in de palmcirkel (het gebied direct rondom de stam) waren deficiënt in respectievelijk N, P en K in 29, 40 en 82% van de plantages, en tekorten werden gemeten in 57, 61 en 80% van de bladmonsters. We vonden statistisch significante correlaties tussen bladconcentraties van nutriënten en vegetatieve groei, maar een groot deel van de variatie in de gegevens bleef onverklaard. De bladgroei was achtergebleven in 80% van de plantages. Gemiddelde opbrengsten werden geschat op 50–70% van de watergelimiteerde opbrengst. Onze resultaten tonen het bestaan aan van wijdverspreide onevenwichtigheden in en tekorten aan voedingsstoffen, met name K en P, als gevolg van ontoereikende en onevenwichtige bemestingspraktijken. Deze tekortkomingen kunnen een belangrijke onderliggende oorzaak zijn van de algehele lage productiviteit, die de economische en ecologische duurzaamheid van de kleinschalige oliepalmboeren bedreigt.

Hoofdstuk 4 gaat dieper in op de implementatie van goede landbouwpraktijken bij zeven types onafhankelijke kleine boeren in het regentschap Rokan Hulu, in de provincie Riau. Het onderzoeksgebied bestond uit twee contrasterende delen: een relatief gevestigd agrarisch gebied op minerale bodems en een gebied van snelle expansie, voornamelijk op veenbodems. De types kleine boeren varieerden van kleine lokale boeren tot zeer grote boeren die gewoonlijk in stedelijke gebieden ver van hun plantage wonen en oliepalmteelt beschouwen als een investeringsmogelijkheid. De onderliggende hypothese was dat grotere boeren meer kapitaal hebben en daarom betere landbouwpraktijken implementeren dan kleine boeren, die meer beperkt zijn qua kapitaal. Er werd een breed scala aan methoden toegepast, waaronder enquêtes, plantage-audits, GIS, bladanalyse en foto-interpretatie door experts. Deze methoden leverden gegevens op over het gebruik van meststoffen, de nutriëntenstatus van de palmen, het gebruikte plantmateriaal, de plantpatronen, en andere landbouwpraktijken in de plantages. De resultaten tonen aan dat de opbrengsten laag zijn, de implementatie van goede landbouwpraktijken beperkt is en dat er veel ruimte is voor verbetering bij alle types boeren. Niet-gecertificeerde plantmaterialen, vierkante plantpatronen en beperkte nutriëntentoepassingen waren bijzonder algemeen onder alle boeren. Dit suggereert dat verschillende types boeren kiezen voor een low-input low-output-systeem, ongeacht of ze voldoende kapitaal hebben of niet. Onder deze omstandigheden zullen initiatieven zoals het verbeteren van de toegang tot financiering of de beschikbaarheid van goed plantmateriaal waarschijnlijk niet voldoende zijn om de productiviteit en duurzaamheid van de kleinschalige oliepalmsector aanzienlijk verbeteren.

Hoofdstuk 5 onderzocht het gebruik van meststoffen door meer dan 300 kleine boeren op Sumatra en Kalimantan, van wie sommigen betrokken waren bij trainingsprogramma's gericht op het verbeteren van de opbrengst. In onze steekproef werd N het meest gebruikt (166 kg per hectare per jaar), gevolgd door K (122 kg per hectare per jaar) en P (56 kg per hectare per jaar). Het gebruik van K was onvoldoende om de afname te compenseren bij een productie van 20 ton trossen per hectare per jaar, terwijl N-gebruik excessief was. Boeren gebruikten gemiddeld 1130 kg kunstmest per hectare per jaar en vertrouwden sterk op gesubsidiëerde meststoffen, met name NPK Ponska (66%) en urea (39%). De gemiddelde kosten voor bemesting waren 225 US-dollars per hectare per jaar. Getrainde boeren gebruikten aanzienlijk meer P in een van de onderzoeksgebieden, maar voor de andere meststoffen en onderzoeksgebieden was er geen significant verschil tussen getrainde en ongetrainde boeren. Plantagegrootte en gebruik van meststoffen waren in sommige gebieden zwak gecorreleerd, maar niet in de steekproef als geheel. Het gebruik van meststoffen in onze studie was hoog in vergelijking met resultaten uit eerder studies, wat suggereert dat de werkelijke nutriëntenbeperkingen mogelijk ernstiger zijn. Om nutriëntenbeperkingen weg te nemen en de efficiëntie van het gebruik van kunstmest te verbeteren, raden we aan dat meststoffen worden gebruikt in de juiste balans; dat een bodembedekkende vegetatie wordt gehandhaafd om te beschermen tegen erosie; en dat het recyclen van leeggeperste trossen (een afvalproduct uit de palmoliefabrieken) wordt aangemoedigd.

In hoofdstuk 6 hebben we een aantal verbeterde landbouwpraktijken getest in een steekproef van kleinschalige plantages, met als doel plantages te rehabiliteren en de opbrengst te verhogen. We hebben verbeterde praktijken (wieden, snoeien, oogsten en bemesting) geïmplementeerd in 14 kleinschalige plantages van 13-15 jaar oud in de provincie Jambi (Sumatra) en in de provincie West-Kalimantan (Kalimantan), voor een duur van drie tot drie-en-een-half jaar. Gedurende deze periode verzamelden we opbrengstdata en deden we metingen en laboratoriumanalyses van palmbladeren. In tegenstelling tot onze verwachtingen waren de oogsten na drie jaar gebruik van verbeterde praktijken niet gestegen, hoewel de omvang van de trossen en de grootte van de palmbladeren in de loop van de tijd aanzienlijk waren toegenomen. De nutriëntenconcentraties in de bladeren namen ook significant toe, hoewel na drie jaar de kaliumconcentraties in de rachis (bladspil) nog steeds onder de kritische waarde lagen. Vanwege de te verwaarlozen stijging van de opbrengst en de extra kosten voor bemesting was de nettowinst van het implementeren van verbeterde landbouwpraktijken minder dan de nettowinst van 'business as usual'. Ondanks deze teleurstellende resultaten werden sommige praktijken, zoals het 10-daagse oogsten en het wieden van palmcirkels en paden, positief onthaald door boeren die de middelen hadden om ze autonoom uit te voeren. We veronderstellen dat verschillende factoren, zoals het gebruik van verbeterde landbouwpraktijken in de controlevelden, bovengemiddelde opbrengsten al bij aanvang van het project, de El Niño-gerelateerde extreme droogte in 2015, overstromingen in Jambi in 2017, conservatief gebruik van kunstmest in de experimentele velden en toegenomen concurrentie voor zonlicht tussen palmen, kunnen hebben geresulteerd in het ontbreken van een significante opbrengstrespons op de behandeling.

De resultaten van de onderzoekshoofdstukken, zoals besproken in hoofdstuk 7, laten zien dat er grote opbrengstkloven zijn in kleinschalige oliepalmproductiesystemen. Deze opbrengstkloven zijn veroorzaakt door niet-optimaal gebruik van meststoffen en door problemen met plantmateriaal, plantmethoden, bodemkwaliteit en oogstmethodes. Klimaatextremen zoals de El Niño in 2015 hebben ook een sterk negatief effect op de opbrengst. Het dichten van opbrengstkloven is een uitdaging, omdat veel interventies niet zijn getest in het veld en omdat overkoepelende beperkingen zoals droogte, wateroverlast, ontwikkelingsachterstand door slechte condities tijdens de eerste jaren na planten, en te lage oogstfrequentie de effectiviteit van de interventies beperken. Er is grote variabiliteit tussen kleine boeren in termen van opbrengst, plantagegrootte, toegepaste landbouwpraktijken en sociaaleconomische omstandigheden. Om de opbrengsten te verbeteren en de integratie in de duurzame palmolietoeleveringsketen te vergemakkelijken, hebben kleine boeren toegang nodig tot de juiste producten (met name gecertificeerde zaden en meststoffen). Andere belangrijke condities zijn meer samenwerking, ondersteuning vanuit palmoliefabrieken, een basiskennisniveau op het gebied van oliepalmteelt, en goede stimulansen en voorschriften.

Kortom, er is veel ruimte voor het verbeteren van de productiviteit en de duurzaamheid van Indonesische kleinschalige olieplantages, maar het is geen gemakkelijk proces. De uitdaging voor de toekomst is om een werkelijk duurzame palmolie-industrie te creëren. In deze sector spelen de kleine boeren, met productieve en duurzaam beheerde plantages en volledig geïntegreerd in de toeleveringsketen, een centrale rol.

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No woman is an island. In my PhD-work, and in life in general, I have been very much dependent on others for my success and for my happiness. This dependency was particularly obvious when I was in Indonesia. To all the farmers who invited me into their house and their fields for discussions, cups of tea, meals, parties, pictures and many other things, I would like to say that you are the cornerstone of my thesis. I am very grateful for your openness, energy and hospitality. Especially the smallholders and the local staff in Sintang and in Muaro Jambi have become friends, whom I will not forget. Thank you all so much for the hard work and for the laughs, lunches and ant bites that we shared. There were also countless other people in Indonesia (restaurant owners, secretaries, security guards, students, karate teachers, kids, grandmothers, mill managers, plantation owners, officials, drivers, translators, researchers, and many more) who were kind to me, helped me, and made me feel welcome. Thank you! Special thanks also to the people at ICRAF (particularly Ibu Vinny, Ibu Diah, Ni'ma, Juliana, and Pak Meine) who made me feel welcome and offered me a place to work. Two other people deserve a special mention: Deccy from Pontianak and Rhina from Jambi. Dear ladies, I will always remember the dinners we had in Pondok Ladang and the after-work dances in our lovely and rickety little house. I really felt at home there, and it was great to share those times with you. Deccy helped me get started, but without Rhina, the project would never have been able to continue. I could not have wished for a more smart, loyal, and enthusiastic project manager. Dear Rhin, I think your future will be wonderful, and I look forward to the moment where you have started your masters programme in Wageningen and we're drinking coffee together and watching the snow fall. You'll always be my friend!

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Curriculum Vitae

Lotte Woittiez (lotte.woittiez@gmail.com) was born in Uithoorn, the Netherlands, on April 11th, 1986. When she was still in primary school she moved with her parents and older sister to Driebergen, and she attended high school in nearby Doorn. There, she followed all the beta-oriented classes that the school offered, plus philosophy and music. After graduating high school *cum laude*, Lotte followed in the footsteps of her father and cousin by pursuing her BSc degree in Wageningen. She studied Plant Sciences, and in her spare time she was active at Youth Association Unitas. After graduating her BSc *cum laude*, Lotte took a one-year break from her studies to be a full-time board member of Unitas. Then she continued her education with an MSc Plant Biotechnology at Wageningen University. When wrapping up her thesis on the artemisinin biosynthesis pathway, she realised that she did not want to spend the rest of her life in a laboratory, so she started with a second MSc in Plant Sciences. Her thesis brought her to Zimbabwe, where she studied the consumption of wild fruits by farmers at times of drought. In 2010, after an internship in Zürich on the biosynthesis of vinblastine and vincristine, Lotte graduated her MSc Plant Biotechnolgy (*cum laude*) and MSc Plant Sciences and was ready to explore the world.

In 2011 and 2012, Lotte toured Latin America for ten months, and after that she worked at the prestigeous McGill University for five months. She then decided to return to the Plant Production Systems Group in Wageningen to do a few months of project work as a run-up to a PhD project. She worked on a report on sustainable intensification in West Africa until February 2013, when she started with her PhD, of which the results are presented in this book.

Lotte describes herself as a plant scientist with an interest in the agronomy of tropical perennial crops. Her research work focuses on sustainable intensification of perennial cropping systems. Currently she works in Wageningen as a Postdoc in the CocoaSoils project, where she is responsible for setting up a set of large-scale cocoa fertiliser trials in Africa, Latin America and Asia. She is actively involved in supervising students and in the dissemination of knowledge to farmers through the CocoaSoils project, committee work (for the RSPO), and several collaborations with companies and NGOs.

Publications

Scientific publications

Jelsma, I., **Woittiez, L.S.**, Ollivier, J., Dharmawan, A.H. (2019) Do wealthy farmers implement better agricultural practices? An assessment of implementation of Good Agricultural Practices among different types of independent oil palm smallholders in Riau, Indonesia. Agricultural Systems 170: 63–76.

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Woittiez, L.S., Slingerland, M., Giller, K.E. (2016) 'Hidden hunger': Poorly balanced plant nutrition in Indonesian oil palm farming. Runner-up in the 2016 Brian Chambers Poster Award for young plant nutritionists, at the International Fertiliser Society Agronomic Conference, 8-9 December, Cambridge, UK.

Selected other publications

Woittiez, L.S. (2017) Nutritional imbalance in smallholder oil palm plantations in Indonesia. Fertilizer Focus, March/April 2017, p. 52–55.

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Woittiez, L.S., Slingerland, M., Giller, K.E. (2015) Yield gaps in Indonesian smallholder plantations: causes and solutions. In: Proceedings of the PIPOC 2015 International Palm Oil Congress and Exhibition, 6–8 October, Kuala Lumpur.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Yield gaps in oil palm: A quantitative review of contributing factors (2017)

Writing of project proposal (4.5 ECTS)

- Improving oil palm yield on smallholder peatland plots in Indonesia

Post-graduate courses (6.1 ECTS)

- Sampling in space and time for survey and monitoring of natural resources; PE&RC (2013)
- APSIM Course on oil palm modelling; CSIRO (2014)
- Linear models; PE&RC (2017)
- Linear mixed models; PE&RC (2017)

Laboratory training and working visits (0.6 ECTS)

- Tissue sampling in oil palm; Bah Lias Research Station, Medan (2013)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Field Crops Research: participatory ISFM in Zimbabwe (2012)
- Agronomy for Sustainable Development: effect of harvesting on oil palm yields in Indonesia (2017)

Deficiency, Refresh, Brush-up courses (3 ECTS)

- Indonesian for beginners; LOI (2013)

Competence strengthening / skills courses (1.9 ECTS)

- Reviewing a scientific paper; WGS (2013)
- PhD Competence assessment; WGS (2014)
- Career orientation; WGS (2016)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

- PE&RC Last year's weekend (2016)
- PhD Workshop carousel (2016)
- PE&RC Symposium (2017)

Discussion groups / local seminars / other scientific meetings (7.3 ECTS)

- Sustainable intensification of agricultural systems discussion group (2013-2016)
- Contested agronomy mini-symposium (2014)
- Resilience in smallholder agriculture mini-symposium (2014)
- Intercropping symposium (2016)
- Debate on food security (2016)
- Project presentations at local research institutes in Indonesia; ICRAF, IOPRI, CPS (2013-2017)
- WACASA Meetings (2013-2017)

International symposia, workshops and conferences (11.3 ECTS)

- SUSPENSE Annual meeting; oral presentation (2015)
- PIPOC Conference; poster presentation; Kuala Lumpur (2015)
- RSPO Conference; oral presentation; Bangkok (2016)
- IPNC; oral presentation; Copenhagen (2017)

Supervision of MSc students (3 ECTS)

- Role of oil palm in smallholders' livelihoods (2014)
- Oil palm root growth (2014-15)
- Fertiliser use and knowledge flows in smallholder plantations (2016)
- Relationships between K nutrition and stomatal conductance in oil palm (2017-18)

Propositions

Nutrient limitations in smallholder oil palm plantations in Indonesia are an important cause of poor yields.
(this thesis)

Achieving sustainable intensification in smallholder oil palm plantations requires extensive field testing of better management practices.
(this thesis)

The field of development agronomy would benefit from more data and fewer opinions.

Highly consistent farmer data should be distrusted.

Yield response studies in perennial crops are unsuitable as a PhD project unless they are embedded in a larger project.

Blaming oil palms for deforestation is as meaningless as blaming tunas for overfishing.

Offsetting carbon emissions from flights through investments in green energy in Europe is not a sustainable solution to climate change.

The art of karate is the same as the art of life: to commit without holding back.

Propositions belonging to the thesis, entitled

On yield gaps and better management practices in Indonesian smallholder oil palm plantations

Lotte Suzanne Woittiez
Wageningen, 10 April 2019

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