Yield Gap Analysis in Oil Palm Production Systems in Ghana

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Tiemen Rhebergen

Thesis

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ABSTRACT

Palm oil is the world's most important edible oil crop, and in the Ghanaian economy, oil palm (*Eleais guineensis*) is the next most important perennial crop after cocoa. Since the early 2000s, the area under oil palm in Ghana expanded but average fruit bunch (FB) yields remained low at ~7 t ha^{-1} yr^{-1} in 2014, resulting in large yield gaps. Despite the pressing need to increase palm oil production and improve yields, knowledge of the underlying causes of poor yields in Ghana is lacking. The objective of this thesis was to analyse the factors that currently limit oil palm production on plantations and smallholder farms in Ghana and to assess opportunities to increase yields with improved agronomic practices. Using land suitability evaluation methods and yield gap analysis, a framework for yield intensification with 'Best Management Practices' (BMP) on existing mature oil palm plantings was developed. Data was acquired from online databases, farm surveys, a three-year trial established on three plantations and twenty smallholder farms across Ghana, and an irrigation and fertilizer experiment established on a large-scale oil palm plantation in Western region, Ghana. The results showed that the oil palm industry in Ghana is limited to expand large-scale plantations due to the lack of suitable and available large and contiguous tracts of lands. A feasible strategy for oil palm expansion can be sought through smallholder production, which can make use of smaller parcels of land. However, yield gaps in oil palm production were large and ubiquitous in Ghana. Using a boundary line analysis, the water-limited yield (*Yw*) over a planting cycle was estimated at 21 t ha^{-1} yr^{-1} FB, with yield gaps of 15.4 t ha^{-1} yr^{-1} FB at smallholder farms and 9.8 t ha^{-1} yr^{-1} FB at plantations. Poor management practices, including incomplete crop recovery (i.e. harvesting all suitable crop) and inadequate agronomic management were the main factors contributing to these yield gaps. Productivity losses were exacerbated by low oil extraction rates (OER) by small-scale processors of 12%, compared with 21% by large-scale processors, resulting in respective crude palm (CPO) oil losses exceeding 5 and 3 t ha^{-1} yr^{-1} in the crop plateau yield phase. Reducing yield gaps with appropriate BMPs can therefore make a significant contribution to closing the supply gap for palm oil in Ghana. The implementation of BMPs at plantations and smallholders was evaluated amongst those that increased yield in the short-term term (≤ 1 year) with 'yield taking' (improved crop recovery), and in the long-term (>1 year) with 'yield making' (better agronomy) practices. Compared with current management practices, average yields and yield gains with BMP were larger, and averaged 17.9 t ha^{-1} at plantations and 17.6 t ha^{-1} at smallholders. About 2.1 t ha^{-1} (+19%) and 4.7 t ha^{-1} (+89%) of the yield increase was attributed to yield taking and 4.7 t ha^{-1} (+36%) and 7.6 t ha^{-1} (+76%) with yield making at plantations and smallholders respectively. Important crop recovery activities included more frequent harvesting events and improved field access (roads, paths, weeded circles) to increase harvester efficiency and productivity, whilst analysis of fertilizer usage and leaf nutrient concentrations suggest a more balanced approach to nutrient management could contribute considerably to yield making, particularly at smallholder farms. The irrigation × fertilizer trial demonstrated the potential to obtain even larger yields with adequate water and nutrient management. Average yields of 32.6 t ha^{-1} FB were achieved with irrigation and fertilizer, which was 4.7 t ha^{-1} greater than the control (27.9 t ha^{-1}) and 4.1 t ha^{-1} greater than with irrigation alone (28.5 t ha^{-1}). Fertilizer was therefore essential for a maximum response to irrigation. The results of this thesis demonstrate the potential to increase production in Ghana by improving current management practices with BMPs. Particularly, large increases in production can be sought by improving management practices at smallholder farms which consist of the majority of growers in Ghana, but require viable integration into the oil palm supply chain to be successful. Increasing average attainable yields to 21.0 t ha^{-1} FB has the potential to increase national FB production almost three-fold from 2.5 Mt to 6.9 Mt (1.4 Mt CPO at 21% OER, worth about 1 billion US$ at US$750 t^{-1} CPO^{-1}) and reduce oil palm expansion with almost 600,000 ha of land. Yield intensification can be achieved without the typical capital expenditure required for new plantings (e.g. road infrastructure, planting cost), and financial returns from investments in yield intensification accrue more rapidly because production starts to increase as soon as agronomic constraints are removed. Rehabilitation of existing mature oil palm plantings may therefore be an important policy for sustainable oil palm development in Ghana and West Africa.

Keywords: *Yield intensification, crude palm oil, land expansion, land sparing, irrigation, fertilizer, agronomic management, yield taking, yield making, West Africa.*

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CHAPTER 1

General introduction

1.1 Background and problem statement

Although the Gulf of Guinea, West Africa, is believed to be the centre of origin of the oil palm (*Elaeis guineensis* Jacq.) (Simmonds, 1976; Zeven, 1964), current average fruit bunch (FB) yields in the region (3.9 t ha^{-1} FB) are far below those achieved in the major producing countries in Southeast Asia (18.9 t ha^{-1} FB) and Latin America (16.5 t ha^{-1} FB) where climatic conditions are more favourable (FAO, 2017; Paramananthan, 2003) (Fig. 1.1).

In West Africa, the oil palm's natural habitat largely consists of swampy locations which are unfavourable for most dicotyledonous trees. At sites usually too wet for the establishment of large forest trees, oil palm will grow for some months in flooded conditions, including the edges of fresh water swamps and along river banks (Simmonds, 1976; Zeven, 1972).

At present, oil palm is grown commercially in more than 40 countries, ranging from 19°N in the Dominican Republic to 15°S in Brazil (FAO, 2017; Lim et al., 2011). However, >90% of the area under oil palm cultivation is in 20 countries within 10°N and S of the Equator (Lim et al., 2011; Paramananthan, 2003). In Africa, oil palm is found between 16°N in Senegal and 15°S in Angola, and eastwards to Zanzibar and parts of Madagascar where suitable microclimates occur (Gilbert, 2013) (Fig. 1.1).

Today, oil palm accounts for nearly 30% of global vegetable oil production and is an important driver in the economic development of many tropical countries (Corley, 2009; Griffiths et al., 2002; Hansen et al., 2015). It is a very efficient crop in terms of input utilization and produces the highest oil yield compared with other oil producing crops (de Vries et al., 2010). Driven by an increasing demand for edible oil (Corley, 2009), oil palm has become one of the world's most rapidly expanding equatorial crops with a global area expansion from 3.6 million ha in 1961 to 18.7 million ha in 2014 (FAO, 2017; Koh and Wilcove, 2008). Southeast Asia is currently the largest producer of palm oil, with Indonesia and Malaysia accounting for approximately 80% of global oil palm production (FAO, 2017). However, with a continued increasing demand in palm oil in the next decades (Corley, 2009) and limited availability of land in Southeast Asia, most expansion of the industry is expected in Central and South America and sub-Saharan Africa (Laurance et al., 2014). Current production increases are therefore sought mainly through area expansion, whilst average yields remained far below its economic potential (Donough et al., 2009). Over the next 50 years, rapid and widespread agricultural expansion is expected to pose a serious threat to natural ecosystems worldwide (Tilman et al., 2001).

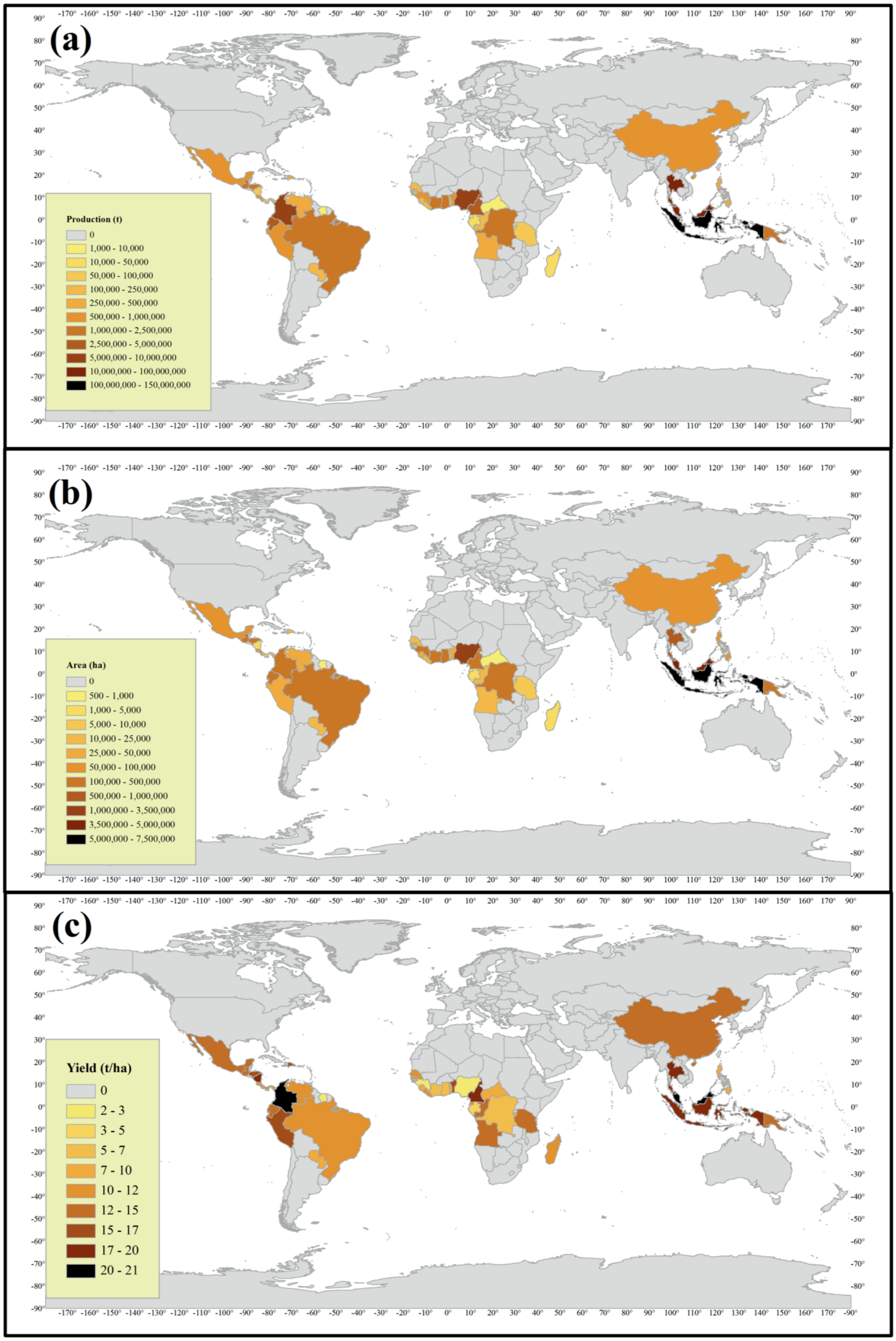

Fig. 1.1. Worldwide oil palm cultivation showing a) production (tonnes), b) area (ha) and c) fruit bunch yield (t ha^{-1}) per country in 2014 (FAO, 2017).

In West Africa, the expansion of the large-scale industrial sector has regained interest from foreign and domestic investors over the past decade (Carrere, 2010). In Ghana, for example, oil palm evolved from its presence in swidden systems into an agricultural crop, with the first plantations established in the nineteenth century (Gilbert, 2013). The plantation system, however, failed to gain significant hold of the industry because complex land tenure arrangements prevented the development of large-scale agricultural production (Gyasi, 1996). As a result, the oil palm sector in Ghana is dominated by independent smallholder farmers, who have been the main driver of expansion over the past 50 years. Currently, however, large-scale plantations are responsible for the largest expansion in the oil palm sector (Ofosu-Budu and Sarpong, 2013).

Whilst some area expansion, that meets the criteria for sustainable oil palm development, may yet be possible, yield intensification to close 'yield gaps' on land already planted to oil palm may be an important aspect in developing policy on sustainable oil palm development in Ghana. Average yields obtained at plantations range between 10–13 t ha^{-1} FB, while smallholder farmers only achieve yields around 3 t ha^{-1} FB (Ofosu-Budu and Sarpong, 2013). With an estimated average yield potential ranging from 20–25 t ha^{-1} FB for sites suitable to grow oil palm (Fairhurst, personal communication), large yield gaps within Ghana, but also between production systems occur.

To avoid the negative environmental impacts associated with agricultural expansion such as forest destruction and loss of biodiversity (Griffiths and Fairhurst, 2003; Griffiths et al., 2002), land sparing through ecological intensification of cropping systems instead of land expansion is commonly proposed to maintain productivity (Phalan et al., 2011; Soliman et al., 2016). Ecological intensification seeks to increase yield per unit of land (e.g. t ha^{-1} FB) and approach the "attainable yield" of farming systems whilst meeting acceptable standards of environmental stewardship (Fairhurst and Griffiths, 2014). It is therefore important to understand which factors explain productivity first. Yield Gap Analysis (YGA) has been commonly used as an approach to assess possibilities for improving land productivity (Woittiez et al., 2017).

1.2 Yield gap analysis

Yield Gap Analysis (YGA) of individual crops have been used to analyse opportunities for increasing crop production at local to global scales, thus providing information crucial to food security (Guilpart et al., 2017). YGA looks to which factors are responsible for yield gaps, and how they can be improved upon by identifying and then correcting management practices. YGA thus provides a systematic process to assess opportunities and identify entry points to increase yields. In production ecology, four production levels are distinguished: i) potential yield (*Yp*) which is determined by growth-defining factors (radiation, temperature, ambient CO_2 concentration, and cultivar features), ii) water-limited (*Yw*) and iii) nutrient-limited yield (*Yn*) where growth is limited by water and/or nutrients respectively, iv) and actual yield (*Ya*), which is determined by yield-reducing factors (weeds, pest & diseases) (van Ittersum et al., 2013; van Ittersum and Rabbinge, 1997) (Fig. 1.2). In YGA, two major steps can be identified. The first is to quantify the yield gap (Yg), which is the difference between *Yp* for irrigated crops, or *Yw* for rainfed crops, and the actual yield (*Ya*). The second is to identify the underlying causes of the yield gap, in order to identify remedial measures with management interventions (Lobell, 2013).

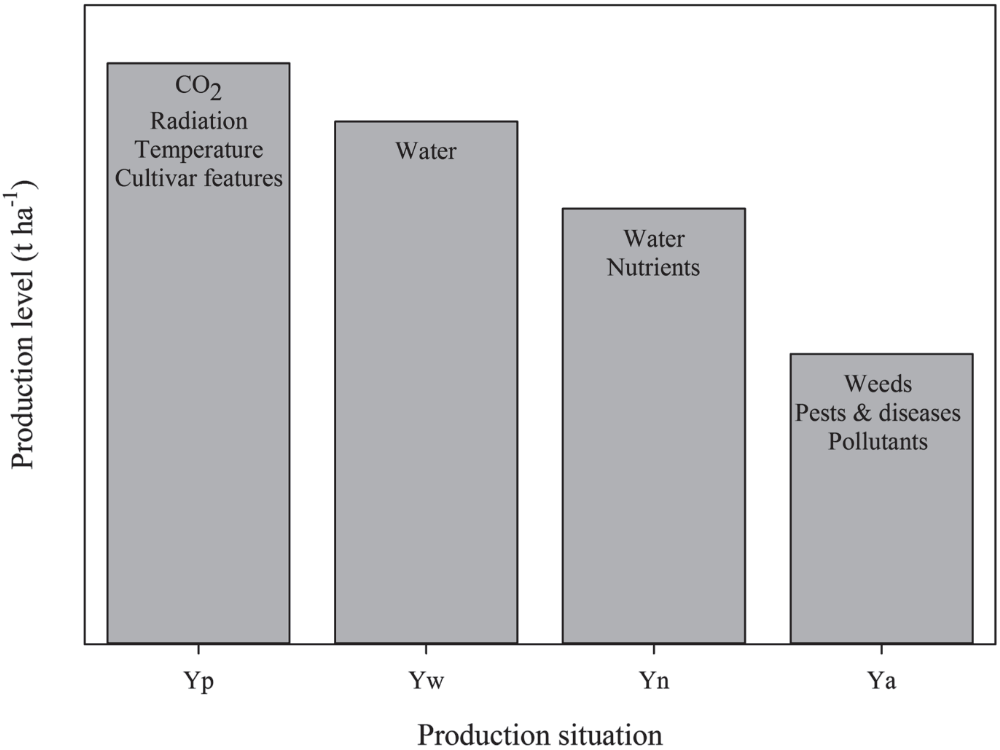

Fig. 1.2. Different production levels and the contributing factors (after van Ittersum et al., 2013).

Most yield gap studies have focussed on annual crops such as wheat (Aggarwal and Kalra, 1994; Anderson, 2010; Bell et al., 1995), cassava (Fermont et al., 2009), rice (Laborte et al., 2012; Yang et al., 2008), and cereals in general (Neumann et al., 2010), whilst little focus has been on perennial crops (Hoffmann et al., 2017; Woittiez et al., 2017). In oil palm, several attempts have been made to quantify and explain yield gaps. At plantation sites located in Malaysia and Indonesia, yield gaps ranged 5–7 t ha^{-1} FB (Hoffmann et al., 2017), whilst management practices such as fertilizer dosage, length of harvesting intervals and plant mortality explained yield gaps at independent

(13.0 t ha^{-1} FB) and supported (9.2 t ha^{-1} FB) smallholder farms in eastern Sumatra, Indonesia (Euler et al., 2016).

However, because perennial crops, like oil palm, are structurally different than annual crops, a slightly different approach to YGA is required. For example, in annual crops, growers can take advantage of new seeds with each growing season, whilst for perennial crops the yield potential is fixed at the nursery and planting stage for each planting cycle over at least 25 years (Woittiez et al., 2017). In addition, like other perennial crops (e.g. rubber, cocoa and coffee) there is a 35–40 month time-lag in oil palm between the occurrence of abiotic and biotic stress events and their impact on yield (Breure, 2003; Fairhurst and Griffiths, 2014), which complicates separating and quantifying the effects of individual factors (Woittiez et al., 2017). For example, a dry period at any time during bunch development, as well as reduced fertilizer applications may both drastically reduce yield. These time-lagged effects related to the complex physiology of oil palm must be taken into account when assessing yield gaps (Hoffmann et al., 2017). Moreover, infrequent, incomplete or incorrect harvesting practices (i.e. harvesting unripe or overripe bunches) may directly reduce actual yields if logistical operations are not carried out adequately (Donough et al., 2010; Fairhurst and Griffiths, 2014). These factors, combined with differing scales of assessment (from smallholder farms of <10 ha to large-scale oil palm plantations of 10,000 ha) make YGA in oil palm a challenge (Hoffmann et al., 2017).

When making an analysis of yield gaps and their management, it is therefore important to distinguish between annual and perennial crops. Opportunities to close yield gaps in annual crops mainly occur between cropping cycles. In perennial crops, there are opportunities to close yield gaps within a cropping cycle (with time lags between the implementation of corrective agronomic interventions and their effect on yield) (Fig. 1.3). There may also be opportunities to close yield gaps between cropping cycles due to the effect of improved germplasm and better crop establishment and management during the immature growth phase.

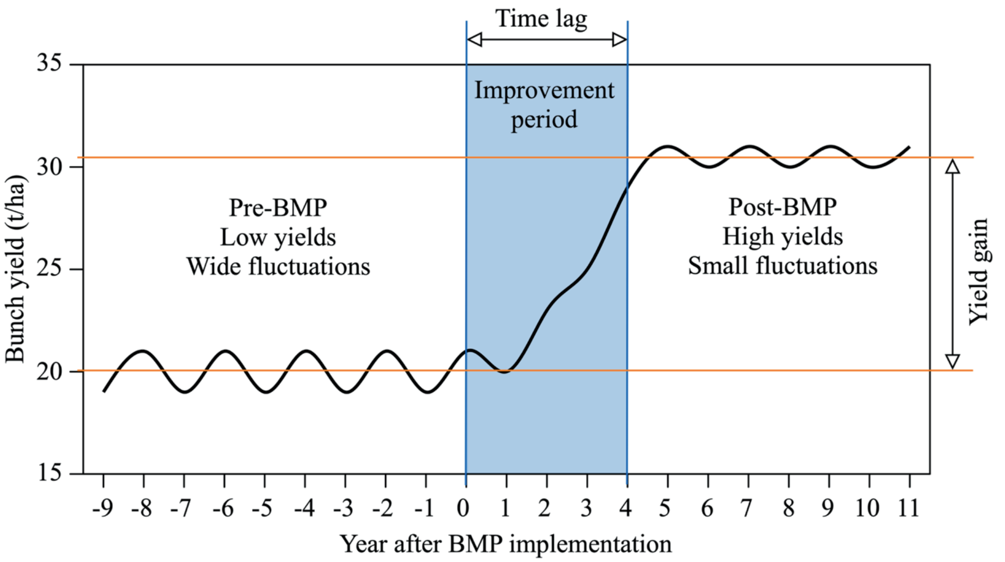

Fig. 1.3. Model showing the time-lagged effect of yield gap reduction in oil palm with Best Management Practices (BMP) (after Fairhurst et al., 2019).

1.3 Reducing yield gaps with Best Management Practices (BMP)

Increases in production are crucial due to multiple interacting challenges such as the need to adapt to a rapidly changing climate, increased competition for agricultural land from other land uses, and societal demands for environmental stewardship (Bryan et al., 2014). Intensification and improvement in resource use efficiency have been identified as two of the most prospective ways to increase agricultural production (Bryan et al., 2014). Closing the yield gap between what farmers achieve and those that can be achieved with best practice and current technology in a given environment is a key strategy for increasing production on existing cropland (Hochman et al., 2016).

In oil palm, the scope to increase production with sustainable intensification is considerable (Donough et al., 2010; Hoffmann et al., 2015; Oberthür et al., 2012; Rhebergen et al., 2014). In Indonesia, yields increased by 6.0 t ha^{-1} FB in South Sumatra with "Best Management Practices (BMP)" (Griffiths and Fairhurst, 2003) and by 3.4 t ha^{-1} (+15%) across six commercial plantations in Indonesia (Donough et al., 2010).

BMPs integrate yield intensification with environmental goals and are defined as *"agronomic methods and techniques found to be the most cost effective and practical means to reduce the gap between actual and site yield potential and minimize the impact of the production system on the environment by using external inputs and production resources efficiently"* (Donough et al., 2009).

In the concept, a set of site-specific BMPs are identified and implemented in several mature oil palm plantings. The BMPs are assessed based on agronomic, economic and environmental performance, in comparison to a parallel set of reference (or control) plantings (REF) where current standard practices are maintained. Yield gaps between BMP and REF can therefore be directly linked to differences in crop recovery, canopy and nutrient management, drainage, and other management practices (Oberthür et al., 2012). BMP implementation and evaluation is largely a trial-and-evaluation process in which a set of agronomic practices is identified and assessed, until the most desirable combination of BMPs for a particular site is developed. This is done in collaboration and full participation of farmers, plantation managers and field staff. Once the BMPs are successfully implemented at scale, they become standard practice, and the cycle of evaluation and implementation starts over (Donough et al., 2010; Donough et al., 2009) (Fig. 1.4).

Modelled after successful projects in Southeast Asia (Donough et al., 2010; Donough et al., 2009; Oberthür et al., 2012), the International Plant Nutrition Institute (IPNI) and Solidaridad's Sustainable West Africa Palm Oil Programme (SWAPP) initiated a project in 2013 to assess the potential to increase oil palm yields in plantations and smallholder farms in Ghana. The main goal of both projects was to enable plantation managers and smallholder farmers to adopt BMP to close yield gaps at plantations and smallholder farms. BMPs were applied at three oil palm plantations (Benso Oil Palm Plantation Ltd. (BOPP), Norpalm Ghana Ltd. and Twifo Oil Palm Plantation Ltd. (TOPP)) and twenty smallholder sites for a duration of 4 years. This thesis largely uses data generated from these projects.

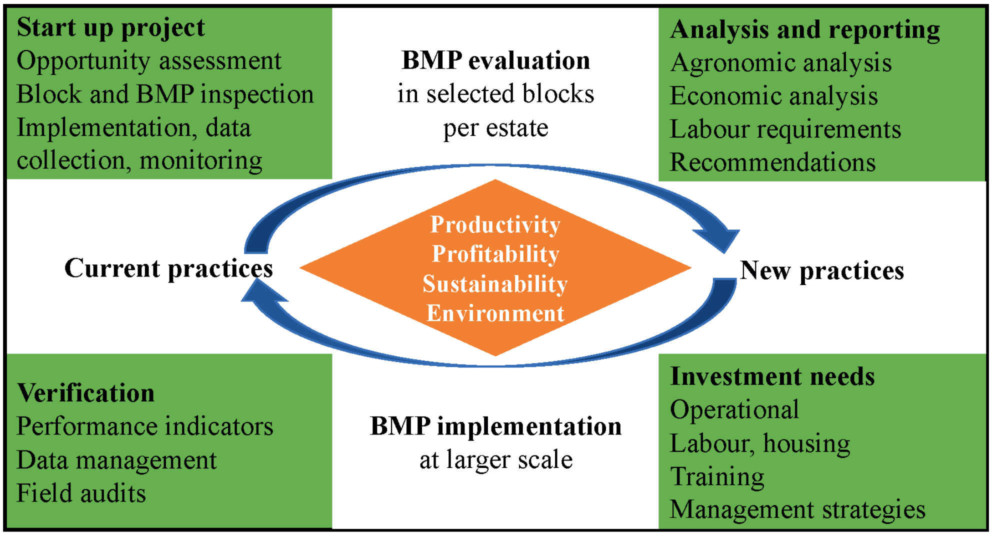

Fig. 1.4. Conceptual framework for evaluation of BMPs in mature oil palm standings (after Witt and Donough, 2007).

1.4 Objectives and thesis outline

Oil palm production in Ghana is well below its potential and the factors determining its efficiency are poorly understood. In this thesis, we developed a framework for YGA in oil palm in order to diagnose production constraints and assess opportunities for increasing yields with BMPs. Analysis of the factors that explain low productivity in Ghana is an important step in identifying entry points for intensifying oil palm production for various producers. The general hypothesis of this thesis is that Yield Gap Analysis (YGA) helps to improve fruit bunch yields in Ghana in a systematic way with Best Management Practices (BMP).

The objectives of this study were therefore first to review and characterize the environment for growing oil palm in Ghana, and to determine the suitability and availability of land to grow it with land evaluation methods (Chapter 2). We then describe the main constraints to oil palm production in Ghana based on land characteristics that limit productivity, and conclude by providing recommendations for the sustainable development of the oil palm sector in Ghana.

Second, we describe the oil palm sector in Ghana, and characterize the various oil palm production systems. We analyse why current productivity is low, and large yield gaps exist with production ecology concepts. In order to assess entry points for increasing productivity in oil palm, we apply Yield Gap Analysis (YGA) to quantify and partition yield gaps between different causes (Chapter 3). We conclude with proposing remedial measures to increase fruit bunch yields.

Third, we identify and implement Best Management Practices (BMP) to close yield gaps in existing mature oil palm plantings (Chapter 4). We analyse the impact of "yield taking" and "yield making" practices on yield components and identify which (management) factors correspond most with yield. We then present a management approach for yield gap reduction in Ghana and a framework for scaling BMPs across a wider scale.

Finally, we investigate the interaction of nutrients and water on the yield performance of oil palm on a large-scale oil palm plantation in Western region, Ghana (Chapter 5). We quantify yield gaps caused by water and nutrient constraints and assess the potential to maximize yields with site-specific management interventions. The relevance of my findings is discussed in Chapter 6 (Fig. 1.5).

Results of this study are expected to generate knowledge on the causes behind yield gaps in oil palm production systems in Ghana, and to provide incentives for site-specific management on closing them. Understanding the mechanisms and variables that determine yield can help eliminate yield differences in- and between sites and enable us improve crop response to natural variation and variation in management practices. The ultimate goal of this study is to contribute evidence and incentives for plantation managers and smallholder farmers across Ghana to adopt and adapt BMP as a management tool in intensifying oil palm production.

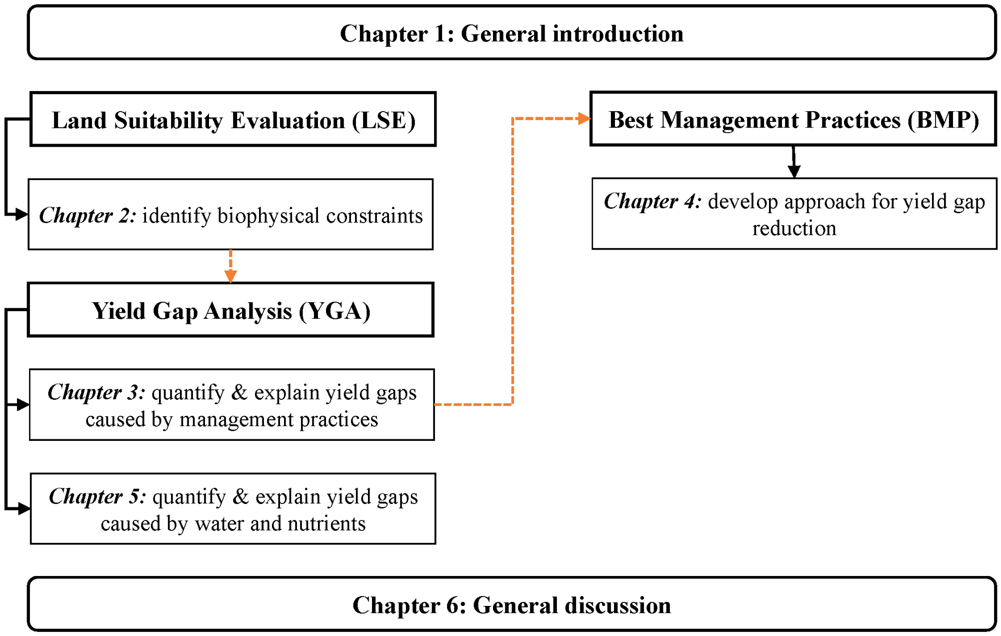

Fig. 1.5. Conceptual overview of the chapters of the thesis.

CHAPTER 2

Climate, soil and land-use based land suitability evaluation for oil palm production in Ghana

This chapter is published as:

Rhebergen, T., Fairhurst, T., Zingore, S., Fisher, M., Oberthür, T. and Whitbread, A., 2016. Climate, soil and land-use based land suitability evaluation for oil palm production in Ghana. Eur. J. Agron., 81: 1–14.

Abstract

In the past decade, oil palm (*Elaeis guineensis* Jacq.) has become the world's most important oil crop. The large demand for palm oil has resulted in a rapid expansion of oil palm cultivation across the globe. Because of the dwindling availability of land in Southeast Asia, most expansion of the industry is expected in Central and South America and sub-Saharan Africa, where land with suitable agro-ecological conditions is available. Using Ghana as a case study, a method for evaluating areas that are both suitable and available for oil palm production is presented. Our assessment used spatial data and GIS techniques, and showed that areas with suitable climatic conditions (annual average water deficit <400 mm) is about 20% greater than was previously identified. The observed differences are the result of using different methods to determine suitability, and climate change. A major climatic factor limiting suitability for oil palm production in Ghana is the annual water deficit, with the most suitable areas located in the rainforest and semi-deciduous forest zones with higher rainfall in southern Ghana. Opportunities for large-scale oil palm plantation development is limited, however, because of the lack of availability of large and contiguous tracts of land that are required for commercial plantation oil palm development. A feasible strategy for oil palm expansion is therefore smallholder production, which can make use of smaller parcels of land. Alternatively, oil palm production in Ghana can be increased by yield intensification on land already planted to oil palm. This can also reduce the requirement for further land clearance for new plantations to meet the growing demand for palm oil. Such assessments will be essential for guiding government policy makers and investors considering investments in oil palm development.

Keywords: *Ghana, oil palm productivity, water deficit, land suitability.*

2.1 Introduction

In the past decade, oil palm (*Elaeis guineensis* Jacq.) has become the world's most important oil crop, contributing nearly 30% of the world's edible vegetable oil requirements (Corley, 2009; Hansen et al., 2015). The large demand for palm oil has resulted in a rapid expansion of oil palm cultivation across the globe. Because of the dwindling availability of suitable land in Southeast Asia, most future expansion is expected in Central and South America and sub-Saharan Africa (SSA), where large areas with agricultural potential are available (Laurance et al., 2014).

In West Africa (WA), the consumption of palm oil and derived products is expected to increase as the population grows. Strong demand for vegetable oil in Africa has resulted in the expansion of the oil palm sector in WA. This has a large economic impact in producer countries by providing employment for millions of workers. In addition, palm oil is now a major source of income and trade along border districts (Ofosu-Budu and Sarpong, 2013). In the Ghanaian economy for example, oil palm is the second most important perennial crop after cocoa (Angelucci, 2013; Ofosu-Budu and Sarpong, 2013). The yield of fruit bunches (FB) in Ghana is poor, however, and has decreased from 6.5 t ha^{-1} in 1990 to 5.4 t ha^{-1} in 2012 (FAO, 2014a). By contrast, FB yields in the major producing countries in Southeast Asia and Latin America, where the climate is more favourable, are more than three times greater at 18.5–19.0 t ha^{-1} (FAO, 2014a). In response to increasing local demand for palm oil and the present requirement for costly palm oil imports (for example, Ghana imported 74,431 t palm oil at a cost of US$ 83 million in 2011) (FAO, 2014a), the governments of some West African countries are encouraging both national and foreign investors to plant more oil palm (Ofosu-Budu and Sarpong, 2013). Area expansion is therefore proposed to increase local production and to reduce imports of crude palm oil.

An analysis of the availability of suitable land for oil palm plantations and the obtainable yields is essential information for government policy makers and investors. Some 45 years ago, van der Vossen (1969) identified areas in Ghana with suitable climatic conditions for oil palm based on 400 and 250 mm mean annual water deficit isolines. As in much of SSA, climatic conditions in the oil palm belt in Ghana have changed since the 1960s (Lemoalle and de Condappa, 2012). Rainfall isohyets and water-deficit isolines have been displaced to the south by about 1° latitude (i.e. about 110 km), possibly due to climate change and the impact of deforestation. Furthermore, total annual rainfall has also become more variable over the past three decades (Manzanas et al., 2014; Owusu, 2009; Stanturf et al., 2011). Whilst total annual rainfall has remained similar, rainfall distribution has changed, with more rainfall now occurring in what was formerly the dry season (Abdul-Aziz et al., 2013; Owusu, 2009). At a local scale, the amount of land with climatic conditions suitable for oil palm production may have either expanded or diminished due to changes in rainfall patterns (Gilbert, 2013).

In this chapter, we provide an up to date and more accurate assessment of land suitability and availability for oil palm based upon geographic information systems (GIS) using spatial data that was not available when van der Vossen (1969) developed his suitability map. Using Ghana as a case study, we describe the agro-ecological conditions and, using information from the literature, derive environmental parameters that define whether or not areas are suitable for oil palm cultivation. We used these parameters together with the spatial data on climate to develop a land suitability classification and estimate the amount of suitable land that is available for oil palm development.

We determine the main constraints to oil palm production in Ghana based on an analysis of land characteristics that limit productivity, and conclude by providing recommendations for the sustainable development of the oil palm sector in Ghana.

2.2 Material and methods

2.2.1 Agro-ecological conditions in Ghana

Ghana is located in the middle of the West African coast along the Gulf of Guinea (4.5–11.5°N, 3.5°W–1.3°E), and is bordered by the Ivory Coast to the west, Burkina Faso to the north, and Togo to the east. The climate of Ghana is strongly influenced by the movement of the tropical rain belt, known as the inter-tropical convergence zone (ITCZ). The ITCZ oscillates between the northern and southern tropics in the course of a year, transporting a dry continental air mass to the north, and a tropical, maritime air mass to the south (Hayward and Oguntoyinbo, 1987). As a result, northern and southern regions of Ghana have distinct climates (McSweeney et al., 2010a; McSweeney et al., 2010b). Six distinct agro-ecological zones have been identified in Ghana, with a gradient of increased aridity from south to north (Antwi-Agyei et al., 2012). In order of increasing aridity they are: rainforest, semi-deciduous forest, coastal savanna, forest-savanna transition, Guinea savanna, and Sudan savanna (Antwi-Agyei et al., 2012) (Appendix 1). Rainfall decreases from the southwest (>2,000 mm yr^{-1}) to the northeast (<1,000 mm yr^{-1}) (Environmental Protection Agency (EPA) and Ministry of Environment, 2011). In the south, the annual mean relative humidity (RH) is ~80% (except for some days during the 'Harmattan' in the dry season), while in the north RH is lower at ~40% (Oppong-Anane, 2006). Northern Ghana has a single wet season between May and November, while the southern regions of Ghana have two wet seasons with long rains usually from March–July and short rains from September–November.

With the exception of the Kwahu Plateau, which runs along the southern edge of the Volta River Basin, the topography in Ghana is relatively flat and low-lying, with more than half the area <150 masl. Because Ghana is in the equatorial belt, mean monthly temperatures below 25°C are seldom recorded. Mean annual temperature ranges from 26°C in the south to 29°C in the north (FAO, 2005). Minimum temperatures less than 18°C only occur in the highlands above 400 masl (e.g. on the Kwahu Plateau) (van der Vossen, 1969). The diurnal temperature range is small in the south (5–9°C) due to maritime influence from the Atlantic, and greater in the north (7–14°C) due to hot and dusty air brought in from the Sahara desert during the Harmattan (McSweeney et al., 2010a; McSweeney et al., 2010b). As a result, climatic conditions are hot and seasonally dry along the southeast coast, hot and humid in the southwest, and hot and dry in the north.

Little solar radiation data is available for West Africa, and Ghana, because of the lack of solar radiation recording stations in the region (Stout, 1990). As a surrogate, sunshine hours are used as an estimate of solar radiation because it is easier to measure and data are more readily available. While solar radiation and sunshine hours are generally well-correlated, the effects of the Harmattan and atmospheric pollution under West African conditions prevents accurate recording of sunshine, even when conditions are cloudless. As a result, much solar radiation is reflected by the atmosphere, and reaches the earth's surface predominantly as diffuse radiation (Corley and Tinker, 2003; Hayward and Oguntoyinbo, 1987). Nevertheless, taking these factors into account, the total hours of sunshine per annum in WA is considerably less than in other oil palm growing regions such as Southeast Asia or Central and South America (Corley and Tinker, 2003; van der Vossen, 1974). In WA, sunshine hours increase with latitude from the Guinea Coast up to the Sahel and the margins of the Sahara, albeit not in a regular pattern. In Ghana, for example, a large land pocket with less sunshine occurs in the west central region (Hayward and Oguntoyinbo, 1987). In general, there are more sunshine hours during the dry season and less during the rainy season because of the effect of cloud cover. However, sunshine hours during the dry season are periodically reduced due to the effect of dust in the atmosphere during the Harmattan.

Soils in the higher rainfall zones in the south of Ghana are generally strongly weathered and highly leached with low pH, and poor soil fertility status (Swaine, 1996). Soil type is strongly related to topography and slope position. The topography in the oil palm belt is undulating to rolling, with slopes ranging from 2–9°. Some relatively flat areas are found with moderate slopes (<5°) but rolling to hilly terrain (5–17°) is more common, with low-lying and poorly drained swamps enclosed by upland areas. In the oil palm belt, the predominant soils are free-draining Acrisols and Ferralsols (Appendix 2). These two soil types are often found together, with Acrisols on eroded slopes of low hills, Ferralsols on nearby stable pediments and uplands. Soils in enclosed, low-lying swamps are commonly Gleysols (FAO, 2014b).

The most common soils in the semi-deciduous forest and parts of the forest-savanna transition zones of the oil palm belt are Orthic Acrisols. They are deep, well drained soils with sandy clay loam texture, strongly weathered, leached, and acid (pH <5.1–6.5). Acrisols are characterized by a distinct argillic B horizon, in which clay particles have accumulated from the upper soil layer. Acrisols are easily eroded once the forest cover vegetation has been removed (Adjei-Gyapong and Asiamah, 2002; Buringh, 1979; FAO, 2014b). Xanthic Ferralsols derived from acid rocks with high quartz content are more common in the high rainfall forest zone of Southwestern Ghana (Buringh, 1979; FAO, 2014b; van Wambeke, 1974). Xanthic Ferralsols have a typically yellowish or pale yellow B horizon, due to low iron content. As a result of their relatively coarse texture and high rainfall, they are strongly leached, acid and poor in nutrients. Well-developed soil micro-aggregates reduce the water holding capacity in these soils. Orthic Acrisols and Xanthic Ferralsols are acid (pH<5.5) low fertility status soils containing small amounts of plant available nutrients (particularly nitrogen (N), phosphorus (P) and potassium (K)), with low cation exchange capacity (e.g. Ferralsols <16 cmol kg^{-1}) and base saturation (e.g. Acrisols <50%). Drainage is related to topography, with poorly drained, flood prone clay to loamy sand textured Gleysols in valley bottoms, and well drained Acrisols and Ferralsols respectively on lower and upper slopes (Annan-Afful et al., 2004; Annan-Afful et al., 2005; Owusu-Bennoah et al., 2000).

2.2.2 Land suitability classification and approach

We used land suitability evaluation methods to identify areas that are both suitable and available for oil palm production in Ghana. Land suitability is defined as '*the fitness of a given type of land for a defined use*' and land suitability evaluation (LSE) is the '*process of assessment of land performance for a specific purpose'* (FAO, 1976). For agriculture, LSE evaluates the ability of a piece of land to meet the agro-ecological requirements of a given crop for maximum yield (Abdel Kawy and Abou El-Magd, 2012). LSE assesses how well all relevant land characteristics such as soil, climate, and topography (FAO, 1976; FAO, 1985) match the requirements of a particular crop.

For the objectives of this study, computer-assisted overlay mapping is a suitable LSE method, in which the evaluation criteria are recorded as superimposed layers (Malczewski, 2004). These layers are then integrated in a single data layer, which can then be used to produce a map showing land suitability classes. We used this method to define suitable locations for oil palm in Ghana.

2.2.3 Suitability classes

LSE was conducted in three-steps. In the first step, we defined climatically suitable areas for oil palm based on mean annual water deficit. Water deficit is considered to be the most important climatic factor affecting oil palm yield (Corley and Tinker, 2003). Severe water deficits are particularly common in WA because of seasonal droughts. In extreme areas, such as Pobé in Benin, average annual water deficits can vary between 300–900 mm yr^{-1}, with an average of 550 mm yr^{-1} (Caliman and Southworth, 1998). The relationship between water deficit and FB yield is complex. Water stress, as well as other environmental factors, reduces FB yield via a time-lagged effect on floral initiation, sex differentiation, and abortion rate (Corley and Tinker, 2003). As a result, yield reduction may only become evident several months or even years after the incidence of drought or other stress events (Caliman and Southworth, 1998). With prolonged water stress, vegetative as well as generative growth is impaired and, in extreme cases, may lead to palm death (Caliman, 1992). The extents to which water deficits affect FB yield have been reported in several studies. In WA, Hartley (1988) found a 10% yield reduction with every 100 mm yr^{-1} water deficit in the year of harvest. In contrast, Olivin (1968) and Ochs and Daniel (1976) reported a 10–20% yield reduction with every 100 mm yr^{-1} water deficit, depending on the soil's water holding capacity. Caliman and Southworth (1998) found an 8–10% yield reduction in the first year, and a 3–4% yield reduction in the second year with a 100 mm yr^{-1} water deficit. Mean annual water deficit is thus a useful parameter in delineating and grouping areas that are climatically similar in terms of oil palm production (Olivin, 1968; van der Vossen, 1969). In general, areas with water deficits > 400 mm yr^{-1} are considered unsuitable for oil palm production because low yields do not provide an economic return (Olivin, 1968; van der Vossen, 1969). The critical water deficit, after which oil palm growth and yield start to be affected is assumed to be 200 mm yr^{-1} (Corley and Tinker, 2003). Based upon these assumptions, and following the suitability assessment methods of Olivin (1968) and van der Vossen (1969), we defined four categories of water deficit as follows:

i. Optimal: areas with a mean annual water deficit <150 mm;
ii. Favourable: areas with a mean annual water deficit <250 mm;
iii. Suitable: areas with a mean annual water deficit <400 mm; and
iv. Unsuitable: areas with a mean annual water deficit >400 mm.

In the second step, we overlaid the areas that were climatically suitable with biophysical and topographic constraints categorized as either 'suitable' or 'not suitable' (Table 2.1). We included solar radiation, temperature, and slope because, after water deficit, they are the most important factors that determine oil palm yields (Paramananthan, 2003).

The amount of solar radiation suitable for oil palm production is not defined precisely, however, because it is difficult to isolate its effect from other factors affecting productivity. Oil palm grows best where solar radiation is > 16 MJ m^{-2}, but excessive amounts of solar radiation can affect stomatal aperture and leaf temperature, limiting the rate of CO_2 absorption and therefore photosynthesis (Corley and Tinker, 2003; Paramananthan, 2003). Additionally, high levels of solar radiation can cause photo-damage to plants (Kasahara et al., 2002). Of these constraints, only topography can be modified by costly management interventions (e.g. installation of individual terraced platforms on moderate to strongly sloping land (5°–10°) and continuous terraces on steep terrain (10°–20°).

Table 2.1. Suitability for oil palm production based on climate and topography parameters (Paramananthan, 2003).

Limitation	Units	Suitable	Unsuitable
Climate			
Solar radiation	MJ m^{-2}	7–21	<7, >21
Temperature	°C	18–37	<18, >37
Topography			
Slope	°	<20	>20

In the third and final step, we integrated the most current land-use and excluded protected areas, which include national parks, forest reserves, World Heritage sites, and Ramsar Wetlands. Protected areas are defined according to IUCN as '*a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values*' (Dudley, 2008). Urban settlements, which were distinguished from rural areas based on a combination of population counts (persons), settlement points and the presence of nighttime lights, were also excluded. Urban settlements are defined as '*contiguous lighted cells from the nighttime lights or approximated urban extents based on buffered settlement points for which the total population is greater than 5,000 persons* (Balk et al., 2006; CIESIN et al., 2011). Because of national differences in distinguishing urban from rural areas, the criteria for urban settlements are country specific (UN, 2013). In SSA, for example, the urban population threshold ranges from settlements of 20,000 to as few as 500 inhabitants for certain areas in South Africa and Zimbabwe (Foote et al., 1993). In Ghana, an urban area is defined as a settlement with >5,000 inhabitants (Ajaegbu, 1979).

2.2.4 Data used

We used historical climate data from the WorldClim database (www.worldclim.org) (Hijmans et al., 2005), including monthly minimum, maximum and average temperature (°C) and average monthly rainfall (mm $month^{-1}$) for the period 1950–2000. The WorldClim data are generated through interpolation of average monthly climate data from meteorological stations distributed throughout Ghana. Elevation data was obtained from the SRTM 90m database (http://srtm.csi.cgiar.org) (Jarvis et al., 2008) and soil properties, including soil texture and soil type from the ISRIC/WDC-Soils database (http://soilgrids1km.isric.org) (ISRIC, 2013) and the Harmonized World Soil Database v1.2 (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/) (FAO et al., 2009). Data on protected areas and urban settlements were obtained from (http://protectedplanet.net) (IUCN and UNEP-WCMC, 2014) and (http://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents/data-download) (CIESIN et al., 2011). The data were compiled in a geographic information system using ArcMap 10. The climatic, biophysical, topographic, and soil spatial datasets were raster files on 30- and 3-arcsecond grids (~1 km and 100 m). Data of urban settlements and protected areas were imported as shapefiles. Data sources are listed in Appendix 3.

2.2.5 Data analysis

We clipped all raster grids and shapefiles to the extent of Ghana's national boundaries and derived slope maps from elevation contours (with Z factor = 9.12×10^{-6}). We estimated solar radiation at a 30-arcsecond resolution for each month from latitude and day of the year (Allen et al., 1998), and then converted solar radiation into water equivalents to calculate monthly potential evapotranspiration (ETP) following Läderach et al. (2013):

$$ETP = 0.0023 \; x \; R_a \; x \; (T - t)^{0.5} \; x \; (t_m + 17.8) \qquad \text{Eq. 2.1}$$

where

ETP = evapotranspiration (mm day^{-1});

R_a = extraterrestrial solar radiation expressed in water equivalent (mm day^{-1});

$T\text{-}t$ = the monthly mean diurnal temperature range (°C); and

t_m = mean air temperature (°C).

We estimated terrestrial solar radiation (R_s) (Hargreaves and Samani, 1982):

$$R_s = 0.16 \; x \; R_a \; x \; (T - t)^{0.5} \qquad \text{Eq. 2.2}$$

where

R_s = terrestrial solar radiation (MJ m^{-2} $month^{-1}$); and

R_a and T-t are as defined in equation (1).

We converted ETP to mean annual water balances (B) (Surre, 1968):

$$B = S_{res} + P - ETP \qquad \text{Eq. 2.3}$$

where

B = monthly water balance (mm);

S_{res} = residual soil water from the previous month (mm);

P = monthly rainfall (mm); and

ETP = monthly potential evapotranspiration (mm).

Epebinu and Nwadialo (1993) found a high correlation (multiple R = 0.980) between available water capacity (AWC) and the soil particle size distribution in Nigeria:

$$AWC = 0.93 + 0.54\ x\ silt + 0.13\ x\ clay \qquad \text{Eq. 2.4}$$

We used equation (4) to estimate AWC for five layers (0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, and 60–100 cm depth) for each soil texture class. The sum estimates the maximum amount of available soil water (ASW) in the top 100 cm of soil, which is the zone exploited by the majority of the roots of oil palm (Nelson et al., 2006). We assumed that excess water was lost as runoff or drainage to depth. Negative values for monthly water balance (B) indicate a water deficit, in which case S_{res} for the following month is zero. If S_{res} was greater than the soil's maximum water storage capacity, it was set to the maximum. Annual water deficit was calculated as the sum of all negative monthly water balances for the year.

Rainfall data for the period 2010–2014 were obtained from five meteorological stations. Three of the stations were located at the commercial plantations Benso Oil Palm Plantation (BOPP), Twifo Oil Palm Plantation (TOPP) and Norpalm Ghana Ltd. located in the Western and Central Regions. The other two sites are Bogoso, a smallholder oil palm project, and the Ghana Oil Palm Research Institute (OPRI) at Kade, respectively in the Eastern and Western Regions. BOPP and Bogoso are located within the rain forest zone, while the other sites are found within the semi-deciduous forest zone. The five production sites cover a wide range of rainfall distribution (mm $month^{-1}$) within the oil palm belt. For all sites, we calculated average annual water deficits using the method of Surre (1968) and evaluated this against the results of our suitability assessment. In the final analysis, we integrated land use information to delineate areas that were suitable on land potentially available for oil palm production. We generated maps of land suitability after excluding land in protected areas and urban settlements.

2.3 Results

2.3.1 Areas suitable for oil palm production

We estimated the area suitable (deficit <400 mm yr^{-1}) for oil palm in Ghana to be 7,350,000 ha, or 31% of the total land area (Fig. 2.1). The area unsuitable for oil palm production, due to poor water availability, is 16,500,000 ha. Optimal areas for oil palm (water deficit <150 mm yr^{-1}) are in the south of the Western Region and a smaller area west of Koforidua in the Eastern Region. Optimal areas are estimated at 580,000 ha (Fig. 2.1).

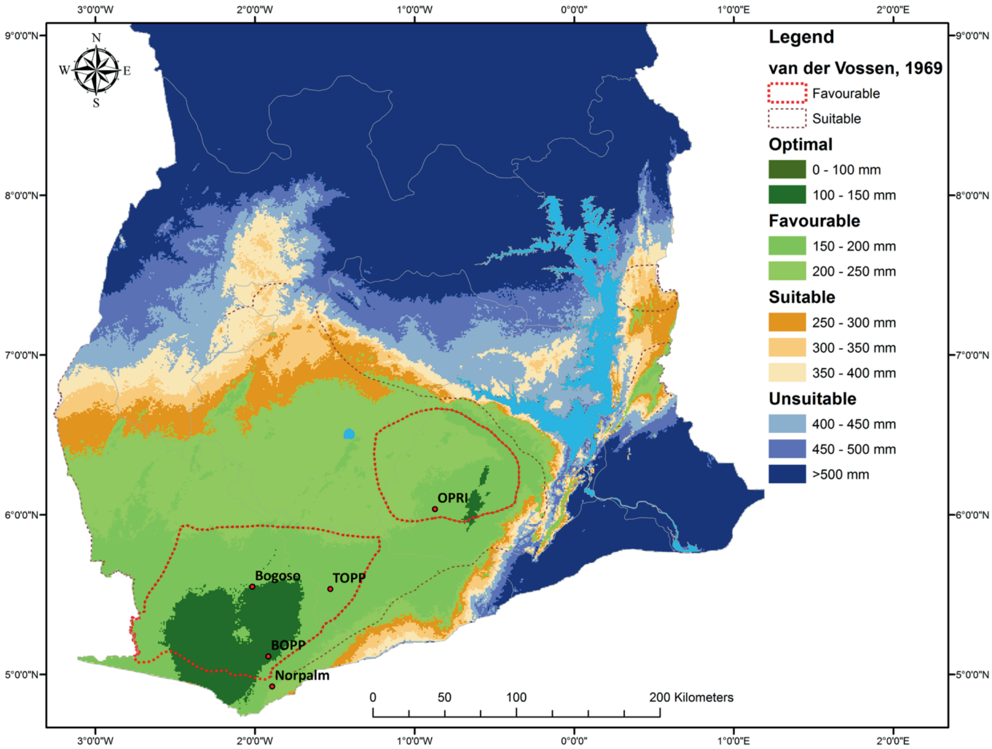

Fig. 2.1. Map of southern Ghana showing areas climatically suitable for oil palm production (≤400 mm yr^{-1} water deficit) in steps of 50 mm water deficit, compared to suitable areas identified by van der Vossen (1969).

Based on our assessment, the area that has climatic conditions suitable for oil palm (deficit <400 mm yr^{-1}) is 20% greater than that identified by van der Vossen (1969) (Table 2.2). The additional area suitable for oil palm is found in the southwestern coast and east of Lake Volta (Fig 2.1). Climatically favourable areas are 170% greater than van der Vossen's (1969) assessment (Table 2.2). The difference is found largely in the Western and Central Regions and the southern parts of the Ashanti and Eastern Regions (Fig. 2.1).

Table 2.2. Land area falling within different suitability classes compared with the results of van der Vossen (1969).

Suitability class	Size		Difference	
	Climatic zones	Van der Vossen (1969)		
		,000 ha		%
Suitable (AWD <400 mm)	7,354	6,100	1,254	+21
Favourable (AWD <250 mm)	5,049	1,889	3,160	+167
Optimal (AWD <150 mm)	580	Not defined	-	-

Average water deficits for five production sites in Ghana ranged between 130 mm yr^{-1} for BOPP and 390 mm yr^{-1} for Norpalm for the period 2010–2014 (Appendix 4). All five sites are located within climatically suitable areas, but only BOPP is located in the area with optimal climate (Fig 2.1).

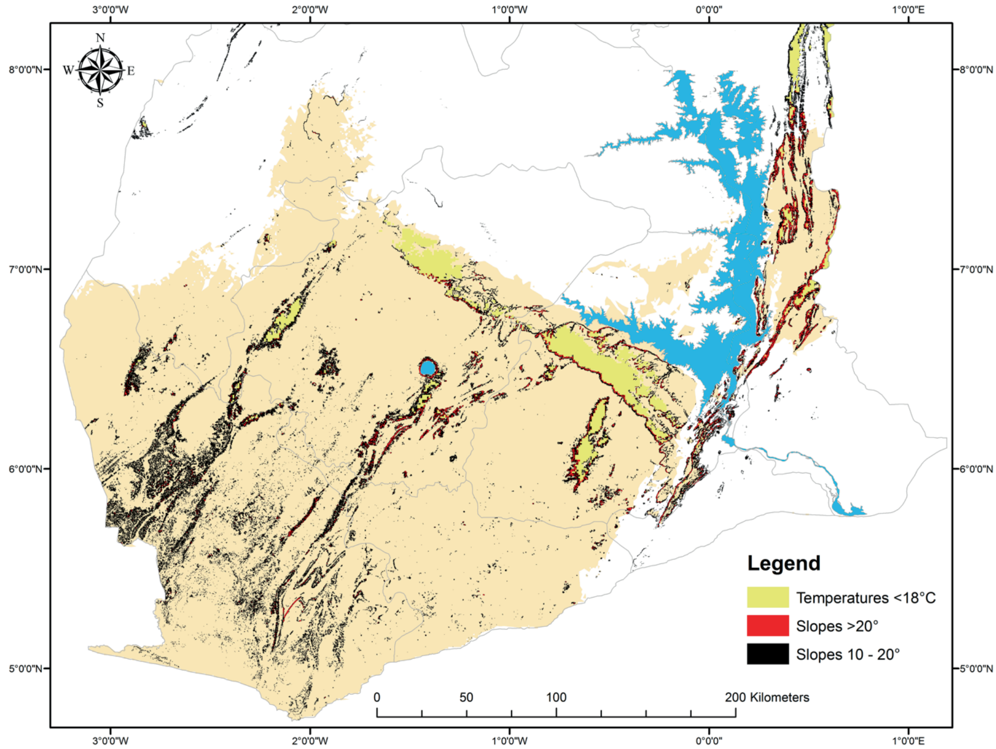

Fig. 2.2. Map showing areas with temperatures <18°C and slopes >10° within the climatically suitable area for oil palm production in Ghana. Land with slopes of 10–20° are suitable for oil palm production, but land with slopes >20° is unsuitable.

The uplifted edges of the Volta Basin lie along the northeastern edge of the semi-deciduous forest zone. They are found at elevations >350 masl and have mean monthly minimum temperatures below 18°C, which is the lower limit for oil palm (Table 2.1). We removed them from the area classified as climatically suitable (Fig 2.2).

In the areas with suitable climate, estimated solar radiation was within the limits for oil palm (7–21 MJ m^{-2}) proposed by Paramananthan (2003) (Table 2.1). Slopes >20°, which occur around the edges of mountainous outcrops, are not suitable for cultivation of oil palm, and were removed from the climatically suitable areas. Hilly and undulating terrain with slopes 10–20° occur throughout the oil palm belt, mostly in the favourable and optimal climate zones.

When we excluded urban settlements and protected areas, the area suitable for oil palm production reduced with 9% to 6,720,000 ha. The reduction was mostly in the optimal area (-30%), where there are large areas of forest reserve and urban settlements (Table 2.3).

Few large, contiguous tracts of land remain available for oil palm within this zone. Areas of land suitable and available for expansion of oil palm in Ghana are shown in Fig 2.3.

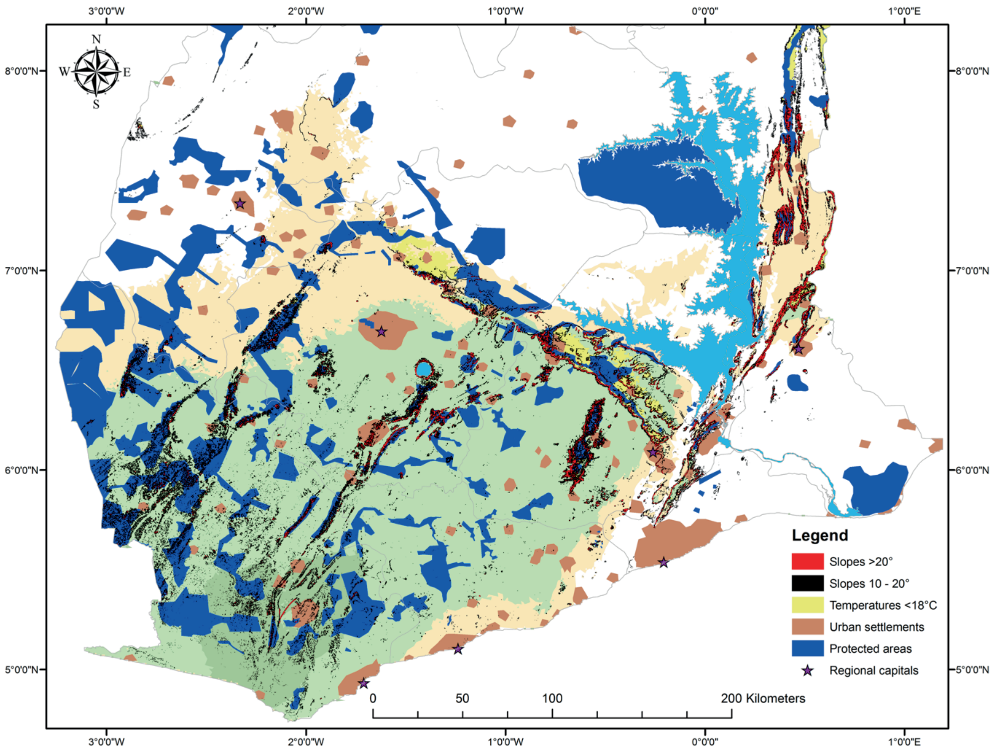

Fig. 2.3. Map of southern Ghana showing suitable and available areas with potential for oil palm expansion, after excluding urban settlements and protected areas.

Table 2.3. Reduction in the areas climatically suitable for oil palm production in Ghana after removing topographic and biophysical constraints, and urban settlements and protected areas.

Suitability class	**Area**							**Reduction**	
	Climatic zones	**Topographic and biophysical constraints**			**Protected areas**	**Urban settlements**	**Suitable and available land**		
		Temperature	**Slope 10–20°**	**Slope >20°**					
	,000 ha								**%**
Suitable	7,354	49	72	20	473	107	6,720	635	-9
Favourable	5,049	158	265	32	961	202	3,786	1,263	-25
Optimal	580	22	72	2.4	152	24	408	172	-30

2.4 Discussion and conclusions

2.4.1 Suitability analysis

We used a simple approach to estimate the amount of suitable and available land for oil palm production in Ghana that can be used to guide investment decisions. The results provide a basis for discussion of the current large-scale expansion of oil palm in Ghana and underlines the importance of evaluating the climatic factors that determine the current and future potential production of oil palm.

Our assessment shows a larger area to be suitable for oil palm production in Ghana than identified by van der Vossen (1969). The observed differences are the result of different methods used to determine suitability, but also because of climate change. We were able to source more detailed climate, soils and topographical data than was available to van der Vossen (1969). Newer techniques (GIS), methodologies (calculation of ETP and AWC) and improved knowledge of the effects of environmental parameters on oil palm production also help to explain the observed differences. To enhance, but also verify the suitability assessment, crop modelling would be of great benefit to simulate and analyze crop responses to the various climate conditions.

In addition, meteorological data shows that the climate in the oil palm belt has changed over the past 40 years. Temperatures increased and there was less rainfall, which was more variable, throughout Ghana between 1960 and 2000. In our assessment, we used the WorldClim climate data derived from actual data for 1960–2000 (Hijmans et al., 2005) to take account of temporal variation.

2.4.2 Climate change and climate predictions in Ghana

The onset and the duration of the dry and rainy seasons and the annual rainfall varies from year to year and between decades (Stanturf et al., 2011). This is caused by variations in the movements and intensity of the ITCZ, which affects the timing and intensity of the West African monsoon. Overall, the climate in the oil palm belt in Ghana has become drier (i.e. decline in annual rainfall) and more variable (onset and duration of the dry seasons) since the 1960s, which were wetter than average (Manzanas et al., 2014; Owusu, 2009; Stanturf et al., 2011). In the late 1970s and early 1980s, annual rainfall decreased substantially but increased again from 1986–2000. During this period, there was less rainfall and fewer rain days per month during the short rains and at the beginning of the long rains, whilst there was more rainfall during the short dry season (Owusu, 2009). Similarly, rainfall was greater during the main dry season, but decreased during the short rain season between 1974–2010 in the Ashanti region (Abdul-Aziz et al., 2013). Expert opinion confirms that rainfall has become more unpredictable, but previously dry months have become wetter.

Projected climate trends predict that mean annual rainfall will decrease further by the year 2050, while temperatures will increase. Mean annual rainfall is expected to decrease by ~10% and temperatures increase by 2.5°C and 2.0°C within the semi-deciduous forest zone, and rainforest zone respectively (Environmental Protection Agency (EPA) and Ministry of Environment, 2011). By contrast, other workers predict that southern Ghana will become slightly wetter, especially in the coastal regions (Läderach et al., 2013). Total annual rainfall is predicted to increase by 20–30 mm yr^{-1}, while the number of cumulative dry months (rainfall <100 mm $month^{-1}$) is predicted to decrease from 4 to 3 months per year by 2050. Mean annual temperatures are expected to increase by between 1.7–2.1°C in the southern (forest) regions, while mean daily temperature ranges are predicted to remain constant up until 2050.

The current and predicted changes in climate suggest that growing conditions for oil palm in Ghana will become more favourable. Although annual rainfall has decreased, it is distributed more evenly with less dry months (rainfall <100 mm $month^{-1}$). Oil palm grows best where rainfall is distributed more evenly throughout the year with no water deficits (Corley and Tinker, 2003). An increase in temperature, on the other hand, will increase evapotranspiration and aggravate soil-moisture conditions during periods of drought. This might adversely affect oil palm production within the semi-deciduous and forest zones.

Weather data from the five production sites in Ghana showed large variability in annual rainfall and water deficits over a period of five years (Appendix 4). At the TOPP plantation, for example, annual rainfall was largest in 2010 with 1,990 mm (annual water deficit 100 mm yr^{-1}), and least in 2013 with 980 mm (annual water deficit 820 mm yr^{-1}). A more accurate assessment of inter-annual variability on the water balance therefore needs to be taken into account to understand the dynamics of climate and its impact on oil palm production. The current WorldClim dataset does not allow for such an approach.

Evaluation of actual annual water deficits against the suitability assessment only resulted in an accurate prediction for the BOPP site. To test the validity of the current methodology, we need comprehensive climate data for sites across Ghana. These datasets are mostly lacking or difficult to find. This is mostly because of an inadequate number of meteorological stations for climate data collection. Also, much data that exists is not digitized and therefore not readily available (UNDP, 2011).

2.4.3 Key constraints to the production of oil palm in Ghana.

Although oil palm originated in West Africa, the suboptimal amount and distribution of rainfall are major factors limiting its production (Corley and Tinker, 2003; Quencez, 1996). Oil palm grows best where rainfall is 2,000–2,500 mm yr^{-1} and evenly distributed throughout the year with no months with < 100 mm rainfall (Goh, 2000; Hartley, 1988; Paramananthan, 2003). In Ghana, the rainforest and semi-deciduous forest zones therefore have the most suitable conditions for oil palm cultivation (Gyasi, 1992; van der Vossen, 1969). Based on our suitability assessment, three of the major plantations are located in the favourable growing areas in the southwest and east of the semi-deciduous forest zone. Only one major plantation is located in the rainforest zone within what we have defined as the optimal growing area. The opportunities to expand oil palm production within the optimal zone are likely limited due to competition from both large-scale mining and smallholder cocoa production. Smallholder farms and small-scale processing mills, on the other hand, are scattered throughout the entire oil palm belt.

In general, water deficit is the main constraint to oil palm production in West Africa (Caliman, 1992; Danso et al., 2008; Olivin, 1968; van der Vossen, 1969). Olivin (1968) found that average FB yields in oil palm plantations in West Africa correlated well with mean annual water deficit. In Ghana, Danso et al. (2008) found an almost linear inverse relationship between FB yield and water deficit. They concluded that availability of soil water is critical for oil palm production to be profitable.

Each 100 mm increase of water deficit reduces yields of FB by 10–15% (Corley and Tinker, 2003; Olivin, 1968). The reduction in yield can be as much as 40–50% if the palms were subjected to severe water stress in the preceding year (Caliman and Southworth, 1998). This emphasizes the need to explore the frequency and intensity of water deficits and the occurrence of drought as prerequisites to planning expansion of the area of oil palm (Caliman, 1992). Nevertheless, smallholders in Ghana grow oil palm in areas that we classify as unsuitable with mean annual water deficits up to 600 mm yr^{-1}. In areas with water deficits >400 mm yr^{-1}, no economic oil palm production can be expected (Olivin, 1968). These areas are considered to be unsuitable for oil palm in Ghana, except in areas where irrigation might be possible, such as the area surrounding Lake Volta.

Rainfall in southern Ghana is distributed bimodally, with long rains March–July and short rains September–November, separated by a short dry spell in August that is quite consistent across years. The dry season occurs between December and February, with less than 50 mm rainfall in January and less than 100 mm in both December and February (Appendix 4) (van der Vossen, 1969). The main period of water deficit, which occurs between November and March when radiation is high and rainfall is low, causes irregular distribution of palm yield. The extent of water stress within these months is considered the main yield-limiting factor for oil palm production in Ghana (van der Vossen, 1974). Across five sites in 2014, 50% of the annual crop from palms aged 7–15 years was harvested during the five-month period of the long rains. Only 23% was harvested in the dry season (Fig. 2.4). This imposes both logistical and operational problems, such as labour shortages during the long rains and underutilized mill capacity in the dry season.

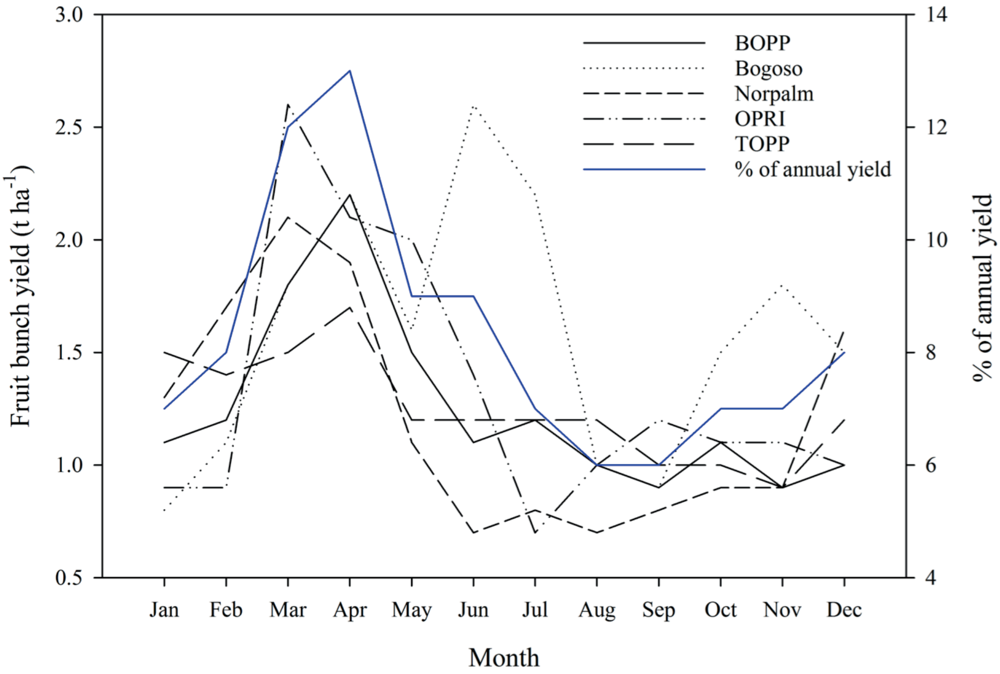

Fig. 2.4. Monthly average fruit bunch yields (t ha^{-1}) for 7-15 year old palms at five Ghanaian oil palm sites in 2014, and the average yield distribution (%) across all sites for 2014.

Temperature does not appear to limit land suitability for oil palm in Ghana, except at elevations above 350 masl where monthly minima can drop below 18°C. Cold-tolerant oil palm hybrids, such as produced by ASD de Costa Rica, are successful in higher, cooler elevations and provide a possible option to extend the area suitable for oil palm production (Chapman et al., 2003). Most higher elevations in Ghana are in mountainous areas with steep (>20°) slopes, which are unsuitable for cultivation.

Solar radiation was within the limits suitable for oil palm. After rainfall, it is considered the second most important climatic factor for oil palm. Whilst solar radiation is of course essential for photosynthesis, the oil palm's requirements, in terms of sunshine hours or photosynthetic active radiation (PAR) are poorly defined (Corley and Tinker, 2003; Paramananthan, 2003). Physiological models can be used to assess the effect of solar radiation on crop production (e.g. Hoffmann et al., 2014). Chan (1991) showed a decrease in yield of 4.8 t FB ha^{-1} yr^{-1} with a decrease in solar radiation of 1 GJ m^{-2} yr^{-1} for Malaysia. Lamade et al. (1996) reported an even larger effect of solar radiation on yield: only 0.73 GJ m^{-2} yr^{-1} more solar radiation in North Sumatra than in the Ivory Coast resulted in 13.6 t FB ha^{-1} yr^{-1} more yield. The authors mention that this large difference is likely partly explained by differences in rainfall and management practices between the two sites. Annual solar radiation measured at three sites in Ghana, Indonesia, and Guatemala for 2014 with similar meteorological stations is shown in Fig. 2.5.

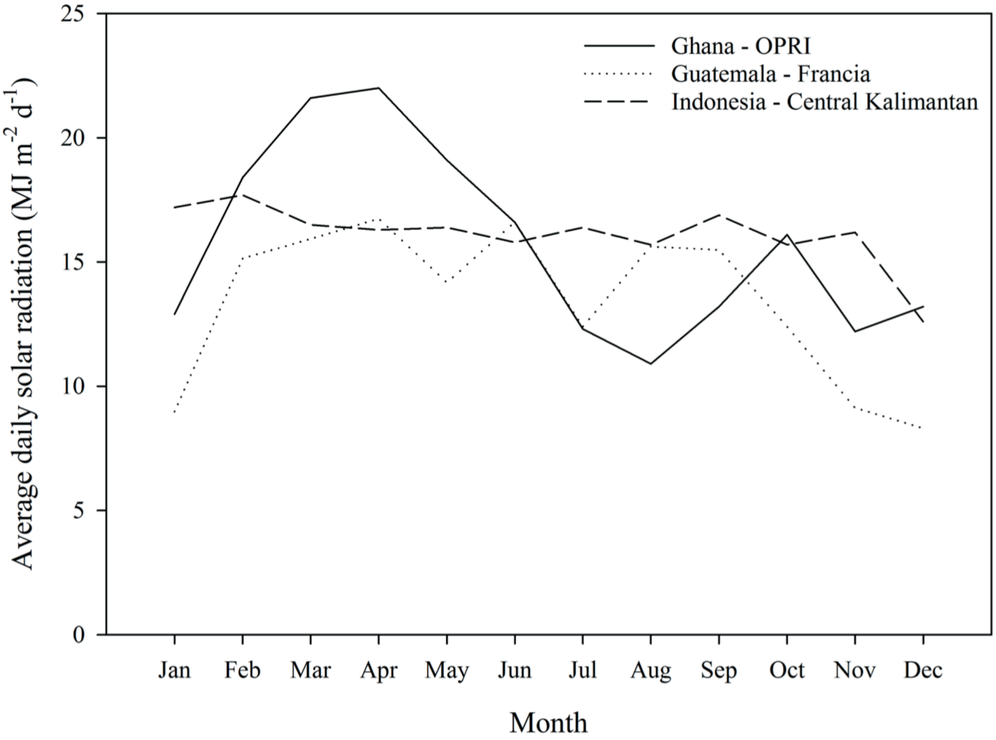

Fig. 2.5. Annual variation in monthly averages of daily solar radiation at oil palm plantations in Eastern region, Ghana, Central Kalimantan, Indonesia, and the Atlantic coast of Guatemala in 2014. Average annual solar radiation (in GJ m^{-2} yr^{-1}) is 5.7 for Ghana, 5.9 for Indonesia, and 4.9 for Guatemala.

Average annual solar radiation in Ghana is slightly lower than that received in Indonesia, with periods of high solar radiation in the dry season. Periods of high radiation coupled with a suboptimal water availability and distribution in Ghana undoubtedly lower the yield potential of oil palm compared with other oil palm growing regions (Hoffmann et al., 2014; van Ittersum et al., 2013). Further research is needed on the effect of solar radiation and its interaction with water on yield. While the amount of solar radiation sets the maximum yield potential of oil palm (Lim et al., 2011; van Ittersum et al., 2013), it is modified by other (climatic) factors such as rainfall and management. These factors need to be taken into account as well when assessing yield gaps. A useful parameter combining both water availability and sunshine hours is effective sunshine defined as the number of sunshine hours during periods of moisture sufficiency. Sparnaaij et al. (1963) found a strong positive and time-lagged correlation between total annual effective sunshine and annual bunch yield of mature palms 28–30 months later.

Slopes steeper than 10° occur throughout the oil palm belt, mostly in the southwestern rainforest, which is the optimal production zone. Oil palm is best planted on slopes <12°, but is sometimes grown on slopes ≤20°. On slopes exceeding 2°, substantial amounts of water are lost through runoff. This negatively affects the water balance and surface water flow can also cause severe erosion (Caliman, 1992). Careful management, including the establishment of legume cover crops and mulching with pruned fronds and empty fruit bunches is required to avoid erosion, and to conserve water. Other options include the installation of terraced planting and silt pits, which increase water infiltration and reduce soil erosion (Paramananthan, 2003).

Oil palm can be cultivated successfully on a wide range of soils, provided the soils are deep enough (>50 cm soil) and properly drained (Paramananthan, 2003; Paramananthan, 2011). Soil physical properties are more important than chemical properties because they are not easily changed by management and because they control the soil's ability to supply water to the crop. Where rainfall distribution is not uniform, soils with high water-holding capacity will be less affected by water deficits than those with low water holding capacity. In Benin, with rainfall less than 1,200 mm and 4–5 dry months (Hartley, 1977), oil palm production was viable because of the soils' high ASW content. In areas with only 100 mm water deficit, yields on a soil with low ASW can be half those on a soil with high ASW (Olivin, 1968). Soils that have high ASW content are therefore desirable to cope with West Africa's climates, but are limited within the oil palm belt of Ghana.

Poor fertility soils can be managed by applying mineral fertilizers and returning crop residues. We did not consider drainage criteria in the assessment, because most soils in the oil palm belt are well-drained. Landscapes in Ghana's oil palm belt are undulating to rolling terrain, with poorly-drained swamps in enclosed valleys that are difficult to drain. These pockets of poorly drained low-lying areas were not identified in the GIS assessment because the resolution of the raster grids was not fine enough to allow for an accurate analysis. The valleys have fertile soils with high ASW (Annan-Afful et al., 2005), and therefore have a high yield potential but often need costly drainage to prevent flooding and water-logging in periods of high rainfall (Rhebergen et al., 2014).

2.4.4 Opportunities to increase oil palm production in Ghana

The annual deficit in crude palm oil (CPO) will likely increase from 35,000 t to 127,000 t by 2024 (MASDAR, 2011) if current production levels are maintained. To meet the projected oil demand in Ghana, suitability mapping provides opportunities for area expansion into the most suitable lands for higher yields. In Ghana, land that is suitable for oil palm is found in the rainforest and semi-deciduous forest zones in southern Ghana, known as the 'oil-palm belt' (Gyasi, 1992; Quencez, 1996; van der Vossen, 1969). Suitable and available land is estimated at 6,720,000 ha. Although it is difficult to obtain accurate data, the total area currently under oil palm in Ghana is estimated at 330,000 ha. This is about 5% of the land area suitable and available to grow oil palm. About 40,000 ha (~12%) of this is managed in plantations, including smallholder and out-grower schemes linked to them. About 140,000 ha (~42%) is cultivated by independent medium- and small-scale farmers, and the remaining 150,000 ha (~45%) is found in wild oil palm groves (MASDAR, 2011; Ofosu-Budu and Sarpong, 2013). The minimum size for an oil palm plantation equipped with a 45-tph mill and an average annual yield of 18 t FB ha^{-1} is about 10,000 ha. The establishment of such a plantation is thus not only dependent on land suitability and availability, but also on milling technology. Whilst area expansion is possible for oil palm plantations, large continuous tracts of areas of suitable and available land are limited, particularly in the optimal growing zone. This land is possibly even more fragmented by other types of land-use that were not taken into account in the assessment. This includes for example land under cocoa and rubber production, but also annual crops, mining, high conservation value (HCV) areas (RSPO, 2013), and fallow land that is part of slash and burn agriculture. Moreover, land acquisition is further complicated by complex land tenure arrangements that prevail in southern Ghana that make it difficult for investors to acquire land for the development of large-scale plantations (Ahiable, personal communication). Such obstacles to land acquisition do not apply to the same extent, however, to the acquisition of smaller parcels of land (<100 ha) by local people. Due to the fragmented nature of available and suitable land, and increasingly complex land tenure with larger parcels of land, a feasible strategy for expansion is smallholder production. That is provided there are enough and efficient milling facilities available to process the fruit.

Alternatively, production in Ghana can be increased by improving productivity (Rhebergen et al., 2014). To identify entry points in improving yields, yield gap analysis (YGA) is a useful tool. YGA partitions yield gaps between different causes, such as environment and management, thus providing a systematic process to assess opportunities in increasing yields. Under good climatic conditions in Ghana, the maximum average attainable bunch yield is estimated at 25 t ha^{-1} (Rhebergen et al., 2014). With a country average bunch yield of 5.4 t ha^{-1}, current yield gaps are mostly the result of inadequate crop agronomic management, and poor crop recovery. Opportunities for increasing production can therefore be sought in improving current management practices. Yield intensification on land already planted to oil palm may therefore be an important policy for sustainable oil palm development in Ghana and West Africa. Adapting 'Best Management Practices (BMPs)' to local conditions can identity the management practices that are responsible for yield gaps (Donough et al., 2010). Improving agronomic management of existing palm stands shows considerable scope for yield intensification in Ghana which can alleviate pressure for further land clearance for new plantations.

2.5 Acknowledgements

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CHAPTER 3

Yield gap analysis and entry points for improving productivity on large oil palm plantations and smallholder farms in Ghana

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Abstract

Oil palm production must increase in Ghana to meet the increasing demand for palm oil and avoid costly imports. Although maximum fruit bunch (FB) yields of >20 t ha^{-1} yr^{-1} are achievable, average FB yields in Ghana are only 7 t ha^{-1} yr^{-1}. Despite the pressing need to increase palm oil production and improve yields, knowledge of the underlying causes of poor yields in Ghana is lacking. Closing yield gaps in existing plantings in smallholdings and plantations offers great opportunities to increase oil production without area expansion, thus sparing land for other uses. This study sought to understand the magnitude and underlying causes of yield gaps in plantation and smallholder oil palm production systems in Ghana based on a detailed characterization of management practices and yield measurements over a two-year period. Using a boundary line analysis, the water-limited yield (*Yw*) over a planting cycle was defined as about 21 t ha^{-1} yr^{-1} FB, with yield gaps of 15.4 t ha^{-1} yr^{-1} FB at smallholder farms and 9.8 t ha^{-1} yr^{-1} FB at plantations. Poor management practices, including incomplete crop recovery (i.e. harvesting all suitable crop) and inadequate agronomic management were the main factors contributing to these yield gaps. Productivity losses were further exacerbated by low oil extraction rates by small-scale processors of 12% as compared to 21% by the large-scale processors. The potential losses in annual crude palm oil (CPO) during the crop plateau yield phase therefore exceed 5 and 3 t ha^{-1} yr^{-1} for small-scale and large-scale production systems respectively. Investment to reduce yield gaps by appropriate agronomic and yield recovery practices across all production systems, while improving access of smallholder producers to more efficient oil palm processing facilities, can make a significant contribution to closing the supply gap for palm oil in Ghana. The impact of such investments on large-scale plantations could result in a doubling of CPO production. Smallholder farmers could benefit the most with a fourteen-fold increase in CPO production and economic gains of > 1 billion US$.

Keywords: *Yield gap analysis, crop recovery, boundary line analysis, sustainable intensification, oil extraction rates.*

3.1 Introduction

The demand for palm oil in West Africa is outstripping supply, with an annual deficit estimated of >1 million t crude palm oil (CPO) for the Economic Community of West African States (ECOWAS) in 2013 (FAO, 2017). Ghana had an annual CPO production shortfall of approximately 106,000 t in 2013. Part of the deficit was compensated by costly imports (165,000 t CPO, at a cost of US$140 million), whilst approximately 60,000 t CPO was exported (FAO, 2017). Oil palm production in Ghana must therefore increase to meet the high demand.

There are three main stakeholders in the Ghanaian oil palm industry: (i) large industrial plantations (≥1,000 ha) with large-scale processing mills (processing capacity >15 t hr^{-1} fruit bunches (FB)) (ii) smallholder farms of up to 100 ha and (iii) small-scale processors using semi-mechanized mills (processing capacities of < 1 t hr^{-1} FB) (Adjei-Nsiah et al., 2012a). In this chapter, we define smallholder farmers as growers that cultivate oil palm on privately owned or rented land. They are not contractually bound to deliver their crop to a particular mill or association (MASDAR, 2011; RSPO, 2015).

Growth defining and limiting factors (e.g. radiation, planting material, climate and nutrient supply), as well as growth reducing factors (e.g. pests and diseases) and the quality of field management all determine the yields that can be achieved at a particular site (van Ittersum et al., 2013). Despite maximum observed FB yields in individual fields of 20 t ha^{-1} yr^{-1} or more, average FB yields on large plantations are estimated to be 10–13 t ha^{-1} yr^{-1}, while smallholder farmers achieve very low average FB yields of about 3 t ha^{-1} yr^{-1} (Ofosu-Budu and Sarpong, 2013). Oil extraction rates (OER) are lower at small-scale processors that provide services to most smallholder producers; 10–14% as opposed to 19–22% achieved at large-scale mills (Adjei-Nsiah et al., 2012a). The yield of crude palm oil (CPO) may therefore be an order of magnitude greater in estates compared with smallholders given the combination of larger fruit bunch yields and higher oil extraction rates.

In response to the increasing demand for palm oil, programmes supported by the Government of Ghana during the period 2002–2013 led to rapid expansion in the area planted with superior *tenera* (i.e. *dura* x *pisifera* (DxP)) oil palm seedlings by smallholder farmers. The area planted increased by 20,000 ha between 2004 and 2010, (MASDAR, 2011) and total FB production increased by >110%, from 1,100,000 t in 2002 to 2,326,920 t in 2013. Over the same period, however, average FB yields stagnated between 5.6–7.3 t ha^{-1} yr^{-1} (FAO, 2017). In 2014, average FB yields in Ghana (7.0 t ha^{-1} yr^{-1}) were slightly less than the average FB yield for West Africa (8.2 t ha^{-1} yr^{-1}), and small compared with FB yields achieved in Southeast Asia (15.9 t ha^{-1} yr^{-1}) and Latin America (12.9 t ha^{-1} yr^{-1}) (FAO, 2017). Whilst several authors have attempted to quantify and explain yield gaps in oil palm (e.g. Corley and Tinker, 2016; Euler et al., 2016; Hoffmann et al., 2017; Woittiez et al., 2017), most have focused on production systems in Southeast Asia. Despite the pressing need to increase palm oil production, knowledge of the underlying causes of poor yields in Ghana is lacking. By closing yield gaps in existing plantings in smallholdings and plantations, palm oil production could be increased without area expansion thus sparing land for other uses.

We analysed yield gaps in oil palm production systems in Ghana due to genetic, environmental (climate and soil), and agronomic management factors. Such analysis helps to identify opportunities and entry points for yield intensification. Recently, Euler et al. (2016) and Hoffmann et al. (2014; 2017) applied the crop simulation model PALMSIM to determine oil palm yield gaps in Southeast Asian production systems. However, without further development, the PALMSIM model is not applicable to regions such as Ghana where rainfall deficit regularly limits crop growth and yield. The size of yield gaps can be estimated by measuring the time-lagged effect of implementing best management practices (BMPs) that effectively eliminate constraints due to poor agronomic management (Fairhurst and Griffiths, 2014). In this context, we define BMPs as agronomic methods and techniques found to be the most cost-effective and practical means to reduce the gap between actual and maximum economic yield and minimize the impact of the production system on the environment by using external inputs and production resources efficiently (Donough et al., 2009).

The BMP approach also provides the means to estimate maximum economic yield (*Ymey*) in a particular field and to quantify yield gaps caused by crop losses (Yield Gap 4) and agronomic management (Yield Gap 3) (Fig. 3.2; Fairhurst and Griffiths, 2014). Yield gap analysis can therefore be used to indicate the aspects of plantation management with the greatest potential for yield improvement. The specific objectives of this study were to: (i) describe the various oil palm production systems in Ghana and their current levels of productivity, (ii) estimate yield gaps on oil palm plantations and smallholder farms, and (iii) assess the underlying causes of yield gaps and identify remedial measures.

3.2 Methods

3.2.1 Study area

Farm surveys and trials were carried out at sites selected to represent a range of environments and production systems in the oil palm belt of southern Ghana. We selected three large oil palm plantations located in the Western and Central regions (Benso Oil Palm Plantation (BOPP) (5°06’47.74”N; 1°54’55.15”W), Norpalm Ghana Ltd. (4°55’29.04”N; 1°53’31.75”W), and Twifo Oil Palm Plantation (TOPP)

(5°32’03.30”N; 1°31’40.67”W)), and 20 smallholder farms distributed across the Western (10), Central (3), Eastern (5), and Ashanti (2) Regions (Fig. 3.1).

Rainfall distribution is bimodal in southern Ghana. Mean annual precipitation is greatest at sites in the southwest (with annual average rainfall of 2,400 mm), and rainfall decreases gradually towards the north. Mean annual relative humidity (RH) is high (~80%), and mean monthly temperatures seldom drop below 25°C, with a small diurnal range of 5–9°C. The topography is predominately undulating (2–9°), with rolling to hilly terrain with slopes >20° at sites in the southwest. The main soil types in the region are coarse-textured, strongly weathered and highly leached Acrisols and Ferralsols (USDA: Ultisols and Oxisols respectively) with low pH and poor soil fertility status (Buringh, 1979; Swaine, 1996). Four climatic zones (CZs) with varying suitability for oil palm have been distinguished in Ghana based upon climate and soil data (Chapter 2; van der Vossen, 1969). CZs were defined according to the mean annual water deficit (mm yr^{-1}), which integrates relevant climate (i.e. rainfall quantity and distribution) and soil properties (i.e. water holding capacity) in a single parameter that delineates oil palm areas with similar water-limited yield potential (Olivin, 1968; van der Vossen, 1969). Areas with a mean annual water deficit <150 mm were designated as optimal CZs, whereas areas with a mean annual water deficit <250 mm were favourable, <400 mm suitable, and >400 mm unsuitable (van der Vossen, 1969). One plantation and 7 smallholder sites were located in the optimal CZ, and two plantations and 13 smallholder sites in the favourable CZ (Fig. 3.1).

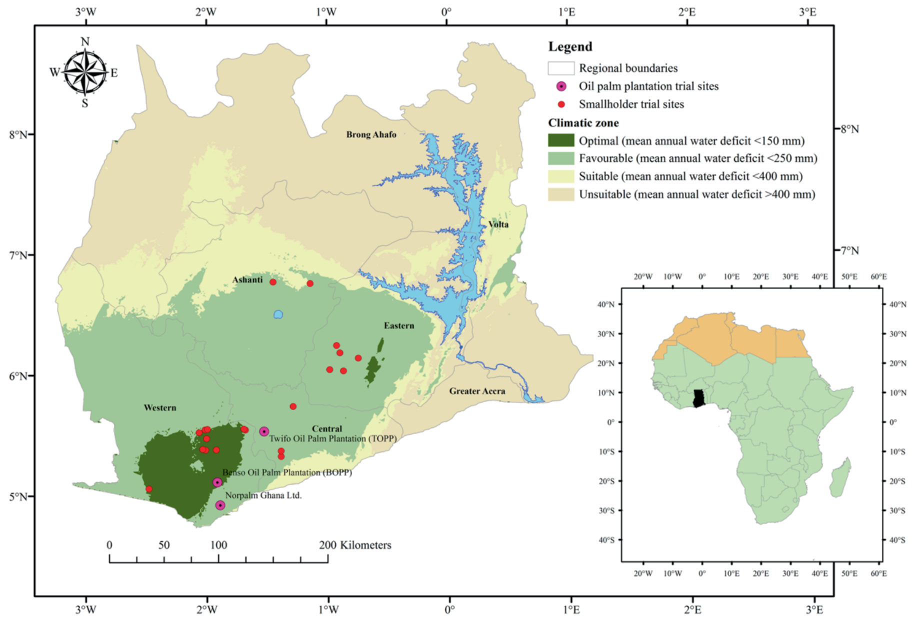

Fig. 3.1. Map showing location of oil palm plantation and smallholder trial sites and suitability zones for oil palm cultivation in the southern regions of Ghana.

3.2.2 Agronomic trials

Each commercial oil palm plantation consisted of several administrative areas called ‘divisions’ (~1,000 to 2,500 ha), which were subdivided into ‘blocks’ (~10 to 50 ha), the smallest management unit. Three to five pairs of blocks planted with *tenera* palms between 1996 and 2010 and ranging in size from 8.9–41.2 ha were selected in each of the three plantations.

The following criteria was used to select the 20 smallholder farm sites: (i) *tenera* palms ≤17 years after planting (ii) farm accessible by road, (iii) farm size ≥3 ha, (iv) triangular palm layout with palm planting distance 8.5 or 9 m, (v) willingness to maintain farm records, and (vi) willingness to implement BMPs on the BMP treatment plot. Farm size ranged from 3.4–292 ha, and fields were planted between 1999 and 2010. Two accurately measured plots (1–4 ha) were delineated in each farm and BMP and REF treatments were allocated randomly within each pair of treatment plots.

The paired treatment plots were similar in size, topography, soil type, year of planting, and planting material and representative of the plantation division or farm. The farmer or plantation field practices were maintained in one of the treatment plots (REF) to document current management practices and production levels. Best management practices were implemented in the other treatment plot (BMP) to assess the potential for yield improvement. Production constraints related to harvesting practices, cultivation and field upkeep, and nutrient management were identified during field inspections in each plantation division or farm and corrective measures were then implemented in the BMP plots in order to maximize yield. Corrective measures included; (i) installation of harvest paths and weeded circles to provide unimpeded access for harvest and palm upkeep, (ii) removal of unproductive fronds with corrective pruning to provide access for harvesting, (iii) introduction of regular and complete harvesting cycles at 7–10 day intervals to ensure complete recovery of fruit bunches and detached fruits, (iv) improved nutrient management and soil conservation by the application of mineral fertilizers, crop residues (empty fruit bunch (EFB) mulch) and box-pattern frond stacking, (v) manual (slashing, uprooting) and chemical (glyphosate, tryclopyr) removal of woody weeds in palm inter-rows and harvest paths to favour establishment of soft weeds, grasses and legume cover plants, (vi) improvement of drainage in swampy areas by installing ‘V’ profile field drains, and (vii) regular patrols to monitor and then control outbreaks of pests and diseases. At all sites, planting density at establishment was either 143 or 160 palms ha^{-1}, with the exception of one smallholder site, which was planted at 151 palms ha^{-1}. Plantation blocks were planted with planting material from the Democratic Republic of Congo (DRC) (*n*=7), Ghana Sumatra (*n*=2), the Oil Palm Research Institute (OPRI) (*n*=2), and Pobé, Benin (*n*=1), while smallholder farmers obtained planting material mostly from the nearest seedling distribution centres, such as industrial plantation nurseries (BOPP, GOPDC, Norpalm, TOPP), as well as OPRI. All trial sites consisted of mature oil palm aged 3–18 years after planting at the start of the project.

3.2.3 Data collection

Data collection at REF plots took place in 2013 and 2014 to document current management practices and yields. Besides BMP yield data used to derive the water-limited yield (*Yw*), we present only data collected at the REF plots in the results section. The full results for the BMP plots are reported in Chapter 4.

At the start of the project, a census was conducted to determine the number of productive palms per ha at each site. Production inputs (labour, fertilizer, empty fruit bunch mulch, and agro-chemicals including herbicides and insecticides) and outputs (bunch production, number of bunches, and FB yield and yield components) were recorded at each maintenance/application or harvest event. Effectiveness of field management practices such as pruning, weeding, drainage, and presence of cover crops were assessed by carrying out detailed field assessments periodically at each site. FB production was measured using a digital scale (smallholder farms) or the mill weighbridge (plantation treatment plots) and bunch production data was used to determine actual yield (*Ya*, t ha^{-1} yr^{-1} FB). To estimate *Yw*, we used FB yield data recorded over a four-year period from BMP plots.

At each site, datum points for leaf and soil sampling were marked and geo-referenced following standard procedures for data collection in oil palm (Foster, 2003). In the plantations, a staggered grid pattern of datum points was used (i.e. every tenth palm in every tenth row) to give a sample palm density of 1% of the plantation block (1–2 palms ha^{-1}). By contrast, every fifth palm in every fifth row was selected in smallholder treatment plots to provide a sampling density of 3–6% at each trial plot (5–9 palms ha^{-1}). Sampling density was greater in the smaller smallholder treatment plots in order to produce sufficient leaf sample material for each treatment plot.

Three upper and three lower rank leaflets were sampled from each side of the rachis of Frond 17 at a point 2/3rds of the distance between the insertion point of the first true leaflets and the frond tip (Chapman and Gray, 1949). Leaflets from each datum point were bulked to produce a composite sample for each treatment plot. Sampled leaflets were cut lengthwise into three equal parts. The middle part was selected as sample material and the midrib removed from each leaflet. Composite leaf samples were cut into small pieces and dried in an oven at 65°C for 48 hours. Dry samples were ground to pass a 20 mm mesh sieve and analysed for N (combustion analyser, Dumas technique), and P, K, Mg, Ca, and B by inductively coupled plasma analyser (ICP) at Yara Laboratory, UK.

Soil was sampled from beneath the weeded circle and beneath the frond stack to a depth of 40 cm at each datum point. Soil samples were bulked to form a composite sample for each zone in each treatment plot. Composite soil samples were air-dried for 3–4 days, and then ground using a pestle and mortar. Samples were passed through a 2 mm sieve to remove stones, gravel and other debris. Composite soil samples were analysed for pH (water), organic matter (Dumas), total N (Dumas), available P (Olsen), and exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, and Na^+) (1 M Ammonium nitrate) at Yara Laboratory, UK. Leaf nutrient concentrations and soil chemical properties were compared with critical levels taken from Fairhurst et al. (2004) and Goh et al. (2007) respectively.

3.2.4 Yield gap analysis

van Ittersum and Rabbinge (1997) reviewed various yield gap analysis studies (i.e. the difference between potential, water-limited, N-limited and actual yield) on annual crops such as wheat and rice. Such studies could be used to first quantify the amount of inputs required to reach a particular yield and then assess whether or not the amount of inputs used was sufficient. A second step involved the identification of reasons for suboptimal input use (e.g. lack of knowledge, risk aversion, government policy, poor economic returns). van Ittersum et al. (2013) used yield gap analysis to produce a global yield gap atlas (http://www.yieldgap.org) that shows the difference between actual and potential yield and between actual and water-limited yield for the major cereals and sugarcane in sub-Saharan Africa.

A different approach to yield gap analysis is required with perennial crops like oil palm. First, potential yield changes as the leaf canopy develops over the period from the onset of harvest 2–3 years after planting (YAP) to replanting at 25–30 YAP. Four phases of growth and production, each with different requirements in terms of agronomic management, can be distinguished during the lifespan of field planted oil palms (Ng, 1983). Following the immature growth phase (IGP), yield increases rapidly during the steep ascent yield phase (SAYP) from years 3–7 after planting, before reaching the plateau yield phase (PYP). The PYP extends from 8–15 YAP before yield starts to decline in the declining yield phase (DYP), which is largely a result of stand loss and incomplete crop recovery with older and taller palms (Goh et al., 1994). The DYP continues until the palm stand is replanted at 25–30 YAP, by which time palms are too tall for economic harvesting and/or replanted palms will likely provide better economic returns (Fairhurst and Griffiths, 2014). Second, there is a time lag between the occurrence of abiotic and biotic stress events and their impact on yield. This is because, in the case of oil palm, flowers are produced continuously and there is a time interval of about 40 months between floral initiation and bunch harvest (Breure, 2003). Third, whilst moisture stress is a frequent limitation to productivity, irrigation is seldom practised because of the scarcity of useable water during dry periods and the capital cost of large scale irrigation systems. Fourth, there may be a significant yield gap due to poor crop establishment that persists over the lifespan of the planting which cannot be fully corrected by remedial agronomic interventions. Fifth, crop losses due to incomplete crop recovery are common in oil palm because maintaining continuous complete crop recovery is problematic in most locations, particularly due to insufficient labour in the peak crop period. For these reasons, it is important to apportion yield gaps between agronomic factors at crop establishment and during the period from harvest to replanting and logistical problems relating to crop recovery.

We used a modified yield gap model developed by Fairhurst et al. (2006) and Fairhurst and Griffiths (2014) that partitions the gap between potential yield (*Yp*), the yield with no water or nutrient limitations, and actual yield (*Ya*) into four gaps (Fig. 3.2).

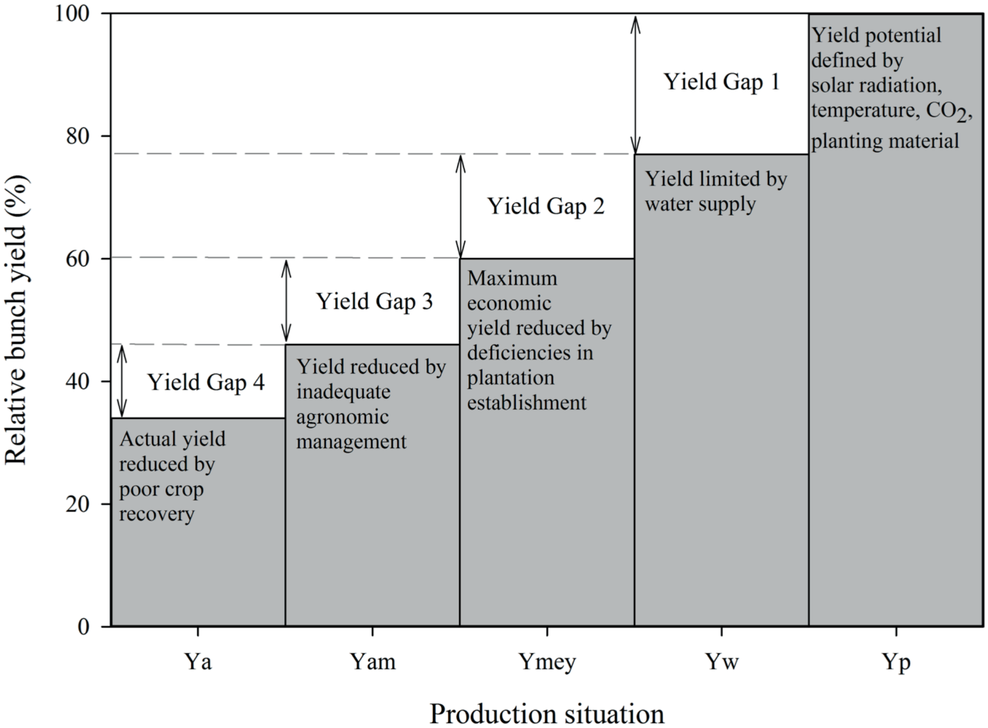

Fig. 3.2. Modified yield gap model for perennial crops used to partition potential yield (*Yp*) and actual yield (*Ya*) into four gaps with the size of each gap depending on site specific factors.

In this model, Yield Gap 1 is the difference between *Yp* and the yield of a well-managed crop under rainfed conditions (*Yw*). Yield Gap 2 is the difference between *Yw* and the maximum economic yield (*Ymey*), which is caused by a suboptimal palm stand, irrespective of good management, proper nutrient and pest management and complete crop recovery. Yield Gap 3 is the difference between *Ymey* and the yield limited by past field, nutrient and pest management (*Yam*). Yield Gap 4 is the difference between *Yam* and the actual yield (*Ya*) and is explained by incomplete crop recovery. Yield gap analysis was conducted in three steps:

(i) First, the water-limited yield (*Yw*) for the study area in Ghana was estimated by fitting a boundary line through the yield data for BMP treatment plots (Schnug et al., 1996; Wairegi et al., 2010; Wang et al., 2015). After sorting the independent variable, i.e. year after planting (YAP) in ascending order, we removed outliers identified by using statistical methods (e.g. box-plots in SPSS Statistics 24) and empirical knowledge on oil palm production (e.g. FB yields exceeding 30 t ha^{-1} yr^{-1} were removed based on empirical results of oil palm production in the region). Boundary lines were then fitted through the selected boundary points, using the model of Fermont et al. (2009):

$$y_1 = \frac{y_w}{1+(K\,exp(-Rx))} \quad \text{Eq. 3.1}$$

where, y_w is the maximum observed water-limited yield, x is the YAP and K and R are constants. The best boundary line (y_1) was obtained by minimizing the root mean squared error (RMSE) between the fitted boundary line and the boundary points.

(ii) Second, the actual plantation and smallholder yields (*Ya*) for two climatic zones were plotted together with the estimated *Yw*, and calculated the yield gaps for each site accordingly. In doing so, it is important to account for yield dynamics with palm age and production phase (SAYP, PYP, DYP). Hence, yield gaps were first calculated as the difference between *Yw* estimated with the boundary line and *Ya* according to planting year and site. The average yield gap across the entire productive lifespan for each production system and climate zone was then determined by taking the mean across all years after planting. Actual yields (*Ya*) for each site were taken as the average for 2013 and 2014, to account for as much variability as possible in climate and management practices.

(iii) Third, the production systems were characterized in terms of production inputs and outputs in order to identify the underlying causes of Yield Gaps 2, 3, and 4.

3.2.5 Data analysis

A nested ANOVA was used to test for significant differences in production inputs and outputs, as well as management practices and soil/leaf data between the different production systems. Statistical analysis of data was performed using IBM SPSS Statistics Version 24.

3.3 Results

3.3.1 Oil palm producers in Ghana

In 1992, there was a total of about 327,600 ha under oil palm cultivation in Ghana, which is about 5% of the total land area within the oil palm belt (6.8 million ha) (Gyasi, 1992). This value is smaller than the 349,040 ha of mature oil palm reported by FAO (2015). The difference between the estimate of Gyasi (1992) and FAO (2015) is most likely explained by different approaches to census and a 23-year gap between both studies. It is not clear which value is the most accurate. About 311,000 ha (95%) was cultivated by smallholder farmers, producing about 897,000 t or 84% of FB production. About 16,600 ha (5%) was managed under industrial plantations that account for 167,000 t of FB (16%) (Table 3.1).

3.3.2 Water-limited yield (*Yw*), actual yields and yield gaps at oil palm plantations and smallholder farms

The boundary line analysis performed on FB yield data recorded at BMP plots followed the typical yield profile of oil palm, illustrating a SAYP at 3 years after planting (YAP) to the point when yield peaks at about 10 YAP (RMSE = 0.061) (Fig. 3.3). The DYP is shown for two scenarios; one in which there is no yield decline expected after the plateau is reached, and one where management practices impair yield with increasing palm age at YAP ≥13. The DYP in the second scenario could not be represented by the boundary line model and was fitted to a select number of data points with linear regression, to accurately capture a decline in yields.

The water-limited yield (*Yw*) over the entire production cycle (3–20 YAP) averaged 21 t ha^{-1} yr^{-1} FB. The average FB yield in the steep ascending phase was 15 t ha^{-1} yr^{-1}, 26 t ha^{-1} yr^{-1} in the plateau phase and 23 t ha^{-1} yr^{-1} in the declining phase (Fig. 3.3). *Ya* was less than *Yw* at all smallholder and plantation sites (Fig. 3.3). Actual yields (*Ya*) at plantations sites averaged 10.8 t ha^{-1} yr^{-1} FB for favourable climatic zones, and 13.4 t ha^{-1} yr^{-1} FB for optimal climatic zones. At smallholder sites, average actual yields (*Ya*) were 7.7 t ha^{-1} yr^{-1} FB and 7.5 t ha^{-1} yr^{-1} FB for favourable and optimal climatic zones respectively.

Yield gaps at smallholder sites were significantly larger ($P \leq 0.05$) than at plantations for both climatic zones. In optimal climatic zones, average yield gaps across all production phases were 15.5 t ha^{-1} yr^{-1} FB for smallholders (n=7) and 9.4 t ha^{-1} yr^{-1} FB for plantations (n=8). In favourable climatic zones, average yield gaps were 15.2 t ha^{-1} yr^{-1} FB for smallholders (n=13) and 10.2 t ha^{-1} yr^{-1} FB for plantations (n=8).

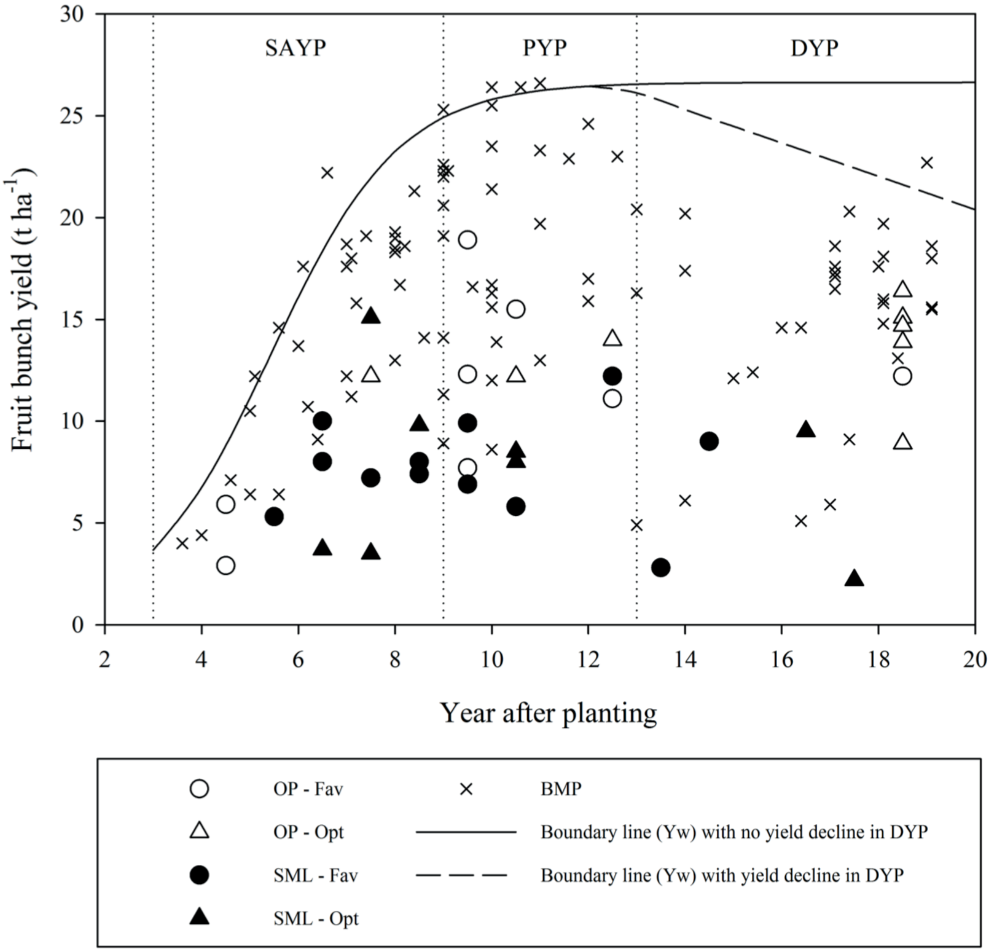

Fig. 3.3. Actual yields (*Ya*) plotted against year after planting for oil palm plantations (OP) and smallholder farms (SML) in the optimal (Opt) and favourable (Fav) climatic zones in southern Ghana. Vertical dotted lines indicate the boundaries between production phases (steep ascent yield phase (SAYP), plateau yield phase (PYP), declining yield phase (DYP)) in oil palm. The boundary line (*Yw*) is a fitted regression line through the upper points of the BMP trial yield data, and was calculated using the model of Fermont et al. (2009). The dashed line was fitted to a select number of data points with linear regression to capture the decline in yield from the 12th year.

Table 3.1. Estimated area, fruit bunch production and yield by sector in Ghana in 2015 based on field surveys carried out in 2015 and data reported by FAO (2015), MASDAR (2011) and Ofosu-Budu and Sarpong (2013).

Sector	Area under harvest		Fruit bunch production		Smallholder fruit purchases	Fruit bunch yield	Mill capacity		Oil extraction rate	CPO yield
							Installed capacity	Operating capacity		
	ha	%	t	%	t	t ha^{-1} yr^{-1}	t hr^{-1}		%	t ha^{-1} yr^{-1}
Oil palm plantations										
TOPP	3,250	1	41,300	4	37,600	12.7	30	30	19.8	2.5
BOPP	4,890	2	42,300	4	54,700	8.7	20	16	20.8	1.8
Norpalm	3,760	1	42,000	4	39,000	11.2	30	25	21.0	2.3
GOPDC	4,700	1	41,400	4	67,300	8.8	60	-	23.0	2.0
Total plantations	16,600	5	167,000	16		10.1				
Smallholders										
Plantation out-grower schemes	18,000	5	162,000	15		9.0	-	-		
Smallholder farmers	140,000	43	420,000	39		3.0	-	-		
Wild oil palm groves	150,000	46	300,000	27		2.0	-	-		
Medium scale farms (>10ha)	3,000	1	15,000	1		5.0	-	-		
Total smallholders	311,000	95	897,000	84		2.9				
Total	327,600	100	1,064,000	100		3.2				
FAOSTAT (2014)	349,040		2,443,270			7.0				

3.3.3 Factors contributing to oil palm yield gaps

Soil chemical properties and crop nutrition

The standard nutrient management practice on plantations is to apply fertilizers over the weeded palm circle whilst spent male flowers, pruned fronds and empty fruit bunches are applied in the inter row space. As a result, soil pH was significantly lower in the weeded circle zone compared with the frond stack zone at plantation sites ($P \leq 0.05$), probably due to acidification caused by the repeated application of ammonia-based N fertilizers (Table 3.2, Table 3.4) (Goh and Härdter, 2003). By contrast, the average soil pH was higher ($P \leq 0.05$) in smallholder soils (5.2) compared with plantation soils (4.6), but differences between zones were less pronounced. At both sites, soil organic carbon (SOC) and nitrogen (N) concentrations were larger in the soil beneath the frond stack (significant at smallholder sites ($P \leq 0.05$)) (Table 3.2). This is likely due to the maintenance of a weed-free zone of about 1.5–2.0 m from the base of the palm trunk to facilitate loose fruit collection, a standard practice in oil palm plantings. Because the weeded circle is kept clean from debris, there is no replenishment in soil organic matter. Average soil available phosphorus (P) was significantly greater in plantation soils (38 mg kg^{-1}) than in smallholder soils (6 mg kg^{-1}) ($P \leq 0.05$), with a larger ($P \leq 0.05$) concentration of available P in soils beneath weeded circles (Table 3.2), due to application of P fertilizers within this zone. Similarly, the concentration of exchangeable potassium (K) was greater ($P \leq 0.05$) in plantation soils (0.296 cmol(+) kg^{-1}), and deficient in smallholder soils (0.125 cmol(+) kg^{-1}). Exchangeable K was significantly larger ($P \leq 0.05$) in the soil beneath weeded circles than in the frond stack at plantation sites (Table 3.2), again explained by past application of K fertilizers. By contrast, the average amount of exchangeable magnesium (Mg) was significantly smaller ($P \leq 0.05$) and less variable in plantation soils (0.58 cmol(+) kg^{-1}) compared with smallholder soils (0.86 cmol(+) kg^{-1}) ($P \leq 0.05$), and also significantly smaller ($P \leq 0.05$) in the soil beneath the weeded circle zone at plantation sites. This suggests that soil Mg reserves are depleted to a greater extent at plantation sites, due to greater Mg offtake in fruit bunches and insufficient replenishment of soil Mg with either crop residues or mineral fertilizer (Table 3.2, Table 3.4). In general, differences in soil chemical properties between zones were less pronounced at smallholder sites, where there was little or no past application of mineral fertilizers.

Leaf N concentration was sufficient but leaf P concentration was generally deficient at plantation and smallholder sites (Table 3.3). Leaf K concentration was adequate in the plantations but deficient in smallholder sites. Leaf Mg concentration was significantly smaller at the plantations ($P \leq 0.05$), but adequate in smallholder sites, where Mg removal in fruit bunches was smaller. Leaf B concentration (mg kg^{-1}) was deficient at both plantation and smallholder sites, but significantly larger in plantations compared to smallholders ($P \leq 0.05$) due to past application of B fertilizer at some sites.

Plantation establishment and agronomic management

The average palm stand (number of productive palms ha^{-1}) at smallholder sites was higher (141 palms ha^{-1}), but also more variable, compared with plantation sites (128 palms ha^{-1}) (Table 3.4). Very dense palm stands indicate inaccurate palm point lining and result in inter-palm competition, and reduced light interception by the palm leaf canopy, while low density palm stands often indicate failure to remove unproductive palms, or infill gaps in the palm stand during the immature phase (Fairhurst and Griffiths, 2014).

Oil palm plantation sites received on average 1.84 kg palm^{-1} nutrients. Average application rates were 0.59 kg palm^{-1} N, 0.16 kg palm^{-1} P, 0.93 kg palm^{-1} K and 0.013 kg palm^{-1} Mg. Nutrients N, P, K, and Mg were supplied in a range of fertilizer products, including compounds (e.g. 10–10–30, 15–15–15) and straight fertilizers (e.g. KCl, kieserite, rock phosphate, ammonium sulphate and urea). In addition, one plantation site received a one-off application of 14 t ha^{-1} empty fruit bunch (EFB) mulch. Fertilizers were not used by any of the smallholders.

Glyphosate was the main herbicide used for controlling weeds in paths and circles in both plantations and smallholdings. Use of this herbicide was greater in smallholdings (3.9 l ha^{-1}) compared with plantations (0.9 l ha^{-1}) ($P \leq 0.05$). Use of tryclopyr for the control of woody plants was also greater in smallholdings (0.3 l ha^{-1}) than in plantations (0.1 l ha^{-1}). Herbicide use was more effective in plantations, however, where better weed control was achieved with smaller amounts of herbicide presumably as manufacturer's recommendations were followed. Furthermore, initial farm surveys showed that herbicide use was not a common practice in smallholder farms in Ghana, and were not used on any of the smallholder trial sites prior to the start of the project. Herbicide use in smallholdings was most likely copied from BMP plots, which explains the high application doses due to the farmers' limited experience.

Table 3.2. Chemical properties of soil samples taken from the weeded circle and palm inter-row (0–40 cm) in oil palm plantations and smallholder farms in Ghana. Critical levels are taken from Goh et al. (1997). * Indicates a significant difference of the mean between oil palm plantations and smallholders at $P \leq 0.05$.

Sector & zone	$pH_{(water)}$	Org. C	N	Available P (Olsen)	Exch. Mg	Exch. K	*n*
	-	%		mg kg^{-1}	cmol(+) kg^{-1}		
Oil palm plantations							
Circle	4.5*	1.17	0.11	61*	0.44*	0.387*	52
Standard deviation (σ)	0.36	0.29	0.02	58	0.15	0.277	
Inter-row	4.9*	1.22*	0.12*	13*	0.73	0.200*	44
Standard deviation (σ)	0.48	0.33	0.03	9	0.51	0.137	
Average	*4.6**	*1.20**	*0.11**	*38**	*0.58**	*0.296**	
Smallholders							
Circle	5.3	1.21	0.12	7	0.82	0.117	52
Standard deviation (σ)	0.50	0.46	0.05	7	0.50	0.070	
Inter-row	5.2	1.43	0.13	5	0.91	0.133	52
Standard deviation (σ)	0.39	0.53	0.05	2	0.55	0.092	
Average	*5.2*	*1.32*	*0.12*	*6*	*0.86*	*0.125*	
Critical level	4.0	1.2	0.12	15	0.2	0.2	

Table 3.3. Leaf nutrient concentration (leaf 17) in oil palm plantations and smallholder farms in Ghana in 2013. * Indicates a significant difference of the mean between oil palm plantations and smallholders at $P \leq 0.05$.

Sector	N	P[a]	Ca	Mg	K	B	TLC	K	Mg	*n*
	% dry matter					mg kg^{-1}	cmol kg^{-1}	% of TLC		
Oil palm plantations										
Average	2.62*	0.15*	0.71	0.31*	0.96*	14*	85*	29*	30*	24
Standard deviation (σ)	0.12	0.01	0.07	0.07	0.16	3.6	5.6	4.6	5.1	
Smallholders										
Average	2.51	0.14	0.72	0.41	0.81	12	91	23	38	28
Standard deviation (σ)	0.17	0.01	0.06	0.05	0.21	1.9	6.7	4.8	4.5	
Optimum concentrations[b]	2.40–2.80	0.15–0.18	0.50–0.75	0.25–0.40	0.90–1.20	15–25				

[a] Average critical leaf P concentrations (calculated with Fairhurst and Mutert (1999)) for oil palm plantations and smallholders are 0.17 (σ = 0.006) and 0.16 (σ = 0.008) respectively.
[b] Taken from Fairhurst et al. (2004).

Table 3.4. Oil palm plantations and smallholder farms in Ghana described by yield gap and yield components.

Yield gap	Parameter	Units	Oil palm plantation blocks (n=16)				Smallholder farms (n=20)			
			Mean	Std. Error	Range		Mean	Std. Error	Range	
					Min.	Max.			Min.	Max.
	Plantation establishment									
2	Palm stand	productive palms ha^{-1}	128	4.7	100	148	141	7.9	59	232
	Agronomic management									
3	Fertilizer use[a]	kg $palm^{-1}$ yr^{-1} fertilizer	4.5	0.69	0.0	9.6	0.0	0.00	0.0	0.0
	Fertilizer N	kg $palm^{-1}$ yr^{-1} N	0.59	0.09	0.00	1.10	0.00	0.00	0.00	0.00
	Fertilizer P	kg $palm^{-1}$ yr^{-1} P	0.16	0.04	0.00	0.59	0.00	0.00	0.00	0.00
	Fertilizer K	kg $palm^{-1}$ yr^{-1} K	0.93	0.14	0.00	1.70	0.00	0.00	0.00	0.00
	Fertilizer Mg	kg $palm^{-1}$ yr^{-1} Mg	0.013	0.009	0.00	0.11	0.00	0.00	0.00	0.00
	Total nutrients	kg $palm^{-1}$ yr^{-1} nutrients	1.84	0.28	0.00	3.55	0.00	0.00	0.00	0.00
	Chemicals use	l ha^{-1} yr^{-1} Glyphosate	0.92	0.077	0.13	1.93	3.92*	0.333	0.00	7.81
		l ha^{-1} yr^{-1} Triclopyr	0.10	0.013	0.00	0.31	0.28	0.119	0.00	4.00
	Crop recovery									
4	Harvest cycles	cycles yr^{-1}	29	1.33	19	50	21*	1.20	10	47
	Harvester output	t man-day^{-1} yr^{-1} FB	1.6	0.14	0.4	2.8	0.7*	0.07	0.1	2.3
		ha man-day^{-1} yr^{-1}	1.9	0.15	0.5	4.2	1.3*	0.10	0.4	3.4
	Harvesting labour	man-days ha^{-1} $cycle^{-1}$	0.75	0.07	0.3	1.9	1.13*	0.08	0.3	2.7
	Field upkeep labour[b]	man-days ha^{-1} yr^{-1}	2.38	0.21	0.53	6.12	2.76	0.17	1.10	5.56
	Number of pruning cycles	cycles yr^{-1}	1.3	0.09	0	3	1.2	0.07	0	2
	Yield components									
	Bunch number	bunches ha^{-1} yr^{-1}	91	5.95	45	180	77	6.30	10	180
	Average bunch weight	kg	12.1	0.81	2.4	17.3	9.1*	0.51	3.5	16.5
	Loose fruit collection	t ha^{-1} yr^{-1} loose fruit	0.9	0.15	0.0	3.4	0.5	0.06	0.0	1.3
	Fruit bunch yield	t ha^{-1} yr^{-1} FB	12.0	0.74	2.8	18.9	7.6*	0.56	1.3	16.7
	Average oil extraction rate (OER)[c]	%	21				12			
	Yield of crude palm oil	t ha^{-1} yr^{-1} CPO	2.5				0.9			

[a] Fertilizer types include: 10–10–30, 15–15–15, KCl, Kieserite, RP, SOA, and Urea. In addition, one estate block received an application of 0.7 t ha^{-1} empty fruit bunches.

[b] Field upkeep labour includes circle-, path-, and interline spraying, (manual) weeding, circle raking, frondstacking, pruning, construction & maintenance of drains and footbridges, and supervision activities.

[c] Reference values for OER taken from Adjei-Nsiah et al. (2012).

* Indicates a significant difference of the mean between oil palm plantations and smallholders at $P \leq 0.05$.

Crop recovery and yield components

On average, plantation sites were harvested more frequently (29 cycles yr^{-1}) than smallholder sites (21 cycles yr^{-1}) (Table 3.4). This corresponds to harvest intervals of approximately 13 and 17 days respectively. As a result, harvesting and field upkeep labour is more efficiently organised at plantations, resulting in a larger harvester output (t $man\text{-}day^{-1}$ yr^{-1} FB) (in terms of crop recovery) as well as more ground covered by harvesters (ha $man\text{-}day^{-1}$ yr^{-1}) (Table 3.4). At smallholder systems, more labour is spent on harvesting (man-days ha^{-1} $cycle^{-1}$) and field upkeep (man-day ha^{-1} yr^{-1}) because of poor field conditions where the lack of harvest paths and weeded circles impeded access for harvest and palm upkeep (Table 3.4).

Average FB yields with standard field practices were larger at plantation sites (12.0 t ha^{-1} yr^{-1}) than at smallholder sites (9.1 t ha^{-1} yr^{-1}) (Table 3.4). Larger FB yields at plantations can partly be explained by more frequent harvest cycles and better field access, resulting in the recovery of more bunches with a larger average bunch weight (mainly due to more complete collection of loose fruits) than at smallholder sites (Table 3.4). Compared with oil extraction rates of >24% reported for the *tenera* hybrid (Ng et al., 2003), present oil extraction rates in Ghana are very poor with 21% for large-scale processors and 12% for small-scale processors.

3.4 Discussion

3.4.1 Oil palm production systems in Ghana, their yield gaps, causes, and remedial measures

The water-limited yield (*Yw*) over the planting cycle of oil palm averaged 21 t ha^{-1} yr^{-1} FB, with yield gaps of 15.4 t ha^{-1} yr^{-1} FB and 9.8 t ha^{-1} yr^{-1} FB at smallholder and plantation sites, respectively, showing a large potential for yield improvement. Current yield gaps are mostly the result of incomplete crop recovery, inadequate agronomic management, especially nutrient management, and poor plantation establishment (Fig. 3.4).

There is considerable scope to improve production on oil palm plantations and smallholder farms in Ghana by closing Yield Gap 4 with better crop recovery (Rhebergen et al., 2014). Continuity in production requires tightly controlled harvesting cycles, as well as sufficient labour for harvesting and fruit collection and field upkeep (Fairhurst and Griffiths, 2014). Yield Gap 4 can be closed by improvements to field access (ground cover control, weeded circles, paths, pruning) and the implementation of three harvest cycles per month (i.e. harvesting intervals of <10 days), particularly during the peak crop months. Shrubs and weeds may obstruct in-field access and compete with oil palm for water and nutrients and may be eradicated by manual removal or herbicides. In addition, a large application of rock phosphate may be effective in triggering a succession of ground cover species composition from weeds adapted to poor soil fertility to grasses and legume cover plants that are more competitive when soil fertility has been improved (Giller and Fairhurst, 2003). In inland valleys, crop recovery is often obstructed by poor drainage, due to a lack of drainage outlets and field drains, or drains that are too shallow and require desilting.

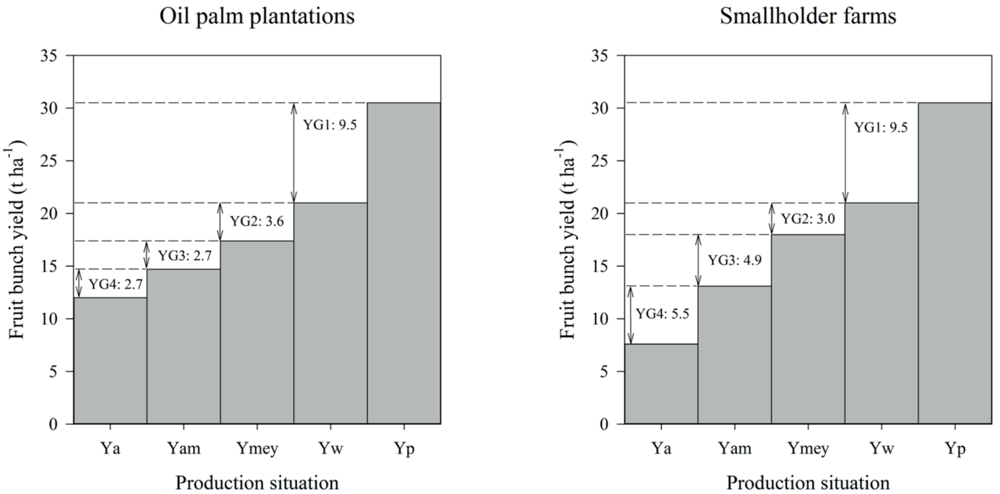

Fig. 3.4. Partitioning yield gaps at oil palm plantations and smallholder farms. Estimates for *Yp* and *Yw* were taken from Rhebergen et al. (2014) and the boundary line approach respectively. *Ymey* was estimated by adjusting *Yw* based on the relationship between the stand per hectare and the planting density (Fairhurst and Griffiths, 2014) for plantation and smallholder sites. *Yam* was estimated by measuring the yield improvement at BMP plots over the first 12 months in which most plots achieved full crop recovery and yields obtained under standard field practices were taken as estimates for *Ya*.

Soil and leaf analysis data shows that there are significant nutrient deficiencies, particularly in smallholder farms, that must be addressed to close Yield Gap 3 (Fig. 3.4). At smallholder sites, for example, a strong relationship between leaf K and P concentrations and exchangeable K and available P in the soil beneath weeded circles was found, where leaf and soil P and K concentrations are generally deficient (Fig. 3.5). Whilst plantations apply moderate amounts of mineral fertilizers and occasionally recycle small amounts of crop residues (Table 3.4), most smallholder farmers apply little if any mineral fertilizer and do not recycle crop residues, resulting in a larger Yield Gap 3 (Fig. 3.4). Smallholder farmers also lack access to empty fruit bunches sold to plantation mills because the empty bunches are usually recycled by plantation-owned mills to their own plantings, albeit in small amounts. Whilst some crop residues are available at small-scale processors, most EFB and fibre at small-scale processors are used as fuel to cook fruit bunches before they are pressed to extract oil (Osei-Amponsah et al., 2012). Furthermore, most smallholder farmers were unaware of the benefits of mulching with EFB.

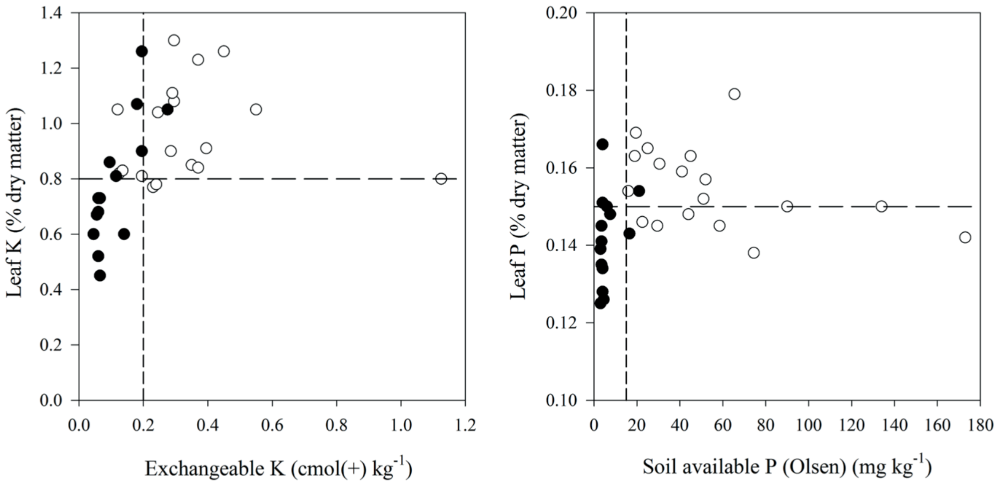

Fig. 3.5. Relationship between leaf K and P concentrations and the amount of exchangeable K and available P in soil beneath weeded palm circles in smallholder (black circles) and plantation sites (open circles. The leaf and soil critical values for K and P are represented by horizontal (long dash), respectively, vertical (short dash) lines.

At plantation sites an average total leaf cation (TLC) of 85 cmol kg^{-1} was reported (Table 3.3). At this value, data from 50 fertilizer trials in Malaysia suggest leaf critical concentrations for N, P, K and Mg of 2.72, 0.169, 1.15, and 0.22 %DM (Foster and Prabowo, 2006). Average leaf nutrient concentrations for plantations were far below these values, suggesting inadequate and unbalanced fertilizer use. However, optimum or critical values for individual nutrient concentrations vary considerably, depending on factors such as palm age, leaf number, leaflet rank, leaf age, planting material, balance with other nutrients, environment, spacing and inter-palm competition (von Uexkull and Fairhurst, 1991; Fairhurst and Mutert, 1999). Therefore, the critical nutrient concentrations applicable to the region and sites under study may vary from the values calculated here. Yield Gap 3 can be closed with a more balanced approach towards nutrient management, taking into account the right source of nutrient applied at the right rate, time and place as guided by the 4R Nutrient Stewardship (IPNI, 2012). In most oil palm fertilizer trials, yields in different treatments are significantly correlated with leaf nutrient concentrations (Foster, 2003). The use of reference leaf critical levels established through site-specific fertilizer trials is therefore a useful way to assess fertilizer requirements for optimal yield levels (Foster, 2003; Foster and Prabowo, 2006). Additionally, placing pruned fronds as a ‘box’ around the palm is a management strategy to improve soil structure, increase the rate of water infiltration and prevent erosion (Fairhurst, 1996; Gillbanks, 2003; Goh et al., 2003). Using crop residues efficiently and addressing these root-soil dynamics, a feeding zone for oil palm can be created in the inter-row and targeted for nutrient application.

Deficiencies in management during the establishment phase that cause Yield Gap 2 were evident at both plantation and smallholder sites (Fig. 3.4). Major problems identified at all sites were insufficient drainage and failure to correct poor drainage in plantings where N-deficiency symptoms were evident, poor and late infilling to replace dead seedlings, lack of removal of abnormal and unproductive palms, poor land forming (terraces) and lack of platforms, poor establishment of legume cover plants due to low soil fertility (in particular P) and poor management of (woody) weed growth. Yield Gap 2 can only be closed at each 20–25 year cycle of replanting, when there are opportunities to introduce improved germplasm and use better planting techniques. Yield Gap 2 can be reduced by careful management to ensure a complete stand of productive palms at maturity. This includes careful land selection, preparation and clearing with minimal soil damage (i.e. compaction, erosion, removal of topsoil), choosing good quality and high yielding planting material, accurate planting procedures such as correct planting density, lining and timely infilling, and proper agronomic management up to the onset of harvest (Fairhurst and Griffiths, 2014). Establishment of (legume) cover plants and placement of pruned fronds and mulch along the contour can help to increase water infiltration and reduce soil erosion (Paramananthan, 2003; Rankine and Fairhurst, 1999). An annual palm census can be used to identify the number of unproductive palms that require replacement to maintain an optimal stand of productive palms, and to reduce Yield Gap 2.

Based on data reported by Rhebergen et al. (2014), the average potential yield (*Yp*) over a planting cycle in Ghana is estimated at 31 t ha^{-1} yr^{-1} FB. *Yw* is smaller than *Yp* when water supply is limited. Yield Gap 1 therefore arises due to the difference between *Yp* and *Yw* and is estimated at 10 t ha^{-1} yr^{-1} FB (Fig. 3.4). This is equivalent to the response to irrigation under similar climatic conditions in Thailand (Tittinutchanon et al., 2008). Yield Gap 1 can be closed over a 35–40 month period by using irrigation to eliminate water stress.

3.4.2 Constraints to increasing palm oil production in Ghana

Besides the requirements to improve FB production, fruit processing offers challenges of its own. For example, at current levels of production and oil extraction rate, the loss of oil in both the large and small-scale sectors are substantial. Maximum crude palm oil (CPO) losses are 5.2 and 3.3 t ha^{-1} yr^{-1} in the plateau yield phase, and the total amount of CPO lost over the entire planting cycle of oil palm is ~75 t ha^{-1} and ~50 t ha^{-1} in small-scale and large-scale production systems respectively (Fig. 3.6). Therefore, to improve oil yields, both FB yields and milling efficiency must be improved.

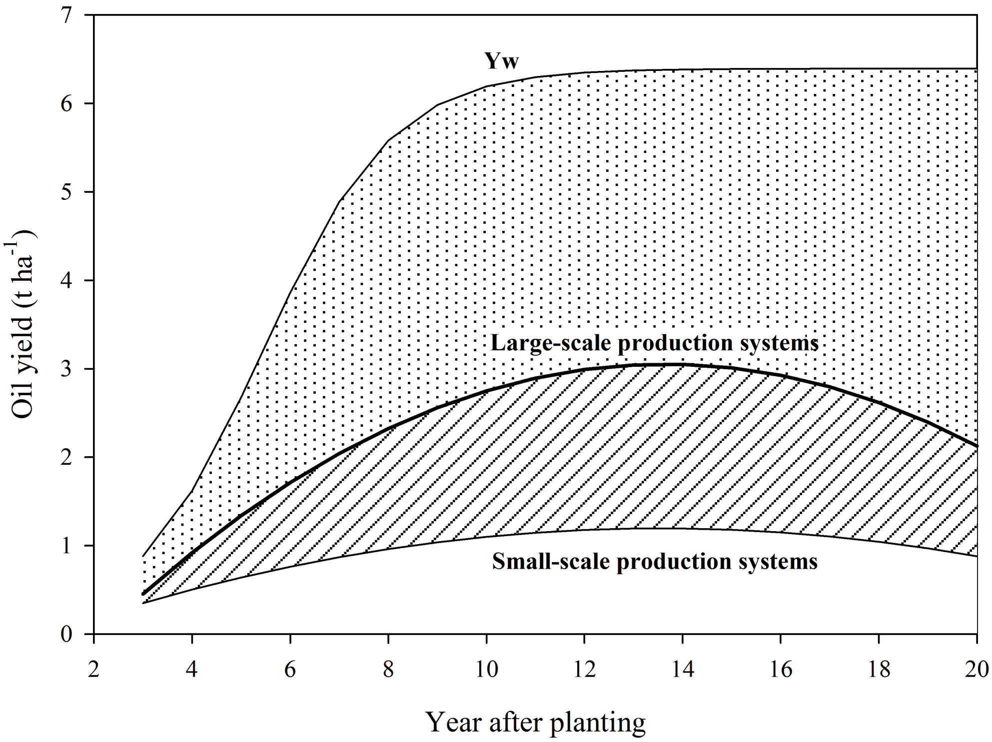

Fig. 3.6. Estimated CPO yield (t ha^{-1}) at large-scale and small-scale production systems. *Yw* was calculated as the product of the boundary line from Fig. 3.2 and an oil extraction rate (OER) of 24%, whilst the curves for large-scale and small-scale production systems were estimated with a regression through the average yields (*Ya*) at oil palm plantations and smallholder farms, multiplied by current oil extraction rates achieved at large-scale (21% OER) and small-scale processors (12% OER). The dotted area shows the total oil loss (CPO) over the production cycle of oil palm at large scale production systems (51 t ha^{-1}) and the dotted + dashed area at small scale production systems (75 t ha^{-1}).

Improving production and oil extraction rates in Ghana's oil palm sector could make a significant contribution to closing the supply gap for palm oil in Ghana, and could lead to greatly increased profitability for investors and farmers alike (Table 3.5). Investments to reduce yield and oil supply gaps will benefit smallholder farmers more, with a fourteenfold increase in CPO production and economic value (worth > 1 billion US$), while a twofold increase in CPO production is projected at plantations (Table 3.5).

Despite the potential for increasing oil palm yields, smallholder farmers face major challenges that include lack of knowledge on appropriate management practices, poor infrastructure and lack access to finance (IPPA, 2010). Currently, working capital is commonly sourced through loans through informal community arrangements (MASDAR, 2011). Inability to purchase agricultural inputs such as fertilizers and/or herbicides/pesticides, results in poor yields and reliance on arduous manual labour.

Table 3.5. Impact of closing current yield gaps and improving oil extraction rates in Ghana on CPO production and economic value based on production data from 2015.

Parameter	Units	Oil palm plantations				Smallholders			
		Before	After	Change	Multiplier	Before	After	Change	Multiplier
Area	ha	16,600	16,600	-	1	311,000	311,000	-	1
Bunch yield	$t\ ha^{-1}\ yr^{-1}$ FB	10.1	20.0	10	2	2.9	20.0	17.1	7
Bunch production	t FB	167,000	332,000	165,000	2	897,000	6,220,000	5,323,000	7
Oil extraction rate	%	21	24	3	1	12	24	12	2
Crude palm oil	t	35,070	79,680	44,610	2	107,640	1,492,800	1,385,160	14
CPO yield	$t\ ha^{-1}\ yr^{-1}$ CPO	2.1	4.8	2.7	2	0.3	4.8	4.5	14
Crude palm oil	US$ $t^{-1}\ yr^{-1}$	750	750	-	1	750	750	-	1
Crude palm oil	US$	26,302,500	59,760,000	33,457,500	2	80,730,000	1,119,600,000	1,038,870,000	14

Because of the 35–40 month time lag between management interventions and yield improvement in oil palm, most farmers also do not invest in agricultural inputs due to the delayed impact on yield and revenue.

Furthermore, distribution and marketing of agricultural inputs such as fertilizer is generally poor in Ghana (Krausova and Banful, 2010). Fertilizer dealers experience high transport costs, lack of customer demand, unreliable suppliers and lack of technical knowledge. In addition, compared with oil palm producing countries in Southeast Asia such as Malaysia and Indonesia, smallholder farmers in Ghana are not part of schemes and are not well integrated into the industry. They do not receive the benefits of plantation-outgrower schemes such as the provision of high-yielding seedlings, agronomic inputs, credit, and advisory services (Fold and Whitefield, 2012).

Most of the smallholder farmers sell their crop to small-scale processors who, combined contribute >80% of the total national CPO production (Table 3.1) (Adjei-Nsiah et al., 2012a; MASDAR, 2011; Osei-Amponsah et al., 2012). However, at current oil extraction rates of 12% and at an average milling capacity of 7 t day^{-1} mill^{-1} FB, small-scale processors combined (*n*=400 (Angelucci, 2013)) can only process 560,000 t yr^{-1} FB, equivalent to 67,200 t CPO (Table 3.6).

Table 3.6. Annual CPO production at large and small-scale mills in Ghana.

Parameter	Units	Large-scale mills	Small-scale processors
Milling capacity	tph	20	<1
Milling hours	hr month^{-1}	550	225
Monthly capacity	t month^{-1}	11,000	210
Peak crop	%	15	15
Annual crop	t FB	73,333	1,400
Number of mills	#	20	400
Total annual crop	t FB	1,466,667	560,000
Oil extraction rate (OER)	%	21	12
Crude palm oil (CPO)	t	308,000	67,200

Small-scale processors are often poorly organised, use inferior processing technology, and lack price incentives. The CPO obtained at small-scale processors is usually of poor quality (in terms of free fatty acid, moisture, and impurity content), and does not meet the standards required to enter local industrial and/or international markets. Most of the CPO ends up being sold at villages or small town markets for local consumption (Adjei-Nsiah et al., 2012a; Gilbert, 2013).

On the other hand, large-scale mills in Ghana combined (*n*=20) have the processing capacity to offset the annual national CPO deficit (106,000 t). Assuming an average milling capacity of 20 t hr^{-1} and a peak crop production of 15%, ~1,5 million t FB can be processed, which is the equivalent of 308,000 t CPO (at 21% OER) (Table 3.6).

Large-scale mills thus have the capacity to process the current total national FB production (including smallholder production), but additional investments in mills would be required were significant yield improvement achieved across all sectors.

3.5 Conclusions

Yield gaps in oil palm production are large and ubiquitous in Ghana. Improving yields through corrective management practices offers considerable opportunities for the oil palm sector. Water-limited yield (*Yw*) over the planting cycle of oil palm were estimated at 21 t ha^{-1} yr^{-1} FB and large average yield gaps estimated at 15.4 t ha^{-1} yr^{-1} FB for smallholder farms and 9.8 t ha^{-1} yr^{-1} FB for plantations. A simple model to partition yield gaps and understand their causes supported the identification of where and why yield gaps occur and how they can be closed with better management practices. Yield gaps associated with poor establishment and poor management practices require different interventions with different potential impact and contrasting time scale for implementation and impact. Opportunities to close yield gaps caused by poor crop recovery (Yield Gap 4) and inadequate agronomic management (Yield Gap 3) are particularly large at smallholder farms. Most smallholder oil palm plantings were severely neglected and poorly accessible, and consequently, incomplete crop recovery was the main cause of low yields. Investments in oil palm management practices to increase productivity and improve yield recovery on plantations and smallholder farms, and improving access to efficient processing mills by smallholder farms offer opportunities to substantially increase the production of crude palm oil without increasing the area planted.

3.6 Acknowledgements

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CHAPTER 4

Closing yield gaps in oil palm production systems in Ghana through Best Management Practices

This chapter is submitted as:

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Abstract

Since the early 2000s, the area under oil palm in Ghana expanded but average fruit bunch (FB) yields remained low, resulting in large yield gaps on plantations and smallholder farms. This study assessed the potential for reducing yield gaps through 'Best Management Practices (BMP)' on plantations and smallholder farms in southern Ghana, compared with current management practices. We evaluated BMPs that increased yields in the short-term (≤ 1 year) with 'yield taking' (improved crop recovery), and in the long-term (>1 year) with 'yield making' (better agronomy) practices and identified the management factors that contributed most to yield improvements. Average yields and yield gains with BMP were larger at plantations and smallholders, compared with the REF treatment. Average FB yield increases with BMP were 2.1 t ha^{-1} (+19%) and 4.7 t ha^{-1} (+89%) with yield taking and 4.7 t ha^{-1} (+36%) and 7.6 t ha^{-1} (+76%) with yield making at plantations and smallholders respectively. Important crop recovery activities included more frequent harvesting events and improved field access (roads, paths, weeded circles) to increase harvester efficiency and productivity. Analysis of fertilizer usage and leaf nutrient concentrations suggest a more balanced approach to nutrient management could contribute considerably to yield making, particularly at smallholder farms. The need to develop new improved fertilizer recommendations is therefore essential to increase yields and to sustainably intensify oil palm production in Ghana. Increasing average attainable yields to 21.0 t ha^{-1} FB can increase national FB production almost three-fold from 2.5 Mt to 6.9 Mt (1.4 Mt CPO at 21% oil extraction rate) and reduce oil palm expansion with 597,636 ha of land.

Keywords: *Yield intensification, crop recovery, fertilizer, smallholder, yield gap, land sparing*.

4.1 Introduction

Oil palm (*Elaeis guineensis* Jacq.) is one of the world's most rapidly expanding equatorial crops, driven by increasing global demand for vegetable oil and biofuel (Corley, 2009; Fitzherbert et al., 2008; Wich et al., 2014). Between 1975 and 2014, the global land area under mature oil palm increased fourfold from 3.5 Mha to 18.7 Mha, with most expansion in Southeast Asia, notably Indonesia (with a total area currently under harvest of 7.4 Mha) and Malaysia (total area of 4.7 Mha) (FAO, 2017). The growth in oil palm production has contributed to improved economic growth and rural poverty alleviation (Corley, 2009; Edwards, 2015; Sayer et al., 2012), though much of the area expansion has been at the expense of logged-over tropical rainforest (Danielsen et al., 2009; Fitzherbert et al., 2008; Koh and Wilcove, 2008). Limited land availability in Southeast Asia has led to a search for suitable land elsewhere, with most future expansion expected in Latin America and sub-Saharan Africa (SSA) (Laurance et al., 2014; Sayer et al., 2012). In SSA, Nigeria, Cameroon and Ghana produce the most palm oil (7.9 Mt yr^{-1}, 2.7 Mt yr^{-1}, and 2.4 Mt yr^{-1} in 2014 respectively), while the largest expansion in area over the past decade (2004–2014) took place in the Democratic Republic of Congo (+118,000 ha), Cameroon (+81,000 ha), Ivory Coast (+74,000 ha) and Ghana (+31,500 ha) (FAO, 2017).

Since expansion of oil palm cultivation is often linked to deforestation, it is suggested that increasing yields on land already planted with oil palm or expanding production only on degraded or abandoned lands can spare land for nature (Fairhurst and McLaughlin, 2009; Wicke et al., 2011). Yield intensification focuses on reducing the yield gap (Yg) between the potential (*Yp* for environments with adequate water supply or *Yw* under rainfed conditions where water is limited) and actual yield (*Ya*) with improved agronomic practices or better management (Fairhurst and Griffiths, 2014; Fischer et al., 2014; van Ittersum et al., 2013). In oil palm, for example, 'Best Management Practices' increased fruit bunch (FB) yields by 6.0 t ha^{-1} in South Sumatra, Indonesia (Griffiths and Fairhurst, 2003), and by 3.4 t ha^{-1} (+15%) across six commercial plantations in Indonesia (Donough et al., 2010).

Oil palm is an important economic crop that provides a major source of employment in Ghana (Gilbert, 2013). In the early 2000s, oil palm was selected by the Ghanaian government as a strategic crop to promote agricultural and industrial growth for poverty reduction and rural development (Asante, 2012; Osei-Amponsah et al., 2012). As part of the program, oil palm seedlings were distributed amongst farmers but field plantings were poorly managed. Additionally, new investments were made in the oil palm industry, attracting interest of foreign investors to develop large-scale plantations. During this period, the area under oil palm expanded but the average yield remained low. The small fruit bunch yields observed in Ghana are associated with multiple constraints that include sub-optimal climate, poor soil fertility and poor management practices, particularly related to crop recovery (Chapter 2, Chapter 3; Rhebergen et al., 2014). With an estimated *Yw* over a planting cycle of 21.0 t ha^{-1} FB (averaged across favourable (areas with a mean annual water deficit <250 mm) and optimal (areas with a mean annual water deficit <150 mm) production sites in Ghana (Chapter 2)), and a *Ya* of ~11.0 t ha^{-1} FB on large commercial plantations and ~6.0 t ha^{-1} FB on smallholder farms, it is clear that large yield gaps (Yg) exist in Ghana (Chapter 3).

Best Management Practices (BMP) are cost-effective and practical agronomic techniques that focus on reducing yield gaps in oil palm by using production inputs and resources efficiently (Donough et al., 2009; Griffiths and Fairhurst, 2003). BMPs aim to increase oil palm productivity through improvements in agronomic management, as well as increased crop recovery. Implementation of BMPs is site-specific, since they are tailored to address the particular production constraints and biophysical conditions of individual locations (Pauli et al., 2014). BMPs are grouped in two broad categories; ‘yield taking’ and ‘yield making’ practices. Yield taking increases yield in the short term by improving crop recovery operations (e.g. field access, harvest intervals, oil content), while yield making includes agronomic practices that contribute to building large and sustainable yields in the longer term (e.g. nutrient and leaf canopy management, higher oil extraction rates (OER)) (Fairhurst and Griffiths, 2014).

In this chapter, we quantify and evaluate the effect of BMPs compared with current plantation and farm management practices on agronomic and yield performance of oil palm with a focus on yield taking, and yield making practices over a 3–year period (2013–2015). Our objectives were to assess: (i) the impact of crop recovery and agronomic practices on yield components of oil palm and to (ii) identify the management factors that contribute most to yield improvements.

4.2 Methodology

4.2.1 Study area

The study was conducted in the oil palm belt of southern Ghana, approximately between latitudes 6°46’N and 4°55’N and longitude 0°47’W and 2°28’W. Within the study area, rainfall distribution is bimodal. Mean annual precipitation is highest in the southwest (~2,400 mm yr^{-1}), and gradually decreases when moving north. Mean annual relative humidity (RH) is high (~80%), and mean monthly temperatures seldom drop below 25°C, with a small diurnal range of 5–9°C. The topography is predominately undulating to rolling (2–9°), with rolling to hilly terrain (with slopes >20°) in the southwest. Soils are predominately strongly weathered and highly leached Acrisols and Ferralsols (USDA: Ultisols and Oxisols respectively) with low pH and poor soil fertility status.

4.2.2 Plot selection

We selected three major plantations located in the Western and Central regions, including Benso Oil Palm Plantation (BOPP) (5°06’47.74”N; 1°54’55.15”W), Norpalm Ghana Ltd. (4°55’29.04”N; 1°53’31.75”W), and Twifo Oil Palm Plantations (TOPP) (5°32’03.30”N; 1°31’40.67”W), and twenty smallholder farmers distributed across the Western (10), Central (3), Eastern (5), and Ashanti (2) regions (see location of trial sites in Chapter 3, Fig. 3.1). At each plantation, three to five paired management blocks were selected. The paired blocks (n=12) were representative of a plantation and comparable in size, topography, soil type, year of planting, and planting material (Appendix 6). Treatments were allocated randomly within each paired plot, with BMPs implemented in one block and current standard practices maintained as reference (REF) in the second block (Appendix 5). At smallholder farms, we accurately measured randomly selected paired plots of 1–4 ha. Smallholder sites were selected based on the following criteria: (i) *tenera* palms ≤17 years after planting (ii) farm accessible by road, (iii) farm size ≥3 ha, (iv) triangular palm layout with palm planting distance 8.5 or 9 m, (v) willingness to maintain farm records and to (vi) implement BMPs.

4.2.3 Best Management Practices (BMP)

BMPs were implemented in a stepwise and time-lagged process. First, we identified agronomic constraints for each site and BMP plot by conducting field agronomic audits, and then implemented site-specific BMPs accordingly. In the first year, we focused entirely on rehabilitating fields to achieve full field access and crop recovery and to close Yield Gap 4 (Fig. 3.2). Once this was accomplished, additional yield making activities such as nutrient management to achieve the yield potential (Yw) were implemented at each site and to close or minimize Yield Gaps 2 and 3 (Chapter 3). The sequence of implementing BMPs is crucial to maximizing economic returns, since closing Yield Gap 4 generates increased cash returns that can be used to implement practices that contribute to closing Yield Gaps 3 and 4.

Field auditing and palm census

Field agronomic audits were performed to (i) identify and quantify field practices that require improvement, (ii) evaluate efficiency of production input and resource use, and to (iii) verify whether BMP standards were achieved. Audits were carried out in collaboration with plantation staff and smallholder farmers to facilitate knowledge transfer and a full understanding of the BMP concepts.

We evaluated fields for (i) harvesting practices, (ii) loose fruit and fruit bunch collection, (iii) pruning and pruned frond management, (iv) ground cover vegetation, including legume cover plants (LCP), (v) soil conservation, (vi) path and circle weeding and maintenance, (vii) drainage, (viii) erosion, (ix) road maintenance, (x) pests and diseases, and (xi) fertilizer and crop residue application. Harvesting and (loose) fruit collection was scored either 1 or 3, while all other parameters 1, 2, or 3. Fertilizer and crop residue application was scored based on compliance with best nutrient management practices as guided by the 4R Nutrient Stewardship (IPNI, 2012). Parameters that were given a score of '1' required immediate remedial action; a score of '2' was considered below standard but no immediate attention required, while parameters that were scored as '3' were considered to be BMP standard. Harvesting practices were only scored as either '1' or '3', because a score of less than 3 implies crop loss and therefore requires urgent attention. Field audit evaluation criteria are given in Appendix 7 (adapted from Rankine and Fairhurst (1998)).

Field audit results were summarized by first calculating the total score for each parameter across all BMP plots at each site, relative to the total possible score for each parameter. We then took the average of the scores for each category (harvesting, cultivation and upkeep, pest and disease control, nutrient management), expressed as percentage. Field audits were done more frequently in the first year to familiarize plantation and field staff with BMP procedures and standards and in recognizing field constraints. The frequency was subsequently reduced towards the end of the three-year period. Reference plots, on the other hand, were not controlled, and no attempt was made to prevent the implementation of BMPs in REF plots.

A palm census was carried out each year to determine the palm stand per hectare (SPH) at each site (i.e. the number of productive palms per hectare). Palm points were plotted on an isometric map indicating the number of mature, immature, new/supply, abnormal, and dead/removed palms, or unplantable points. On the BMP plots where the SPH was poor (<80%), corrective action was taken to optimize the SPH by infilling clusters of vacant planting points. Based on the field audit and palm census results, a portfolio of site-specific BMPs was developed for each field, prioritizing certain remedial actions above others. Implementation of BMPs commenced on different dates at each site, but all were regularly monitored for 35–40 months to maintain high standards in field management and maintenance.

Yield taking and yield making BMPs

In oil palm, there is a time lag of 35–40 months between the removal of agronomic constraints and their impact on yield, which is related to the time interval between floral initiation and bunch ripening (Breure, 2003; Fairhurst and Griffiths, 2014) (Fig. 4.1).

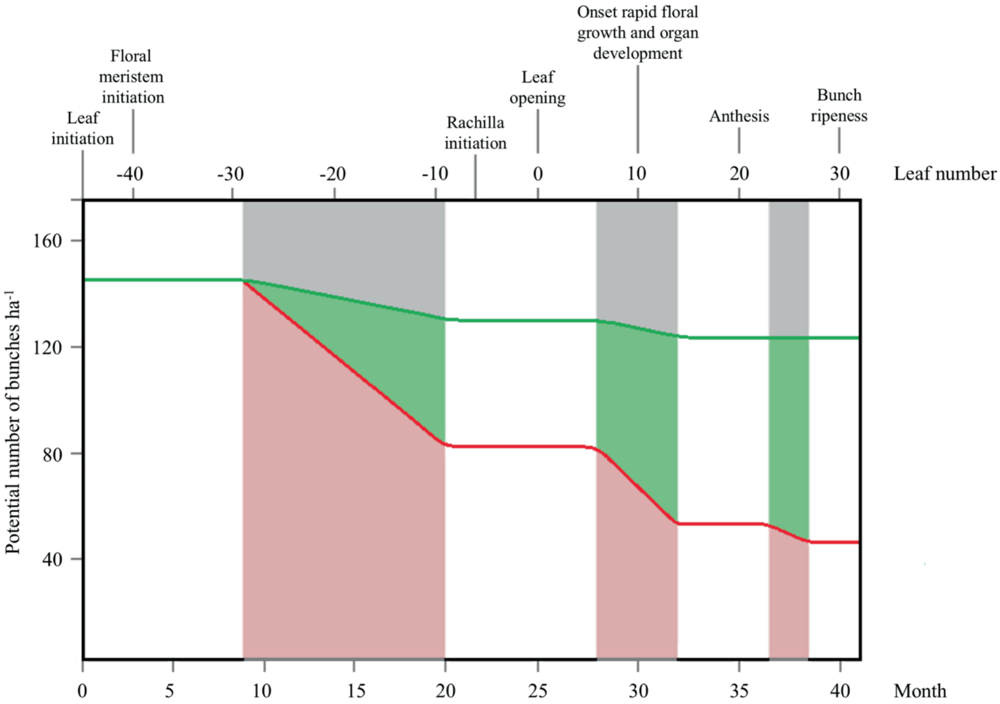

Fig. 4.1. Diagram on the effect of stress (red line) and elimination of stress (green line) on bunch number in oil palm (after Woittiez et al. (2017)). The vertical bars represent three periods where bunch production is sensitive to stress: sex determination (left), inflorescence abortion (middle), and bunch failure (right).

The exact time lag depends on stresses imposed by unfavourable growing conditions and poor agronomic management (e.g. poor nutrient management, pruning or drainage) which trigger complex feedback mechanisms that reduce the sex ratio (i.e. the ratio of female to total inflorescences) and inhibit floral initiation (Corley and Tinker, 2016; Jones, 1997). The sex ratio determines the number of bunches that reach harvest and is affected by both sex determination and floral abortion. Sex differentiation is believed to occur at Leaf -29 (at approximately 6 months after floral initiation) (Corley and Tinker, 2016), while developing inflorescences are most sensitive to abortion 4–6 months before anthesis (Broekmans, 1957). Changes in FB yield are due to changes in one or both of the yield components, bunch number and bunch weight. In oil palm, bunch number contributes more to yield than does bunch weight (Corley and Tinker, 2016). Fruit maturation time varies from 140–180 days (depending on genetic and environmental factors), and starts about two weeks after anthesis. Bunch weight is determined mostly by assimilate availability and the number of flowers that are pollinated effectively (Woittiez et al., 2017).

BMPs need to be adapted to local conditions and aim to reduce stress in oil palm with appropriate management and agronomic techniques so that the number of bunches that reach harvest is greater and bunches are larger. Whilst improved agronomy might already have an effect on bunch number after only six months, increases in yield during the first year of BMP implementation are mainly caused by improvements in crop recovery resulting in an increase in the number of available bunches harvested, and an increase in the recorded bunch weight (because of less loose fruit loss) (Fairhurst and Griffiths, 2014). Once full crop recovery is achieved (and sustained), additional yield increases in subsequent years can be attributed solely to the time-lagged effect of improved agronomic management practices on bunch weight and bunch number. Yet the full beneficial effects of improved agronomic management practices on yield may be masked by periods of unfavourable climatic conditions (e.g. large water deficits and reduced photosynthetic active radiation (PAR) caused by cloud cover) and pest and disease incidence.

Because of the time-lag between flowering and bunch ripening, at least four years are recommended to capture the full effect of improved agronomy on yield (Fairhurst and Griffiths, 2014). Nevertheless, major changes in bunch number and weight are already expected within a period of 3 years (Fig. 4.1). Rapid increases with crop recovery are expected in year 1, whilst improved agronomy increases yields by reducing stress at three critical phases (sex determination, floral abortion and bunch failure) in years 2 and 3. In year 4, yield usually plateaus as all inflorescences initiated in month 0 (Fig. 4.1) have differentiated into harvestable bunches. In this research, we intended to demonstrate the potential of BMP to increase yields: our goal was not to reach the yield plateau *per se*. We therefore present data measured over a period of 36 months, which is sufficient to illustrate the process of yield intensification with BMP within a time-frame where great changes in production are expected. Continuation into the fourth year was not possible given funding limitations.

We partitioned BMPs between those that increase yield in the short-term (i.e. ≤ 1 year after BMP implementation) with yield taking, and in the long-term (i.e. >1 year after BMP implementation) with yield making. Yield taking BMPs included:

i. Frequent harvesting to ensure complete crop recovery. At plantations, harvest intervals of 7–10 days were recommended as a balance between excessively frequent (where bunches are scarce and the harvester's output is poor) and infrequent harvesting (with large amounts of uncollected loose fruits and where many bunches rot and must be discarded). At smallholder farms, harvest intervals of 10 days were recommended in the peak season and 14 days in the low-crop season to compensate for labour costs when bunches are few,
ii. Minimum ripeness standard of five loose fruit (LF) before harvest to ensure maximum oil content without excessive loose fruit collection,

iii. Unimpeded in-field access, including clear harvesting paths and footbridges to cross drains and creeks to allow access to all palms,
iv. Clean weeded circles to allow unimpeded harvesting and collection of fruit bunches and loose fruit, as well as for efficient uptake of ammonia-based N fertilizers,
v. Corrective pruning, to facilitate bunch ripeness assessment and to allow unimpeded harvesting,
vi. Harvested crop delivered to the mill within 24 hours of harvest, to reduce the amount of free fatty acids (FFA) in the crude palm oil produced.

Yield making BMPs included:

i. Maintenance pruning, including removal of surplus fronds (i.e. old, dead, damaged or diseased fronds) to maintain a full and healthy palm canopy,
ii. Removal of unproductive and abnormal palms and replanting to improve the palm stand,
iii. Selective thinning where there was evidence of inter-palm competition (e.g. for light),
iv. Installation of drains to remove excess water during the wet season and to conserve water in the dry season,
v. Regular patrols to monitor outbreaks of pests and diseases in order to minimize fruit loss and palm damage,
vi. Eradication of plants which compete with the palms for nutrients, sunlight and moisture (e.g. hard grasses (e.g. *Panicum maxima*), woody plants (e.g. *Baphia nitida*)) and replacement with soft weeds and grasses to control erosion during heavy rains,
vii. Timeliness and accuracy of application of fertilizer and crop residues (e.g. empty fruit bunches and pruned fronds) to match crop demand and to reduce soil erosion.

The timing and sequence of BMP implementation is of great importance to achieve the full beneficial returns on yield. For example, nitrogen (N) fertilizer application is ineffective if the area is not properly drained, or if woody weeds are not first fully eradicated.

4.2.4 Measurements

Crop production

Number of bunches, fruit bunch (FB) weight (kg), loose fruits (kg), and number of harvesters were recorded at each harvest event. Fruit bunch weight was determined at the mill weighbridge at plantations, and with a tripod and digital scale at smallholder sites. We derived yield components (bunches ha^{-1}, average bunch weight (kg), t ha^{-1} loose fruit, t ha^{-1} FB), harvester productivity (t man-day^{-1} FB, bunches man-day^{-1}, ha man-day^{-1}), harvesting labour (man-days ha^{-1} cycle^{-1}) and the average harvest cycle (cycles yr^{-1}) from the crop production data.

Field upkeep

Field upkeep included circle and path weeding (chemical and manual), circle raking, interline and selective weeding (chemical and manual), pruning and frond stacking, installation and maintenance of drains and construction of footbridges, steps and silt pits. Operations were grouped into five categories; i) access (circle and path weeding), ii) drainage, iii) interline and selective weeding, iv) pruning and making frond-stacks and v) other. At each field upkeep event, we recorded the number of man-days and area covered and derived the average labour spent on each category (man-days ha^{-1}).

Leaf analysis

Permanent datum palm points were established at each site for leaf sampling. Datum palm points were selected following a systematic layout in a staggered grid pattern of every tenth palm in every tenth row, providing a sampling density of 1% palms at plantation sites, or 1–2 palms ha^{-1}. Only healthy and productive palms were selected (if the candidate palm was not healthy, the nearest neighbour in front of or behind the candidate palm was selected). Because smallholder sites were considerably smaller, we selected every fifth palm in every fifth row, providing a sampling density of 3–6 %, or 5–9 palms ha^{-1}. The same datum palm point was sampled each year to reduce the variability that could otherwise be attributable to sampling different palms at each sampling event and for greater operational convenience. Leaf and rachis samples were taken to determine palm nutritional status and to guide fertilizer recommendations. Samples were taken at each datum palm point from a point approximately two thirds of the distance between the insertion point of the first true leaves on the leaf petiole and the distal end of the leaf rachis of Leaf 17 (Chapman and Gray, 1949; Fairhurst et al., 2004). Composite leaf and rachis samples were analysed for N using a combustion analyser (Dumas technique), and P, K, Mg, Ca, and B by inductively coupled plasma analyser (ICP). Leaf tissue samples were taken annually.

4.2.5 Fertilizer recommendations

Site-specific fertilizer recommendations were prepared for all BMP plots. Fertilizer recommendations followed a “4R nutrient stewardship” approach, which entails applying the (1) right source of plant nutrients, at the (2) right rate, at the (3) right time, and in the (4) right place (IPNI, 2012). Guidelines for ‘4R’ recommendations were as follows:

- Right source. For plantations we used straight fertilizers, while for smallholders we used primarily compounds for greater convenience. We selected commonly available nutrient sources in Ghana (i.e. urea as the N source, triple super phosphate (TSP) for phosphorus (P), potassium chloride (KCl) for potassium (K), kieserite (magnesium sulphate) for magnesium (Mg), and borate for boron (B). Compound fertilizers for smallholders included NPK 10–10–30, which was supplemented with rock phosphate (RP) and urea at some sites.
- Right amount. In year 1, plantations and smallholder farmers followed their own fertilizer programmes, whilst from year 2, and after full field access and crop recovery was achieved, BMP fertilizer recommendations were implemented. Fertilizer recommendations were designed to improve palm nutritional status and reach maximum economic yield, based on (un)published information from fertilizer trials carried out in West Africa (e.g. Danso et al., 2010; van der Vossen, 1970) and Southeast Asia. For each plantation and smallholder BMP plot, we first determined whether a particular nutrient was deficient by comparing leaf nutrient concentrations from the preceding year with critical leaf and rachis nutrient concentrations based on the results of fertilizer trials (Foster and Prabowo, 2006; von Uexkull and Fairhurst, 1991). Where nutrient status was assessed as ‘sufficient’ we applied only a maintenance dose. Where nutrient status was assessed as ‘deficient’, we applied a corrective dose in addition to the maintenance dose. Where leaf K concentration was deficient but rachis K concentration was sufficient, we applied a corrective dose of N fertilizer, which has been shown to increase leaf K concentration in palms with low leaf K status but large reserves of K in the leaf rachis (Foster and Prabowo, 2006) (Appendix 8). Expert knowledge was used to adjust fertilizer rates from year 3, depending on the response in leaf levels. For example, fertilizer rates were reduced if leaf and/or rachis levels exceeded critical levels. If no response was observed where nutrient status was poor, fertilizer application rates were increased. Fertilizer recommendations (elements) varied between 0.75–1.15 and 0.60–1.15 kg palm^{-1} N, 0.50–1.35 and 0.30–0.50 kg palm^{-1} P, 1.25–1.50 and 1.25–1.50 kg palm^{-1} K, 0.01–0.02 and 0.00–0.02 kg palm^{-1} B for plantation and smallholder BMP plots respectively, and 0.08–0.16 palm^{-1} Mg for plantation BMP plots (Mg

fertilizer was not applied in smallholder BMP plots). The general recommendation for smallholders was approximately 6 kg palm^{-1} NPK 10–10–30, which delivers 0.6 kg palm^{-1} N, 0.26 kg palm^{-1} P and 1.49 kg palm^{-1} K. Average recommended application rates on smallholder farms were smaller than on plantations because of the project's assessment of farmer's attitude to risk (due to the time-lagged effect of fertilizer on yield, no immediate economic returns are expected). To lower the threshold in purchasing fertilizer products, 50% of the costs for smallholder farmers were paid for by the project in all years.

- Right time. All fertilizers were applied during the short and long rains (March-July and September-November). Urea, TSP, RP, and KCl were applied in two split applications to optimize nutrient recovery and compound fertilizers in three split applications.
- Right place. All fertilizers were applied over the edge of the palm circles and the frond stack, apart from urea, which was applied in the weeded circle to reduce volatilization losses, and borate, which was applied in a band 1 m wide and 1 m from the palm trunk. Compared with palm circles, root development in the frond stack is more favoured due a larger nutrient supply and a higher water conservation as a result of the accumulation of organic debris (Bachy, 1964; Fairhurst, 1996; Purvis, 1956; Tailliez, 1971). Fertilizers are also less susceptible to surface runoff and are washed into the soil under the frond stack where water infiltration rates are greater than in soil beneath the path and the weeded circle.

In order to control noxious woody growth in smallholder and plantation BMP blocks, we aimed to increase the competiveness of soft weeds and grasses that otherwise do not establish under poor soil fertility, with an integrated approach to ground cover management. We recommended a combination of manual control (slashing, uprooting), chemical control with tryclopyr (Garlon^{TM}) herbicide, the introduction of legume cover plants (*Pueraria phaseoloides*), and improving soil fertility (to overcome acute soil phosphorus (P) deficiency) with a one-off application of RP (0.5 t ha^{-1}, ~65 kg ha^{-1} P) at project start.

For BMP blocks at plantations, mulching with empty fruit bunches (EFB) was recommended at 30–40 t ha^{-1}, and repeated once fully decomposed (i.e. every two years). If there was a shortage of EFB, we focussed application on sloping BMP blocks to reduce erosion and to conserve soil moisture. However, the amounts of nutrients applied were too small to include in the overall nutrient budgeting.

4.2.6 Data analysis

All agronomic data was recorded and collated in OMP, an agronomic database designed for oil palm (Agrisoft Systems, 2018). Production data was recorded at monthly intervals but all data was summarized on an annual basis. We first present an overview of the agronomic management procedures in BMP and REF plots and then analyze differences between treatments according to year with a nested UNIANOVA or paired sample t-test where appropriate. The UNIANOVA consisted of (i) yield components, (ii) harvest cycles, (iii) harvester productivity and harvesting labour parameters, (iv) field upkeep labour, (v) palm stand, and (vi) leaf nutrient concentrations as dependent variables, and production system, site and treatment as factors. The model design consisted of a main effect *Production system*, a nested effect *Site* within *Production system*, and an interaction effect of *Treatment* with *Production system*:

y = Production system + Site(Production system) + Treatment + Production system x Treatment

Production system contained two levels: i) plantations and ii) smallholder farms, each with three (BOPP, Norpalm, TOPP) and two (SWAPP East, SWAPP West) sites and two treatments (BMP, REF) respectively. For plantations, we also compared BMP yields with neighbouring blocks as a ‘second’ control (of the same year of planting, planting material, soil type), since it is likely that REF blocks did not provide an absolute reference as they too were undergoing improvement, due to a gradual and unavoidable adoption of BMPs by plantation management.

Despite random allocation of BMP and REF treatments within each paired plot at plantations and smallholder farms, initial starting differences in e.g. yield, can be expected. Thus, we also evaluated the magnitude of change achieved with each treatment between years using a two-tailed t-test.

Second, we applied linear regression to identify which variables correlated most with yield. We used total annual yield (t FB ha^{-1}) as dependent variable and yield taking and yield making parameters as independent variables. For this analysis, we investigated only BMP components whose effect on yield was direct and not time-lagged. For yield taking practices we investigated the number of harvest cycles, harvester productivity (t FB man-day^{-1}, bunches man-day^{-1}, ha man-day^{-1}), harvesting labour (man-days ha^{-1} harvest $cycle^{-1}$) and field upkeep labour (man-days ha^{-1}), and for yield making practices we investigated leaf nutrient concentrations (%DM), the number of pruning rounds and palm stand (productive palms ha^{-1}). The linear regression was performed separately for oil palm plantations and smallholder farmers across all years. We started by entering all variables in the model and removed the least significant parameters (P<0.05) one at a time until we had a reasonably small model. Where applicable, we tested for squared transformations and interactions to see if this would improve the model. All statistics were performed using IBM SPSS Statistics Version 24.

4.3 Results

4.3.1 Yield components and harvesting cycles

The BMP approach allowed for a comparison of fruit bunch yields with a baseline (pre-BMP), between treatments (BMP vs. REF) and between project years. The baseline fruit bunch yields for plantations averaged 11.1 t ha^{-1} in BMP blocks and 10.4 t ha^{-1} in REF blocks. No baseline data was available for smallholders since they did not have historical harvesting records. Despite this, the average fruit bunch yield at smallholders at project start was estimated at about 5.3 t ha^{-1}.

The average fruit bunch yield with BMP at plantation sites increased with 2.1 t ha^{-1} (+19%) in year 1 to 13.2 t ha^{-1}, compared with an increase of 1.0 t ha^{-1} (+10%) to 11.4 t ha^{-1} in REF plots. The increase in yield can largely be attributed to improvements in crop recovery (yield taking). The difference between treatments in year 1 was 1.8 t ha^{-1} (+16%) (Fig. 4.2, Table 4.1). In year 2, BMP yields were 14.6 t ha^{-1}, and significantly ($P \leq 0.05$) larger (2.9 t ha^{-1}; +25%) than yields obtained in REF plots, which averaged 11.7 t ha^{-1}. Yields increased in year 3 for both treatments ($P \leq 0.05$), with BMP plots at 17.9 t ha^{-1} and REF yields at 14.5 t ha^{-1}, a significant difference ($P \leq 0.05$) of 3.4 t ha^{-1} (+23%). Compared with the baseline yields, average yields with BMP increased with 6.8 t ha^{-1} (+61%) over a three-year period, whilst the increase with REF was 4.1 t ha^{-1} (+39%). The difference in yield between year 1 and 3 can be attributed to yield making, and is estimated at 4.7 t ha^{-1} (+36%) with BMP and 3.1 t ha^{-1} (+27%) with REF. The largest improvements with BMP were at the Norpalm site. Average fruit bunch yields with BMP were 3.6 t ha^{-1} (+47%) greater than yields obtained with REF in year 1, 4.7 t ha^{-1} (+53%) greater in year 2 and 8.3 t ha^{-1} (+58%) greater in year 3. The overall increase in yield from year 1 to 3 was 11.2 t ha^{-1} (+100%) with BMP and 6.5 t ha^{-1} (+85%) with REF. At the BOPP site, only small improvements were made with BMP, whilst at TOPP, fruit bunch yields with BMP increased consistently each year (Appendix 9).

There were no significant differences ($P \leq 0.05$) in average fruit bunch yield between the REF and second control plots at plantations sites for all years, indicating minimal influence of BMP on REF treatments. However, plantation management and farmers improved the management of REF plots as their knowledge of better practices increased. While BMP yields increase, REF plots often increase as well, even if fertilizer is not applied and implementation of BMPs is less rigorous than in BMP plots.

Across smallholder sites, treatment differences between the average fruit bunch yield were significant ($P \leq 0.05$) in all years and larger than on the plantations. Average fruit bunch yields with BMP increased with 4.7 t ha^{-1} (+89%) in year 1 to 10.0 t ha^{-1}, compared with an increase of 2.0 t ha^{-1} (+38%) to 7.3 t ha^{-1} in REF plots, a result of an increase in crop recovery (yield taking). The difference between treatments in year 1 was 2.7 t ha^{-1} (+37%). In year 2, BMP yields increased (P≤0.05) with 3.1 t ha^{-1} (+31%) to 13.1 t ha^{-1}, whilst the increase on REF plots was smaller at 1.6 t ha^{-1} (+22%), averaging 8.9 t ha^{-1}. The difference between treatments in year 2 was 4.2 t ha^{-1} (+47%). In year 3, both BMP and REF yields increased significantly (P≤0.05) compared with year 2. BMP yields increased with 4.5 t ha^{-1} (+34%), and averaged 17.6 t ha^{-1}, whilst REF yields increased with 2.8 t ha^{-1} (+31%) to 11.7 t ha^{-1}. The difference between treatments in year 3 was 5.9 t ha^{-1} (+50%) (Fig. 4.2, Table 4.1). Compared with the estimated baseline yield for smallholders (5.3 t ha^{-1}), average yields with BMP increased with 12.3 t ha^{-1} (+232%) over three years, whilst the increase with REF was 6.4 t ha^{-1} (+121%). Approximately 7.6 t ha^{-1} (+76%) of the increase in yield with BMP can be attributed to the effects of yield making and 4.4 t ha^{-1} (+60%) with REF. The overall increase in fruit bunch yields with BMP was greater at SWAPP West (+9.0 t ha^{-1}; 88%) compared with SWAPP East (+6.2 t ha^{-1}; 64%). The largest difference between treatments occurred in year 3 at SWAPP East (6.0 t ha^{-1}, +61% in year 3) and in year 2 at SWAPP West (5.8 t ha^{-1}, +60%) (Appendix 9). The REF treatment at SWAPP West also showed a considerable increase in yield of 6.2 t ha^{-1} (+85%) by the end of year 3, indicating the adoption of BMPs by farmers as their knowledge increased.

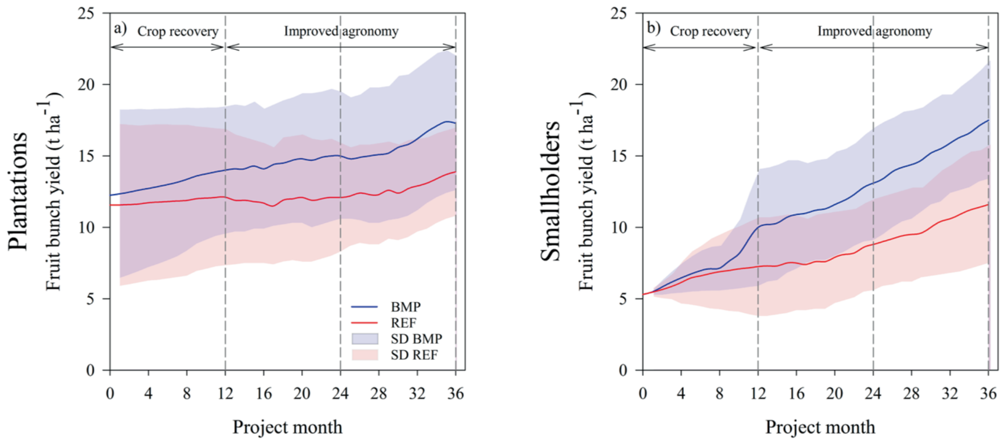

Fig. 4.2. Twelve-month rolling fruit bunch yields at plantation blocks, and b) average cumulative monthly yields for the first 12 project months and twelve-month rolling yields for project months 12–36 on smallholder farms. Average yields are uncorrected and include standard deviations (SD)) for BMP and REF treatments. The dashed vertical lines indicate 12 month periods.

Differences in yield between treatments were largest in the plateau (PYP) and declining yield phase (DYP) at plantations and in the steep ascending (SAYP) and plateau yield phase (PYP) on smallholder plots (Fig. 4.3). However, more samples are required for each treatment and growth phase to understand the underlying causes. Furthermore, yields are still in a strongly upward mode at the end of the project (Fig. 4.2), suggesting that yields in the plateau phase are greater than reported, especially in the smallholder fields (Fig. 4.3).

Larger (increases in) yields with BMP were partly explained by more frequent harvesting and complete crop recovery after the installation of proper access (weeded circles and paths, pruning) in BMP plots. On the large plantations, harvesting events (cycles yr^{-1}) were significantly more ($P \leq 0.05$) frequent at BMP plots compared with REF for all years, whilst at smallholder sites the difference in harvesting events was smaller with each consecutive year (Table 4.2). Improved crop recovery resulted in a greater number of harvested bunches (bunches ha^{-1}) and larger average bunch weight (kg) at BMP plots (except at plantations year 1, where ABW was higher at REF plots), particularly at smallholder sites where access with BMP was better than in the REF plots (Table 4.1).

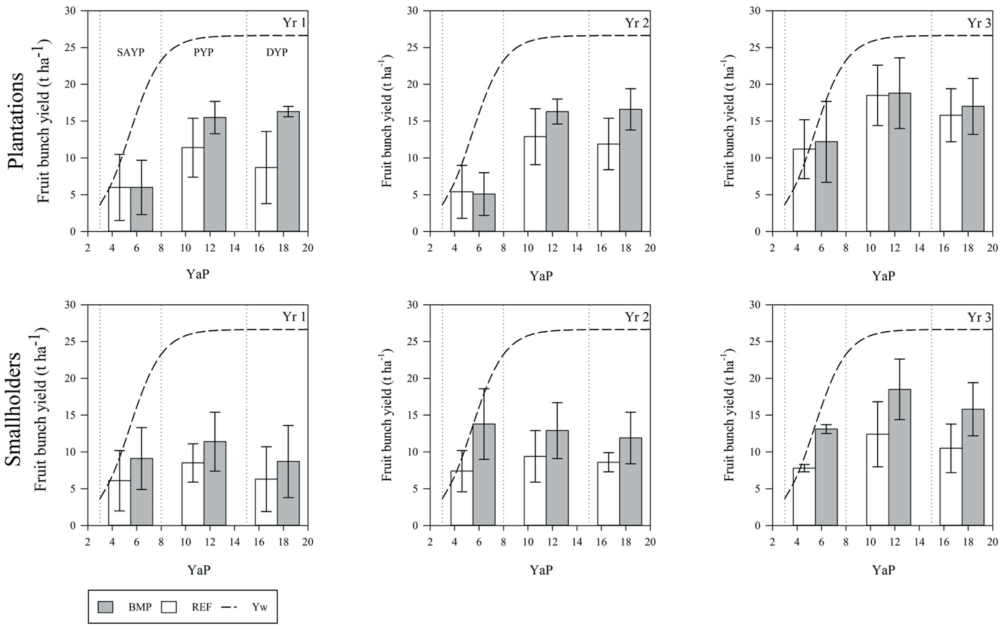

Fig. 4.3. Average BMP and REF yields with standard deviations (SD) for plantation blocks and smallholder farms according to growth phase (steep ascending yield phase (SAYP), plateau yield phase (PYP) and declining yield phase (DYP)) for project years (Yr) 1, 2 and 3. The dashed line shows the water-limited yield profile (*Yw*) of oil palm in Ghana (averaged across favourable (areas with a mean annual water deficit <250 mm) and optimal (areas with a mean annual water deficit <150 mm) production sites across Ghana (Chapter 2)) plotted against year after planting (YaP) (Chapter 3).

Table 4.1. Averages of yield components on plantation blocks and smallholder farms for BMP and REF treatments, project years (Yr) 1, 2 and 3. The final column indicates whether a significant interaction of *Treatment* with *Production system* was found (*for significant at $P \leq 0.05$, NS for not significant; see Appendix 10 for model parameters), whilst a post-hoc test (LSD) shows where significant differences occur in the interaction effect.

Parameter	Units	Yr	Oil palm plantation blocks		Yr	Smallholder farms		Model
			BMP (*n*=16)	REF (*n*=16)		BMP (*n*=19)	REF (*n*=19)	
Bunch number	bunches ha^{-1}	1	1,381	1,210	1	1,217^{d}	936^{d}	NS
		2	1,243	1,051	2	1,265^{d}	957^{d}	NS
		3	1,351	1,144	3	1,448	1,181	NS
Av. bunch weight	kg	1$^{e; g}$	10.3	10.4	1$^{e, f; g}$	8.7	8.1	NS
		2	12.8	12.4	2^{e}	11.6	10.2	NS
		3$^{e; g}$	14.7	14.3^{c}	3$^{f; g}$	13.3	11.4^{c}	NS
Loose fruit collection	t ha^{-1} loose fruit	1	0.49	0.79^{c}	1$^{e; g}$	0.47	0.41^{c}	NS
		2	0.65	0.80	2^{e}	0.89	0.66	NS
		3	0.82^{a}	1.01	3$^{e; g}$	1.51$^{a, d}$	0.93^{d}	*
Fruit bunch harvest	t ha^{-1} FB	1$^{e; g}$	12.8^{a}	10.6^{c}	1$^{e; g}$	9.5$^{a, d}$	6.8$^{c, d}$	NS
		2$^{f; h}$	13.9^{b}	10.9$^{b, c}$	2$^{e; h}$	12.3^{d}	8.2$^{c, d}$	NS
		3$^{e, f; g, h}$	17.1^{b}	13.5$^{b, c}$	3$^{e; g, h}$	16.1^{d}	10.8$^{c, d}$	NS
Total yield**	t ha^{-1}	1$^{e; g}$	13.2^{a}	11.4^{c}	1$^{e; g}$	10.0$^{a, d}$	7.3$^{c, d}$	NS
		2$^{f; h}$	14.6^{b}	11.7$^{b, c}$	2$^{e; h}$	13.1^{d}	8.9$^{c, d}$	NS
		3$^{e, f; g, h}$	17.9^{b}	14.5$^{b, c}$	3$^{e; g, h}$	17.6^{d}	11.7$^{c, d}$	NS

^{a,b,c,d} Indicates a significant difference at $P \leq 0.05$ between treatment means.
^{e,f} Indicates a significant difference between project years for BMP treatment means at $P \leq 0.05$.
^{g,h} Indicates a significant difference between project years for REF treatment means at $P \leq 0.05$.
** Sum of loose fruits and bunches.

4.3.2 Harvester productivity and harvesting labour

At plantation sites, harvesters' output in terms of weight of bunches (t man-day^{-1} FB) and number of bunches (bunches man-day^{-1}) was lower at BMP plots for all years. On average, harvesters also significantly (*P*≤0.05) covered less area (ha man-day^{-1}) in BMP plots, compared with REF (Table 4.2). This is most likely related to shorter harvesting intervals at BMP plots where less crop (including loose fruits) is expected to be harvested during each harvesting event.

At smallholder sites, harvester output (t man-day^{-1} FB and bunches man-day^{-1}) was slightly higher at BMP plots compared with REF, whilst there were no differences in ground covered between treatments. Because the number of harvesting cycles for BMP and REF plots were similar, the difference is likely due to better access in BMP plots where more crop was harvested at each harvesting event (bunches ha^{-1}) (Table 4.1, Table 4.2). The greater bunch availability due to yield improvement therefore more than offset the effect of shorter harvesting intervals on harvester productivity.

The labour allocated to harvesting (man-days ha^{-1} cycle^{-1}) did not differ between treatments at plantation and smallholder sites. However, harvesting labour increased significantly (*P*≤0.05) from year 1 to 2 at smallholder sites for BMP and REF treatments, which was a result of an increase in yield (Table 4.1, Table 4.2).

4.3.3 Field upkeep

Field upkeep activities were recorded at the BOPP and Norpalm plantations but not at TOPP. On average, field upkeep labour (man-days ha^{-1} yr^{-1}) did not differ between treatments at plantation and smallholder sites for all years (Table 4.2). However, significantly more (*P*≤0.05) labour was spent at BMP smallholder sites in year 1 compared with other years, particularly to provide in-field access with circle and path weeding and interline and selective weeding. After providing access, field upkeep activities became less intensive with each consecutive year.

At BOPP, total field upkeep labour was largest in year 1, with most labour allocated towards providing in-field access (circle and path weeding) and access on terraces (category 'other'), as well as the construction of silt pits for water conservation on BMP plots ('other'), whilst small differences in field activities were observed between treatments and years at Norpalm (Fig. 4.4). At smallholder sites, most labour was allocated to providing access with weeding activities, as well as sowing legume cover plants to improve the ground cover vegetation ('other'), particularly in the first year (Fig. 4.4). Total field upkeep labour activities decreased with each year at smallholder sites.

Table 4.2. Averages of management parameters on plantation blocks and smallholder farms for BMP and REF treatments, project years (Yr) 1, 2 and 3. The final column indicates whether a significant interaction of *Treatment* with *Production system* was found (*for significant at $P \leq 0.05$, NS for not significant; see Appendix 10 for model parameters), whilst a post-hoc test (LSD) shows where significant differences occur in the interaction effect.

Parameter	Units	Yr	Oil palm plantation blocks		Yr	Smallholder farms		Model
			BMP (n=16)	REF (n=16)		BMP (n=19)	REF (n=19)	
Harvest cycles	cycles yr^{-1}	1	$43^{a, b}$	$27^{b, c}$	1	$26^{a, d}$	$21^{c, d}$	*
		2	$46^{a, b}$	$29^{b, c}$	2	24^{a}	22^{c}	*
		3	$42^{a, b}$	26^{b}	3	25^{a}	23	*
Harvester productivity	t $man\text{-}day^{-1}$ FB	1^{e}	$1.1^{a, b}$	$1.5^{b, c}$	1^{e}	0.7^{a}	0.6^{c}	*
		2	1.3	1.5^{c}	2	1.0	0.7^{c}	NS
		3^{e}	1.5	1.8^{c}	3^{e}	1.2^{d}	$0.8^{c, d}$	*
	bunches $man\text{-}day^{-1}$	1	121	154^{c}	1	92	80^{c}	NS
		2	102	120	2	104	86	NS
		3	109	133^{c}	3	104	84^{c}	NS
	ha $man\text{-}day^{-1}$	1	1.3^{b}	$1.9^{b, c}$	1	1.0	1.2^{c}	NS
		2	1.1^{b}	$1.7^{b, c}$	2	1.1	1.2^{c}	NS
		3	1.1^{b}	$1.7^{b, c}$	3	0.9	0.9^{c}	*
Harvesting labour	man-days ha^{-1} $cycle^{-1}$	1	0.34^{a}	0.34^{c}	$1^{e, f; g, h}$	0.60^{a}	0.70^{c}	NS
		2	0.34^{a}	0.37^{c}	$2^{e; g}$	0.66^{a}	0.72^{c}	NS
		3	0.37^{a}	0.43^{c}	$3^{f; h}$	0.67^{a}	0.76^{c}	NS
Field upkeep labour**	man-days ha^{-1} yr^{-1}	1	1.73	1.80	$1^{e, f}$	1.93	1.45	NS
		2	1.49	1.72	2^{e}	1.24	1.23	NS
		3	1.39	1.39	3^{f}	1.12	1.29	NS

**Only includes plantation data for BOPP and Norpalm (n=11 for BMP and n=11 for REF), since field upkeep practices were not recorded at TOPP. Labour for field upkeep activities was taken as the average across five categories, i) access (circle & path weeding), ii) drainage, iii) interline & selective weeding, iv) pruning & frondstacking, and v) other.

^{a,b,c,d} Indicates a significant difference at $P \leq 0.05$ between treatment means.

^{e,f} Indicates a significant difference between project years for BMP treatment means at $P \leq 0.05$.

^{g,h} Indicates a significant difference between project years for REF treatment means at $P \leq 0.05$.

Only a small amount of labour was allocated to drainage at plantation and smallholder sites. Particularly at plantation sites, where large areas were located in valley bottoms, crop recovery activities were obstructed by poor drainage due to lack of drainage outlets and field drains, or drains that were too shallow and required desilting.

4.3.4 Leaf nutrient concentrations and fertilizer application

There were no significant ($P \leq 0.05$) differences in leaf nutrient concentrations between treatments at plantation and smallholder sites at project start and end (Fig. 4.5). Average leaf nutrient concentrations for N, P, Mg, and calcium (Ca) fell within their optimum nutrient ranges (Fairhurst and Mutert, 1999), suggesting no nutrient deficiencies. Because of the synergism between N and P uptake, leaf P concentration was assessed in relation to leaf N concentration (Fairhurst and Mutert, 1999; Ollagnier and Ochs, 1981). The critical leaf P concentration (calculated based on Tampubolon et al. (1990)) fell within the optimum range for P for plantations and smallholders for both treatments and years, suggesting a balance in leaf P and N concentration. Average leaf K concentration was within optimum range at project start at plantation sites, but deficient at all sites at project end, whilst average leaf Mg concentration was sufficient at both plantation and smallholder sites for all years. However, when taking into account the relative concentrations of the leaf cations (TLC, calculated according to Foster (2003)), the average leaf K concentration (K as % of TLC) was deficient at plantations and smallholders for all years, whilst the average leaf Mg concentration (Mg as % of TLC) was only sufficient at smallholder sites. Average leaf B concentrations were deficient at project start at plantation and smallholder sites, but sufficient at project end at both treatments, most likely due to application with B fertilizers at BMP plots (Fig. 4.5, Fig. 4.6).

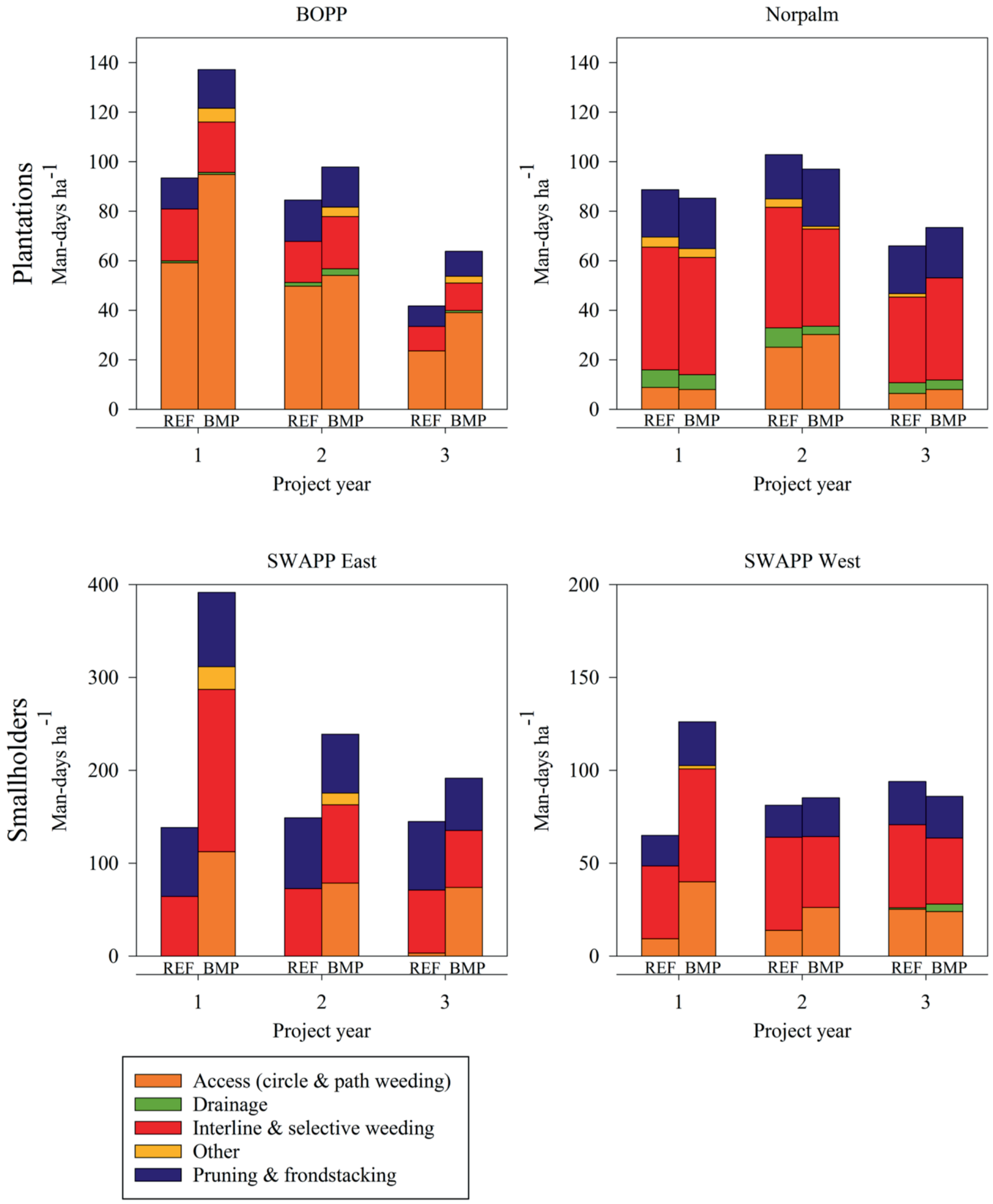

Fig. 4.4. Total labour (man-days ha^{-1}) spent on field upkeep activities on plantation and smallholder sites for project years 1, 2 and 3.

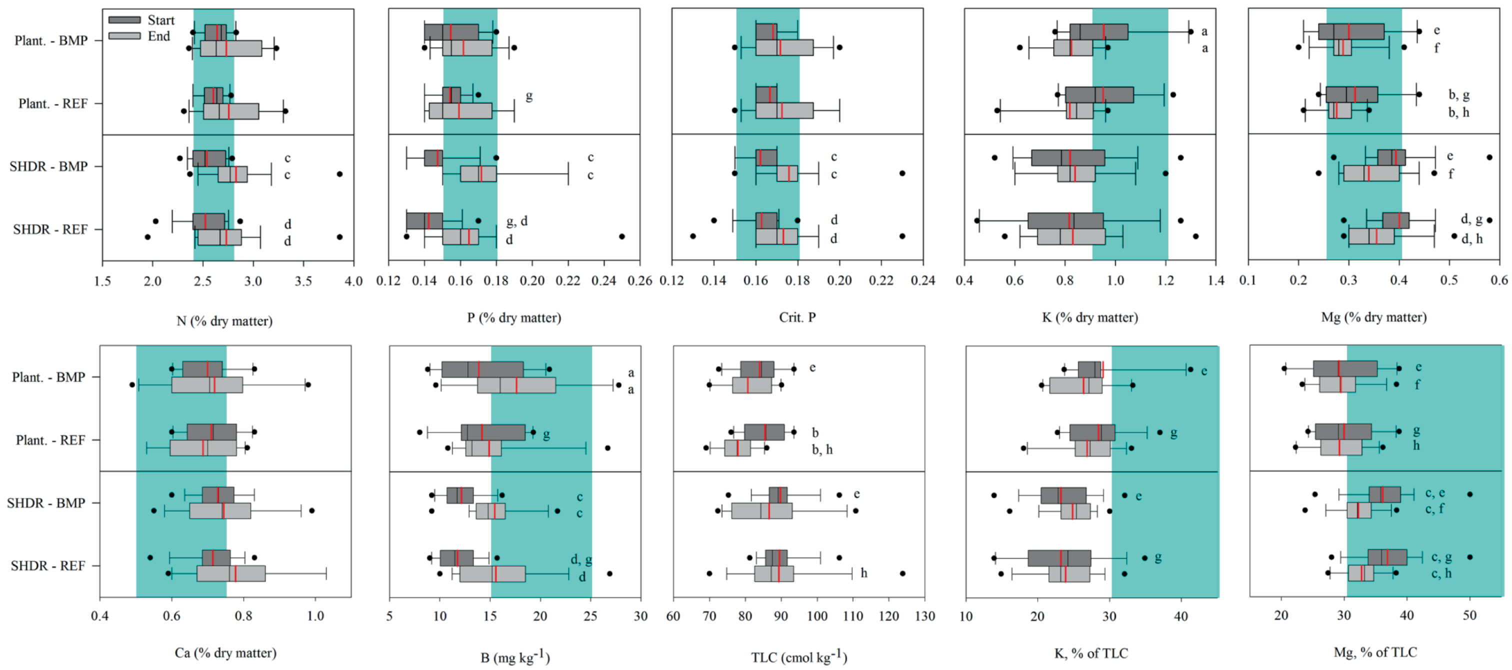

Fig. 4.5. Box plots showing leaf nutrient concentrations at oil palm plantations (n=11 for BMP and n=11 REF) and smallholder farms (n=18 for BMP and n=18 REF) at project start and end. The vertical red line shows the average leaf nutrient concentration and the blue shaded area indicates the optimum leaf nutrient concentrations (Fairhurst and Mutert, 1999). Critical P (Crit. P) is leaf P concentration assessed in relation to Leaf N concentration. Outliers are plotted as individual points. Significant differences (at $P \leq 0.05$) between treatment means and years are indicated with a, b, c, d, e, f, g, h.

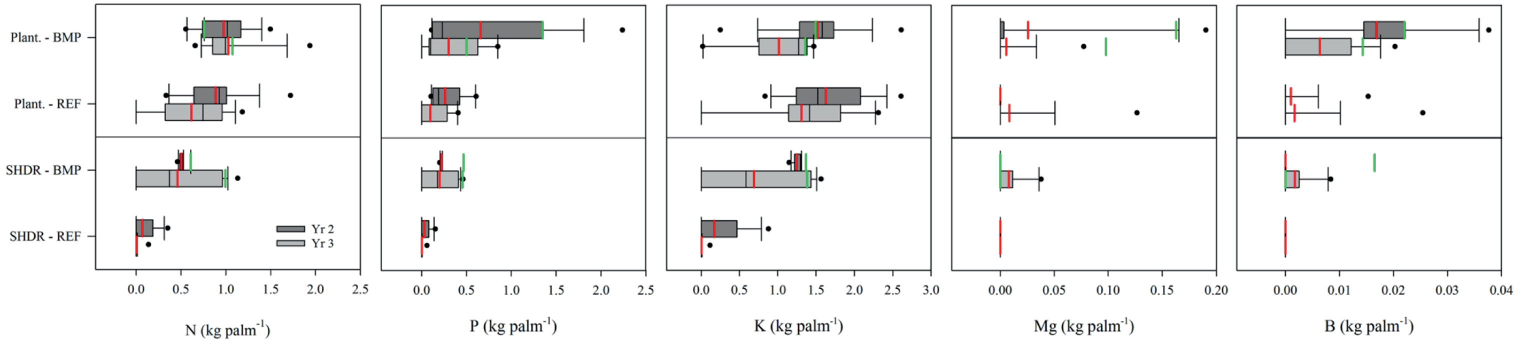

Fig. 4.6. Box plots showing fertilizer nutrients (elements) N, P, K, Mg, B applied at oil palm plantations (*n*=15 for BMP and *n*=15 REF) and smallholder farms (*n*=18 for BMP and *n*=18 REF) in project years (Yr) 2 and 3. Average applied rates of application are indicated with a red vertical line, and average recommended rates of application for BMP plots are indicated with a green vertical line. Outliers are plotted as individual points.

Whilst fertilizer nutrient applications were significantly larger ($P \leq 0.05$) in the BMP treatment for N, P, Mg (year 2 only) and B at plantation sites and N, P, K at smallholder sites, BMP fertilizer recommendations were not accurately implemented. As a result, large nutrient gaps between what was recommended and actually applied were observed, particularly at plantation sites (Fig. 4.6). Failure to implement fertilizer recommendations partly explains the large variability in leaf nutrient concentrations (Fig. 4.5).

4.3.5 Palm stand

At plantation sites the average number of productive palms (i.e. mature, immature and supply palms) was significantly less ($P \leq 0.05$) than the initial planting density for both treatments in all years, whilst at smallholder sites no significant differences were found (Fig. 4.7). Between treatments, no significant differences ($P \leq 0.05$) in the number of productive palms were found for all years for plantation (n=16 for BMP, n=16 for REF) and smallholder sites (n=10 for BMP and n=10 for REF). However, infilling was only successful at Norpalm where large vacant clusters (≥3 consecutive palms) were replanted at project start in the BMP treatment. By the end of year 3 the average palm stand with BMP improved greatly, with most supplied palms in production, partially closing Yield Gap 2 (Fig. 4.7). At SWAPP West smallholder sites, the number of productive palms was close to the initial planting density for both treatments, mainly because experimental plots were selected based on complete and productive palm stands. Experimental plots at smallholder sites therefore contained less unproductive palms (abnormal or dead palms) which were more common at plantation blocks. Yield Gap 2 was therefore smaller at smallholder sites compared with plantations.

4.3.6 Yield determinants

Using linear regression across oil palm plantations, three predictors explained 69% of the variance in yield (R^2=.69, $F(3,68)$=51.876, P=0.000); the number of harvest cycles (ß=0.266, P=0.000), harvester productivity (t FB man-day^{-1}, ß=6.289, P=0.000) and harvesting labour (man-days ha^{-1} harvest cycle^{-1}), ß=20.429, P=0.000), whilst at smallholder farmers, 83% of the variance (R^2=.823, $F(3,100)$=160.190, P=0.000) was explained by harvester productivity indicators t FB man-day^{-1} (ß=9.369, P=0.000) and ha man-day^{-1} (ß=-8.148, P=0.000)) and by leaf P concentration (%DM) (ß=78.341, P=0.000). The linear regression results suggest the importance of crop recovery activities such as frequent harvesting events (i.e. short harvest intervals) and improving access for a more efficient harvester productivity (i.e. more bunch weight harvested and less area (ha) covered per harvester) at both plantations and smallholders, and the larger importance of improved nutrition at smallholder farms.

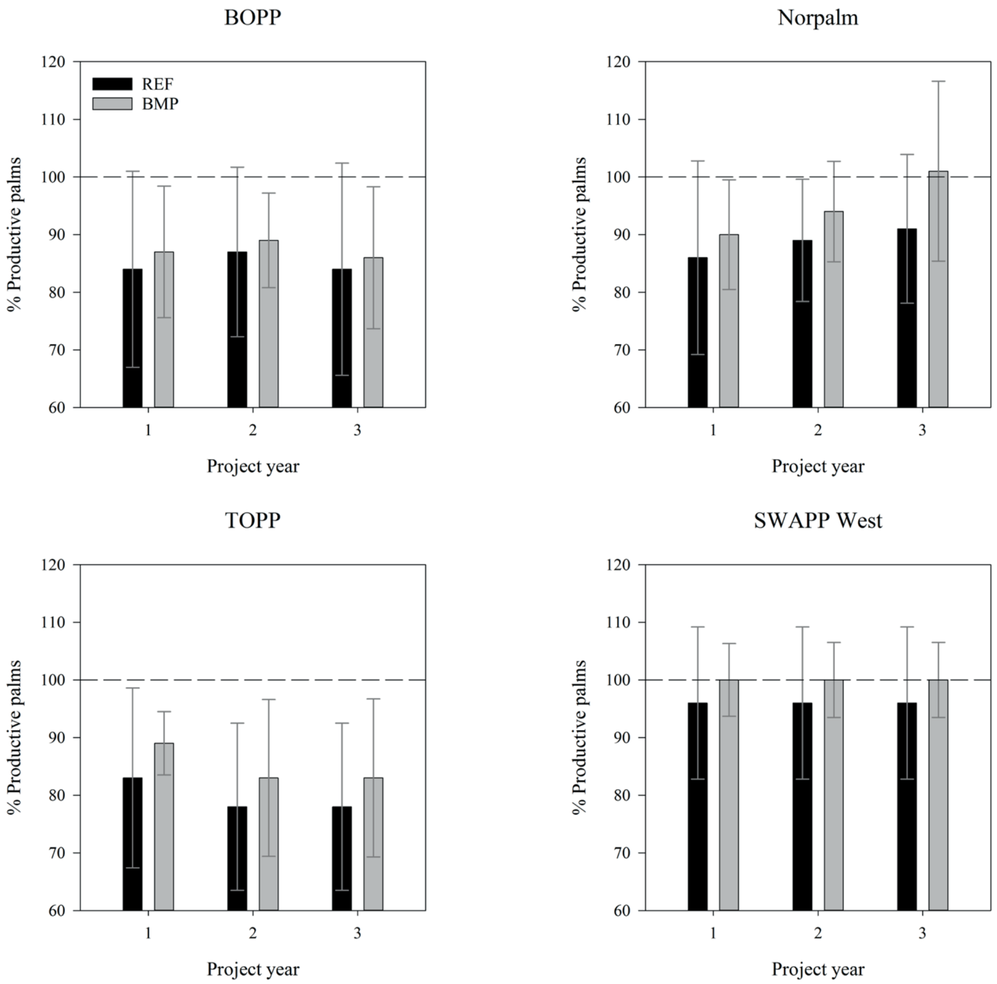

Fig. 4.7. Palm census results expressed as proportion of productive palms (palms ha^{-1}) in relation to the initial planting density (palms ha^{-1}, see Table A1 for initial planting densities) for BMP and REF treatments at plantation blocks and smallholder farms for project year 1, 2 and 3. Error bars represent standard deviations.

4.4 Discussion

Best Management Practices (BMP) were applied successfully in a West African context using Ghana as a case study. The BMP approach provided the means for systematic identification and elimination of yield gaps in mature plantings. The three-year process started with a review of current yields and agronomic standards and an estimate of the yield potential (*Yw*) by age of palm and site. Field audits were a useful method to determine the causes of yield gaps (agronomic and management factors) and to identity the respective corrective measures (Chew and Goh, 2003; Fairhurst and Griffiths, 2014; Goh et al., 2004). The results present a case for using BMPs as a technique for yield intensification on land already planted with oil palm, rather than expanding oil palm plantings into areas that can be used for other purposes.

4.4.1 Increasing yields with BMP

In this research, we present oil palm yields measured over a period of 36 months to demonstrate the potential of BMP to increase oil palm yields. Within this time frame, large increases in yield were gained with improvements in bunch weight and number. Yield improvement with BMP was partitioned in two distinct phases; i) the short-term (≤1 year) effect of improvements in operational management of crop recovery (‘yield taking’), and ii) the longer-term (>1 year) effect of improved agronomic management (‘yield making’) on reducing stress (Fig. 4.1). However, the full benefits of BMP on yield may be masked by abiotic stresses, such as periods of moisture stress, which were not assessed in this study (Fairhurst and Griffiths, 2014). In contrast, biotic stress events, such as pests (e.g. leaf miner (*Coelaenomenodera* spp.), rhinoceros beetle (*Oryctes rhinoceros*)) and diseases (e.g. *Fusarium* spp.), were regularly monitored during the project and did not pose a significant risk.

Average fruit bunch yield increases with BMP were 2.1 t ha^{-1} (+19%) and 4.7 t ha^{-1} (+89%) with crop recovery at oil palm plantations and smallholders respectively, whilst yield increases of 4.7 t ha^{-1} (+36%) and 7.6 t ha^{-1} (+76%) were obtained with yield making. Average yields and yield gains with BMP were larger at plantations and smallholders, compared with the REF treatment over the project period. At plantations, average yields in year 3 with BMP were 17.9 t ha^{-1}, compared with 14.5 t ha^{-1} for REF (3.4 t ha^{-1} yield difference), whilst the overall yield gain was 6.8 t ha^{-1} (+61%) and 4.1 t ha^{-1} (+39%) for BMP and REF respectively. At smallholder farms, however, the response with BMP was greater compared with plantations. Average yields with BMP in year 3 was 17.6 t ha^{-1}, compared with 11.7 t ha^{-1} for the REF treatment (a difference of 5.9 t ha^{-1}). The overall yield gain was 6.4 t ha^{-1} (+121%) with REF, whilst the response with BMP was almost double, at 12.3 t ha^{-1} (+232%).

The larger yield response at smallholder farms was largely due to the very poor initial field conditions, where the benefits from yield taking BMPs where greater than at plantations. Important crop recovery activities included more frequent harvesting events (10-day harvest intervals) and improved field access (roads, paths, weeded circles) to provide the means for increased harvester efficiency and productivity. Because of the time-lagged effect of improved agronomy on yield, the contribution of individual yield making components are more difficult to quantify. Fertilizer use and leaf analysis data (Fig. 4.5, 4.6) suggest considerable nutritional constraints that must be addressed and implemented correctly to intensify yields. While past research has generated important nutrient management strategies, there are still considerable knowledge gaps which could help our understanding of the contribution of nutrients to yield gap closure (Tiemann et al., 2018). With the oil palm sector expanding into new frontiers, including marginal and degraded lands, more work on agronomic needs, including nutrients, of currently used commercial planting materials as well as new materials now being bred will be needed to determine optimal fertilizer rates to maximize yields (Tiemann et al., 2018). Development of new improved fertilizer recommendations is therefore essential to increase yields and to sustainably intensify oil palm production in Ghana. The need to establish multi-factorial, multi-locational nutrient response trials across different agroecological zones in Ghana is therefore essential to guide future fertilizer recommendations.

To capture the full beneficial effect of BMP, a period of at least 4 years is recommended until yields start to plateau as all initiated inflorescences have reached maturity. Whilst average plantation yields seem to have plateaued already within the time-frame of the project, average yields at smallholder farms are still in a strong upwards mode, indicating that the site yield potential has likely not yet been reached at the project sites (Fig. 4.2). The response to yield making BMP's on smallholder farms is therefore expected to be larger than reported in our results. Whilst the design of the project did not allow us to explore yields beyond 36 months, we were able to monitor the phase where the most rapid changes in yield were expected, hence allowing us to answer questions related to short-term yield trends and their drivers.

Rehabilitating neglected or abandoned oil palm requires significant initial investments to achieve complete crop recovery and eliminate all agronomic constraints, particularly in the first year when additional labour is required to establish proper access to the palms (Fig. 4.4). Once unimpeded access was achieved, the greatest additional costs were fertilizers. However, at project start, most smallholder farmers lacked financial inputs and were unwilling to purchase inputs. Lack of access to credit coupled with the time-lagged response to fertilizer use in terms of yield response inhibits fertilizer use by smallholders and is a major reason for low yields at smallholder farms (Corley and

Tinker, 2016). In the BMP project, half of the major inputs were therefore financed for smallholders, since the goal of the project was to provide evidence of the potential increase in profit should BMPs be applied. Once farmers were convinced with the benefits, introducing and applying BMPs became easier. However, most smallholder farmers are not in a position to make significant investments in fertilizer and other inputs, particularly given the four-year payback period. A key input is therefore the provision of credit, but banks are always reluctant to lend to farmers that lack land titles. Instead, the provision of inputs to smallholder oil palm growers is best carried out by milling companies that advance fertilizer materials to smallholders secured against budgeted future crop deliveries to the respective mill.

In theory, short-term improvements to economic returns at smallholder farms can be achieved by simply improving crop recovery, which can help to finance inputs needed for the yield making phase. Over the long term, fertilizer use is considered essential to maximise yield and to avoid depleting the low fertility status soils found in the oil palm belt. For example, nutrient depletion in soils under cocoa without the use of mineral fertilizers is a major factor in the decline of cocoa production throughout Ghana (Kongor et al., 2018; Appiah et al., 1997). For policy makers, there is an obvious trade-off between intensifying production with mineral fertilizer use on existing plantings and allowing continued expansion of low-yield oil palm smallholdings that results in forest destruction.

At plantations, the implementation and maintenance of BMPs was, at times, constrained by lack of financial resources (e.g. insufficient budget provision for fertilizer inputs), conflicts with, or willingness to implement program recommendations (e.g. installation of a proper drainage system), and labour constraints for field maintenance and/or harvesting (Appendix 11). Whilst smallholder farms are generally family operated (Mensah-Bonsu et al., 2009), plantations, on the other hand, rely solely on the use of hired labour. Plantations therefore tend to involve higher labour costs, are often plagued by labour disputes between workers and management and appear less adaptable to short-term changes than small-scale diversified systems (Gyasi, 1996). Shortage of labour during the peak crop months mean that harvesting intervals often become extended to >20 days (i.e. <3 harvest cycles month^{-1}), resulting in significant crop loss. Moreover, the high turnover in labour force at plantations results in a scarcity of skilled labour needed to maintain good standards for particular field operations such as harvesting and pruning.

The economics of closing yield gaps indicated by field audits and ex-ante analysis should be considered before implementing BMPs to determine whether the cost of remedial measures will be repaid in increased productivity over the improvement cycle.

Implementing BMPs in a representative sample of blocks provides proof of present yield gaps and the cost and time period required to close the gaps. If the BMP trial shows that yield gaps can be closed profitably, wide-scale adoption can be implemented (Fairhurst and Griffiths, 2014). However, an economic analysis is beyond the scope of this work and should be dealt with in a separate analysis.

4.4.2 Yield intensification versus area expansion

Most of the increases in the production of palm oil in Ghana have been achieved through area expansion (Chapter 3). By contrast, increasing yields with BMP offers scope to reduce the requirement for future area expansion to meet the increasing demand for palm oil (preferably if *tenera* planting material is used). At present, approximately 327,600 ha is under oil palm cultivation (16,600 ha under plantations and 311,000 ha under smallholders) with current FB yields (11.4 t ha^{-1} at plantations and 7.3 t ha^{-1} at smallholders) resulting in production of 189,240 t FB and 2,270,300 t FB at plantations and smallholders respectively. With moderate BMP implementation (increasing FB yields to 17.9 t ha^{-1} and 17.6 t ha^{-1} at plantations and smallholders respectively), production would increase to 5,770,740 t FB, thus avoiding 448,273 ha area expansion at present yields. However, at potential production levels (i.e. increasing FB yields to 21.0 t ha^{-1} at plantations and smallholders), about 597,636 ha land can be spared. Additionally, closing yield gaps in Ghana under current land area has the potential to increase fruit bunch production almost three-fold from 2,5 Mt to 6,9 Mt. If all crop is processed at an oil extraction rate (OER) of 21%, approximately 1.4 Mt CPO can be produced (worth about 1 billion US$ at US$750 t^{-1} CPO^{-1}). This is more than enough to meet Ghana's current annual demand of 106,000 t CPO, and does not require the need to plant additional land (Chapter 3).

Provided there is sufficient milling capacity, yield intensification can be achieved without the typical capital expenditure required for new plantings (e.g. road infrastructure, planting cost), and financial returns from investments in yield intensification accrue more rapidly because production starts to increase as soon as agronomic constraints are removed (Donough et al., 2009; Fairhurst and McLaughlin, 2009). Ghana has large swathes of land planted to *tenera* palms that could be rehabilitated. Instead of investing in new plantings that are likely to up end as abandoned plots, due to lack of know-how, rehabilitation of existing mature plantings may instead be an important policy for sustainable oil palm development in Ghana and West Africa.

Increasing yields does not necessarily reduce area expansion, unless supporting policies are in place and properly enforced, but is an important step towards reducing pressure on land and deforestation (Angelsen, 2010; Woittiez et al., 2017). Higher yields will also make the crop more profitable, and if demand is elastic, expansion is likely to be encouraged (Corley and Tinker, 2016).

4.5 Conclusions

Best Management Practices (BMP) offer immense potential to increase yields on mature plantings at plantations and smallholder farms in Ghana. As such, implementing BMP's on neglected oil palm fields is a step-wise process and should be implemented in the correct sequence in order to eliminate all agronomic stress effectively. Most important is to first provide unimpeded access for harvesting operations and palm upkeep with the installation of harvest paths and weeded circles, and removal of unproductive fronds with corrective pruning. The second step involves the introduction of regular and complete harvesting events at 7–10 day intervals to ensure complete crop recovery. After yield taking constraints have been completely removed, yield making operations should focus on: i) improving nutrient management and soil conservation with balanced mineral nutrition and mulching with crop residues, ii) manual and chemical removal of woody weeds in palm inter-rows and harvest paths to favour the establishment of soft weeds, grasses and legume cover plants (LCP), iii) improving drainage in swampy areas by installing 'V' shaped drains, and iv) regular patrols to monitor outbreaks of pests (e.g. leaf miner (*Coelaenomenodera* spp.) and rhinoceros beetle (*Oryctes rhinoceros*) and diseases.

Significant yield improvements were achieved at sites representative of the Ghanaian oil palm industry, thus proving the applicability of the BMP process, which has also been successfully implemented in Southeast Asia and Latin America. The BMP process allowed for a systematic elimination of yield gaps in mature plantings by i) diagnosing agronomic constraints, ii) identifying and interpreting causal factors, and iii) implementing steps for corrective action. Improved field access, short harvesting intervals and balanced palm nutrition were essential to yield intensification, particularly at smallholder farms. The success of BMPs depends on total commitment and support from senior plantation management and smallholder farmers alike, as well as sufficient budget provision and resources (particularly in the first year) to implement BMPs diligently and on time.

4.6 Acknowledgements

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CHAPTER 5

The influence of water and nutrient management on oil palm yield trends on a large-scale plantation in Ghana

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Abstract

Oil palm (*Eleais guineensis* Jacq.) production in West Africa is limited by poor soils and suboptimal climate. The potential to improve fruit bunch (FB) yields with appropriate water and nutrient management in Ghana is thus considerable. To assess the effects of water and nutrient management on oil palm yields, a 2 x 2 factorial randomized complete block design with irrigation and fertilizer was implemented for three years in the main oil palm production area of Western region, Ghana. Treatments included i) zero irrigation + zero fertilizer (control), ii) zero irrigation + fertilizer, iii) irrigation + zero fertilizer and iv) irrigation + fertilizer, all replicated four times. Fertilized treatments received annual nutrient application rates of 2.0 kg palm^{-1} nitrogen (N), 0.4 kg palm^{-1} phosphorus (P), 2.5 kg palm^{-1} potassium (K), 0.3 kg palm^{-1} magnesium (Mg) and 0.15 kg palm^{-1} boron (B). Irrigation (using sprinklers) was scheduled using tensiometers, and was given to meet the daily evaporation of oil palm (~450 l palm^{-1} day^{-1}, or 6.5 mm day^{-1}). Average attainable yields of 32.6 t ha^{-1} FB were achieved with irrigation and fertilizer, which was 4.7 t ha^{-1} greater than the control (27.9 t ha^{-1}) and 4.1 t ha^{-1} greater than with irrigation alone (28.5 t ha^{-1}). Fertilizer was therefore essential for a maximum response to irrigation. Whilst yield increases were mostly attributed to increases in bunch number, large variations in monthly yield persisted at all treatments despite the use of irrigation, with production peaks typically coninciding with the onset of the long rain season (March–July). Whilst a number of factors may contribute (e.g. vapour pressure deficit), the process(es) regulating yield cycles remain unclear and require further research.

Keywords: *Irrigation, fertilizer, water deficit, yield cycle, yield gap.*

5.1 Introduction

Although oil palm (*Eleais guineensis* Jacq.) is indigenous to West Africa, the soils and climatic conditions in the region are considered suboptimal for its cultivation (Chapter 2). In southern Ghana, soils are predominately coarse-textured, strongly weathered and highly leached Acrisols and Ferralsols (USDA: Ultisols and Oxisols respectively) with low pH and poor soil fertility status (Buringh, 1979). The major climatic constraint is the prolonged dry season of 4–5 months with mean annual water deficits up to 600 mm yr^{-1} (Chapter 2; van der Vossen, 1969).

A recent land suitability assessment showed that large areas within the oil palm belt of Ghana are susceptible to annual water deficits approaching 400 mm (Chapter 2). There is a time lag of 35–40 months between the occurrence of abiotic and biotic stress events and yield response in oil palm, which makes it difficult to unravel the effects of environmental factors on fruit bunch (FB) yield (Breure, 2003; Corley and Tinker, 2016). Several authors have attempted to explain yield responses in relation to the annual water deficit in West Africa. For example, Hartley (1988) reported a 10% yield reduction with every 100 mm of annual water deficit. Caliman and Southworth (1998) observed that moisture stress negatively affected floral initiation (1–3%), sex differentiation (3–4%) and abortion rate (8–10%) per 100 mm of deficit, with a concomitant yield reduction of 8–10% per 100 mm deficit in the first year and 3–4% in the second. A yield reduction of 40–50% was recorded when severe water stress occurred in the previous year. In the Ivory Coast, Olivin (1968), reported a yield reduction of 10–20% with 100 mm annual water deficit, depending on the soils' water storage capacity, while Ochs and Daniel (1976) reported similar yield penalties based on observations made in the Ivory Coast, Benin and Cameroon. In Ghana, yields ranged from 22–25 t ha^{-1} FB for areas with annual water deficits of 150 mm, 16–18 t ha^{-1} FB for areas with annual water deficits of 250 mm, and 6–7 t ha^{-1} FB for areas with an annual water deficit of 400 mm, suggesting an almost linear relationship between yield and water deficit (Danso et al., 2008). Therefore, there are strong prospects for reducing the negative impact of moisture stress on yields in areas affected by large annual water deficits in Ghana.

Supplementary water supply through irrigation provides an opportunity to increase oil palm yields in regions with sub-optimal rainfall (Corley and Hong, 1982). Prioux et al. (1992) obtained maximum yields of 22 t ha^{-1} FB with irrigation in Ivory Coast, a 21% increase in production over non-irrigated palms, while yields increased four-fold with irrigation in a trial described by Desmarest (1967).

In addition to moisture stress, oil palm yields in Ghana are limited by poor soil fertility and inadequate nutrient supply (Chapter 3). Analysis of soil and plant samples from trial sites in Ghana showed severe and widespread deficiencies of soil phosphorus (P) and potassium (K) on large plantations and smallholder farms (Chapter 3). In addition, several trials in West Africa confirmed that K is deficient on sedimentary soils, P on basement complex-derived soils, and that Mg may be needed on acid, sandy soils (Corley and Tinker, 2016).

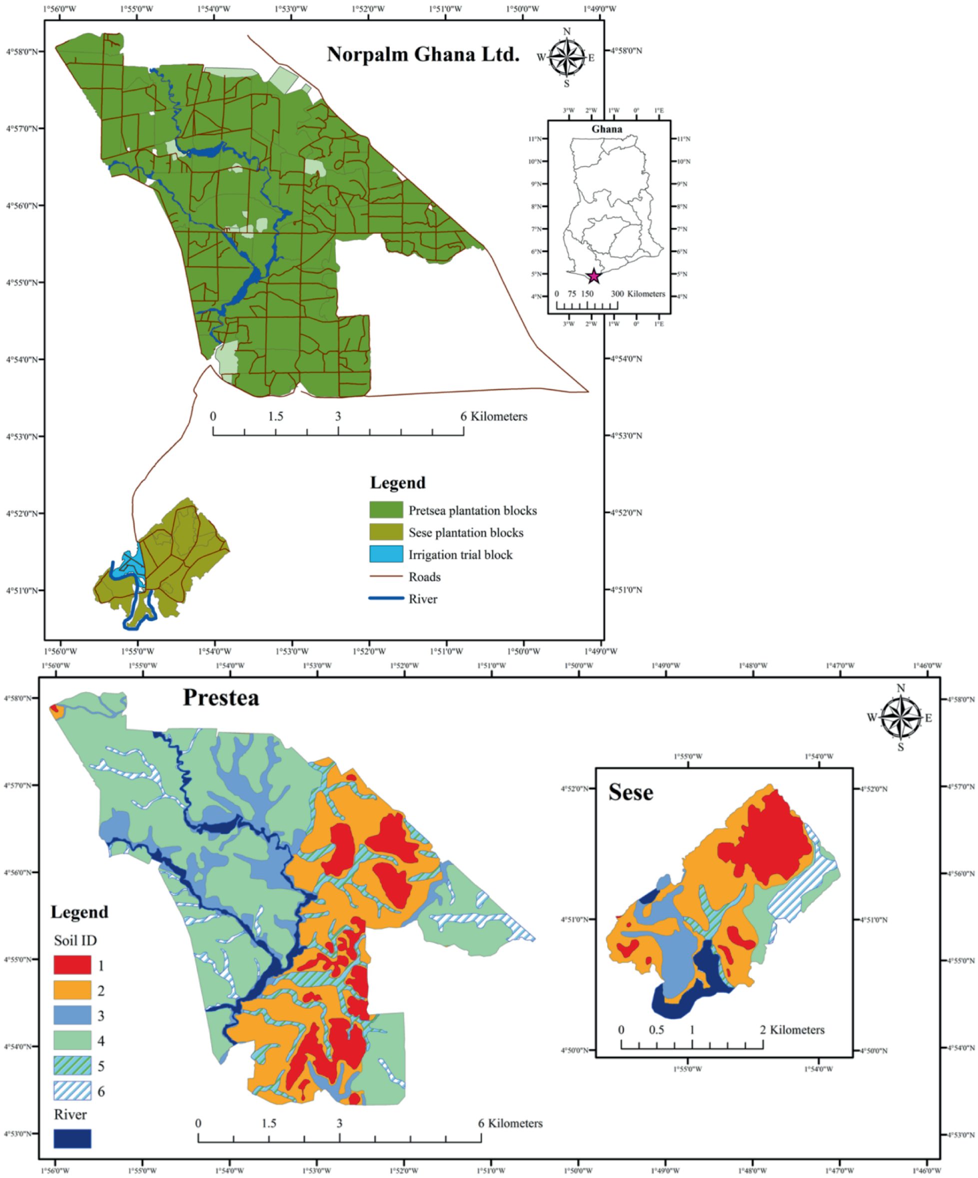
The potential to improve oil palm production with appropriate water and nutrient management in Ghana is thus substantial and could greatly increase profitability for oil palm producers, as well as sparing land for nature. In this chapter, we evaluated the interaction of irrigation and nutrient application on the yield of oil palm on a large-scale oil palm plantation over three years in Western region, Ghana. The objectives were: (i) to quantify yield gaps caused by water and nutrient constraints and (ii) to analyse the interaction of water and nutrients on yield trends and yield components.

5.2 Methods

5.2.1 Study area

A trial was established to assess the effects of irrigation and fertilizer on oil palm yields at the Norpalm Ghana Ltd. plantation (NGL) (4°55’29.04”N; 1°53’31.75”W, 11 masl), which is located in the Ahanta West District of the Western region, Ghana. NGL’s nucleus estate consists of approximately 4,500 ha distributed between the Sese (500 ha) and Pretsea (4,000 ha) sites (Fig. 5.1).

Slopes at NGL are gentle to hilly (4–40 %) and soils are classified as Gleysols in poorly drained valley bottoms and flood plains and Lixisols on sloping terrain (Fig. 5.1). Rainfall at NGL is bimodal, with long rains from March-July and short rains from September-November. Average rainfall from 2011–2016 was lower at the Sese site (1,136 mm) than at Pretsea (1,511 mm), with considerable variability between months and years. As a result, the average annual water deficit (calculated using the method of Surre (1968)) over the same period was higher at Sese (608 mm) than in Pretsea (355 mm) (Fig. 5.2).



Parent material	Terrain	ID	Soil series	Classification (WRB)	Description	Area (ha)	Percentage (%)	Limitations
Upper Birrimian Phyllite	Hilly	1	Atewa Asikuma	Cutanic Lixisol Plinthic Lixisol	Deep (>100 cm), well drained, silty loam, topsoil overlying gravel free silty clay (Atewa series) as the major soils and gravelly silty clay subsoil Asikuma series). Slopes are steep (20-40%)	489	10.7	Steep slope
	Undulating to rolling	2	Asikuma Atewa Ansum	Plinthic Lixisol Cutanic Lixisol Gleyic Lixisol	Deep (>100 cm), well to moderately well drained, moderately steep slopes (10-20%); soils similar to the hilly terrain unit except that the gravelly soils (Asikuma series) is dominant	1,099	24.1	Moderately steep, gravelly subsoil for most soils
	Lowland (valleys)	3	Oda Temang	Haplic Gleysol Gleyic Arenosol	Deep (>100 cm), poorly drained, clay (Oda series) and loamy sand (Temang series)	296	6.5	Poor drainage
Granite	Uplands	4	Agona Nkwanta Akroso	Plinthic Lixisol Plinthic Lixisol Gleyic Lixisol	Deep (>100 cm), well to imperfectly drained, sandy loam topsoil overlying gravely sandy clay loam subsiol (Agona and Nkwanta series). Middle to lower slopes are gravel-free clay loam (Akroso series)	1,837	40.4	Gravelly subsoil
	Lowlands	5	Nta Ofin	Epigleyic Arenosol Haplic Gleysol	Deep (>100 cm), imperfectly to poorly drained loamy sand and sand (Nta series) and poorly to very poorly drained coarse sand containing quartz gravles (Ofin series)	181	4	Drainage, texture
Mixed Alluvium	Flood plains of the major rivers	6	Butre	Haplic Gleysol	Deep (>100 cm), imperfectly to poorly drained clay loam and clay (Butre series) and pockets of sandy soils (Nta and Temang series)	651	14.3	Drainage

Fig. 5.1. Location of Norpalm Ghana Ltd. and its soil type and terrain properties.

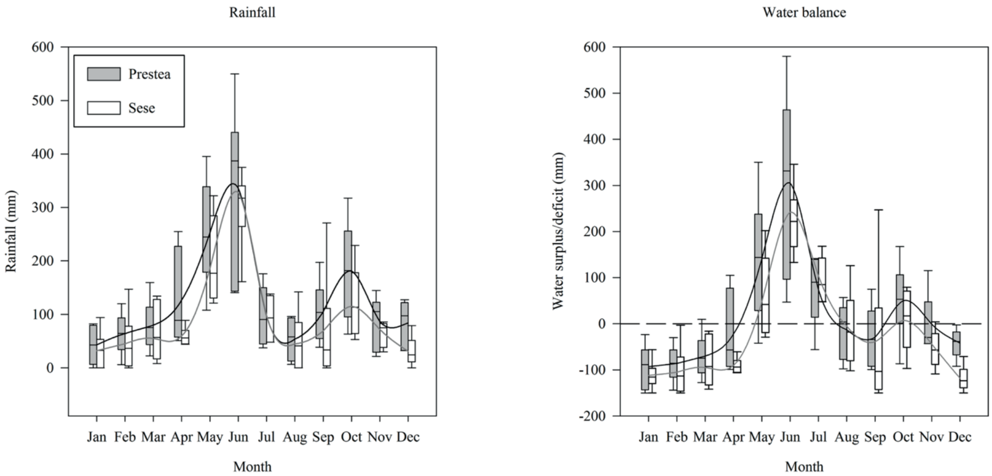


Fig. 5.2. Monthly rainfall (a) and the water balance (b) at the main plantation (Prestea) and Sese for 2010–2016. Black and grey lines show the average for Prestea and Sese respectively. Water balance values below the zero line in graph (b) are water deficits while positive values are water surplus.

5.2.2 Trial setup and management

The trial was established at the Sese plantation on February 2015 in a 34 ha block that had been planted in 2002 (Fig. 5.1). The trial block was planted at 143 palms ha^{-1} using triangular spacing, and consisted entirely of *tenera* (i.e. *dura* x *pisifera* (DxP)) palms of Pobé, Benin material, which had been planted 13 years before at the time of trial establishment. The topography was flat.

An isometric map of the trial block was produced, including the number of mature, immature, new/supply, abnormal, and dead/removed palms, or unplantable points, and was used to delineate the trial plots. Each plot consisted of clusters of 36 palms (6 x 6), of which the inner 16 palms (4 x 4) were used for taking measurements (recording palms) and the outer palms provided a guard row (Fig. 5.3). The recording palms consisted entirely of productive and healthy palms, while the guard row included some abnormal and immature palms. Each recording plot (4 x 4) was approximately 0.11 ha. All plots were bounded by a trench of at least 50 cm deep to avoid nutrient and water movement between trial plots and access from bordering palms. At least two palm rows were also kept as a buffer between plots. The entire trial block was managed with "Best Management Practices" (BMP) (Donough et al., 2009), to ensure that yields were not constrained by other factors besides nutrients and water.

5.2.3 Experimental design

The trial was established at the Sese plantation division because of its proximity to a river for irrigation. The trial was designed to quantify the bunch yield potential (*Yp*) without moisture stress, and to investigate the interaction of nutrient and water supply on oil palm yield components. A 2 x 2 factorial randomized complete block design was used, which included four treatments: i) zero irrigation + zero fertilizer (I0F0, i.e. control), ii) zero irrigation + fertilizer (I0F1), iii) irrigation + zero fertilizer (I1F0) and iv) irrigation + fertilizer (I1F1). Each treatment was replicated four times, with blocks following moisture gradients. In total 16 plots were installed (Fig. 5.3).

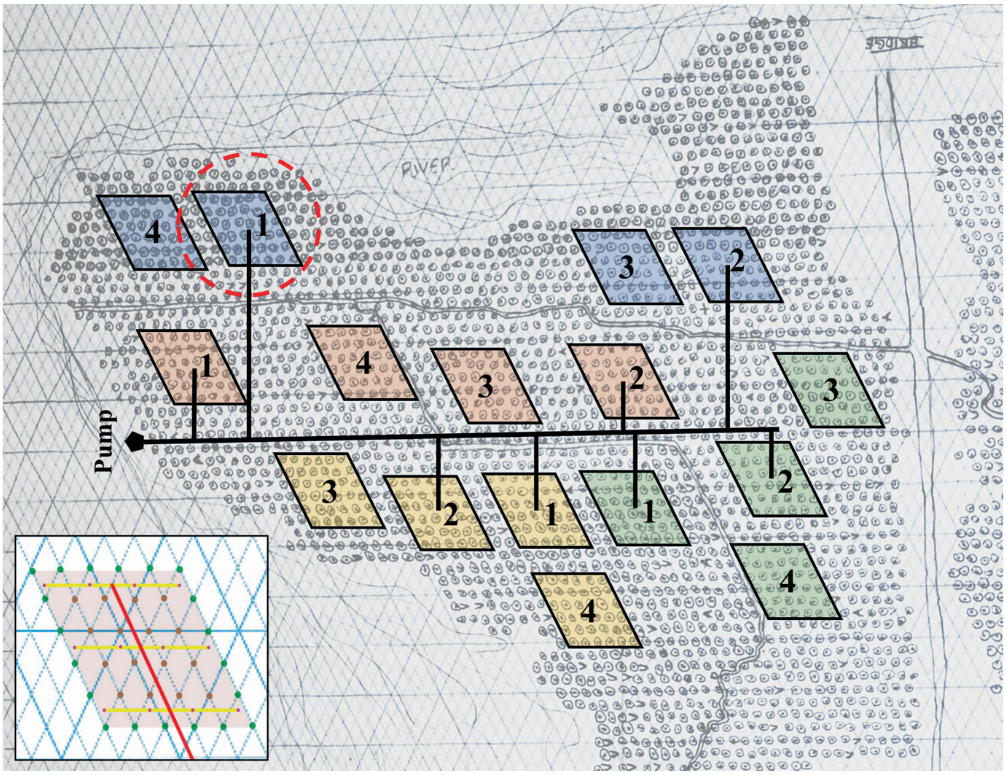


Fig. 5.3. Experimental layout of the irrigation x fertilizer trial at Sese, Norpalm Ghana Ltd drawn on isometric paper. The coloured plots indicate the separate blocks (*n*=4), whilst the numbers indicate the treatment (1=irrigation + zero fertilizer (I1F0), 2=irrigation + fertilizer (I1F1), 3=zero fertilizer + zero irrigation, i.e. control (I0F0), 4=zero irrigation + fertilizer (I0F1)). The insert shows the experimental layout within an irrigated plot. The red and yellow lines are irrigation pipes (main and laterals respectively) and the pink dots the sprinkler locations. The green dots are the outer palms (guard row) and the brown dots the recording palms.

Fertilizer treatments covered the main limiting nutrients: nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg), applied as urea, triple superphosphate (TSP), muriate of potash (MOP) and kieserite respectively. Annual application rates of nutrients (elemental form) were 2.0 kg palm^{-1} N, 0.4 kg palm^{-1} P, 2.5 kg palm^{-1} K and

0.3 kg palm^{-1} Mg. In addition, all fertilizer treatment plots received an annual application of 0.15 kg palm^{-1} boron (B), to overcome B deficiency. Fertilizer application rates were based on previous fertilizer experiments, and were drafted to ensure nutrients were not limiting. Fertilizers were applied to all palms in each fertilizer treatment plot, including the guard row. P, K and Mg fertilizers were broadcast over the edge of the weeded circle into the frond stack, whilst B was applied with sodium borate in a band 1 m wide and 1 m from the palm trunk, and urea in the weeded circle to reduce volatilization losses. All fertilizers were applied during the rainy seasons. Sodium borate was applied in March, urea in April and August, MOP in May and September, TSP in June and kieserite in July. Fertilizer application rates and timing followed the same schedule each year and no mill residues (e.g. empty fruit bunches (EFB)) were applied to the palms during the experiment.

Irrigation needs were based on the soil water potential (kPa), which was measured using tensiometers. Tensiometers were installed in each block (n=4) at 20 cm depth, where most of the fine roots are located (Taillez, 1971). Because the soil was relatively coarse-textured, the critical soil water potential for irrigation was set at 20 kPa (Alam and Rogers, 1997). Irrigated plots consisted of 12 sprinklers (Senninger ® SmoothDrive), each with a radius of 9.3–10.2 m. Each sprinkler thus covered three palms (see insert Fig. 5.3). At an operating pressure of 207 kPa, approximately 150 minutes of irrigation was given to meet the daily evaporation of oil palm (~450 l palm^{-1} day^{-1}, or 6.5 mm day^{-1}) (Carr, 2011; Corley and Tinker, 2016), which was recorded during each irrigation event. To ensure that the right quantity of water was supplied, a flow meter was installed in-line with the irrigation discharge pipe.

In order to evaluate the effect of irrigation in eliminating soil-moisture stress, we calculated the water balance for irrigated and non-irrigated plots following the method of Surre (1968):

$$B = S_{res} + P - ETP \qquad \text{Eq. 5.1}$$

where B = monthly water balance (mm); S_{res} = residual soil water from the previous month (mm); P = monthly rainfall (mm); and ETP = monthly potential evapotranspiration (mm).

Scorching of palm leaves was briefly experienced in the dry season in the first year due to tidal saline water incursions, and a corrective measure was taken to use EC meters to monitor the salinity of the irrigation water at each irrigation event. No irrigation was given when EC exceeded 3000 μS cm^{-1} to prevent scorching of the palm leaves and ground cover (Fipps, 2003). Piezometers were installed in eight plots (two per replicate), and monitored weekly to assess the groundwater level. Tensiometers were removed from the field during periods of flooding, which occurred with heavy rainfall in March, June and October 2016, and May and June 2017.

5.2.4 Data collection

Crop production

Bunch number, fruit bunch weight (kg) (including loose fruits) and number of male flowers were recorded at harvest intervals of 7 days at each plot. Crop production data were reported as the total for each plot (inner 16 palms). Fruit bunch weight was measured with a tripod and digital scale and bunch production data was used to derive yield totals (t ha^{-1} FB). Bunch number and the number of male flowers were used to determine the sex ratio, i.e. the ratio of female to total inflorescences.

Leaf sampling

Palm nutritional status and fertilizer recommendations for mature oil palm are commonly made based on leaf and rachis nutrient concentrations from frond 17, due to their high correlation with yield (Fairhurst, 1996; Foster and Prabowo, 2006). Leaf and rachis samples for nutrient determination were therefore taken annually at each recording palm (inner 16 palms) at a distance of approximately two thirds between the insertion point of the first true leaves on the leaf petiole and the distal end of frond 17 (Chapman and Gray, 1949; Fairhurst et al., 2004). Composite leaf and rachis samples were produced for each plot and analysed at Yara Laboratory (UK) for N using a combustion analyser (Dumas technique), and P, K, Mg, and B (only leaf) by inductively coupled plasma analyser (ICP), with averages derived per treatment.

Physiological measurements

Physiological measurements were taken to investigate the effects of drought and water stress on oil palm development and production. The following effects of drought or water stress on physiology and yields of oil palm are known to occur (Corley and Hong, 1982):

i. longer immature period (Nouy et al., 1999),
ii. stomatal closure and a decrease in transpiration from the leaves (Ng, 1972; Rees, 1961),
iii. delayed leaf opening, decrease in frond production rate, and the accumulation of unopened leaves (spears) in the crown (Nouy et al., 1999; Ochs and Daniel, 1976; Paramananthan, 2003),
iv. vegetative damage and palm death with severe drought (Maillard et al., 1974),
v. longer flowering time (i.e. the time interval between the opening of a leaf and flowering of the inflorescence in its axil), shorter maturation time (i.e. the time between anthesis and bunch ripening) (Nouy et al., 1999; Olivin, 1966), delayed

fruit abscission (Chan, 1972), and delayed bunch ripening (Ochs and Daniel, 1976),

vi. decrease in sex ratio and increases in male inflorescence number (Corley, 1976),
vii. irregular distribution of yield with a shorter production peak (Carr, 2011),
viii. bunch and early inflorescence abortion (Paramananthan, 2003), and
ix. reduction in fruit bunch oil content (Ochs and Daniel, 1976; van der Vossen, 1974).

Physiological measurements included maturation time and number of unopened fronds, and were carried out at weekly intervals on each individual recording palm (inner 16 palms) with averages derived per plot. Maturation time was measured as the time interval (days) between anthesis and harvesting (ripeness). All bunches were labelled with wire tags embedded in the flower to record the date and frond position at anthesis and at harvest. Newly emerging bunches were monitored routinely on each palm during each recording event. Crop production data including bunch number, and the number of male flowers were used to determine the sex ratio and monthly yield distribution for each treatment.

Calculation of yield gaps

We adjusted the yield gap model presented in Chapter 3 to include the nutrient-limited yield (*Yn*). Because the trial was managed with BMP and only complete (productive) palm stands were used, production level *Ymey* (the yield reduced by deficiencies in plantation establishment) and *Yam* (the yield reduced by inadequate agronomic management) were not included in the model. The average yield achieved with I1F1 in year 3 served as a proxy for the potential yield (*Yp*), the average yield with I0F1 in year 3 provided an estimate of oil palm production assuming optimal nutrient management and served as a proxy for the water-limited yield (*Yw*), while the I1F0 treatment served as a proxy for the yield limited by nutrients only (*Yn*) and I0F0 for the water- and nutrient limited (*Yw+n*). The difference between average yields achieved with *Yp* and *Yw* therefore gives us an estimate of the yield gap caused by water (Yield Gap 1 (*YG1*)) and was calculated as:

$$YG1 = Yp - Yw \qquad \text{Eq. 5.2}$$

while nutrient-limited yield gaps (Yield Gap 2 (*YG2*)) were calculated as:

$$YG2 = Yp - Yn \qquad \text{Eq. 5.3}$$

The gap caused by both water and nutrient limitations (Yield Gap 3 (*YG3*)) was calculated as the difference between *Yp* and *Yw+n*:

$$YG3 = Yp - Yw + n \qquad \text{Eq. 5.4}$$

5.2.5 Data analysis

All data was summarized on an annual basis unless indicated. Differences between treatment means were analysed with a UNIANOVA for each year, including yield components (yield, bunch weight and bunch number) and leaf and rachis nutrient concentrations as dependent variables, and replication and treatment as factors.

In oil palm, there are three periods where production is sensitive to water stress (Caliman and Southworth, 1998; Dufour et al., 1988); i) 30–33 months before harvesting, which corresponds to the sex differentiation period, ii) 19–24 months before harvesting, which corresponds to the fast growth of the leaf supporting the inflorescence, and iii) 7–13 months before harvesting, which corresponds to the period of abortion. For each water-stress sensitive period, we used simple linear regression with fruit bunch yield as the dependent variable and the water balance as the independent variable, to determine which months were most significant in predicting yield for each treatment. We then entered the most significant months in a multiple linear regression model for each treatment and removed the variables that did not make a significant (P<0.05) contribution to the regression. All statistics were performed using IBM SPSS Statistics Version 24.

5.3 Results

5.3.1 Yield components

The pre-trial annual yield was 17.7 ha^{-1} FB across the whole block. In year 1, average FB yields were 6.9 t ha^{-1} greater at 24.6 t ha^{-1} in the control treatment (I0F0), compared with 7.0 t ha^{-1} greater in the I0F1 treatment (24.7 t ha^{-1}), 6.3 t ha^{-1} in the I1F0 (24.0 t ha^{-1}) and 6.6 t ha^{-1} larger in the I1F1 treatment (24.3 t ha^{-1}) (Table 5.1). We attribute the larger yields in year 1 to the fact that trial plots consisted entirely of productive palms as well as improved crop management including more frequent and complete harvesting events. Average FB yields increased in year 2 and 3, with the I1F1 treatment yielding significantly more than other treatments, at 32.6 t ha^{-1}. The large FB yield increase with I1F1 suggests that there was a significant irrigation x fertilizer interaction. Average bunch weight (ABW, kg) decreased with each year for all treatments, whilst bunch number per palm (BN) increased. The increase was largest for the I1F1 treatment, where bunch number increased from 7.5 to 11.1 bunches palm^{-1} (+48%). Bunch number per palm depends on the frond production rate, the sex ratio, the abortion rate and the bunch failure rate (Carr, 2011). The increase in bunch number coincided with a decrease in the number of male flowers and an increase in the sex ratio for all treatments (Table 5.1), whilst increases in bunch number with irrigation are mostly due to changes in both abortion rate and sex ratio (Corley and Hong, 1982).

Monthly yield components fluctuated widely for all treatments, with most notably the clear seasonality in bunch number (Fig. 5.4). In mature palms, variation in bunch number contibutes much more to yield cycles than does bunch weight, with sex variation commonly regarded as the prime cause of yield variation (Corley and Tinker, 2016; Henson and Dolmat, 2004). In regions with high and regular rainfall (e.g. parts of North Sumatra, Indonesia and Sabah, Malaysia), sex ratios tend to vary little throughout the year, whilst in areas with a marked dry season (West Africa), sex ratios fluctuate widely (Adam et al., 2011). Peaks in bunch number and yield, and to a lesser extent sex ratio, typically conincided with the onset of the long rain season (March–July, Fig. 5.2).

In year 3, the average number of bunches ha^{-1} month^{-1} was 120 for the I0F0 treatment, 124 for I0F1 and 128 and 132 for I1F0 and I1F1 respectively. Most bunches were harvested in February with 228 bunches (16% of the annual bunch production) for the I0F0 treatment, 273 (18%) bunches for I0F1, 226 (15%) for I1F0 and 239 (15%) for I1F1 (Fig. 5.5). The peak months were February–May where 55% of the annual number of bunches were harvested for the I0F0 treatment (an average of 199 bunches ha^{-1} month^{-1}, opposed to an average of 81 bunches ha^{-1} month^{-1} during the other months), 53% for I0F1 (196 bunches ha^{-1} month^{-1} vs. 88 bunches ha^{-1} month^{-1}), 49% (186 bunches ha^{-1} month^{-1} vs. 98 bunches ha^{-1} month^{-1}) for I1F0 and 45% for I1F1 (179 bunches ha^{-1} month^{-1} vs. 108 bunches ha^{-1} month^{-1}), indicating a slightly lower peak for irrigated treatments.

The coefficient of variance (COV) for monthly fruit bunch production was 56% for the I0F0 treatment, 55% for I0F1, 51% for I1F0, and 48% for the I1F1 treatment, suggesting a slightly more regular annual bunch number production with irrigation. For comparison, Prioux et al. (1992) obtained a COV of 30% with irrigation, opposed to 60% without irrigation, suggesting irrigation was essential in regulating monthly production distribution.

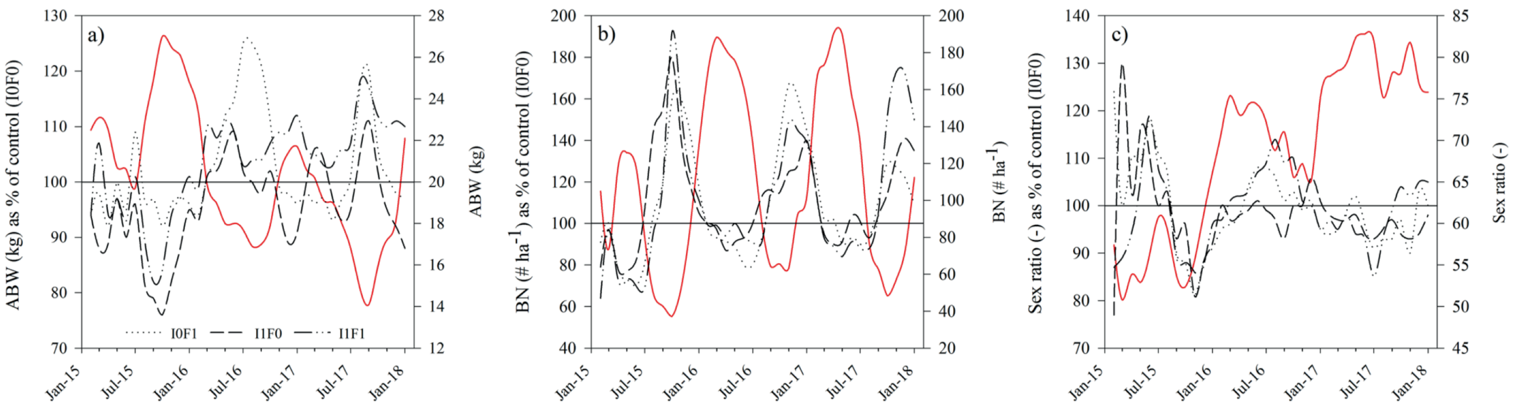


Fig. 5.4. The relative response of three-month rolling averages for a) average bunch weight (ABW, kg), b) bunch number (BN, # ha^{-1}) and c) sex ratio (-) for all treatments to the control (I0F0) (bold horizontal line). The three-month rolling averages for the control plot (I0F0) are indicated with a red solid line on the right y-axis, showing the actual response.

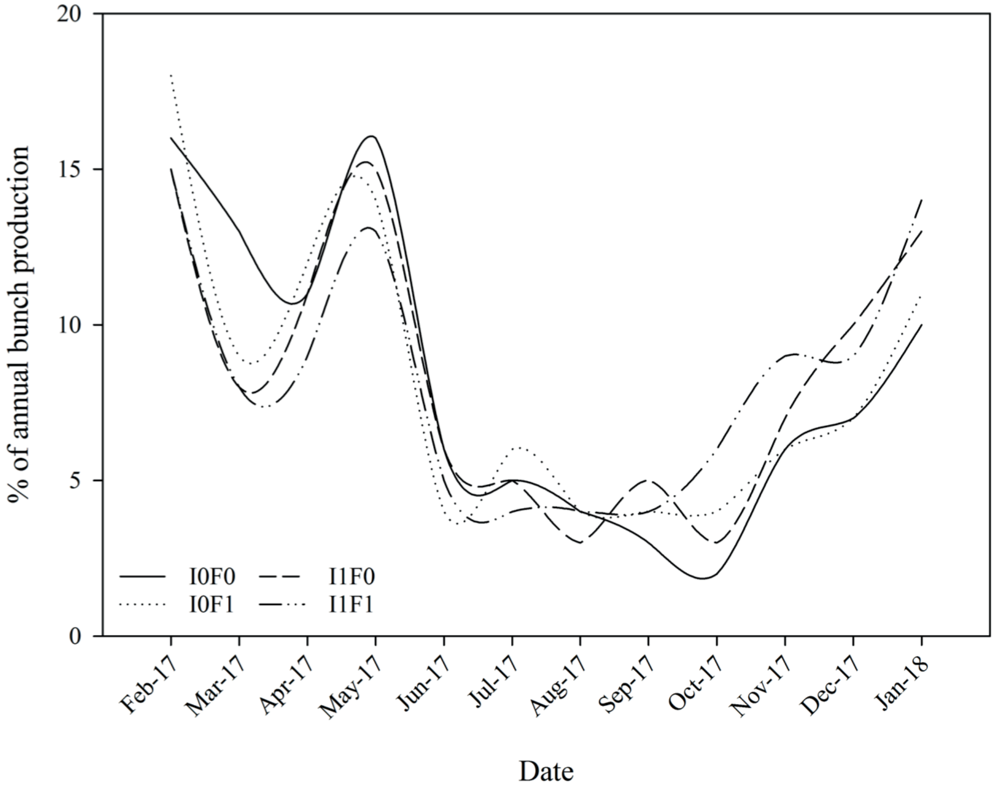


Fig. 5.5. Annual bunch number distribution (in %) for all treatments in year 3.

5.3.2 Water balance

I1F0 and I1F1 treatments received 656 mm of water with irrigation in year 1, 711 mm irrigation in year 2 and 496 mm irrigation in year 3. As a result, the annual water deficit in year 1 was 735 mm and 96 mm for non-irrigated and irrigated plots respectively, 709 mm and 80 mm in year 2, and 735 and 331 mm in year 3 (Table 5.1). The deficits were largest in the months August, September and December–March, which coincided with dry spells.

Irrigation events were succesfully planned using tensiometers, but water deficits could not be fully erradicated due to pump failures and periods when the irrigation water was too saline to be used.

Simple linear regression indicated that 31 months before harvest, 20 months before harvest and 8 months before harvest were the three most sensitive periods to water stress in the I0F0 treatment, whilst 30 months, 19 months, and 7 months before harvest accounted for most of the observed variation in yield for all other treatments (Fig. 5.6, Table 5.2).

Table 5.1. The annual water deficit (WD, mm) and averages with standard deviations (SD) for fruit bunch yield (FBY, t ha^{-1}) and yield components, including average bunch weight (ABW, kg), bunch number (BN, # palm^{-1}), the number of male flowers (MF, # palm^{-1}) and sex ratio determined at harvest (SR, %) for different irrigation x fertilizer treatments after 12, 24 and 36 months. Statistics were performed with a nested UNIANOVA.

Treatment	Months 0–12						Months 13–24						Months 25–36					
	WD	FBY	ABW	BN	MF	SR	WD	FBY	ABW	BN	MF	SR	WD	FBY	ABW	BN	MF	SR
	mm	t ha^{-1}	kg	# palm^{-1}		%	mm	t ha^{-1}	kg	# palm^{-1}		%	mm	t ha^{-1}	kg	# palm^{-1}		%
Zero irrigation + zero fertilizer (I0F0)	735	24.6 (3.0)^{1}	22.5 (1.1)^{2,3}	7.7 (0.6)^{2,3}	5.7 (0.7)^{2,3}	58 (2.6)^{2,3}	709	27.5 (3.5)^{a}	19.1 (1.3)^{a,2}	10.1 (0.8)^{2}	4.1 (0.2)^{2,4}	71 (2.0)^{2,4}	735	27.9 (2.5)^{c,1}	19.4 (2.6)^{3}	10.1 (0.7)^{3}	2.8 (0.2)^{c,3,4}	79 (1.3)^{a,3,4}
Zero irrigation + fertilizer (I0F1)		24.7 (1.6)^{1,2}	22.4 (1.5)^{3}	7.8 (0.9)^{2,3}	6.5 (1.5)^{2,3}	55 (4.5)^{2,3}		31.5 (3.5)^{2}	20.6 (1.8)	10.7 (1.1)^{2}	4.4 (0.6)^{2,4}	71 (1.8)^{2,4}		27.9 (2.6)^{d,1}	18.9 (2.4)^{3}	10.5 (1.5)^{3}	3.2 (0.4)^{3,4}	77 (2.5)^{3,4}
Irrigation + zero fertilizer (I1F0)	96	24.0 (2.5)^{2,3}	21.1 (1.5)^{1,2}	8.0 (1.4)^{2,3}	6.4 (0.9)^{2,3}	56 (4.1)^{2,3}	80	29.1 (3.9)^{2}	19.0 (1.2)^{b,2}	10.7 (1.0)^{2}	4.2 (0.4)^{2}	72 (1.5)^{2}	331	28.5 (3.2)^{a,3}	18.6 (1.2)^{1}	10.7 (1.2)^{3}	3.6 (0.9)^{c,3}	75 (3.3)^{a,3}
Irrigation + fertilizer (I1F1)		24.3 (1.2)^{2,3}	22.7 (1.2)^{1}	7.5 (0.3)^{2,3}	6.2 (1.9)^{2,3}	56 (7.7)^{2,3}		32.0 (3.1)^{a,2}	20.8 (1.3)^{a,b,1}	10.8 (1.0)^{2}	4.0 (0.8)^{2}	73 (1.8)^{2,4}		32.6 (2.4)^{a,c,d,3}	20.8 (0.9)	11.1 (1.3)^{3}	3.4 (0.3)^{3}	77 (1.0)^{3,4}

^{a,b} Indicates a significant difference at $P \leq 0.10$ between treatment means.
^{c,d} Indicates a significant difference at $P \leq 0.05$ between treatment means.
^{1} Indicates a significant difference at $P \leq 0.10$ between project years.
^{2,3,4} Indicates a significant difference at $P \leq 0.05$ between project years.

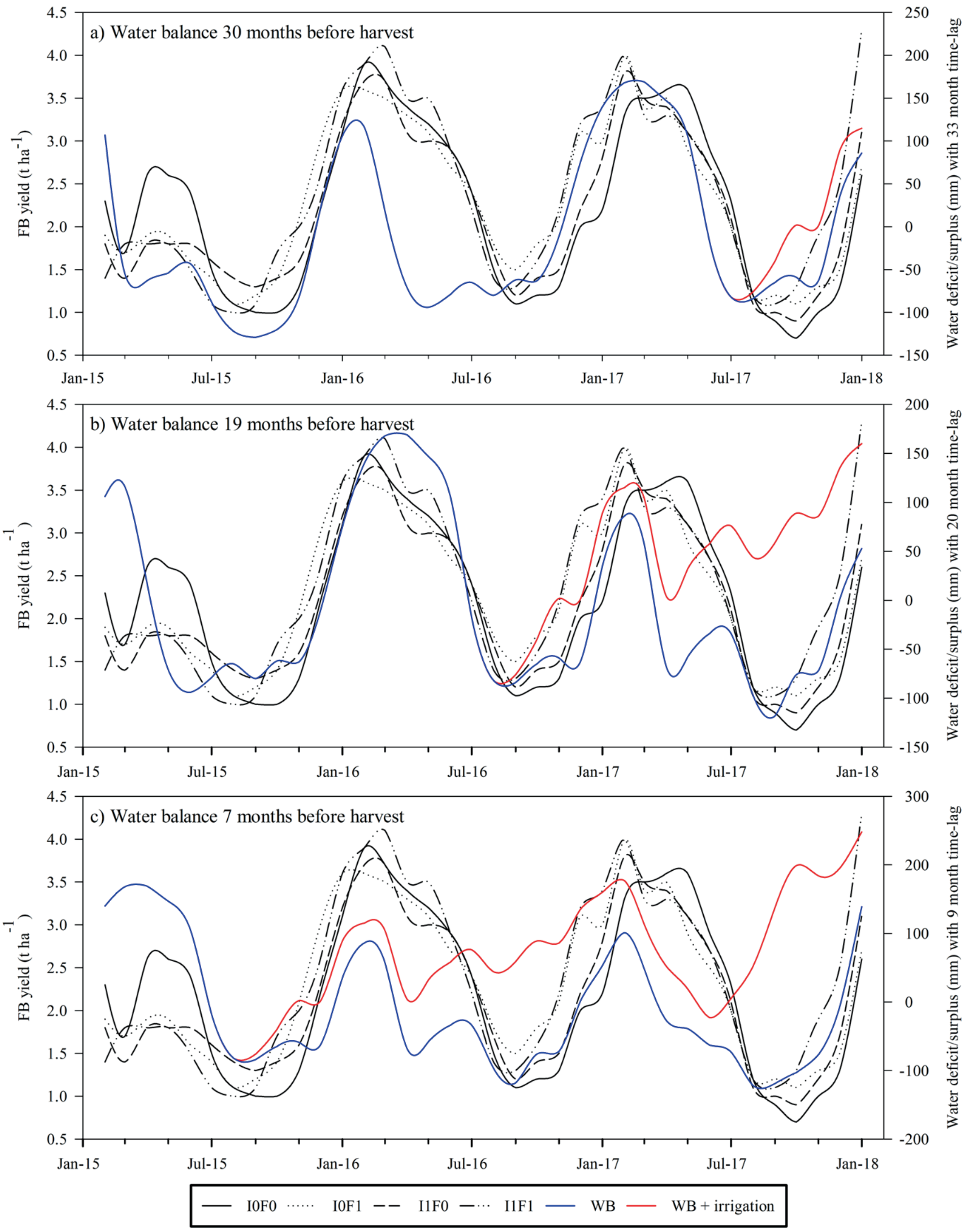


Fig. 5.6. The relationship between three-month rolling averages for monthly fruit bunch (FB) yield (t ha^{-1}) and three periods of sensitivity to water stress before harvesting: a) 30–33 months before harvest in which sex differentiation occurs, b) 19–24 months before harvest, which corresponds to the fast growth of the leave supporting the inflorescence, and c) 7–13 months before harvest, which is the aborting period (Caliman, 1998) for irrigated (I1F0, I1F1) and non-irrigated (I0F0, I0F1) treatments.

Additionally, multiple linear regressions suggested that the period corresponding to bunch abortion (7–13 months before harvest) gave the least significant prediction of yield for all treatments (Table 5.2). The main sensitive phase for drought effects was estimated to be 30 months before bunch harvest (i.e. the period of inflorescence sex determination) for all treatments except the control. This is in line with results reported by Legros et al. (2009), but in contrast to results reported by Dufour et al. (1988) and Caliman and Southworth (1998) where the period associated with bunch abortion had the greatest impact on yield.

Repeating both analyses, including the effect of irrigation on the water balance, showed a weaker coefficient of determination (R^2), suggesting that irrigation did not influence yield cycles in irrigated plots and that environmental factors other than rainfall may also contribute to yield oscillations (Corley and Tinker, 2016).

5.3.3 Leaf nutrient concentrations

There were no significant differences ($P \leq 0.05$) between average leaf nutrient concentrations for nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and boron (B) for all treatments and years, except in year 2 where leaf N concentration in I1F1 and I1F0 treatments was significantly larger ($P \leq 0.05$) than the I0F0 treatment, and where leaf K concentration in I1F1 was significantly larger ($P \leq 0.05$) than the I1F0 treatment (Fig. 5.7). All leaf nutrient concentrations increased from year 1 to 3, except for N, where a decline was observed (significant ($P \leq 0.05$) for the I1F0 treatment). The increase was significant ($P \leq 0.05$) for K for all treatments but I0F0, for Mg for the I0F0 treatment, and in all treatments for B. In year 3, N was within the optimal range for the I1F1 treatment, whilst all other treatments were deficient. P was only sufficient for the I0F0 treatment in year 3, whilst K was deficient in all treatments. All treatments were sufficient in Mg and B, in year 3.

No significant differences ($P \leq 0.05$) between average rachis nutrient concentrations for N, P, K and Mg were observed for all treatments and years, but for rachis N concentration in year 3 between the I0F0 and I1F1 treatment and for rachis P concentration in year 1 between the I1F0 and I1F1 treatment. Rachis N concentrations declined for all treatments from year 1 to 3, whilst rachis P, K and Mg concentrations increased for all treatments (significant ($P \leq 0.05$) for P and K, and for the I0F0 treatment in Mg). Rachis N concentration was deficient for all treatments, whilst rachis P, K and Mg were all sufficient in year 3.

Table 5.2. Simple linear regression model parameters for all treatments for three water-stress sensitive periods, and multiple linear regression for all treatments.

Treatment	Month	Model parameters: Simple linear regression	Model parameters: Multiple linear regression
I0F0	-31	R^2=.47, F(1,34)=29.868, P=0.000; y=2.226+0.007x	R^2=.71, F(2,33)=39.689, P=0.000; y=2.248+0.005(-31)+0.006(-20)
	-20	R^2=.48, F(1,34)=31.205, P=0.000; y=2.224+0.008x	
	-8	R^2=.25, F(1,34)=11.395, P=0.002; y=2.237+0.006x	
I0F1	-30	R^2=.52, F(1,34)=36.130, P=0.000; y=2.346+0.007x	R^2=.70, F(2,33)=37.031, P=0.000; y=2.353+0.005(-30)+0.005(-19)
	-19	R^2=.42, F(1,34)=24.717, P=0.000; y=2.310+0.007x	
	-7	R^2=.11, F(1,34)=4.127, P=0.050; y=2.305+0.003x	
I1F0	-30	R^2=.47, F(1,34)=30.149, P=0.000; y=2.249+0.007x	R^2=.69, F(2,33)=36.148, P=0.000; y=2.257+0.005(-30)+0.005(-19)
	-19	R^2=.46, F(1,34)=29.168, P=0.000; y=2.217+0.007x	
	-7	R^2=.14, F(1,34)=5.528, P=0.025; y=2.215+0.004x	
I1F1	-30	R^2=.47, F(1,34)=30.301 P=0.000; y=2.445+0.008x	R^2=.69, F(2,33)=36.731, P=0.000; y=2.454+0.006(-30)+0.006(-19)
	-19	R^2=.47, F(1,34)=29.572 P=0.000; y=2.408+0.008x	
	-7	R^2=.13, F(1,34)=4.878 P=0.034; y=2.404+0.004x	

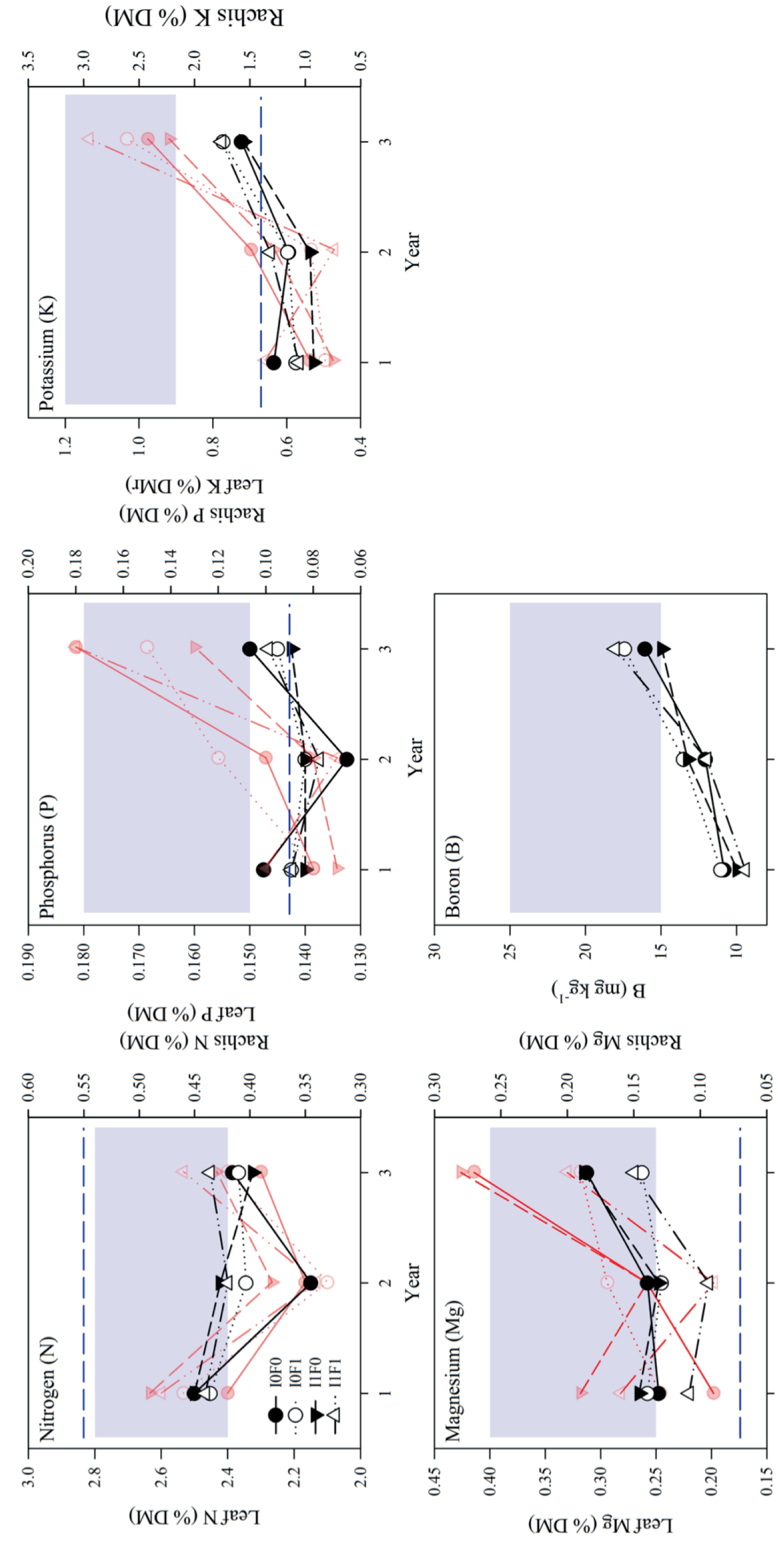


Fig. 5.7. Leaf (dark lines) and rachis (red lines) nutrient concentrations for irrigated (I1F0, I1F1) and non-irrigated (I0F0, I0F1) treatments for project years 1, 2 and 3. The blue shaded area indicates the optimum leaf nutrient concentrations (Fairhurst and Mutert, 1999) and the blue dashed line the critical rachis nutrient level (Foster and Prabowo, 2006).

5.3.4 Physiological measurements

The maturation time and accumulation of unopened leaves (spears) in the crown are direct physiological responses to water stress. Whilst no clear relationships were found between time of maturation and the actual water balance (no time-lag included), data suggests a shorter bunch maturation time and an increase in the accumulation of unopened leaves in the crown following periods of water stress (particularly after the long dry season from December–February) for the I0F1 treatment (Fig. 5.8). A shorter maturation time is likely caused by an increase in ethylene production initiated by water stress (Abeles et al., 1992), which could accelerate fruit ripening. It is known that variations in maturation time and frond production rate exacerbate production irregularities (Nouy et al., 1999). During the dry season, leaflets often accumulate as unopened spears in the palm crown whilst the bunch maturation time is shorter. Frond production rate therefore shows a clear seasonality in West Africa, with a minimum during the dry season and a maximum immediately after the dry season (Corley, 1977). Thus, after the rains have started, a flush of leaf opening is commonly observed (Carr, 2011). However, no significant differences ($P \leq 0.10$) were found for the average maturation time between treatments for year 2.

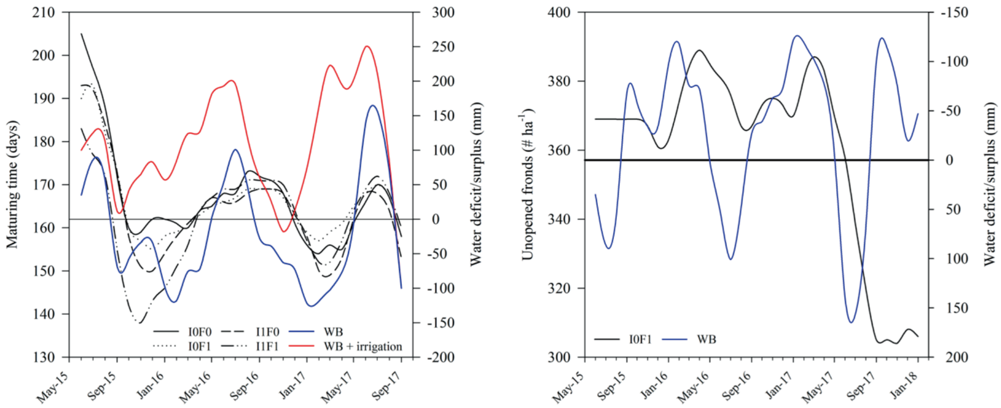


Fig. 5.8. Three-month rolling averages for a) maturation time (the time between anthesis to ripeness in days) for irrigated (I1F0, I1F1) and non-irrigated (I0F0, I0F1) treatments, plotted with the actual water balance (WB) and b) the number of unopened fronds (# ha^{-1}) for the I0F1 treatment plotted with the water balance in reverse order. The graphs suggest a shorter bunch maturation time and an increase in the accumulation of unopened leaves in the crown under periods of water stress, although no clear correlations were found.

5.3.5 Yield gaps

Oil palm is in the plateau yield phase at 16 years after planting (YAP), with the nutrient-limited yield (*Yn*) estimated at 28.5 t ha^{-1} FB, the water-limited yield (Yw) at 27.9 t ha^{-1} FB and the potential yield (*Yp*) at 32.6 t ha^{-1} FB. The average *Yw* was similar to the average *Yw* in the plateau yield phase (26.6 t ha^{-1} FB) reported in Chapter 3, which was determined from yield data across 23 trial sites in the oil palm belt of Ghana. Short-term yield gaps caused by nutrients (YG2) were estimated to be 4.1 t ha^{-1} FB, while yield gaps caused by water and water + nutrients (YG1, YG3) were both estimated to be 4.7 t ha^{-1} FB.

5.4 Discussion

5.4.1 Water and nutrient-limited yield gaps

We investigated the short-term fruit bunch yield performance of mature oil palm under several fertilizer and irrigation treatments. Because of the long time-lag between sex-differentiation of the inflorescences and harvesting of ripe fruit, it is only possible to begin to assess the effectiveness of irrigation and fertilizer after 28 months, provided it is sustained over the whole time period (Carr, 2011). The full treatment response is therefore only expected in the third year after trial implementation. Compared with the control treatment (I0F0; 27.9 t ha^{-1} FB), the I1F1 treatment increased fruit bunch yields by 4.7 t ha^{-1} while the effect of irrigation alone (I1F0) was 0.6 t ha^{-1}, indicating that fertilizer was critical for a maximum response to irrigation. This is similar to findings reported by Tittinutchanon et al. (2008) where fertilizer was essential for maximizing yields with irrigation. The benefit of adding fertilizer with irrigation was therefore estimated at 4.1 t ha^{-1} FB, which is approximately 0.9 t ha^{-1} crude palm oil (CPO) at 21% oil extraction rate (OER).

Leaf nutrient concentrations are known to vary due to a wide range of factors, such as rainfall, soil type and fertilization (Fairhurst and Mutert, 1999). Clear trends were found in leaf and rachis nutrient concentrations in all treatments, including a decrease in N concentration and an increase in all other nutrient concentrations from start to end of the experiment. Whilst treatments did not have a clear significant effect on nutrient concentrations by year 3, leaf nutrient concentrations for N, K and B were largest in the I1F1 treatment and largest in the I0F0 treatment for P. By comparison, Cheng-xu et al. (2011), found that water and nutrient stress decreased leaf N and P concentrations in oil palm seedlings, but increased K concentration compared with irrigated treatments. Lee et al. (2011), on the other hand, found lower leaf nutrient concentrations for N, P, K and Mg in irrigated palms ≥5 YAP, but higher rachis nutrient concentrations, particularly for K and B, and a larger storage of rachis P, K, S and B contents (due to a larger increase in dry matter) (Lee et al., 2014). Lee et al. (2011) suggests that higher yields with irrigation demands larger amounts of plant nutrients to support optimal growth and yield, which is reflected by lower leaf nutrient concentrations. Furthermore, leaching losses of soluble nutrients K and Mg are expected to be higher with irrigation as well (Lee et al., 2011).

Despite efforts to ensure nutrients were non-limiting with fertilization, leaf nutrient concentrations for P and K were deficient in all treatments, whilst rachis P, K and Mg concentrations were excessive, indicating a nutritional imbalance in the palm. Particularly for P and K, rachis concentrations were largest with the I1F1 treatment, supporting the hypothesis that palms grown under more favourable conditions have higher rachis nutrient concentrations and are able to store larger amounts of nutrients (Lee et al., 2014). Given the nutritional imbalance between the leaf and rachis, it is therefore essential to consider the nutrients stored in the reserve tissues (i.e. rachis) as well as the leaf while preparing fertilizer recommendations (Foster and Prabowo, 2006). For example, to increase a deficient concentration of leaf P, if rachis P is satisfactory, an increase in either fertilizer N or fertilizer K is generally effective, depending on whether N or K is most deficient. To increase a deficient concentration of leaf K, if rachis K is satisfactory, an increase in fertilizer N is generally effective (Foster and Prabowo, 2006). Given these complex interactions, determination of the specific nutrients and optimal application rates following a 4R Nutrient Stewardship (IPNI, 2012) approach with and without irrigation requires further research.

Because the yield in the control treatment (I0F0) improved from year 1 to year 3 (Table 5.1), it is likely that the actual yield response with irrigation and fertilizer was underestimated. Yield improvements were most likely due to better management in trial plots, but it is also possible that water and nutrient poaching from neighbouring plots occurred, since oil palm roots can spread laterally up to 25 m from the trunk (Carr, 2011). The I0F0 average yield for year 1 therefore provides a better baseline for the water- and nutrient limited yield, giving a YG3 of 8.0 t ha^{-1} FB. For comparison, Tittinutchanon et al. (2008) reported fruit bunch yield increases of up to 10 t ha^{-1} (to 28 t ha^{-1}) with irrigation and high rates of fertilizer in Thailand, in a climate similar to that of Ghana. The increase in yield can be attributed to an increase in bunch number, with little to no effect of bunch weight. Increases in bunch number were, therefore, most likely caused by improvements in the sex ratio and a reduction in the abortion of immature inflorescences.

5.4.2 Understanding mechanisms that determine yield fluctuations

Results from the multiple linear regression indicated that the period associated with inflorescence sex determination was most sensitive to drought and likely to contribute most to yield oscillations in Ghana (Fig. 5.6). However, because of the unique vegetative structure of oil palm (stem and leaves) together with the long time-lag between floral initiation and fruit bunch harvest, causal links between environmental factors and yield are difficult to establish (Carr, 2011). Whilst the effects of water stress on oil palm are well known, the extent to which the monthly yield cycles are affected is poorly understood (Corley and Hong, 1982). The environmental factor most likely to explain yield oscillations in regions with severe and regular annual dry seasons is the soil water supply (Henson and Dolmat, 2004). However, because of the trial block's proximity to a river, it is likely that palms in all treatments had access to water in the dry season due to a high-water table, which can modify the actual water deficit (Caliman and Southworth, 1998). While piezometer readings indicate the existence of a water table ≥2 m (which was the limit of measurement) at the onset of the long rains, it is uncertain to which depth the palms extracted water exactly since no root profiles were done. Observations from the Ivory Coast, for example, have shown that palms can access water from the soil at a depth of at least 5 m (Caliman, 1992) and that large yields can be obtained under drier conditions when the lack of rainfall is compensated for by a high water table (Quencez et al., 1987). Given that all palms may have had access to groundwater, this suggests that yield cycles were not solely regulated by the soil water supply. In support of this, whilst irrigation ameliorated the water deficit and increased fruit bunch yields, the use of irrigation did not affect yield cycles (Fig. 5.6). This is consistent with findings reported by Chan et al. (1985), Foong and Lee (2000) and Kee and Chew (1991), suggesting that yield cycles are controlled by factors other than rainfall (Corley and Tinker, 2016).

Alternatively, Henson and Dolmat (2004) suggested that factors associated with dry conditions other than the soil water supply, such as high temperature, high atmospheric vapour pressure deficit and high evaporation rate may be involved in yield cycling; all of which correlate well with rainfall. In particular, the stomata are considerably sensitive to vapour pressure deficit; an increase in which causes the stomata to close, even when there is a good water supply (Caliman, 1992; Carr, 2011). Stomatal closure is therefore an important factor limiting photosynthesis and hence dry matter production in oil palm (Dufrene et al., 1990). Smith (1989), for example, showed that high atmospheric vapour pressure deficits may limit production even in parts of the world where oil palm do not normally suffer from water stress. While it can be expected that the use of sprinkler irrigation might overcome stomatal closure in dry air by wetting the soil surface, and humidifying the atmosphere, no evidence has been provided yet

(Tittinutchanon et al., 2008). It is therefore likely that atmospheric conditions were similar in the trial, but measurements of stomatal conductance or vapour pressure deficit are required to confirm this.

Annual cycles of meteorological variables other than rainfall may also contribute to yield cycle patterns. Henson and Dolmat (2004) demonstrated that it was possible to match oscillations in solar radiation and evaporation rate with annual yield using appropriate time lags, although the relationship may not be causal. Additionally, Legros et al. (2009), assumed that seasonal peaks of flowering in oil palm are controlled by photoperiod response within a phytomer, even at oil palm sites close to the equator. They further suggest these patterns are confounded with drought effects that affect fruit bunch yield with long time-lags, but results remain to be confirmed. Using a modelling approach, Combres et al. (2013) also suggested the involvement of photoperiod in bunch production dynamics, whilst Dufrene et al. (1990) observed that sunlight and vapour pressure deficit combined may explain variations in maximal yield between west Africa and southeast Asia. It is therefore possible that present monthly yield may be affected by multiple past stress events at different time lags before harvest, which complicates attempts to understand the effects of climate.

In the absence of external constraints, it has been proposed that yield cycles are regulated by endogenous mechanisms whereby current yield levels may impact future bunch number through sex differentiation and abortion (Corley, 1977). However, it has been argued that the time lags involved in these processes would not readily lead to annual yield cycles, unless abortion levels were high and sex differentiation occurred at a relatively late stage (Henson and Dolmat, 2004).

5.4.3 Managing oil palms under water stress

In West Africa, where rainfall patterns are characterized by a long and short rainy season and a long and short dry season, irregular patterns in production are typical. For all treatments ≥15% of the annual bunch production in year 3 was harvested in February, with as little as ≤4% in low crop months (Fig. 5.5). Understanding local yield cycles of oil palm is of economic importance, because the volume of fruit in the peak month determines the size of the mill, and hence the scale of investment, needed by a plantation (Corley and Tinker, 2016). Furthermore, irregular distribution of production has several consequences for plantation management, including lack of milling capacity during peak crop months and underutilization in the production trough, lack of sufficient harvesters in the peak months resulting in extended harvest intervals and crop loss, and fluctuations in fruit bunch oil content with in particular a sharp drop at the end of the dry season (Caliman, 1992; Nouy et al., 1999). Forecasting future yields on a monthly basis therefore helps plantation managers to better plan labour and milling requirements and is also useful to marketers as forward selling of palm oil is common (Corley and Tinker, 2016). Because climate is becoming increasingly unpredictable, the need for simple predictive models to forecast future yields will therefore become more essential in plantation management.

A practical way of reducing annual fluctuations in production is to plant a mixture of planting materials with different yield patterns (Corley and Tinker, 2016) as demonstrated in North Sumatra (Nouy et al., 1996) and Benin (Cros et al., 2013), implying that genetic diversity partly regulates the annual bunch production profile in oil palm, or by partially disbudding palms to shift yield peaks out of phase and reducing yield fluctuations of the area as a whole (Corley, 1977). Management implications to mitigate the effect of water stress on oil palm include the use of irrigation to correct water deficits, planting in sites with a high water table, adequate drainage to remove excess water, since prolonged flooding is known to reduce stomatal conductance and gas exchange processes (photosynthesis and transpiration) and to kill young palms (Lamade et al., 1998), preventing water runoff on sloping terrain (e.g. contour planting, terraces, appropriate frondstacking techniques), improving structure in compact soils to allow for better root development, mulching with organic materials (e.g. empty fruit bunches) to reduce soil surface evaporation and removal of inflorescences on young oil palms to stimulate root development and improve drought tolerance (Caliman, 1992; Carr, 2011). Furthermore, potassium (K) is an essential macronutrient needed in large amounts by oil palm and is directly involved in several physiological processes, including transport of assimilates and stomatal regulation (Taulya, 2013). K is therefore essential in avoiding water loss during water stress situations. Maintaining adequate plant K with balanced fertilization is thus important for plant drought resistance (Wang et al., 2013).

5.5 Conclusions

Results of the trial show the potential of irrigation and fertilizer to close yield gaps in mature oil palm stands in Ghana. Average FB yields of 32.6 t ha^{-1} were obtained with a combination of irrigation and fertilizer, while FB yields with irrigation only averaged 28.5 t ha^{-1} FB. The benefit of adding fertilizer with irrigation was therefore estimated at 4.1 t ha^{-1} FB, which is approximately equivalent to 0.9 t ha^{-1} crude palm oil (CPO) at 21% oil extraction rate (OER). Fertilizer was therefore essential for a maximum response to irrigation, but information on which nutrients are most important and optimal application rates are lacking to ensure balanced nutrition in oil palm with irrigation. While yield increases were mostly caused by increases in bunch number, annual yield cycles persisted despite the use of irrigation. Irregular distribution of production leads to lack of mill capacity and insufficient harvesters in the peak crop months. Many factors have been proposed that cause these fluctuations, both external and endogenous, indicating a complicated interaction of several components. Yield cycles and yield-determining process(es) therefore remain unclear and require further research.

5.6 Acknowledgements

We thank the management and staff of Norpalm Ghana Ltd. for their support and management of the trials. We also thank Chris Donough for his early comments on the trial protocols , Yuval Levi (Dizengoff Ghana Ltd.), Wim Rhebergen and Paul Schofer for their contributions in designing the irrigation system, Rob Verdooren for his assistance with the statistics and Lotte Woittiez for her helpful comments. Special thanks goes to Solidaridad West Africa for funding the trial.

CHAPTER 6

General discussion

6.1 Introduction

In the early 2000s, the oil palm (*Elaeis guineensis* Jacq.) sector in Ghana developed extensively, partly due to a growing interest of investors to expand and develop the area planted to oil palm. As a result, Ghana became the third largest producer of palm oil in Sub-Saharan Africa in 2017 at 2.5 Mt yr^{-1} (next to Nigeria (7.8 Mt yr^{-1}) and Cameroon (3.1 Mt yr^{-1})) (FAO, 2019), with oil palm the second most important perennial crop in the Ghanaian economy after cocoa (Ofosu-Budu and Sarpong, 2013). Despite large increases in production the past 15 years, fruit bunch (FB) yields remained low (Fig. 6.1, FAO, 2019). With an estimated water-limited yield potential of 21 t ha^{-1} FB (Chapter 3), and actual yields of 11.0 t ha^{-1} on plantations and 6.0 t ha^{-1} on smallholder farms in Ghana (Chapter 3, 4), large yield gaps exist.

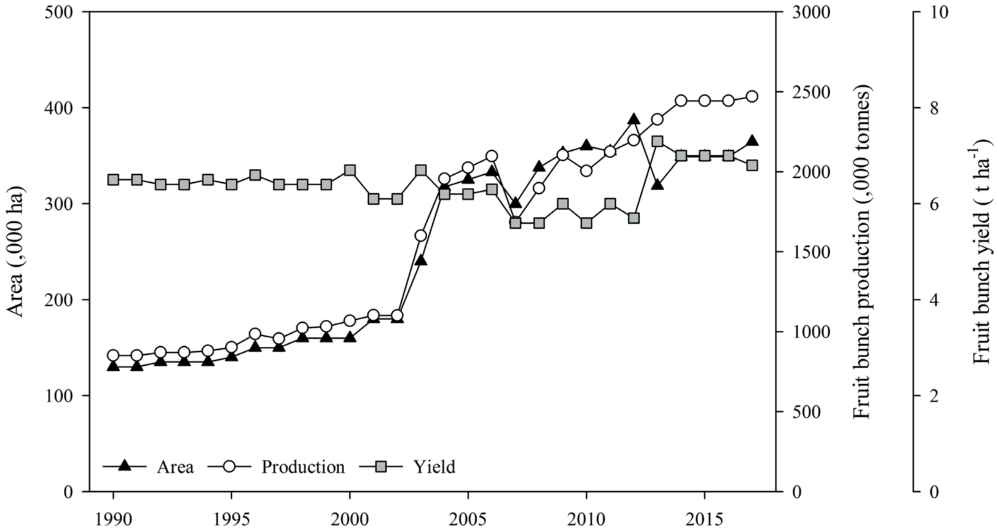


Fig. 6.1. Changes in the area (ha) under oil palm cultivation, bunch production (tonnes) and fruit bunch yield (t ha^{-1}) in the Ghanaian oil palm industry from 1990 to 2017 (FAO, 2019).

Although the oil palm's origin lies in West Africa (WA), larger yields are achieved outside its natural habitat, such as in Southeast Asia and Latin America (Fig. 1.1c). While differences in climatic conditions (e.g. rainfall, solar radiation) and management practices can be attributed to this yield variability, there have always been many misconceptions on the yield potential and its key drivers in WA. Before we initiated our work in Ghana, we had a poor understanding of the oil palm sector in the region, which was partly due to the limited amount of published work on oil palm in WA the past two decades. With this work, we therefore provide an up-to-date understanding of the state of oil palm in Ghana, that can be useful to guide decisions and investments in the West African region.

At the core of the project was obtaining a reliable estimate on the yield potential of oil palm in Ghana. This was essential to analyse yield gaps and their drivers at plantation and smallholder oil palm production systems, and to develop an approach for yield intensification. Using early publications (e.g. van der Vossen (1969)) and (more recent) production data from oil palm plantations in Ghana, we estimated the maximum yield in the plateau phase (PYP) at 18 t ha^{-1} FB at project start. However, results from our trials far exceeded expectations, with yields approaching 28 t ha^{-1} FB at the best performing BMP sites. It was therefore fundamental to our research to develop a framework for yield gap analysis in oil palm, to allow for a systematic diagnosis of production constraints and to assess opportunities for increasing yields with Best Management Practices (BMPs).

Using Ghana, this thesis aimed to elucidate the factors that currently limit oil palm production in West Africa, by evaluating agronomic factors, and to adopt BMPs as a measure for yield gap reduction. The agro-ecological conditions that determine the suitability and availability for its cultivation are dealt with in Chapter 2, and causes for low productivity amongst various production systems in Chapter 3. In Chapter 4, we investigated the potential for yield intensification with improved agronomic practices, and in Chapter 5 we assessed the effects of water and nutrient management on oil palm yields. While detailed discussions are provided in each chapter, the main purpose of this discussion is to integrate findings from the different chapters, and to generate insights for sustainable intensification of the oil palm sector in a West African context.

6.2 Water and nutrients limit oil palm cultivation in Ghana

6.2.1 Water limitations

Compared with regions in Southeast Asia that receive high and regular rainfall (e.g. parts of North Sumatra, Indonesia and Sabah, Malaysia), the climate in WA is marked by regular dry seasons (Carr, 2011). In the oil palm belt of Ghana, for example, a short dry spell occurs in August and the long dry season between December and February. A key constraint to oil palm cultivation in Ghana, as in many other parts in WA, is therefore the annual water deficit, which can result in a large Yield Gap 1 (Fig. 3.2). This is likely to be aggravated in the future due to climate change induced droughts.

Water stress in oil palm reduces the yield potential and partly influences the distribution of yield during the year. In countries such as Malaysia, seasonal changes are less distinct, and yields are relatively uniform throughout the year. In contrast, in regions where there is marked dry season, such as in Ghana, yield peaks are larger (Fig. 5.5), which can result in several harvesting and processing implications (section 1.3). Irrigation is often recommended as an option to mitigate the effect of water stress on oil palm, and it is likely to become increasingly relevant due to projected increases in the frequency and intensity of droughts and due to oil palm cultivation expanding into drier areas (Woittiez et al., 2017). While the effects of drought on oil palm are well known, there is limited reliable data on actual yield responses to irrigation (Carr, 2011).

In the irrigation trial installed in Western region, Ghana, large yield increases with irrigation and fertilizer were achieved, whilst seasonality in production persisted (Fig. 5.6). The average yield response to irrigation and fertilizer over a three-year period was 32.6 t ha^{-1} FB (Table 5.1). The yield gap caused by nutrients (YG2) was estimated at 4.1 t ha^{-1} FB and 4.7 t ha^{-1} FB for water. The response to irrigation alone was therefore 0.6 t ha^{-1} FB, indicating that fertilizer was essential for increasing yields with irrigation. Whilst the scale of the trial was too small to allow a full cost-benefit analysis, assuming high capital costs (US$2,500 ha^{-1}) and running costs (US$150 ha^{-1} yr^{-1} (450 l $palm^{-1}$ day^{-1} irrigation)) for sprinkler irrigation (Tittinutchanon et al., 2008; numbers corrected for inflation), the yield increase with irrigation alone is likely not profitable, whilst combined with fertilizer, irrigation is likely to provide considerable increase in profits.

Whilst fertilizer is essential with irrigation, fertilizer *requirements* supplemented with irrigation need further investigation. Because the yield response is expected to be larger with irrigation than without irrigation, fertilizer rates are likely to be larger as well. Also, which nutrient(s) are critical with irrigation remains uncertain (Tittinutchanon et al., 2008). Because the response to irrigation may differ between locations, depending on the severity of moisture stress, and whether dry seasons occur annually (e.g. West Africa), or at irregular intervals (e.g. Indonesia) (Carr, 2011), the costs and benefits of different irrigation regimes (with and without fertilizer) under a range of environmental conditions therefore need further investigation (Woittiez et al., 2017). Where irrigation is not profitable, drought mitigation strategies, such as selecting sites with a good water holding capacity, mulching with organic materials, and reducing plant populations can be considered instead (Carr, 2011).

6.2.2 Nutrient limitations

A second constraint to oil palm production in Ghana is poor nutrient management. Soil and leaf analysis data (Table 3.2, Table 3.3) showed that there are also considerable nutritional constraints, particularly phosphorus (P) and potassium (K), that must be addressed to close Yield Gap 3 (Fig. 3.2). This was mainly caused by low fertilizer applications in plantations, whilst smallholder farms applied no fertilizers at all (Table 3.4). Particularly in Ghana’s drought-sensitive climate, K is likely to be critical because it mitigates the impact of water-stress through osmotic adjustment (Taulya, 2013). Improved K management on K-deficient soils is therefore likely to improve productivity and enhance water use efficiency of Ghana’s rain-fed oil palm plantings. Development of new improved fertilizer recommendations is therefore essential to increase yields and to sustainably intensify oil palm production in Ghana. In Southeast Asia for example, fertilizer trials have given planters useful information on the site-specific estimates of fertilizer requirements for oil palm based on leaf nutrient values from analysis. This information however, is currently still lacking for Ghanaian oil palm production systems.

In this research, we assessed the nutritional status of the palm, as well as fertilizer needs, by comparing leaf nutrient concentrations to reference leaf critical levels accessed through literature. Whilst the use of leaf nutrient concentrations in oil palm fronds are important diagnostic tools to assess nutrient requirements, leaf nutrient contents may not have general applicability (Fairhurst et al., 2004). Optimum, or critical values for individual nutrients can vary over a considerable range, depending on such factors as the age of palms, soil moisture regime, soil type, ratio to other nutrient concentrations, type of planting material, spacing, and inter-palm competition (Fairhurst and Mutert, 1999). For a more accurate and economical management of fertilization, it is therefore desirable that the results of fertilizer trials are available for major soil types across the oil palm belt so that the optimum leaf level can be defined in the light of the ecological conditions, the nature and age of the palms and the most economic fertilizer rates (Ochs and Olivin, 1977). In order to provide adequate fertilizer recommendations for future oil palm production in WA, multi-factorial, multi-locational nutrient response trials across different environments and production phases are required, as well as nutrient omission trials to identify the nutrients that limit crop growth most. The interaction between potassium nutrition and drought stress deserves particular focus as this provides a mechanism for adaptation to climate change and to increase yields.

6.3 Increasing production with sustainable yield intensification

Despite persisting water and nutrient limitations, it was possible to achieve large yields at plantations and smallholder farms through ‘Best Management Practices’ (BMPs), with improvements in crop recovery (yield taking) and agronomy (yield making) (Table 4.1). Particularly, crop recovery was fundamental for achieving high yields, which was achieved with improved field access at smallholder farms and more frequent harvesting events at plantations. Because oil palm continuously produces bunches, complete crop recovery must be maintained throughout the year to avoid crop losses. As soon as harvest intervals extend beyond 10 days, there will be crop loss because a proportion of the crop is either over-ripe or rotten at harvest (Fairhurst and Griffiths, 2014). However, maintaining short harvest intervals is problematic for plantations, particularly in the peak crop months when labour availability is short.

Most plantations in Ghana rely on the extensive use of hired labour (Gyasi, 1996), which is usually sourced through contractors. During the lean season, the number of harvesters is reduced due to low bunch availability. Also, since harvesting-work is paid by piece-rate, and low crop densities result in lower earnings, many workers chose to work elsewhere instead. In contrast, more labour is required during the peak crop months, in order to meet FB production. However, plantations often struggle to find sufficient labour for harvesting during the peak crop months, resulting in significant crop losses. Efficient use of labour for harvesting therefore poses many operational and logistical challenges for plantations throughout the production cycle. A good balance between labour requirements and expected crop losses must therefore be considered. At the same time, seasonality in production poses other challenges, such as insufficient milling capacity in the peak, and underutilization of the mill in the lean season due to low crop harvests.

6.4 Labour limitations

A major reason to why BMPs were not fully implemented or sustained (Appendix 11), was the high reliance on sufficient (skilled) labour to maintain good standards, which was lacking at times throughout the project. Although oil palm plantations offer abundant employment opportunities, the work is not very attractive, since the tasks are perceived as arduous and dangerous, particularly harvesting (Ismail, 2013). The isolation of plantation life, unattractive terms and conditions provided to workers (e.g. low wages), and competitiveness from other employment opportunities in large-scale agri-businesses and mining might also play a role in labour shortages.

A possible solution is to reduce labour requirements and workload through mechanisation of certain field operations, such as harvesting and FB collection, to make the work more attractive. Devices related to crop collection and transport (e.g. mechanical grabber, compact transporter, mechanical buffalo, battery-powered wheelbarrow, loose fruit collectors) and the development of lighter, powered and more ergonomically efficient fruit cutters, increase labour productivity, and decrease the cost of production, whilst improving the health and safety of the workforce (Anon, 2004; Jayaselan and Ahmad, 2011; Murphy, 2014; Shuib et al., 2010; Teo, 2000). Currently, little to no mechanisation is used in plantations in Ghana.

Although the mechanization of the oil palm sector has progressed well over the years, there is still room for improvement (Shuib et al., 2010). R&D efforts on mechanization should therefore be increased, particularly on the process of fruit bunch harvesting, since this includes a number of steps that are difficult to mechanize (e.g. assessment of FB ripeness, cutting a heavy fruit bunch and its subtending frond at a height of 10–20 m) (Murphy, 2014). Alternative efforts include redesigning the architecture of the oil palm where advanced breeding might be used to develop high yielding palms with greatly reduced height to facilitate access and harvesting of fruit bunches instead

(Arolu et al., 2016; Murphy, 2009). Short to dwarf palms may offer other potential benefits as well, including higher planting densities (and thus larger yields), resulting in more efficient land use, and a longer economic life due to a slower growth, thus reducing costs associated with new plantings (Zulkifli et al., 2017). However, efforts to produce palms with these traits are still ongoing.

Whilst mechanisation offers perspective for the oil palm industry in Ghana, it should be pursued with caution. The oil palm industry provides the means to generate significant economic and social development, by providing employment to a large number of the rural population. Whilst oil palm plantations struggle with labour shortages, the introduction of mechanization to reduce labour dependency could be perceived as a threat to plantation workers. While this is true to a certain extent, more correctly, mechanization is aimed at increasing productivity with the same number of workers, by reducing the workload, so that the worker can work at a faster pace and cover a bigger area (Anon, 2004; Shuib et al., 2010). The social context and sensitivity of the labour force therefore needs careful consideration. Depending on how management approaches the subject, local plantation workers could either embrace or dismiss mechanization. Consultation, education and illustrations on the advantages of mechanization take time. A well-planned and coordinated programme is therefore a prerequisite to successful implementation of plantation mechanization (Anon, 2004). Taking this into account, mechanization is likely to be more readily (socially) accepted.

6.5 Sustainable intensification in oil palm should focus more on increasing oil yields

Whilst the BMP approach is designed to increase the yield of oil palm through the production of more fruit bunches per unit of land, the final economic product is crude palm oil (CPO). CPO yield depends on the quantity and weight of fruit bunches harvested (and loose fruit collected), as well as the oil and kernel content of these bunches. Yield intensification strategies should therefore not only focus on increasing FB production, but also the oil extraction rate (OER) of FB.

Oil content is affected by a number of factors, including planting material (*dura* has an OER of 16–18%, whereas the *tenera* hybrid has an OER of 22–30%), fertilization (Mg fertilization increases oil content, while K fertilization (sometimes) decreases oil content (Ochs and Ollagnier, 1977)), and is negatively correlated with rainfall, and positively correlated with available radiation (Woittiez et al., 2017). The oil content therefore depends on site-specific factors, and is to some extent influenced by management practices. Research at a number of locations in Indonesia, for example, showed a reduction in OER with BMP (up to 1%), but total oil and kernel yields were still larger than standard estate practices due to better FB collection and reduced loose fruit losses (Donough et al., 2010; Oberthür et al., 2012). Whilst the effect of yield taking and yield making effects on OER was inconclusive, it is likely that a lower OER with BMP was caused by harvesting practices, where shorter harvest intervals (7 days) resulted in the collection of harvested bunches with less loose fruits (i.e. lower average ripeness).

Whilst a trade-off between higher FB yield with BMP or higher OER seems to exist, oil yield gains from increased FB were larger than the effects of BMP on oil and kernel extraction rates (Donough et al., 2010; Oberthür et al., 2012). It is therefore important to balance oil content (i.e. lower oil content with BMP leading to higher cost of production) and potential crop losses in the field (i.e. lower loose fruit losses with BMP increasing recoverable oil yield and thus revenue) (Donough et al., 2010). However, efforts to increase oil contents with management practices (such as fertilization) should be pursued, but with caution, so that increases in FB yields are not compromised. Alternative efforts should focus on increasing milling efficiency, particularly at small-scale processors (described in more detail in Chapter 3), and increasing smallholder access to improved varieties such as the *tenera* hybrid (Adjei-Nsiah et al., 2012a).

6.6 Seasonality in production persists despite appropriate management interventions

Even if the focus is on increasing oil yields and milling efficiency, seasonality in production persists (Fig. 5.5). While water supply is the most likely factor to explain annual cycles in production, results from the irrigation trial (Chapter 5) found no effect on yield cycles with supplemental irrigation (Chapter 5). Instead, it is argued that seasonal peaks in flowering might be controlled by day-length (photoperiod), even near the equator (Combres et al., 2013; Legros et al., 2009), and are confounded with drought effects. On the other hand, Henson and Dolmat (2004), suggest that factors associated with dry conditions such as high temperature, vapour pressure deficit and high evaporation rate are responsible for yield oscillations. Other authors propose that yield cycling in oil palm is partly a result of internal feedback mechanisms, whereby a current high yield leads to a future low yield and *vice versa* (Breure and Corley, 1992; Corley, 1977; Corley and Teo, 1975). Whilst conclusions on the primary cause of yield cycling may vary, efforts must continue to unravel the process(es) behind these yield cycles in order to more efficiently plan the milling process and labour requirements. Furthermore, multiple time-lagged stress events may affect current yields, which complicate unravelling the interaction between various climatic variables even more. Understanding the causes behind yield oscillations will give insight to whether this will be possible to manipulate through management interventions and whether it would be practical or not.

Much work on the effects of weather on FB yield has involved a search between correlations between climatic factors and yield components (Ong, 1982a; Ong, 1982b). However, the existence of a correlation does not necessarily indicate cause and effect, since it is almost inevitable that correlations between monthly means of two factors that both vary seasonally exists. Also, without prior knowledge on the time-lag and direction of the effect, a correlation may mean nothing (Corley and Tinker, 2016). Whilst simple linear regression showed large correlations between monthly yield and the water deficit with appropriate time-lags at the irrigation trial (Fig. 5.6, Table 5.2), Ong (1982b) notes that it can be misleading to study a particular climatic factor in isolation without considering the possibility of overshadowing effects by other climatic factors. Because climatic factors tend to be highly interrelated (White, 1979), (time-lagged) interactions between climatic factors should therefore be considered when analysing monthly yield oscillations.

Since controlled experiments in growth chambers are impractical in mature oil palm, the use of crop simulation models can offer insight into understanding the interaction between several components on yield. A challenge for oil palm (and other perennial crops), however, is evaluating model performance against observed results due to the lack of comprehensive yield data sets over a complete planting cycle (Hoffmann et al., 2014). While most models seek to limit the number of input data needed, they therefore do not fully explore the full range of environmental parameters and interactions that could potentially affect yield oscillations in oil palm. As indicated in Chapter 2, comprehensive climatic datasets across Ghana were also lacking, or difficult to find. While this issue was sought to overcome by installing automatic weather stations (Spectrum Technologies WatchDog 2000 Series) at all plantation sites and the Oil Palm Research Institute (OPRI), we experienced multiple breakdowns, resulting in the loss of significant data including measurements on solar and photosynthetic active radiation (PAR), relative humidity (RH) and temperate amongst others. Coupled with in-field measurements on stomatal conductance and vapour pressure deficit (VPD) at the irrigation trial at Norpalm Ghana Ltd. (Chapter 5), this would have been valuable information to understanding interactions between climatic variables on yield oscillations in Ghana. However, these measurements were unfortunately not taken due to budget and logistical constraints.

6.7 Reflections on my PhD research

Looking back on my research, *yes*, I would have done things differently with the knowledge that I now have. Most changes would not concern the *setup* of the trials or BMP work, but would be mostly related to the *scale* of implementation. For example, I would have liked to add a greater number of BMP sites in different stages of production and installed more fertilizer and irrigation trials across a larger range of environments. Unfortunately, due to budget and time constraints, as well as the local capacity needed to run oil palm trials in good order (e.g. skilled technicians, high turnover in trial managers), this was not possible.

Since management practices depend also on the age of the palm, having more BMP sites in different stages of production (i.e. steep ascending yield phase, plateau yield phase, declining yield phase) would have allowed for a more detailed yield gap analysis across a range of agro-ecological conditions and a more accurate assessment of the production constraints within each age group (Chapter 3, Chapter 4). This would have been very valuable information for oil palm practitioners in Ghana. My research looked only at yield gaps and production constraints across the entire planting cycle, since I did not have enough replications within each production phase for a strong statistical analysis.

The irrigation trial (Chapter 5) was installed in close proximity to a river, so the likelihood that this affected treatment yields is quite large. The decision to install the trial at that particular location, however, was driven more by practical considerations and budget constraints. Preferably, the trial would have been located further from the river to minimize its influence. Furthermore, I would have implemented the trial at the block level, instead of embedding plots in one plantation block. This would have greatly reduced the need to install trenches and the likelihood of water and nutrient poaching between treatments. However, these requirements would have added significantly to the budget, as more pipework and a more powerful pump would have been needed.

Oil palm is a crop that takes time to learn and understand. New research ideas arise constantly, but implementing them is time-consuming. Since a PhD program is 4 years and oil palm has a time-lagged response of 35–40 months to management interventions, implementing new agronomic trials along the way was in most cases already too late to ensure a significant yield response within my PhD research. A clear understanding of the crop and research objectives is therefore required at the very beginning.

6.8 Implications of my research at the broader scale

6.8.1 Increasing production through area expansion or yield intensification?

Currently, agricultural expansion poses a serious threat to natural ecosystems worldwide and is expected to increase over the next 50 years (Tilman et al., 2001). During the past few decades, oil palm has become one of the most rapidly expanding crops worldwide (Fitzherbert et al., 2008; Koh and Wilcove, 2008), and has often become the subject of international protest due to its impact on deforestation. As available land becomes increasingly scarce in the traditional production centres in Southeast Asia, oil palm production is expanding rapidly across tropical regions in Latin America and Africa (Hansen et al., 2015; Laurance et al., 2010).

Whilst expansion of oil palm plantations is often linked to deforestation, a recent study shows that the proportion of plantations replacing forests across Indonesia's major oil palm producing islands of Sumatra, Kalimantan and Papua decreased from 54% during 1995–2000 to 18% during 2010–2015 (Austin et al., 2017). In another study, Fitzherbert et al. (2008) indicates that forest conversion to oil palm accounted for at most 16% of deforestation between 1990–2005, while Koh and Wilcove (2008) suggest that oil palm expansion accounted for at least 50% of deforestation in Malaysia and Indonesia during the same time period. According to Fairhurst and Härdter (2003), only 7.6% of deforestation between 1990–2000 can be attributed to oil palm, while Vijay et al. (2016) reveals that 45% of oil palm plantations in Southeast Asia came from areas that were forests in 1989, 31% in South America, and 2% and 7% for Mesoamerica and Africa respectively. The exact percentage of forest conversion to oil palm is therefore debatable and depends largely on the (quality) of data used, the inclusion of immature area in the analysis, as well as the history of land-use previous to oil palm (e.g. some oil palm plantings have been established on land previously occupied by rubber and grassland) (Fairhurst and Härdter, 2003; Wicke et al., 2011). Although the extent to which oil palm has been a direct cause of past deforestation is difficult to quantify, its potential to contribute to future deforestation is considerable (Fitzherbert et al., 2008). This raises major conservation and environmental concerns.

Despite much international scrutiny, the expansion of land to increase production is likely to continue for many years due to an increasing global demand for palm oil. It is therefore imperative to find and implement solutions for agriculture and biological conservation to co-exist. A valuable approach to assess strategies for increasing food production whilst minimizing the negative consequences for biodiversity is the land sparing-sharing model (Green et al., 2005). In land sparing, homogeneous areas of farmland are managed to maximize yields, while separate reserves target biodiversity conservation. In contrast, wildlife-friendly farming, or land sharing, integrates conservation and production within more heterogeneous landscapes, often resulting in lower yields (Green et al., 2005). Baudron and Giller (2014) note that both approaches have their benefits and disadvantages and should be assessed according to local circumstances. For oil palm agriculture, however, a number of studies suggest land sparing to be the best strategy in reconciling food production and biodiversity conservation (Edwards et al., 2010; Fitzherbert et al., 2008; Phalan et al., 2009; Phalan et al., 2011).

Compared with natural forests, oil palm plantations support little biodiversity (Butler and Laurance, 2009; Edwards et al., 2013; Edwards et al., 2014; Fayle et al., 2010; Fitzherbert et al., 2008; Koh and Wilcove, 2008; Mendes-Oliveira et al., 2017). Attempts to increase biodiversity within plantations following a land sharing approach, by retaining forest fragments within the oil palm matrix, proved ineffective in a number of studies (Edwards et al., 2010; Yue et al., 2015). They concluded that land sparing strategies by retaining contiguous forest would be the most effective approach for conserving biodiversity in an oil palm landscape. Phalan (2018) further notes that most species will have larger populations if food is produced on as small an area as possible, while sparing as large an area of native vegetation as possible and that the potential benefits of land sharing or intermediate strategies for wild species are more limited. In another study, Lee et al. (2014) indicated that oil palm expansion following a high-yielding land-sparing approach had less environmental costs than a land sharing approach in terms of forest conversion, greenhouse gas emissions and biodiversity losses, though the latter would be more favourable for socio-economic development by creating more employment opportunities.

Land sparing in oil palm could in theory be attained if yields are increased. Chapter 4, for example, shows that increasing average attainable yields at plantations and smallholder farmers to 21 t ha^{-1} FB could potentially reduce oil palm expansion in Ghana by almost 600,000 ha of land. Oil palm produces the highest oil yield and is the most resource-use efficient amongst the world's major oil crops (de Vries et al., 2010). Because of its high yield potential and low production costs (Fairhurst and Griffiths, 2014), oil palm uses land more efficiently than any other oil crop, thus rendering the crop particularly suitable for intensification (Corley, 2009). Yield intensification on land already planted to oil palm may therefore be an important policy for sustainable oil palm development in Ghana and West Africa.

However, intensification does not *per se* lead to land sparing for conservation. Most notably, intensification might create financial incentives for oil palm expansion if yield increases raise the opportunity costs for nature conservation, i.e. the potential income that is lost if land is not converted to oil palm (Laurance et al., 2014; Phelps et al., 2013).

Since oil palm is a highly profitable crop, the opportunity costs of not planting oil palm are substantial. Moreover, if the demand for palm oil is elastic, increasing yields can in effect increase production targets, thereby adding to the willingness to acquire more agricultural land (Green et al., 2005). For example, an increase in the supply of palm oil as a result from their use may not reduce palm oil prices, and the overall incentive for increasing production through cultivating more land remains. In contrast, a price decrease may also increase land expansion in order to maintain income (Baudron and Giller, 2014).

Inherent to land sparing, or yield intensification, is the high reliance on, and access to, modern agricultural technologies. In Ghana, for example, large yield gaps existed amongst smallholder farmers, due to a lack of knowledge on appropriate management practices, poor infrastructure and lack of access to credit to purchase agricultural inputs such as fertilizers (Chapter 3). Access to, and adoption of, modern agricultural technologies, such as the implementation of BMPs, is therefore essential to the land sparing approach, and needs to be managed adequately to minimize its environmental impact (Baudron and Giller, 2014). Key priorities to the land sparing approach are therefore to ensure improvement and adoption of agricultural technologies amongst oil palm producers, and implementation of policies that promote more ecologically efficient food production, while strategically optimizing the allocation of lands to conservation and agriculture (Laurance et al., 2014).

Recognizing the challenges around the global oil palm industry, oil palm plantations are looking for ways to produce palm oil in an environmentally and socially responsible way. A positive example are the current operations in Gabon. Gabon, a country covered with more than 76% in forest, with 11% of its land area protected in national parks, sees industrial agriculture as an important part of the nation's future, and has developed a national land-use plan that attempts to balance oil palm production and forest preservation. Cooperation between government, plantations and conservationists has shown that profitable farms, thriving rural communities and healthy ecosystems can coexist with good land-use planning (National Geographic, 2018).

Alternatively, oil palm expansion might be accommodated by targeting lands that have already been degraded, such as anthropogenic grasslands (Fairhurst and McLaughlin, 2009). Conversion of such landscapes to oil palm has shown to have limited negative impacts on biodiversity (Gilroy et al., 2015) and could potentially supply all the oil required for edible purposes in 2050, without any forest clearing (Corley, 2009).

6.8.2 Stronger collaboration between plantations and smallholders is required to increase production in Ghana

Area expansion is limited for large plantations in Ghana because of the lack of large contiguous tracts of land and complicated land tenure systems (Chapter 2). The major factor driving area expansion in Ghana is therefore not plantation development, but rather an expansion of the smallholder sector (Rhebergen et al., 2014). Because most large plantations in Ghana would like to increase their processing capacity, expansion of fruit bunch supply may therefore come from smallholder farmers, which occupy about 95% of the total area under oil palm cultivation and/or yield improvement strategies.

Whilst plantations in Ghana are distinguished by their large size, mono-cultural character and systematic layout (Gyasi, 1996), the smallholder sector is largely shaped as an unorganized mosaic of low-yielding small farms within a highly fragmented agricultural landscape, inherent to the land-sharing approach (Phalan et al., 2009). Moreover, compared with e.g. Malaysia, where smallholders are tightly integrated into the industry structure such as through the FELDA scheme (Shamsul Bahrin and Lee, 1988), smallholders in Ghana are not well integrated (Fold and Whitfield, 2012). In Ghana, some smallholders are attached to plantation schemes as nucleus-smallholders or out-growers (5%), but most are independent farmers with private farms (90%) (Table 3.1) (Adjei-Nsiah et al., 2012a; Osei-Amponsah et al., 2012). Despite smallholder-plantation schemes, the volume of crop is too little to fulfil the processing needs of plantation mills, which are thus dependent on outside fruit purchases for the mill to run efficiently. Whilst smallholder-plantation schemes receive technical advice and inputs (e.g. high-yielding seedlings, fertilizers) on credit, in return that all crop goes to the plantation mill, independent smallholder farmers are completely self-reliant. They are not contractually bound to deliver their crop to a particular mill or association, and will sell their fruits to the highest bidder. In areas where there are several estates in close proximity, competition for fruit bunches is therefore high, which has led to price wars between plantations as well as with local buyers for the home consumption market. Furthermore, the uncoordinated establishment of new mills too close to existing ones exacerbates competition for fruit bunches, demonstrating the need for better spatial planning in the industry (Fold and Whitfield, 2012) (Fig. 6.2).

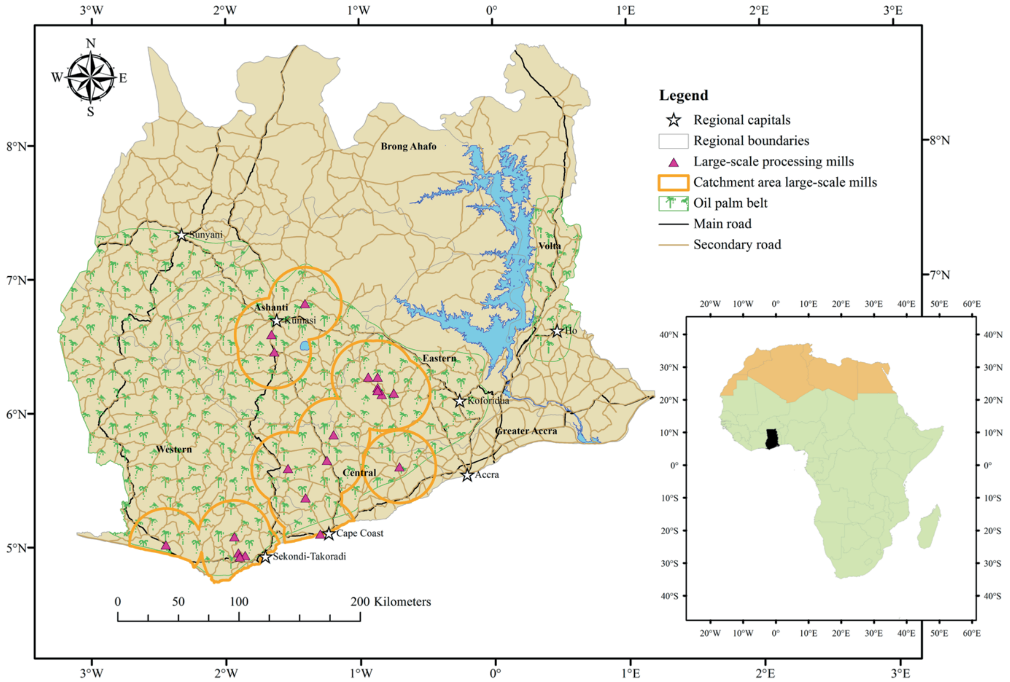


Fig. 6.2. Large-scale mills and their catchment areas (30 km radius) in southern Ghana. Only 2.5 M ha, or 37%, of the total land area within the oil palm belt (6.8 M ha) is covered, indicating a large overlap in catchment area and increased competition between mills.

Viable integration of smallholder farmers into the oil palm supply chain, for example through farmers' groups or smallholder schemes, and better integration with existing mills has considerable potential to increase production and regulate expansion. Jelsma et al. (2017), for instance, suggests that with a strong institutional arrangement, smallholder farmers can participate in supply chains on advantageous conditions and substantially increase their productivity. Organizing smallholder farmers in large concessions (akin to smallholder schemes as in e.g. Malaysia and Indonesia) following a more land sparing approach, could potentially open up areas for biodiversity conservation as well, but would require good supporting policies and a significant restructuring of land allocated to oil palm and conservation in Ghana.

As discussed in section 6.8.1, yield intensification with BMP (i.e. the land sparing approach), offers scope to increase production in existing plantings, and potentially reduce the requirement for future area expansion. With improved crop recovery and agronomic management, average yields in mature plantation and smallholder palm stands approached 18 t ha^{-1} FB (Table 4.1). If average attainable yields of 20 t ha^{-1} FB can be achieved, plantations in Ghana would be more self-sufficient and reliance on outside fruit purchases would greatly reduce (Table 6.1). However, yield intensification depends on the feasibility of scaling up BMPs and would require a proper economic analysis to assess its potential.

Smallholder farmers in Ghana face major challenges in increasing yields, such as lack of knowledge on appropriate management practices, poor operating conditions (e.g. poor infrastructure), and lack of access to high-yielding seedlings, agronomic inputs, credit, and extension advice. Key to successful implementation and up-scaling of BMP's is therefore the provision of adequate services to smallholders. Improvements to infrastructure (particularly feeder roads to the farm) reduces the cost of production, whilst a 'one-stop-shop' approach could provide provision of milling, inputs and advice to the industry, particularly smallholders. Because large-scale mills benefit from investments in smallholder production to secure sufficient crop supply, they could potentially provide these services as extension agents, by advancing inputs (e.g. fertilizers, agrochemicals, tools, quality DxP seedlings) and advice to smallholders under credit, against budgeted future crop deliveries to the respective mill. To effectively monitor smallholder production (e.g. budgeted production versus actual delivery) and to identify yield gaps at scale, collection of farm data in a database (e.g. OMP (Agrisoft Systems, 2018)) is essential. This could further assist milling companies as extension agents in providing adequate feedback to growers for yield intensification in Ghana. Monitoring each smallholder farm diligently furthermore reduces the risk attached to making loans and provides the means for targeted extension work (Fig. 6.3).

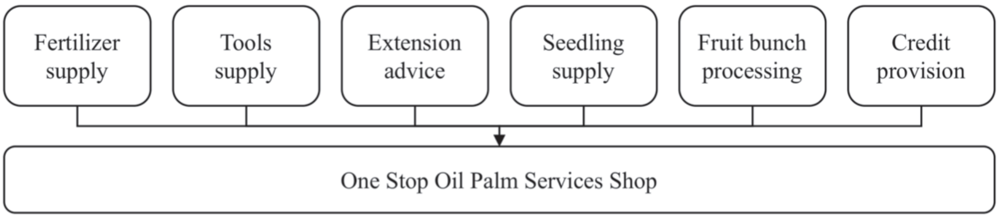


Fig. 6.3. Large-scale mills can serve as one stop shops to provide services and inputs for the development of the smallholder sector in Ghana.

Increasing fruit supply by organizing the expanding smallholder sector and implementing yield intensification strategies (BMPs) on existing plantings is largely an unexploited potential for the sustainable intensification of oil palm production in Ghana, and is essential to move the industry forward in a sustainable manner. However, suitable organizational models have to be further explored for Ghana's complex oil palm sector as well as pathways on how these models can be implemented. This will require collaborative action between industry actors (e.g. plantations, smallholders) and governments alike.

6.9 Conclusions: opportunities for the sustainable development of the oil palm sector in Ghana

The oil palm industry in Ghana faces many challenges, mostly related to low productivity and the unorganized expansion of the oil palm sector. As described in sections 1.2–1.4, productivity is limited by water and nutrient constraints, as well as labour shortages to fully implement or sustain BMPs. The industry is furthermore challenged by limitations to large-scale plantation expansion due to the lack of land and complicated land tenure systems. Increases in production thus have to be sought from smallholder farms and/or yield intensification strategies. However, this is a major challenge, since smallholder farmers are poorly organized and are not yet well incorporated in the oil palm supply chain. Good supporting policies are therefore required for the viable integration of smallholders in the industry.

Production increases can alternatively be sought by applying BMPs to land already planted with oil palm. Opportunities for increasing production can therefore be sought by improving current management practices. Adapting BMPs to local conditions is thereby a useful strategy to identity the management practices that are responsible for yield gaps. My research has demonstrated that yield intensification of existing palm stands shows considerable scope in Ghana (Chapter 4), and can be achieved through adequate nutrient management, irrigation and yield taking (crop recovery) and yield making (agronomy) practices. Results show that average FB yields of 17.9 t ha^{-1} and 17.6 t ha^{-1} can be achieved with BMP at plantations and smallholders respectively. Average yield increases of 16% (+1.8 t ha^{-1} FB) and 37% (+2.7 t ha^{-1} FB) were achieved in the short-term (≤1 year) with yield taking, whilst yield making contributed to additional increases of 36% (+4.7 t ha^{-1}) and 76% (+7.6 t ha^{-1}) over the long term (>1 year) at plantations and smallholders (Chapter 4). Moreover, results from the irrigation trial demonstrated the potential of irrigation x fertilizer to increase average yields even further, at 32.6 t ha^{-1} FB in the plateau yield phase, but indicated the need for more research on the specific water and nutrient needs of oil palm across different environments and production phases in Africa (Chapter 5).

By increasing yields with moderate BMP implementation (average FB yields of 17.9 t ha^{-1} and 17.6 t ha^{-1} at plantations and smallholders), approximately 450,000 ha of area expansion can be reduced when compared with present yields (11.4 t ha^{-1} at plantations and 7.3 t ha^{-1} at smallholders). At potential production levels (i.e. average FB yields of 21.0 t ha^{-1} at plantations and smallholder farms), however, about 600,000 ha of land can be spared. Additionally, closing yield gaps in Ghana under current land area (327,600 ha) has the potential to increase FB production almost three-fold from 2,5 Mt to 6,9 Mt. If all crop is processed at an OER of 21%, about

1.4 Mt CPO can be produced, which is more than enough to meet Ghana's current annual demand of 106,000 t CPO, and does not require the need to plant additional land. Yield intensification strategies therefore offers considerable scope to reduce the requirement for future area expansion, and may therefore be an important policy for sustainable oil palm development in Ghana and West Africa.

Table 6.1. Impact of yield intensification on the land area needed to accommodate production shortages at current milling capacity and potential annual processing capacity (at a peak crop of 16%) at three large-scale plantations in Ghana.

Plantation	Milling capacity	Potential annual capacity	Current status					Yield intensification with BMP			
			Area	FB production	FB yield	Production shortfall	Area needed	FB yield	Area needed	Change in area	Production shortfall
	tph	t FB	ha	t	t ha^{-1}	t	ha	t ha^{-1}	ha	ha	t
BOPP	20	73,333	4,890	42,300	8.7	31,033	3,588	20	3,667	-1,223	-24,460
Norpalm	30	110,000	3,760	42,000	11.2	68,000	6,088	20	5,500	1,740	34,800
TOPP	30	110,000	3,250	41,300	12.7	68,700	5,406	20	5,500	2,250	45,000
Total	80	293,333	11,900	125,600	10.6	167,733	15,892	20	14,667	2,767	55,340

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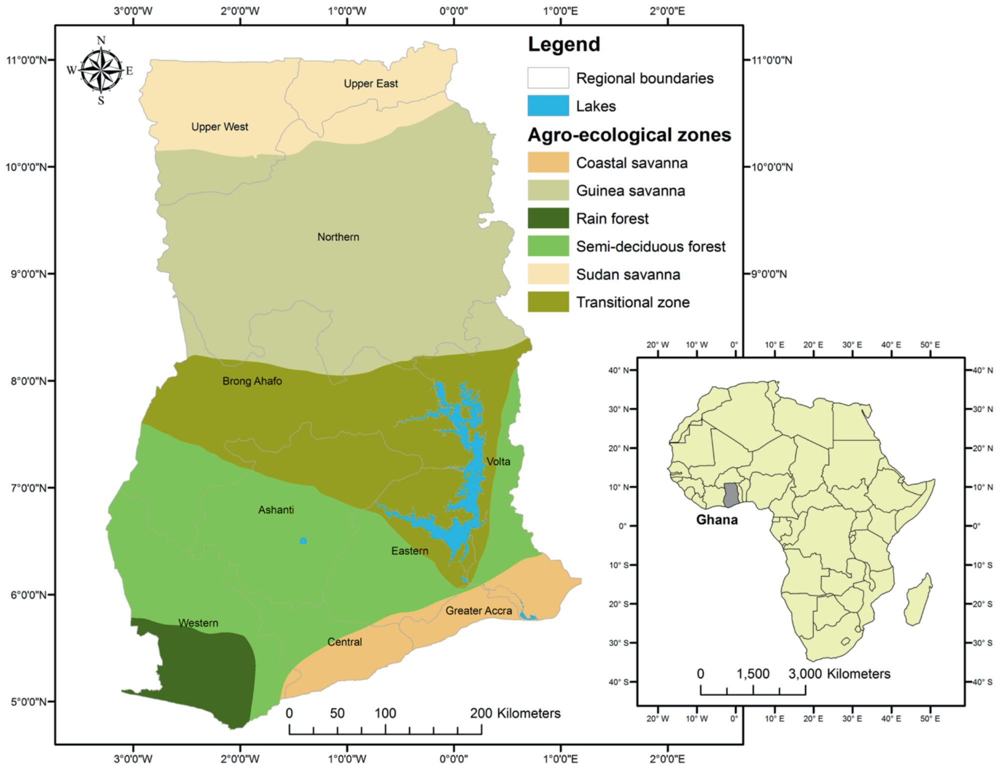
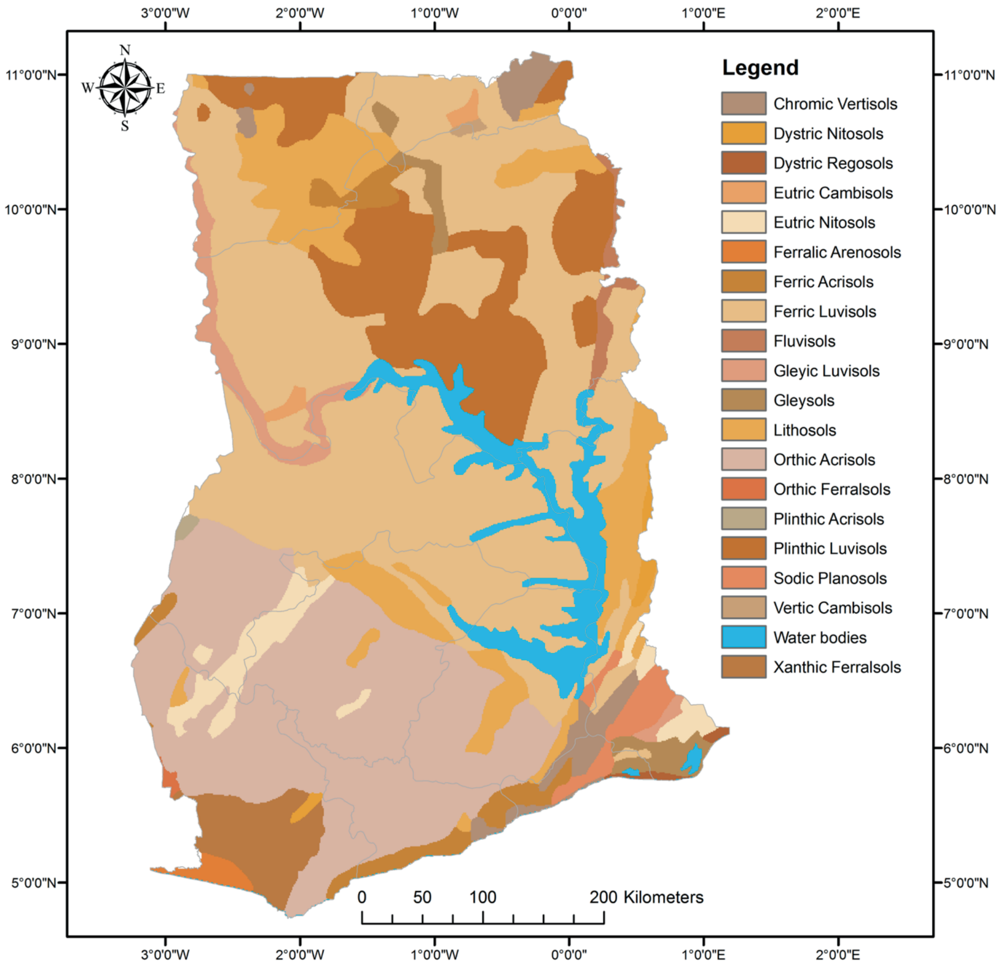
Appendix 1. Map showing six agro-ecological zones in Ghana.



Appendix 2. Soil units of Ghana (FAO, ISRIC).



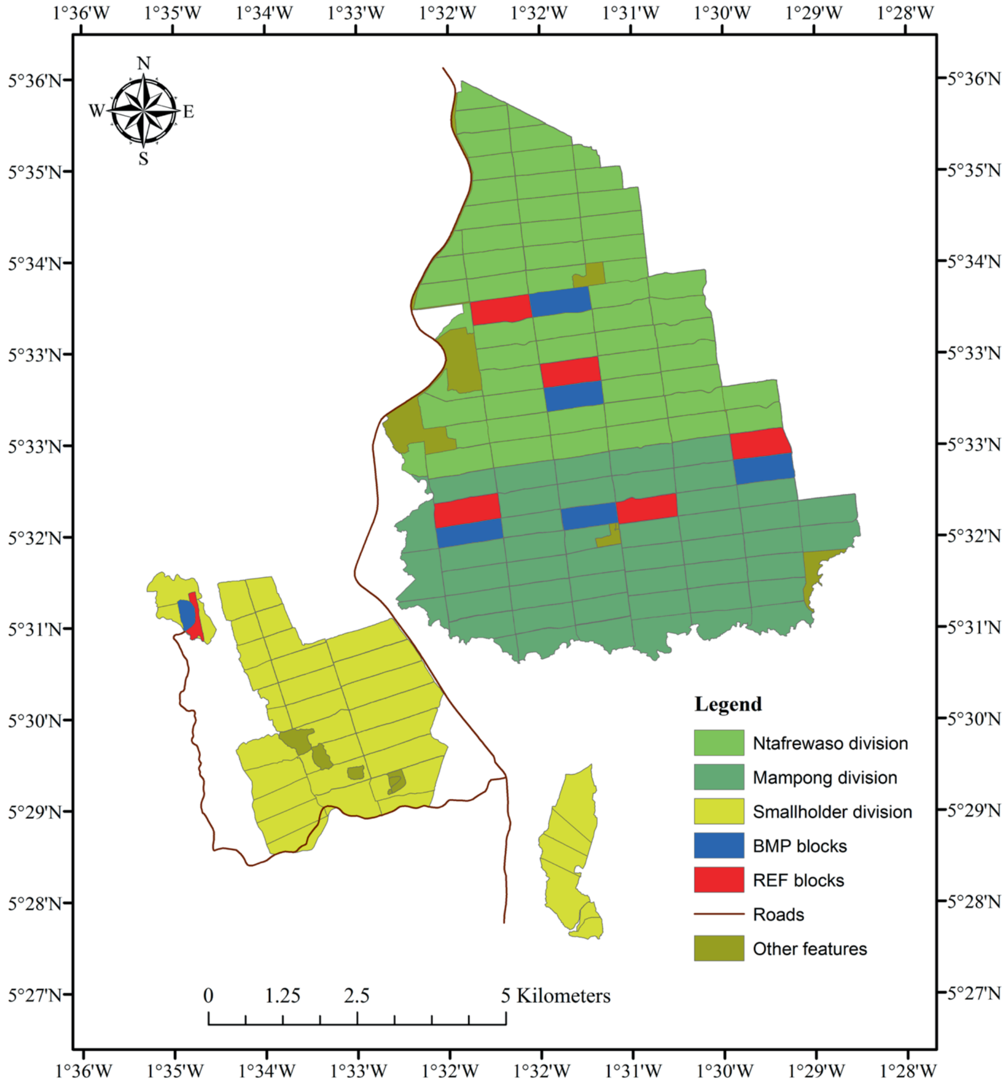
Appendix 3. Data sources.

Data	Variable	Unit	Format	Resolution	Period/year	Source
Protected areas	Protected areas	-	Shapefile	-	-	Protectedplanet; http://protectedplanet.net Accessed on 09.10.2014
Land cover	Agro-ecological zones	-	Shapefile	-	-	(Antwi-Agyei et al., 2012)
Urban extent	Urbanized places (places with 5000+ inhabitants)	-	Raster	30 arc-seconds (~1 km)	2000	NASA; http://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents/data-download Accessed on 09.10.2014
Rainfall	Average monthly rainfall	mm $month^{-1}$	Raster	30 arc-seconds (~1 km)	1950–2000	WorldClim; http://www.worldclim.org Accessed on 29.08.2014
Temperature	Monthly min-, max-, and mean temperature Min temp of the coldest month Max temp of warmest month	°C	Raster	30 arc-seconds (~1 km)	1950–2000	WorldClim; http://www.worldclim.org Accessed on 29.08.2014
Elevation		M ASL	Raster	3 arc-seconds (~100 m)	2008	CGIAR; http://srtm.csi.cgiar.org Accessed on 29.08.2014
Soil properties	Soil texture	% Silt % Clay	Raster	30 arc-seconds (~1 km)	-	ISRIC; http://soilgrids1km.isric.org Accessed on 02.10.2014
	Soil type	unit	Raster	30 arc-seconds (~1 km)	2012	FAO; http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ Accessed on 01.09.2014

Appendix 4. Average rainfall, rain days, water deficits (calculated using the method of Surre (1968)) and their standard deviation (σ) at five sites in Ghana from 2010 to 2014.

Site	Region and geo-reference	Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Bogoso	Western region	Rainfall (mm)	41	71	113	175	243	258	179	60	211	194	83	42	1,670
	5°34'06.81"N	σ	*27*	*31*	*70*	*76*	*63*	*122*	*99*	*31*	*128*	*83*	*32*	*11*	*368*
	2°00'58.94"W	Rain days	4	8	10	12	19	16	16	14	20	20	14	4	157
		σ	*2*	*1*	*5*	*2*	*1*	*3*	*3*	*4*	*6*	*2*	*4*	*2*	*16*
		Water deficit (mm)	-70	-65	-23	76	193	253	198	62	147	173	73	-35	-193
		σ	*80*	*47*	*84*	*113*	*120*	*128*	*98*	*30*	*163*	*111*	*60*	*57*	*174*
BOPP	Western region	Rainfall (mm)	46	111	114	140	214	268	166	67	159	194	158	106	1,743
	5°06'47.65"N	σ	*48*	*38*	*14*	*50*	*46*	*96*	*59*	*53*	*69*	*77*	*58*	*64*	*413*
	1°54'55.09"W	Rain days	2	6	6	7	12	12	9	6	11	12	10	6	99
		σ	*2*	*1*	*1*	*1*	*2*	*3*	*2*	*4*	*3*	*4*	*1*	*3*	*11*
		Water deficit (mm)	-58	-33	-29	-10	100	225	124	17	61	134	115	51	-131
		σ	*63*	*39*	*19*	*50*	*76*	*171*	*94*	*73*	*98*	*125*	*70*	*93*	*191*
Norpalm	Western region	Rainfall (mm)	32	34	56	117	220	335	107	44	127	132	98	65	1,367
	4°55'26.84"N	σ	*28*	*18*	*29*	*56*	*109*	*90*	*44*	*29*	*74*	*49*	*29*	*34*	*261*
	1°53'31.54"W	Rain days	1	3	3	5	8	13	7	4	12	8	6	3	74
		σ	*1*	*1*	*2*	*2*	*3*	*2*	*2*	*3*	*7*	*3*	*1*	*1*	*6*
		Water deficit (mm)	-88	-110	-94	-33	96	302	96	-9	10	32	0	-60	-394
		σ	*65*	*19*	*29*	*56*	*124*	*152*	*34*	*56*	*88*	*75*	*60*	*36*	*185*
TOPP	Central region	Rainfall (mm)	40	41	62	138	201	290	140	84	122	225	92	44	1,479
	5°32'40.10"N	σ	*24*	*30*	*43*	*97*	*98*	*112*	*38*	*62*	*96*	*66*	*83*	*27*	*368*
	1°31'12.38"W	Rain days	2	3	4	6	8	11	7	6	7	11	6	4	74
		σ	*1*	*2*	*3*	*3*	*3*	*2*	*3*	*2*	*5*	*3*	*3*	*2*	*19*
		Water deficit (mm)	-65	-92	-88	-12	95	235	135	60	49	159	57	-56	-314
		σ	*82*	*48*	*43*	*97*	*158*	*123*	*37*	*50*	*138*	*98*	*129*	*76*	*258*
OPRI	Eastern region	Rainfall (mm)	43	70	131	162	163	211	168	72	225	250	89	50	1,634
	6°2'7.15"N	σ	*40*	*46*	*29*	*70*	*31*	*78*	*50*	*54*	*110*	*120*	*19*	*42*	*301*
	0°52'17.04"W	Rain days	3	7	10	9	13	16	12	11	15	18	15	6	135
		σ	*2*	*2*	*3*	*3*	*3*	*3*	*2*	*6*	*3*	*3*	*2*	*3*	*17*
		Water deficit (mm)	-47	-59	-8	34	91	176	173	69	185	225	96	-4	-118
		σ	*85*	*60*	*41*	*85*	*50*	*67*	*70*	*93*	*159*	*131*	*37*	*73*	*153*

Appendix 5. Example of the experimental design including paired BMP (blue) and REF (red) blocks at the nucleus plantation of Twifo Oil Palm Plantation (TOPP).



Appendix 6. Site and block characteristics of plantations and smallholder farms.

Site	Block/farm	Year of planting	Plantation (nucleus)/farm size	Block size			Planting material	Topography	Planting density	Soil group (FAO)	Rainfall	
				BMP	REF	Second control					Annual average	
			ha						palms ha^{-1}		mm	period
Plantations												
BOPP	19/03A & B	2003	4,890	25.6	27.1	50.0	DRC (Zaire)	Undulating	160	Ferralsol	1,571	2010–2015
	7/01 & 8/01	2001		45.3	41.2	61.0	DRC (Zaire)	Undulating	160	Ferralsol	1,571	2010–2015
	C4/1 & C4/2	2006		38.1	31.1	55.0	DRC (Zaire)	Undulating	160	Ferralsol	1,876	2010–2015
	SHDR*	1996		20.8	21.3	19.5	DRC (Zaire)	Sloping	160	Ferralsol	1,571	2010–2015
Norpalm	2	2002	3,760	28.9	19.0	39.5	CIRAD	Flat	143	Lixisol	1,136	2011–2015
	25	2010		8.9	8.9	49.3	Ghana Sumatra	Undulating	143	Lixisol	1,668	2010–2015
	92	2005		19.2	21.2	73.3	OPRI	Flat	143	Lixisol	1,668	2010–2015
TOPP	220 & 221	2005	3,250	18.0	22.0		DRC (Zaire)	Undulating	160	Lixisol	1,488	2010–2015
	214 & 224	2004		20.0	20.0		DRC (Zaire)	Undulating	160	Lixisol	1,488	2010–2015
	300 & 301	2005		22.0	21.0		DRC (Zaire)	Undulating	160	Lixisol	1,488	2010–2015
	351 & 352	2010		19.0	23.0		Ghana Sumatra	Undulating	160	Lixisol	1,488	2010–2015
	Datano	1996		10.8	10.3		OPRI	Undulating	143	Lixisol	n/a	
Smallholders												
SWAPP East	Adu farm	2009	6.8	3.4	3.4		OPRI	Undulating	143	n/a	n/a	

Appendix 6. Site and block characteristics of plantations and smallholder farms (*continued*).

Site	Block/farm	Year of planting	Plantation (nucleus)/farm size	Block size BMP	REF	Second control	Planting material	Topography	Planting density	Soil group (FAO)	Rainfall Annual average	
			ha						palms ha^{-1}		mm	period
	Amo palm	2005	100	2.7	2.7		TOPP	Undulating	160	n/a	1,002	2014–2016
	BOA farm	2005	10.8	2.4	2.4		PSI	Undulating	143	n/a	n/a	
	Central oil mill	2005	12	1.4	1.4		TOPP	Undulating	160	n/a	1,512	2014–2016
	Clement farm	2005	48	1.4	1.4		TOPP	Flat	143	n/a	1,200	2014–2016
	Joe farm	2007	3.4	1.3	1.3		OPRI	Undulating	143	n/a	1,028	2014–2016
	Juaben oil mill	2004	292	2.0	2.0		PSI	Undulating	143	n/a	762	2014–2016
	Obooma	1999	66	1.4	1.4		OPRI	Undulating	143	n/a	1,619	2014–2016
	OPRI	2001	5.5	2.0	2.0		OPRI	Sloping	151	n/a	1,737	2014
	Oti	2010	3.8	1.3	1.3		OPRI	Sloping	160	n/a	n/a	
SWAPP West	GSOPP Bogoso	2006	275	3.6	3.6		BOPP	Flat	160	n/a	1,643	2014–2015
	GSOPP Chujah	2008	120	4.0	3.8		BOPP	Undulating	160	n/a	1,684	2014–2015
	GSOPP Wassa 07	2007	180	4.0	4.0		BOPP	Undulating	160	n/a	1,579	2014–2015
	GSOPP Wassa 08	2008	70	4.0	4.0		BOPP	Flat	160	n/a	1,579	2014–2015
	Justice	2008	13	3.0	1.1		BOPP	Sloping	143	n/a	n/a	
	Kado	1998	13	1.8	1.8		Norpalm	Sloping	143	n/a	n/a	
	Somprey	1997	15	3.9	1.6		OPRI	Sloping	143	n/a	n/a	
	Vikwam	2003	30	1.5	1.5		BOPP	Sloping	143	n/a	n/a	
	Yam farm	2007	15	3.0	1.4		OPRI	Flat	151	n/a	n/a	

* Consists of five ~4-hectare plots managed by individual farmers for each treatment. However, for the project the separate plots were management as one single unit.

Appendix 7. BMP field audit evaluation criteria grouped according to harvesting practices, cultivation & upkeep, pests & diseases and nutrient management for mature oil palm stands (adapted from Rankine and Fairhurst (1998)). All BMP fields at oil palm plantations and smallholder farms were assessed to achieve full compliance with the auditing criteria. Harvesting, loose fruit collection and fruit collection were awarded a score of either 1 or 3, while all other parameters were scored 1, 2, or 3. Parameters awarded with 1 required immediate action, a 2 required action, but not urgent, while a 3 meant full compliance with BMP standards. Once a block was awarded 3 for all parameters, the block was considered BMP standard.

Category	Parameter	Auditing criteria
Harvesting practices	Harvesting	• Full access (paths, circles, palm pruning) implemented to provide harvesters with full access for harvest and in-field crop transport using wheelbarrows • Rounds maintained at 7–10 day harvest intervals • Minimum ripeness standard of five loose fruits before bunch harvest implemented • No missed palms • No evidence of crop loss • Fronds removed at harvest according to pruning standards
	Loose fruit collection	• No evidence of loose fruit loss • Loose fruit collected within 24 hours of harvest
	Fruit collection	• Same day transport of harvested crop to palm oil mill • All bunches and loose fruit delivered to crop collection point
Cultivation & upkeep	Pruning	• Pruning rounds carried out according to budgeted programme (two rounds per year) • Remove senescent fronds on palms <3 years after planting, two subtending fronds on palms 3–7 YAP (48–56 green fronds), one to two subtending fronds on palms 8–15 YAP (40–48 green fronds), and one subtending frond on palms >15 YAP (32–40 green fronds).
	Ground cover vegetation	• Eradication of woody weeds and other noxious weeds • Establishment of soft weeds in between palms, the palm inter-row, and along the harvest path
	Soil conservation	• Platforms installed at slopes 5–10° (9–18%) • Terraces or contour harvest paths installed at slopes 10–20° (18–36%)
	Frond stacking	• Pruned fronds stacked in a box pattern to improve soil properties, provide mulch, and to create a zone conducive to nutrient uptake from fertilizers • Fronds cut into two pieces. The petiole is stacked with the thorns facing towards the ground in the palm inter-row. The remainder is stacked at right angles to the harvest path in between the palms with the frond base facing the inter-row.
	Circle weeding and maintenance	• Circle weeding implemented according to budgeted programme

Appendix 7. BMP field audit evaluation criteria grouped according to harvesting practices, cultivation & upkeep, pests & diseases and nutrient management for mature oil palm stands (adapted from Rankine and Fairhurst (1998)). All BMP fields at oil palm plantations and smallholder farms were assessed to achieve full compliance with the auditing criteria. Harvesting, loose fruit collection and fruit collection were awarded a score of either 1 or 3, while all other parameters were scored 1, 2, or 3. Parameters awarded with 1 required immediate action, a 2 required action, but not urgent, while a 3 meant full compliance with BMP standards. Once a block was awarded 3 for all parameters, the block was considered BMP standard (*continued*).

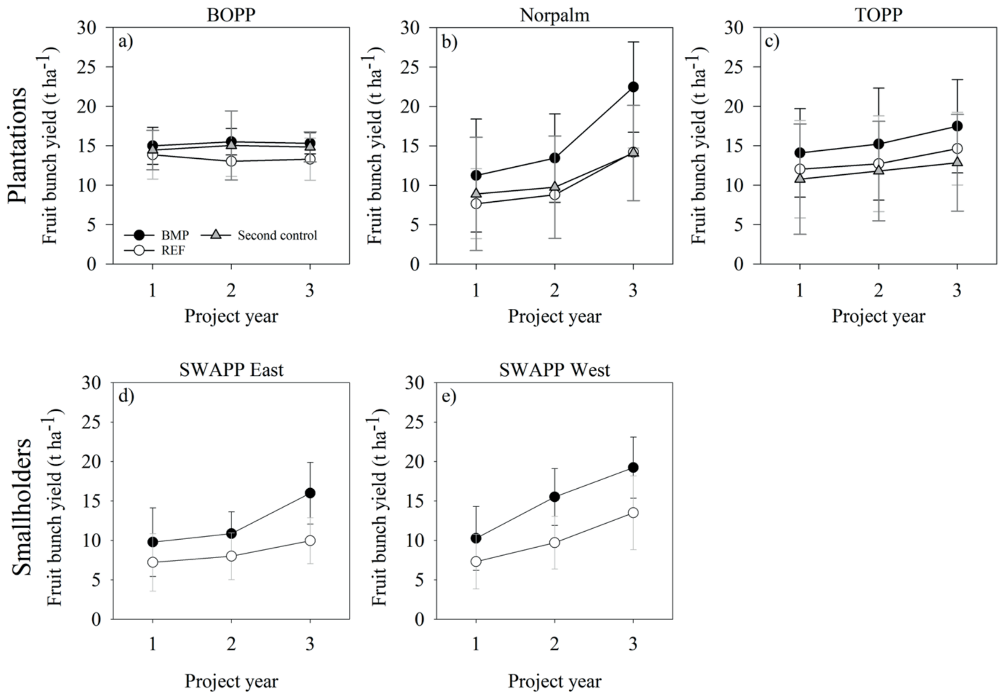
Category	Parameter	Auditing criteria
Cultivation & upkeep	Circle weeding and maintenance	• Clean palm circles and free of obstructions (logs, debris, old loose fruit) • Supply palms properly weeded • No volunteer oil palm seedlings • Weed growth in line with interval between rounds of circle weeding in work programme
	Path weeding and maintenance	• Path maintenance implemented according to budgeted programme • Unimpaired wheel barrow access to every palm • Installation of footbridges (over drains) to provide access
	Drainage	• Adequate installation of V shaped drains • No standing water where topography permits drainage • Drains properly maintained (siltation removed, culverts allow unimpeded flow of drainage water) • Water gates fully functioning (gates, flaps) and water levels controlled as required • Drains blocked in the dry season with sand bags to conserve moisture
	Erosion	• Soil conservation measures implemented as required
	Legume cover plants	• Establishment of shade tolerant cover plants
	Roads	• Roads maintained to allow full all weather access by vehicle to the field • Sufficient collection/in-field roads with a maximum carry distance of 200 m to the centre of the field
Pests & diseases	Pests and diseases	• All pest damage (rats, leaf eating insects (LEID) such as leaf miner (*Coelaenomenodera* spp.) and rhinoceros beetle (*Oryctes rhinoceros*) and diseases (*Ganoderma*, *Fusarium*)) reported, and control measures implemented based on results of monitoring
Nutrient management	Fertilizer application	• Fertilizer applied accurately according to given recommendations, following the "4R nutrient stewardship" guidelines. All fertilizers are spread over the boxed frond stack in the rain season, apart from urea, which is spread evenly in the weeded circle, and B fertilizers, which are applied in a band 1 m wide and 1 m from the palm trunk
	Crop residue application	• Mulching with empty fruit bunches (40 t ha^{-1} (~300 kg $palm^{-1}$)) applied as a mattress, one bunch deep between palms points within palm rows
		• At short supply of EFB, prioritize application on the slopes

Appendix 8. Example of fertilizer recommendations for year 3 for plantation and smallholder BMP plots showing application rates for each nutrient (elements) (kg palm^{-1}). Application rates were based on the results of the leaf analysis and (un)published information on fertilizer responses in West Africa and elsewhere. All BMP plots received a maintenance dose. If leaf nutrient concentrations fell below the pinnae and rachis critical concentrations (after von Uexküll and Fairhurst (1991) and Foster and Prabowo (2006) respectively), plots additionally received a corrective dose (i.e. maximum dose). Expert knowledge was used to adjust fertilizer rates for each plot, depending on the response in leaf and rachis nutrient concentrations with previous years.

Nutrient	**Fertilizer source**	**Leaf critical level**		**Maintenance dose**	**Corrective dose**	**Maximum dose**
		Pinnae	**Rachis**			
		%		**kg nutrient palm^{-1}**		
Nitrogen (N)	Urea	2.60	0.55	0.92	0.23*	1.15
Phosphorus (P)	TSP	0.16	0.09	0.30	0.20	0.50
Potassium (K)	KCL	0.95	1.4	1.25	0.25	1.50
Magnesium (Mg)	Kieserite	0.25	0.07	0.08	0.08	0.16
Boron (B)	Borate	15	-	0.01	0.01	0.02

* A corrective dose of N is applied where rachis K is sufficient and pinnae K is deficient.

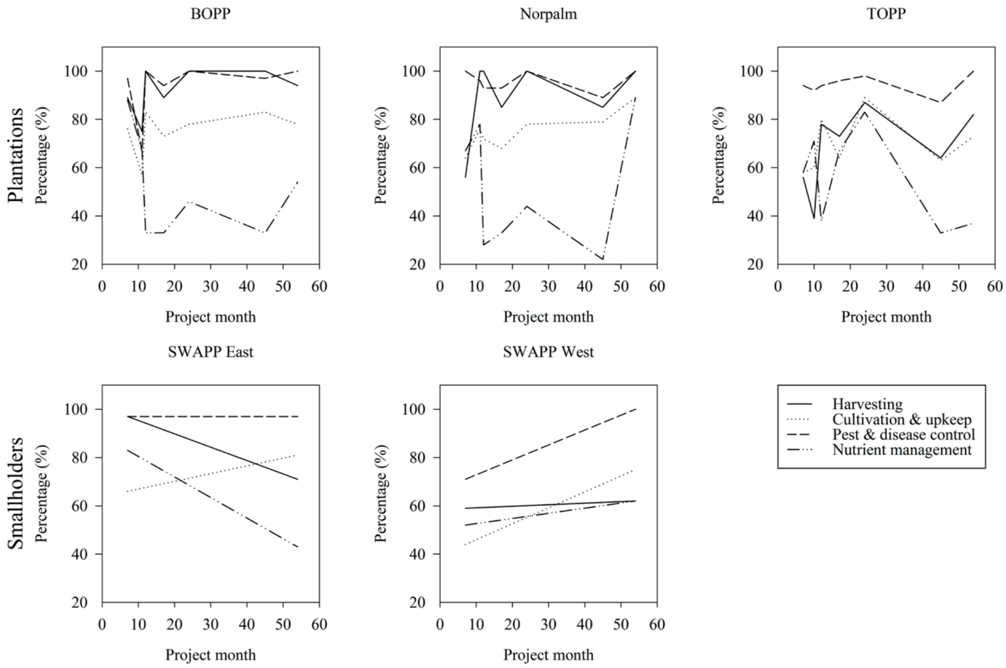
Appendix 9. Average yields + SD for each project year for BMP and REF treatments on plantation (BOPP, Norpalm, TOPP) and smallholder sites (SWAPP East, SWAPP West). The grey triangles for plantation sites show average yields for the second control plots which serve as an absolute reference for plantation performance, since REF treatments were also undergoing improvement.



Appendix 10. Model parameters for the interaction term of *Treatment* with *Production system*. *Indicates a significant interaction at $P \leq 0.05$.

Parameter	**Units**	**Yr**	**Model parameters**
Yield components			
Bunch number	bunches ha^{-1}	1	F(1,63) = 0.320, MSE = 52570.574
		2	F(1,63) = 0.330, MSE = 58454.058
		3	F(1,63) = 0.062, MSE = 15909.774
Av. bunch weight	kg	1	F(1,63) = 0.225, MSE = 2.946
		2	F(1,63) = 0.290, MSE = 4.731
		3	F(1,63) = 0.534, MSE = 8.995
Loose fruit collection	t ha^{-1} loose fruit	1	F(1,63) = 2.166, MSE = 0.559
		2	F(1,63) = 2.778, MSE = 0.615
		3*	F(1,63) = 5.885, MSE = 2.586
Fruit bunch harvest	t ha^{-1} FB	1	F(1,63) = 0.067, MSE = 1.024
		2	F(1,63) = 0.369, MSE = 4.349
		3	F(1,63) = 0.975, MSE = 12.536
Total yield	t ha^{-1}	1	F(1,63) = 0.189, MSE = 3.164
		2	F(1,63) = 0.620, MSE = 8.132
		3	F(1,63) = 1.807, MSE = 26.019
Management			
Harvest cycles	cycles yr^{-1}	1*	F(1,63) = 9.052, MSE = 474.908
		2*	F(1,63) = 12.487, MSE = 907.295
		3*	F(1,63) = 13.903, MSE = 838.448
Harvester productivity	t man-day^{-1} FB	1*	F(1,63) = 4.726, MSE = 1.229
		2	F(1,63) = 3.330, MSE = 1.023
		3*	F(1,63) = 8.923, MSE = 2.376
	bunches man-day^{-1}	1	F(1,63) = 3.283, MSE = 9028.540
		2	F(1,63) = 1.456, MSE = 5733.746
		3	F(1,63) = 3.860, MSE = 8445.528
	ha man-day^{-1}	1	F(1,63) = 3.146, MSE = 1.408
		2	F(1,63) = 3.703, MSE = 1.338
		3*	F(1,63) = 5.954, MSE = 1.222
Harvesting labour	man-days ha^{-1} cycle^{-1}	1	F(1,63) = 1.329, MSE = 0.042
		2	F(1,63) = 0.221, MSE = 0.009
		3	F(1,63) = 0.073, MSE = 0.004
Field upkeep labour*	man-days ha^{-1} yr^{-1}	1	F(1,254) = 1.056, MSE = 3.956
		2	F(1,254) = 0.327, MSE = 0.327
		3	F(1,254) = 0.154, MSE = 0.345

Appendix 11. Field audit results summarized according to category (harvesting practices, cultivation and upkeep, pests & diseases and nutrient management) for oil palm plantation and smallholder BMP plots. Percentages were calculated as the total score across all BMP plots at each site relative to the total possible score for each parameter and then averaged per category. A 100 percent score means full compliance with BMP for that particular category. The field audit evaluation criteria are given in Appendix 7. Field audits were performed periodically (*n*=6) at plantation sites and only twice at smallholders, at project start and end.



Appendix 12. Key lessons in rehabilitating neglected mature oil palm plantings in West Africa: a practitioner's guide.

Thomas Fairhurst[a], Francis Ohipeni[b], Charles Frimpong[b], Tiemen Rhebergen[c], Rosemary Addico[b], Rob Moss[d]

Introduction

The oil palm sector in Ghana is diverse, consisting of a variety of stakeholders in oil palm production and processing. The majority of growers are smallholder farmers that cultivate oil palm on privately owned or rented land ranging in size up to 100 ha, with the majority of the farms below 5 ha. Smallholders comprise the largest share of the area under oil palm cultivation in Ghana (95%) and account for most of the national fruit bunch (FB) production (60–80 %, Moss, personal communication). However, most smallholder farms in Ghana are poorly managed with large opportunities for yield improvement. Compared with oil palm plantations, average FB yields at smallholder farms are much smaller (6 t/ha versus 11 t/ha in estates) and far below the yield potential (~20 t ha^{-1}) (Chapter 3, 4).

Farmers commonly lack knowledge on appropriate cultivation techniques, such as harvesting and canopy, nutrient, groundcover and water management required to achieve large FB yields. In this appendix, we summarize our experience in rehabilitating neglected mature oil palm plantings with Best Management Practices (BMP), by presenting a step-wise guide for smallholder farmers. Whilst the techniques described in this booklet are based on practical experience gained from working with farmers across the oil palm belt in Ghana, the methods presented have general applicability for the West African region and elsewhere.

BMP's are 'cost-effective and practical agronomic techniques that aim to reduce yield gaps in oil palm by using production inputs and resources efficiently' (Donough et al., 2009). BMPs are grouped in two broad categories; 'yield taking' and 'yield making' practices. Yield taking increases yield over the short term by improving crop recovery operations (e.g. field access, harvest intervals), while yield making includes agronomic practices that contribute to building large and sustainable yields over the longer term (e.g. pruning, nutrient management).

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We provide guidance on the implementation of BMPs with yield taking and yield making to improve palm performance. Aspects related to harvesting practices, cultivation and upkeep, and nutrient management are discussed in detail in the sections below. We conclude with a section on the time lags in oil palm improvements and a simple cost-benefit analysis using results from a rehabilitation project in Ghana. We show the rapid increase in farm production and return on investment that can be obtained by rehabilitating existing *tenera* palms, to demonstrate that rehabilitating farms is usually a better medium-term financial investment than new plantings.

Photo 1. Neglected oil palm farm. Provided the palms are planted with DxP material, such fields can be transformed into productive oil palm plantings over a period of three to four years.

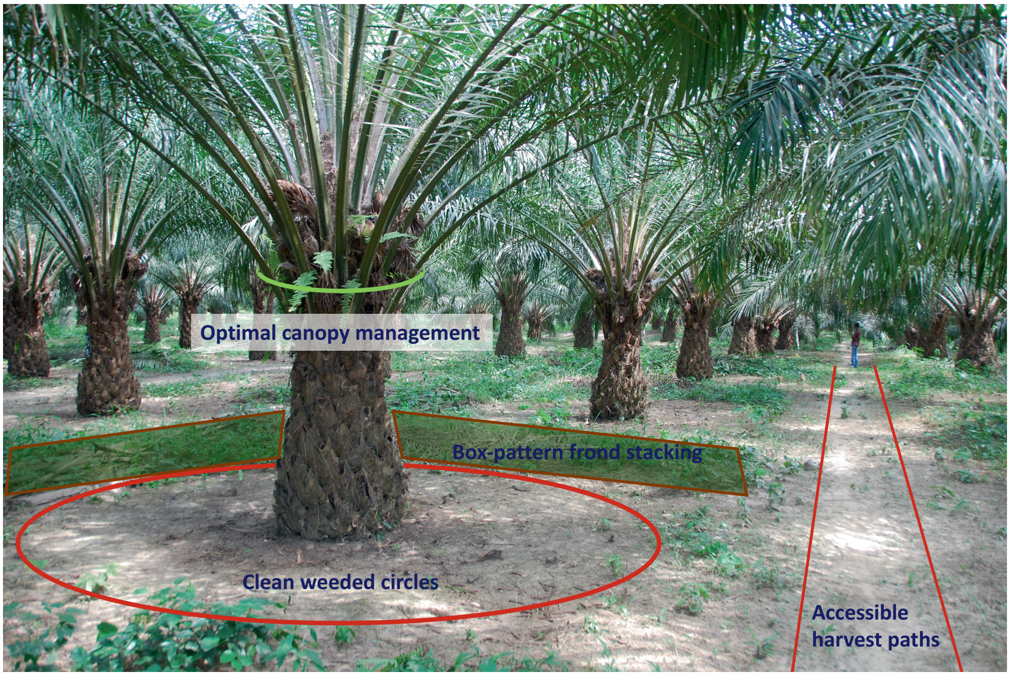

Photo 2. Oil palm farm after rehabilitation showing improved leaf canopy, weeded circles and harvesting paths.

Step 1: yield taking

1 Access to palms

The first step is to create field access within, and to the farm. Farms with poor access usually produce low yields due to inability to evacuate the crop. Furthermore, bushy weed growth competes with the palms for light, nutrients and water.

Unrestricted access is required, from the road to palm, so that the farmer can:

i. Identify ripe bunches at optimal ripeness easily,
ii. Harvest bunches from the palms efficiently,
iii. Collect all loose fruits,
iv. Transport bunches from the palm to the roadside using a wheelbarrow, and
v. Carry out field/maintenance operations, such as pruning and fertilizer application.

In oil palm farms, access is provided by:

i. An access road from the nearest government road to the farm,
ii. Paths between alternate palm rows,
iii. Clean weeded circles around the base of each palm, and
iv. Adequate frond removal so that the harvester can access fruit bunches located in the palm crown.

It may be necessary to upgrade or improve the road that provides access from the government road to the farm. Better access roads will make it easier to negotiate for a better price and lower transport costs for fruit bunches.

If the farm lacks good access in the field:

i. Use a hoe and cutlass to install paths (about 1 m wide) by removing all woody growth and weeds to leave bare soil (3–5 md/ha),
ii. Use an arboricide (e.g. tryclopyr) to poison shrubs and small trees (0.5–1.0 md/ha),
iii. Use a cutlass and hoe to install weeded circles by removing all woody growth, weeds, oil palm seedlings, rotten bunches to leave bare soil for about 1.8 m from the base of each palm (4–6 md/ha), and
iv. Use a knapsack sprayer and herbicides to control weeds in palm circles every three to four months (0.5–1.0 md/ha).

Unimpeded field access helps increase fruit bunch yields in the short-term by 'yield taking'. Yield taking is largely the result of an increase in crop recovery, which increased average yields by almost 5 t/ha FB at smallholder farms in Ghana (Chapter 4).

Photo 3. Clean weeded circles provide the means for ripe bunch identification (detached fruits easily visible) and rapid bunch and loose fruit collection.

Photo 4. A proper access path has been installed in a mature oil palm plantation, but inter-row vegetation requires improvement.

2 Harvesting

Proper harvesting standards and techniques are required to ensure complete crop recovery and for maximum bunch oil content at harvest. The following points should therefore be considered to achieve these goals:

i. Oil palm produces fruit bunches continuously throughout the year. Therefore, to avoid any crop losses, harvesting intervals (i.e. the number of days between successive harvests) must be maintained to ensure complete crop recovery. Harvest intervals of 7–10 days are recommended as a sensible compromise between excessively frequent harvesting (where bunches are scarce, the harvester's output is poor and the temptation to harvest unripe bunches is high) and infrequent harvesting (large amounts of loose fruits require collection and fruit bunches may rot before they are harvested).
ii. Whilst industrial mills prefer ripe bunches to maximize oil yield, artisanal mills prefer over-ripe bunches because it easier to separate the fruits from the bunch. As such, a minimum ripeness standard (MRS) of five loose fruits (LF) per bunch on the ground before harvest is recommended for industrial mills and >10 LF before harvest for artisanal mills.
iii. Once proper access has been installed (weeded circles and paths; Section 2) and pruning has been carried out to remove surplus fronds (Section 3), harvesting

becomes much easier and less costly. With good field conditions, a harvester can cut and carry 1.0–1.2 t/md compared with 0.6–0.8 t/md in a poorly maintained farm (Table 2, Chapter 4).

iv. Loose fruits contain 40% oil, whilst bunches contain about 20% oil. It is therefore important to collect all loose fruit at harvest. This can only be achieved if there are clean-weeded circles around the base of each palm (Section 2).

v. At present, fruit bunches are mostly transported to the roadside using head pans (25–30 kg/load). However, wheelbarrows (70–80 kg/load) are a less costly means to transport fruit bunches from the field. Wheelbarrows can only be used where proper paths have been installed (Section 2).

vi. Palms <7 years after planting (YAP) are harvested with a chisel (blade width 10–12 cm) and palms ≥ 7 YAP with a sickle when the palms have grown too tall for chisel harvesting (>2 m from ground level to ripe bunch position).

vii. In palms ≤4 YAP, fruit bunches can be removed without cutting any fronds, to maximise the number of green leaves retained on each palm. From four years after planting onwards, fronds under the ripe bunch should be removed and stacked in the inter-row (Section 4).

viii. Use a rake or scraper to collect all loose fruits from weeded circle and place them in an empty fertiliser bag for transport to the roadside.

Photo 5. Well prepared fruit bunches ready for collection at a smallholder farm.

Step 2: yield making

1 Pruning and leaf canopy management

Farmers sometimes misunderstand the issue of pruning – they sometimes think that pruning 'damages' the palm and reduces yield. Pruning is required to maintain a full, healthy palm canopy and an optimal leaf area[e] (L=5.5–6.0) to maximize the conversion of sunlight, nutrients and water into vegetative dry matter and bunch production. To achieve proper pruning standards, it is important to carry out the following:

i. Remove surplus fronds (Table 1),
ii. Remove dead, damaged, diseased or old fronds,
iii. Provide field access for harvesting,
iv. Prevent loose fruit becoming trapped behind frond butts, and
v. Provide the palm with the correct number of fronds to maximise yield (Table 1).

In West Africa, pruning is best carried out twice each year:

i. One cycle in January or February (i.e. before the peak crop season), and
ii. Once cycle in October or November (i.e. at the end of the main crop season).

Table A12.1. Pruning standards for oil palm according to palm age.

Growth stage*	Years after planting	Fronds	Spirals	Number of subtending fronds	Tool
IGP	<4	Remove senescent fronds	-	-	Chisel
SAYP	4–7	48–56	6–7	2	Chisel, sickle
PYP	8–14	40–48	5–6	1–2	Sickle
DYP	>15	32–40	4–5	1	Sickle

*IGP = Immature Growth Stage, SAYP = Steep Ascending Yield Phase, PYP = Plateau Yield Phase, DYP = Declining Yield Phase.

Consider the following points when pruning:

i. Pruning is easier when carried out with very sharp tools.
ii. Old, dead fronds and debris should be raked out from around the base of the palm after pruning to facilitate harvesting and field maintenance operations.
iii. Rehabilitation (or corrective) pruning is very laborious (3–10 md/ha) compared with maintenance pruning (1–2 md/ha).
iv. After pruning, cut fronds in half at the point where thorns change to leaflets, and stack them in a three-sided "box" at the outer edge of the weeded circle (see next section).

[e] The leaf area index (L) is a dimensionless parameter, and is defined as the leaf area per unit area of land (L = leaf area (m^2) / ground area (m^2))

Photo 6. Un-pruned palms are impossible to harvest efficiently.

Photo 7. Future yields are reduced by excessive frond removal.

Photo 8. Correct pruning standards lead to larger yields in the future.

2 Frond stacking

Pruned fronds contain large amounts of nutrients, which benefit the palm when returned to the soil. Pruned fronds also provide a barrier to reduce surface wash and soil erosion. The following method for frond stacking is therefore recommended:

i. Remove the thorny petiole from the frond rachis.
ii. Stack the pruned fronds in a three-sided box-pattern around the palm, up to the edge of the weeded circle:
    a. The rachis is placed between palms, with the sharp end facing the harvest path. The goal is to cover as much of the soil surface as possible whilst keeping the circle and path clear.
    b. The petiole is placed in the inter-row, with the thorns facing down to prevent injuries to workers.
    c. Do not place any fronds on the side of the harvesting paths, so that workers can enter the weeded circle without any obstructions for maintenance and harvesting operations.
iii. Do not stack fronds on top of each other in a narrow band in between palm rows!

Box-pattern frond stacking provides the following benefits:

i. Physical protection of the soil surface to minimize erosion, and reduce the amount of applied fertilizer lost due to surface wash,
ii. Improved soil structure, water infiltration rate in soil beneath the frond stack,
iii. Oil palm roots proliferate in the soil beneath the frond stack, and

iv. Easy checking of plant nutrient deficiency symptoms, leaf eating insects, or other pests and diseases on removed fronds.

By stacking fronds in a box pattern, soil properties are improved in the soil beneath the inter-row area that is not occupied by weeded circles and paths. It therefore makes sense to apply P, K, and Mg fertilizers over the box frond stack where the fertilizer is less susceptible to surface wash, and there is a large amount of active fine feeder roots.

Photo 9. Box-pattern frond stacking in a mature plantation reduces surface run-off and provides an erosion barrier.

3 Ground cover management

Many smallholder farms in West Africa are overgrown by dense woody plants (e.g. *Baphia nitida* as well as volunteer palm seedlings), which should be removed to reduce competition for nutrients, moisture and light and to provide access for harvesting and field maintenance operations. Unsuitable groundcover vegetation should be replaced by groundcover such as soft grasses and herbaceous weeds. Competitive woody plants in palm inter-rows should be eliminated with an integrated approach that includes manual control (slashing, uprooting), chemical control, and improvements to soil fertility.

The following methods are recommended to control woody growth and to improve the quality of the inter-row vegetation:

i. Slash woody growth to knee height, wait for regrowth (2–4 weeks). Spray woody plants with a mixture of tryclopyr and diesel (1:5). Repeat spraying (i.e. two to three cycles) may be required to eliminate stubborn woody plants.
ii. At farms with little woody growth, a targeted approach is more appropriate:
    a. Slash the woody plant at knee height and immediately apply a mixture of tryclopyr and diesel (1:5) to freshly cut surface of the stump with a brush.
    b. Alternatively, dig out the woody plants using an old harvesting chisel.
iii. Broadcast 3–7 kg/palm reactive rock phosphate to encourage the establishment of soft weeds, grasses and ferns (e.g. *Nephrolepis biserrata*) over the inter-row space. Apply large applications of RP in several split applications.
iv. Establishment of legume cover plants in the inter-row (3 plants/palm). *Pueraria* and *Mucuna* spp. are more common and easier to establish in West Africa than the plant shade tolerant *Calopogonium* spp.

Photo 10. Woody growth (*Baphia nitida*) competes with the palms for nutrients and water.

Photo 11. An inter-row vegetation consisting of ferns and soft weeds is less likely to compete with palms for nutrients and water, and is less costly to manage than woody growth.

4 Drainage and water management

Most oil palm farms in West Africa include low-lying areas that are poorly drained. Low lying areas have the potential to produce large yields due to their more fertile soils and higher water holding capacity, but require costly drainage to prevent flooding and water-logging during periods of high rainfall.

In poorly drained areas, palms are unable to extract water and nutrients because the roots cannot breathe, resulting in poor palm growth and reduced yields. To increase production in poorly drained low-lying areas, a water management system is required to remove excess water in the rain season and to conserve water in the dry season.

Before any drainage work is undertaken, it is advised to draft a drainage plan first and mark the direction of drains in the field with coloured pegs. Drains can be installed effectively using excavators fitted with a trapezoidal or 'V' bucket. V-shaped drains with sloping sides are less prone to collapse and the narrow bottom is self-cleaning and less prone to silting-up. The following steps are recommended:

i. Check whether the farm drain outlets provide the means to carry drainage water away from the farm. It may be necessary to dig new outlet drains ($\geq$1.5 m deep) or deepen existing drains to provide effective drainage outlets. If a number of farms require main drains it may be less costly to employ a contractor with an excavator and ‘V’ bucket to install the drains.

ii. The main drain should run through the lowest points in the field.

iii. Always start drain installation and rehabilitation at the outlet-end (i.e. lowest point) of the drain.

iv. Once the main drain has been installed, install field drains (≥1 m deep) every four palm rows and connect them to the main drain.

v. Additional sub-field drains (about 0.5 m deep) may be required in areas that are difficult to drain.

vi. Install culverts as required (e.g. where main drains cross a road).

vii. In hilly areas, it may be necessary to install a foot-hill drain (about 0.5 m deep) at the base of the hill and along the contour to divert run-off water into the main drains. This lessens the requirement for drainage within valley bottoms.

viii. Accessibility in drained areas must be provided by constructing footbridges over the drains.

ix. To conserve water in the dry season, field drains can be blocked at the end of the wet season by using used fertilizer bags filled with sand/soil.

Photo 12. Poor drainage in low-lying areas imposes stresses on the palms and impedes access for complete crop recovery in the rain season.

Photo 13. A well-drained oil palm farm will give larger yields and better access for maintenance and harvesting operations.

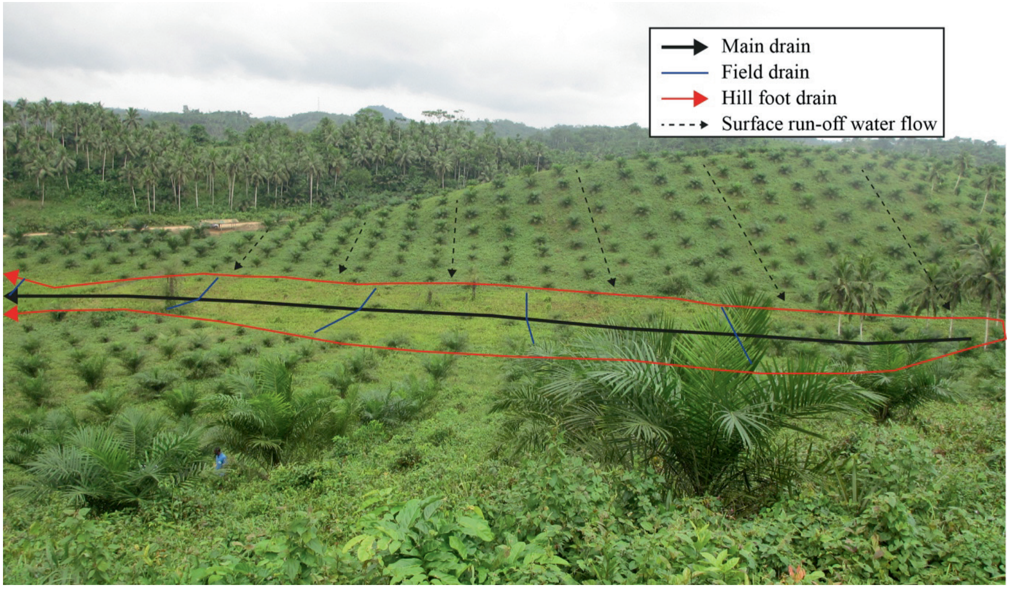

Photo 14. Example of a drainage plan for an immature oil palm field, showing the main drain, field drains and hill-foot drains.

5 Nutrient management

In the oil palm belt in West Africa, most soils contain very small amounts of nutrients, especially potassium (K) and phosphorus (P) (Chapter 3). The efficient use of fertilizers and crop residues is therefore necessary to optimize FB yields and profits in oil palm. In this section, we provide a guideline for nutrient management, following the ‘4R nutrient stewardship approach” (IPNI, 2012), where plant nutrients are applied with the *right* source (1), at the *right* rate (2), at the *right* time (3), and in the *right* place (4).

Right source:

i. Large amounts of nutrients are removed from the farm in harvested fruit bunches. On low fertility status soils, it is essential to compensate for nutrient removal by adding nutrients with mineral fertilizers.
ii. A suitable product is the compound fertilizer NPK 10–10–30+1.5MgO+0.2B, because it contains the correct combination and balance of nutrients and trace elements for oil palm. If compound fertilizers are not available, straight fertilizers (which usually contain a single nutrient) can be used instead (Table 2).

Right rate, or amount:

i. To achieve healthy palm growth and targeted yields, sufficient quantities of each essential nutrient (nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and boron (B)), must be provided to meet the palm demand for vegetative growth and yield.
ii. Fertilizer rates take into account site yield potential (based on climate, palm age, and planting material), soil fertility and the results of annual leaf nutrient assessments (nutrient analysis and nutrient deficiency scores). For example, larger application rates are necessary to maximise yield where rainfall is plentiful, while smaller application rates are recommended where rainfall is low.
iii. Based on (un)published information from fertilizer trials in West Africa[f,g], the optimal amount of fertilizer for mature oil palms is 4–6 kg/palm NPK 10–10–30+1.5MgO+0.2B, which provides 0.4–0.6 kg/palm N, 0.4–0.6 kg/palm P_2O_5, 1.2–1.8 kg/palm K_2O, 0.06–0.09 kg/palm MgO and 0.08–0.12 kg/palm B.
iv. If resources are limited, start with 1 kg/palm NPK, and increase the application rate each year.
v. If NPK 10–10–30+1.5MgO+0.2B is not available, a combination of straight fertilisers can be used instead to provide the major nutrients (Table 2). For

[f]Danso, I., Nuertey, B., Asamoah, T., Tetteh, F., Danso, F., Afari, P., Safo, E. and Logah, V., 2010. The effect of rock phosphate on soil nutrient dynamics, growth, development and yield of oil palm in the semi-deciduous forest zone of Ghana. J. Sci. Technol., 30(1): 30-44.
[g]van der Vossen, H.A.M., 1970. Nutrient status and fertilizer responses of oil palms on different soils in the forest zone of Ghana. Ghana J. Agric. Sci., 3: 109–129.

example, 1.3 kg urea, 1.3 kg TSP and 3.0 kg KCl is equivalent to 6 kg NPK 10–10–30.

vi. A calibrated cup or dish should be used to measure the correct amount of fertilizer for each palm.

Table A12.2. Amount of straight fertilizer (kg palm^{-1}) equivalent to NPK 10–10–30 compound fertilizer.

NPK 10–10–30 compound fertilizer	Equivalent straight fertilizer				
	Nitrogen (N)		Phosphorus (P)		Potassium (K)
	Urea	Ammonium sulphate	Rock phosphate	TSP	KCl
kg palm^{-1}					
1	0.2	0.5	0.3	0.2	0.5
2	0.4	1.0	0.7	0.4	1.0
3	0.7	1.4	1.0	0.7	1.5
4	0.9	1.9	1.3	0.9	2.0
5	1.1	2.4	1.7	1.1	2.5
6	1.3	2.9	2.0	1.3	3.0

Right time:

i. Nutrients should be applied on time, in order to provide the palms with a fairly continuous supply of nutrients.

ii. Losses of N from ammonia-based N fertilizers (e.g. urea) can be reduced by applying fertilizer when there is a strong likelihood of moderate rainfall (i.e. 10–20 mm/day) within the 3–4 days following application. Urea application should therefore be timed to take place during the wet season but not in months where very high rainfall over short periods is likely.

iii. Avoid fertilizer application during periods of very heavy rainfall (i.e. >20 mm/day) where fertilizer losses due to leaching and surface water run-off will be significant.

iv. Fertilizers should be applied in several split applications. For example, 6 kg/palm NPK 10–10–30 compound fertilizer should be applied in four split applications each of 1.5 kg/palm. In most parts of Ghana's oil palm belt the optimal months for fertilizer application are March–June and August–September (Table 3).

Right place:

i. It is important to apply fertilizers where nutrient uptake by the palms is most efficient and where the risk of losses due to surface water run-off and erosion are minimized.

ii. Compound and P, K, and Mg fertilizers are less susceptible to surface water runoff after application when there is a protective layer of mulch over the soil surface.

Table A12.3. Example of a fertilizer application schedule for 4 and 6 kg/palm (in cursive, bold) NPK 10–10–30 and its equivalent in straight fertilizers. Nitrogen can be applied with straights as either urea or SOA and phosphorus with RP or TSP.

Fertilizer		**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
		kg/palm												
NPK				1.5		1.5				1.0				4.0
10–10–30				***1.5***		***1.5***			***1.5***	***1.5***				***6.0***
Equivalent in straights:														
N	Urea				0.9									0.9
					1.3									***1.3***
	SOA				1.0				0.9					1.9
					1.5				***1.4***					***2.9***
P	RP					1.3								1.3
						1.0				***1.0***				***2.0***
	TSP					0.9								0.9
						1.3								***1.3***
K	KCL				1.0				1.0					2.0
					1.5				***1.5***					***3.0***

iii. Correct placement means applying fertilizer where there is a large amount of fine feeder roots. In mature oil palm plantations, where pruned fronds have been stacked in a box pattern, the greatest amount of fine feeder roots is found in soil beneath the frond stack. Fertilizer placement is recommended as follows:
   a. In the first year after rehabilitation (i.e. whilst hard weeds and woody growth are being removed from the palm inter-rows), fertilizers should be spread evenly over the weeded circles.
   b. In the second and subsequent years after rehabilitation, and once woody growth and hard weeds in the inter-row space have been controlled, compound and P, K, and Mg fertilizers should be broadcast over the frond stack.

iv. Urea fertilizers should be spread evenly over the clean weeded circle.

v. To achieve an even distribution of fertilizer in the field, flick the fertilizer from a plate using the fingers of one hand whilst holding the plate in the other hand.

Mill residues, such as empty fruit bunches (EFB), decanter cake and palm oil mill effluent (POME), are an important source of nutrients for oil palm. When they are recycled and applied to the field, fertilizer application can be reduced as follows:

i. An application of 40 t/ha (or 300 kg/palm) EFB, spread evenly between palms within rows and in the palm inter-rows, provides the palms with sufficient P, K and Mg for about one year. A small amount of N fertilizer (e.g. 0.5 kg/palm as either 1 kg/palm urea or 2.5 kg/palm ammonium sulphate) should be applied to provide an adequate supply of nitrogen.

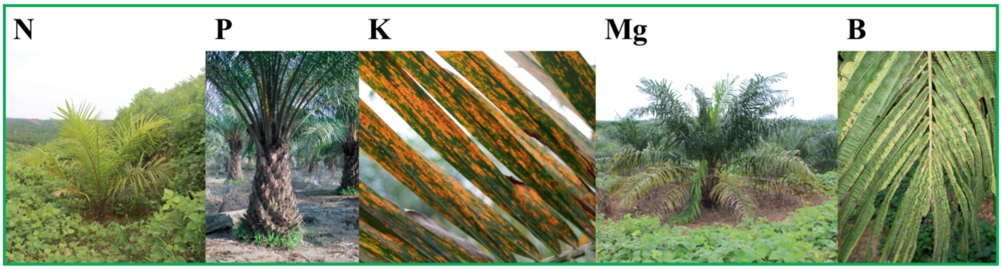

Photo 15. Nutrient deficiencies in oil palm (N, P, K, Mg, B) can be overcome with balanced nutrient management, such as the 4R nutrient stewardship approach.

Photo 16. Calibrating fertilizer rates using a plastic dish allows for rapid and efficient application in the field.

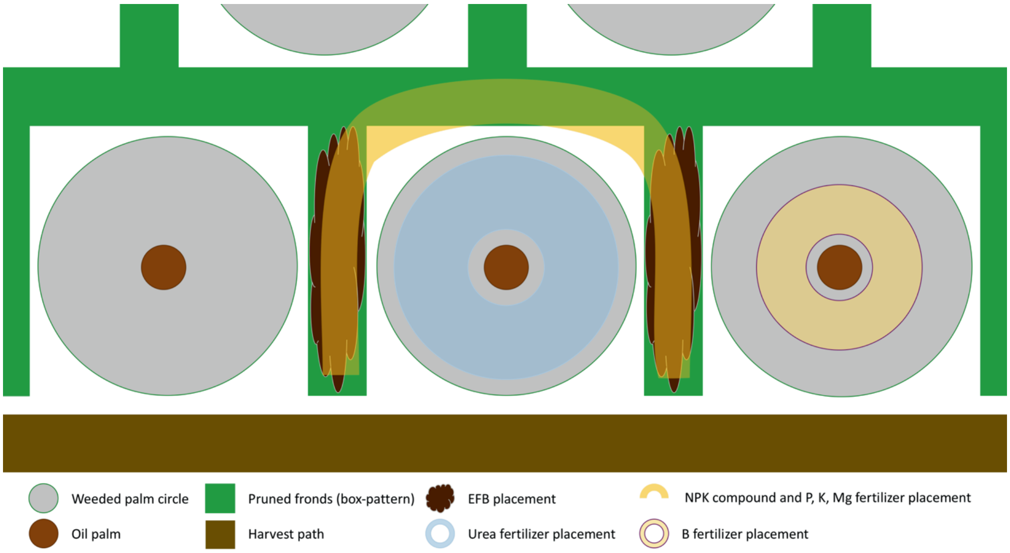

Photo 17. In mature oil palms, fertilizers should be applied to ‘target areas’, where nutrient uptake is most effective and losses are minimized.

Photo 18. Using the flick method for fertilizer application provides even distribution over the frond stack and better uptake of nutrients.

Photo 19. Recycling crop residues, such as empty fruit bunches (EFB), reduces annual fertilizer requirements.

Time lags between stress events and their effect on yield in oil palm

The oil palm is adapted to respond to different kinds of stress. A significant stress event (e.g. three months of drought, full leaf defoliation by leaf miner insects, lack of fertilizer application) triggers several responses by the palms:

i. More male flowers and less female flowers are produced at sex determination, resulting in a 'male flower phase' and less fruit bunches 30–33 months later.
ii. Flowers may abort, resulting in less bunches 7–13 months later.
iii. Pollinated bunches may abort, resulting in a large number of poorly formed bunches (bunch failure) 2–5 months later.

Photo 20. Abiotic and biotic stresses can reduce the number of bunches at sex differentiation of the inflorescences at approximately 30–33 months before harvest.

Photo 21. Bunch failure occurs at about 2–5 months to harvest and depends on the magnitude of stresses (e.g. drought, pest incidence) imposed on the palms.

In this way, the palm avoids excessive bunch production following periods of stress. Clearly, the time lag between a single stress event and a change in production may range from 2–40 months. In reality, stress events may occur more frequently. For example, a drought period may be followed several months later by defoliation caused by an outbreak of leaf miner insects. Whilst the drought stress (an abiotic stress factor) cannot be avoided (but there are options to improve water management), the leaf miner outbreak (a biotic stress factor) can be avoided by early pest identification (i.e. with an effective early warning system) and prompt implementation of control measures when pest pressure exceeds the respective threshold but before extensive leaf canopy damage occurs.

During crop scene investigations, it is important to try to relate the present condition of the palms (e.g. bunch production, black bunch count, sex ratio (i.e. the ratio of female to male plus female flowers)) to past stress events (e.g. drought, delayed fertilizer application, pest outbreaks). To do this, proper record keeping is essential.

Rehabilitating neglected oil palm farms is a step-wise process and should be implemented in the correct sequence in order to minimize agronomic stress effectively.

Yield taking:

i. Most important is to first provide unimpeded access for harvesting operations and palm upkeep with the installation of harvest paths and weeded circles, and removal of unproductive fronds with corrective pruning.
ii. The second step involves the introduction of regular and complete harvesting events at 7–10 day intervals to ensure complete crop recovery.

Yield making:

iii. After yield taking constraints have been completely removed, yield making operations should focus on the following practices:
    a. Improving nutrient management with balanced mineral nutrition.
    b. Soil conservation and mulching with mill residues.
    c. Maintenance of optimal leaf canopy by implementing two cycles of pruning per year.
    d. Maintenance of optimal ground cover by the manual and chemical removal of woody weeds in palm inter-rows and harvest paths to favour the establishment of soft weeds, grasses and legume cover plants (LCP). An application of P fertilizer may be required to improve the competitiveness of soft weeds, grasses and LCP.
    e. Improving drainage in swampy areas by installing ‘V’ shaped drains.

The long time-lag between flowering and bunch harvest means that complete rehabilitation of neglected palms takes about four years (Fig. 1.3). It is possible to measure the separate effects of yield taking and yield making:

iv. ‘Yield taking’ takes place during the short period of 3–6 months required to achieve crop recovery. There may be an increase in bunch number due to complete crop recovery and bunch weight due to complete loose fruit collection.

v. ‘Yield making’ practices start to impact yield after about six months, by which time there may be a significant increase in bunch weight. An increase in bunch number due to increased floral initiation and changes in sex ratio occur respectively 12–30 months after agronomic constraints have been removed.

Cost-benefit analysis

Rehabilitating neglected or abandoned oil palm requires significant initial investments to achieve complete crop recovery and to eliminate all agronomic constraints. Thereafter, field upkeep costs usually decrease, often to amounts less than pre-BMP costs.

The majority of the costs occur in the first year, when additional labour is required to rehabilitate the farm with corrective pruning, installation of paths and palm circles and the removal of woody growth (Table 4). Farmer income therefore decreases in the first year of rehabilitation when yields have not yet started to increase significantly. Once proper access to the palms has been established, harvesting is easier and less costly, resulting in improved crop recovery and profitability.

In the short-term, improvements to economic returns in smallholder farms can be achieved by simply improving crop recovery, which helps to finance inputs needed for the yield making phase, such as fertilizers. By the third year after rehabilitation, the benefits of investing in yield making start to become apparent, with larger returns on investments than before starting BMP. By Year 4, profits are more than double the pre-BMP phase (Table 4). The best farms will likely produce yields of 20–25 t/ha FB, so profits will be even larger.

Most smallholder farmers have insufficient funds to complete rehabilitation over a large area, particularly given the four-year full payback period. It is therefore recommended to carry out rehabilitation in parcels, according the farmer’s access to labour and funds.

Table 4. Example cash flow for the rehabilitation of a neglected mature oil palm farm with BMP, using trial data from Ghana.

Parameter	Units	Pre-BMP		BMP			
		Year					
		0	1	2	3	4	5
Fruit bunch yield	t ha^{-1}	7	10	13	18	20	20
Revenue	US$/ha	529	755	982	1,360	1,511	1,511
Material costs							
Fertilizer	US$/ha	0	148	197	246	246	246
Herbicide	US$/ha	0	36	36	36	36	36
Garlon	US$/ha	0	58	0	0	0	0
Diesel	US$/ha	0	20	0	0	0	0
Total material costs	US$/ha	0	262	233	283	283	283
Machine costs							
Excavator	US$/ha	0	76	0	76	0	0
Grader	US$/ha	0	76	0	0	76	0
Total machine costs	US$/ha	0	151	0	76	76	0
Labour costs							
General labour	US$/ha	4	225	99	102	102	102
Harvesting labour	US$/ha	127	63	82	109	118	118
Total labour costs	US$/ha	131	289	181	211	220	220
All costs	US$/ha	131	702	414	569	578	503
Margin over costs	US$/ha	398	53	568	790	932	1,008

Conclusions

Rehabilitating farms with BMPs shows considerable scope for increasing yields and profitability in smallholder oil palm farms (Table 4). In Ghana, average yields with BMP approached 18 t/ha FB after 3 years; an increase of 12 t/ha (+200%) over initial yields. These results show that rehabilitation of existing *tenera* plantings is a better option than investing in new plantings. Yield intensification can be achieved without the capital expenditure required for new plantings (e.g. road infrastructure, planting cost), and financial returns from investments in yield intensification accrue more rapidly because production starts to increase as soon as field management and agronomic constraints have been removed.

Rehabilitation of neglected mature oil palm farms can be highly profitable provided the following conditions are met:

i. Farmers have access to competitively priced fertilizers,
ii. Farmers have access to competitively priced markets for fruit bunches. This means access to a modern palm oil mill achieving commercial extraction rates (≥23% oil extraction rate) where part of the benefits of high extraction rates are passed back to the smallholder in terms of FB price.
iii. Inputs are used effectively:
    a. No wasted herbicide,
    b. Fertilizer applied correctly,
    c. Mill residues are utilized in the field, and
    d. Labour is used effectively.
iv. Field conditions up to BMP standard (field access, ground cover management, pruning, pruned frond management).
v. Full crop recovery with 7–10 day harvest intervals, and complete bunch and loose fruit collection.

Mature oil palm farms should be rehabilitated in steps and according to the farmer's capacity to invest in labour, inputs and supervision.

The farmer must adjust to more intensive enterprise management, including the following:

i. Need for financial planning,
ii. Likely requirement to borrow funds, and
iii. Need to supervise larger investments in field labour.

It will be necessary for farmers to forge a close relationship with a commercial bank by implementing financial transactions via a bank. Once a farmer has demonstrated significant cash flow, the bank may be willing to provide working capital.

It is important for governments and investors (NGOs, banks) to consider the benefits of investing in the rehabilitation of existing oil palm plantings to improve farm profitability and increase palm oil production whilst reducing the requirement for area expansion to satisfy market demand for palm oil.

SUMMARY

The large demand for vegetable oil has resulted in a rapid expansion of global oil palm cultivation. Most of the current expansion is taking place in sub-Saharan Africa and Latin America as land available for new oil palm plantings is now limited in Southeast Asia. In Ghana, for example, oil palm (*Elaeis guineensis* Jacq.) experienced a tremendous resurgence since the early 2000s, partly due to a growing interest by investors to expand and develop the area planted to oil palm. As a result, Ghana became the third largest producer of palm oil in sub-Saharan Africa in 2017 at 2.5 Mt yr^{-1} (next to Nigeria (7.8 Mt yr^{-1}) and Cameroon (3.1 Mt yr^{-1})). Oil palm is currently the second most important perennial crop in the Ghanaian economy after cocoa. Despite large increases in total production the past 15 years, fruit bunch (FB) yields remained low. With an estimated yield potential (Yw) of 21 t ha^{-1} FB, and actual yields of 11.0 t ha^{-1} FB on plantations and 6.0 t ha^{-1} FB on smallholder farms in Ghana, large yield gaps exist.

This thesis analysed the factors that currently limit oil palm production in Ghana and assessed opportunities to increase yields with improved agronomic practices. Firstly, a review and characterization of the environment for growing oil palm in Ghana was conducted, and used as a basis to determine the suitability and availability of land for production (Chapter 2). Detailed characterization of the oil palm sector in Ghana was then conducted, and yield gaps and their underlying causes analysed using the concepts of production ecology (Chapter 3). Third, the potential of 'Best Management Practices' (BMP) to close yield gaps in existing mature oil palm plantings was evaluated (Chapter 4). Finally, an experiment to investigate the interaction of nutrients and water on the yield performance of oil palm was conducted on a large-scale oil palm plantation in Western region, Ghana (Chapter 5).

In Chapter 2, land suitability evaluation (LSE) methods were used to identify areas that are both suitable and available for oil palm production in Ghana. A major climatic factor limiting oil palm production in Ghana is the annual water deficit, with the most suitable areas located in the rainforest and semi-deciduous forest zones with higher rainfall in southern Ghana. Opportunities for the large-scale oil palm sector to develop was constrained due to the lack of availability of large and contiguous tracts of land that are required for commercial plantation oil palm development. The results suggest that a feasible strategy for increasing oil palm production is through smallholders, which can make use of smaller parcels of land. Alternatively, oil palm production in Ghana can be increased by yield intensification on land already planted to oil palm.

To guide yield intensification practices, one must first understand the magnitude and the underlying causes of yield gaps. In Chapter 3, Yield Gap Analysis (YGA) was used

to elucidate the factors that were responsible for yield gaps at plantations and smallholder farms. Farm surveys were conducted to characterize plantations and smallholder farms in terms of production inputs (labour, fertilizer, empty fruit bunch mulch, and agro-chemicals including herbicides and insecticides) and outputs (bunch production, number of bunches, and FB yield and yield components). To provide a benchmark for the yield potential (*Yw*) in Ghana, a boundary line was fitted through yield data obtained from well-managed mature oil palm fields. Yield gaps were calculated as the difference between *Yw* and yields obtained from smallholder and plantation, and averaged 15.4 t ha^{-1} FB at smallholder farms, and 9.8 t ha^{-1} FB at plantations. The analysis revealed that poor management practices, including incomplete crop recovery (i.e. not harvesting all available crop) and inadequate agronomic management were the main factors contributing to these yield gaps. Particularly smallholders face major challenges in increasing yields, due to a lack of knowledge on appropriate management practices and poor operating conditions (e.g. poor infrastructure and lack access to credit). Productivity losses were exacerbated by low oil extraction rates (OER) by small-scale processors of 12% as compared to 21% by the large-scale processors. The potential losses in annual CPO during the crop plateau yield phase were estimated to be 5 and 3 t ha^{-1} yr^{-1} for small-scale and large-scale production systems respectively. The results of this study suggest that investments in yield gap reduction, by improving agronomy and crop recovery at plantations and smallholders, whilst improving access of smallholder producers to more efficient oil palm processing facilities, can make a significant contribution to closing the supply gap for palm oil in Ghana.

The potential of closing yield gaps on plantations and smallholder farms through implementation of 'Best Management Practices' (BMPs) was assessed in Chapter 4. BMPs were evaluated against current management practices, amongst those that increased yield in the short-term term (≤ 1 year) with 'yield taking' (improved crop recovery), and in the long-term (>1 year) with 'yield making' (better agronomy) practices. Experimental results indicate that yield increases with BMP are large. Average yields with BMP increased with 2.1 t ha^{-1} (+19%) and 4.7 t ha^{-1} (+89%) with yield taking and with 4.7 t ha^{-1} (+36%) and 7.6 t ha^{-1} (+76%) with yield making at plantations and smallholders respectively. Improvements in crop recovery, including more frequent harvesting events (i.e. short harvest intervals) and improved field access (roads, paths, weeded circles) for more efficient productivity (i.e. more bunch weight harvested and less area (ha) covered per harvester) contributed considerably to yield increases with BMP. Longer-term yield increases were more complicated to explain, due to a time-lagged effect of improved agronomy on yield, but analysis of fertilizer usage and leaf nutrient concentrations suggest a more balanced approach to nutrient management could contribute considerably to yield making, particularly at smallholder farms. There is therefore need to develop improved fertilizer recommendations to further increase yields and to sustainably intensify oil palm production in Ghana.

Chapter 5 focuses on the assessment of the interaction of nutrients and water on the yield performance of oil palm on a large-scale oil palm plantation in Western region, Ghana. Average yields of about 32.6 t ha^{-1} were achieved with irrigation and fertilizer. Yield gaps caused by nutrients were estimated at 4.1 t ha^{-1} and 4.7 t ha^{-1} for water, whilst the response to irrigation alone without fertilizer was 0.6 t ha^{-1}. These results suggest that fertilizer is essential for increasing yields with irrigation, but information on the specific nutrients required and their optimal application rates is lacking, and requires further investigation. Despite the use of irrigation, annual yield cycles in oil palm persisted. This can lead to irregular distribution of production and lack of mill capacity and insufficient harvesters in the peak crop months. Many factors have been proposed that cause these fluctuations, but the processes behind these yield cycles remain unclear.

The research conducted in this thesis shows that there are large yield gaps in plantation and smallholder production systems in Ghana, which are caused by sub-optimal climate conditions (e.g. water) and poor management practices (e.g. crop recovery, nutrient management), amongst others. The potential to increase productivity with BMP, however, is considerable. The significant yield improvements achievable with BMPs at sites representative of the Ghanaian oil palm industry offer scope to reduce the requirement for future area expansion to meet the increasing demand for oil palm cultivation. Increasing average national yields to 21.0 t ha^{-1} FB, for example, could spare almost 600,000 ha of land. In addition, closing yield gaps in Ghana under current land area (327,000 ha) has the potential to increase fruit bunch production almost three-fold from 2,5 Mt to 6,9 Mt. If all crop is processed at an OER of 21%, approximately 1.4 Mt CPO can be produced. This is more than enough to meet Ghana's current annual demand of 106,000 t CPO, and does not require the need to plant additional land. Yield intensification strategies may therefore be an important policy for sustainable oil palm development and land use in Ghana and West Africa.

SAMENVATTING

Door de grote vraag naar plantaardige olie is het oliepalm (*Elaeis guineensis* Jacq.) areaal sterk toegenomen in de wereld. Het merendeel van de recente toename vindt plaats ten zuiden van de Sahara in Afrika en Latijns-Amerika, omdat Zuidoost-Azië nog maar slechts beperkte mogelijkheden heeft om nieuwe oliepalm aan te planten. Ghana bijvoorbeeld, kent sinds het begin van de 21^{e} eeuw een enorme opleving van oliepalm, onder meer door een groeiende interesse van investeerders. Het resultaat is dat Ghana de op twee na grootste producent van palmolie in Afrika ten zuiden van de Sahara is met jaarlijks 2.5 megaton productie (na Nigeria (7.8 megaton per jaar) en Kameroen (3.1 megaton per jaar)). Oliepalm is tegenwoordig het op één na belangrijkste gewas in de Ghanese economie, na cacao. Ondanks de toename in productie van de afgelopen 15 jaar, bleven de opbrengsten van de oliepalmvruchten laag. Met een geschatte potentiële opbrengst (*Yw*) van 21 ton per ha aan oliepalmvruchten en een werkelijke opbrengst op de plantages van 11 ton per ha en 6 ton per ha bij kleine boeren, bestaan er in Ghana grote verschillen tussen de potentiële en werkelijke opbrengsten (de zogenaamde opbrengstverschillen of 'yield gaps').

In deze thesis werden de factoren die de oliepalmproductie in Ghana limiteren, geanalyseerd. Ook werd gekeken naar mogelijkheden om de opbrengsten te verhogen d.m.v. verbeterde landbouwkundige praktijken. Eerst werd de groeiomgeving van oliepalm in Ghana beschreven, om vervolgens de geschiktheid en beschikbaarheid van land voor productie te bepalen (hoofdstuk 2). Daarna werd de oliepalm sector in Ghana bestudeerd en werden de oorzaken voor de yield gaps geanalyseerd, daarbij gebruikmakende van de concepten van ecologische productiefactoren (hoofdstuk 3). Ten derde volgde er een analyse van de mogelijkheden om yield gaps te dichten via 'Best Management Practices' (BMP) (hoofdstuk 4). Tenslotte werd een experiment uitgevoerd om de interactie tussen nutriënten en water op de oliepalmopbrengst te onderzoeken op een grootschalige oliepalmplantage in Western Region, Ghana (hoofdstuk 5).

In hoofdstuk 2 werden 'land suitability evaluation' (LSE) methoden gebruikt om gebieden te identificeren die zowel geschikt als beschikbaar zijn voor oliepalmproductie in Ghana. Hieruit bleek dat de oliepalmproductie in Ghana beperkt werd door het jaarlijkse watertekort. De meest geschikte gebieden voor oliepalmproductie waren te vinden in het regenwoud en semi-loofboszones met hogere regenval in zuidelijk Ghana. Mogelijkheden voor de grootschalige oliepalmproductie om zich beter te ontwikkelen werden ook geremd door een tekort aan grote, aaneengesloten stukken land, wat een vereiste is voor de commerciële ontwikkeling van oliepalmplantages.

Een mogelijke geschikte strategie is daarom om de oliepalmproductie te verhogen via kleine boeren, die gebruik kunnen maken van kleinere percelen land. Een andere mogelijkheid voor een grotere oliepalmproductie is door verhoging van de opbrengst op land waar al oliepalm aangeplant is.

Om opbrengst verhogende praktijken uit te voeren moet men eerst de grootte van de yield gaps en de onderliggende oorzaken ervan begrijpen. In hoofdstuk 3, werd 'Yield Gap Analysis' (YGA) gebruikt om de factoren toe te lichten die verantwoordelijk waren voor yield gaps op plantages en kleine boeren. Plantages en bedrijven van kleine boeren werden ingedeeld volgens hun productie inputs (o.a. arbeid, kunstmest, oogstresten, en bestrijdingsmiddelen) en outputs (o.a. palmvrucht productie, aantal palmvruchten en palmvrucht opbrengst per ha). De opbrengstdata van goed producerende oliepalmvelden werd gebruikt als maatstaf voor de potentiële opbrengst (*Yw*). Yield gaps werden berekend als het verschil tussen *Yw* en werkelijke opbrengsten, en bedroegen gemiddeld 15.4 ton per ha bij kleine boeren en 9.8 ton per ha op plantages. De analyse liet heel wat suboptimale managementpraktijken zien. De belangrijkste factoren die bijdroegen aan de yield gaps waren het niet volledig oogsten van het gewas en ontoereikend landbouwkundig management. Vooral de kleine boeren staan tegenover grote uitdagingen om de opbrengsten te verhogen vanwege een gebrek aan kennis en passende managementpraktijken en slechte exploitatieomstandigheden (bijvoorbeeld slechte infrastructuur en geen toegang tot kredieten). Verliezen in productie werden verergerd door lage olie-extractie (OER) van 12% door kleinschalige verwerkers, vergeleken met grootschalige verwerkers van 21%. De potentiële verliezen in jaarlijkse ruwe palmolie (CPO) gedurende de plateau opbrengstfase werd geschat op jaarlijks 5 en 3 ton per ha voor respectievelijk kleinschalige en grootschalige productiesystemen. De resultaten van deze studie suggereren dat het tekort aan palmolie in Ghana aangepakt kan worden door meer te investeren in het dichten van yield gaps door verbeterde agronomie en oogstpraktijken op plantages en bij kleine boeren, alsook om ervoor te zorgen dat de kleinere boeren betere toegang krijgen tot oliepalmverwerkers en door de verhoging van de efficiëntie van oliepalmverwerkers zelf.

Best Management Practices (BMPs) zijn een manier om yield gaps van plantages en kleine boeren te dichten (hoofdstuk 4). BMPs werden vergeleken met huidige managementpraktijken, en werden ingedeeld onder maatregelen welke de opbrengsten verhoogden op de korte termijn (≤ 1 jaar) met 'yield taking' (verbeterde oogstpraktijken) en op de lange termijn (>1 jaar) met 'yield making' (betere agronomische praktijken). Resultaten uit experimenten lieten zien dat de toenames in opbrengsten groot zijn met BMP. De gemiddelde opbrengsten met BMP stegen met 2.1 ton per ha (+ 19%) en 4.7 ton per ha (+ 89%) bij 'yield taking' en met

4.7 ton per ha (+ 36%) en 7.6 ton per ha (+ 76%) bij ‘yield making’ voor respectievelijk plantages en kleine boeren. Verbeteringen in ‘crop recovery’ (oogstpraktijken) met inbegrip van frequenter oogsten (d.w.z. kortere oogstintervallen) en verbeterde toegang tot het veld (wegen, paden, ‘weeded circles’ (boomspiegels)) voor een efficiëntere productiviteit (d.w.z. hoger geoogst palmvruchtgewicht en kleiner oppervlak (ha) per oogster) droegen aanzienlijk bij tot een verhoogde opbrengst. De volledige langere termijn impact van BMPs was moeilijker vast te stellen, omdat de verbeterde landbouwpraktijken nog lang effect na kunnen hebben. Maar de analyse van kunstmestgebruik en van nutriënten in bladmonsters suggereerden dat een evenwichtigere benadering van nutriëntenmanagement aanzienlijk kan bijdragen aan ‘yield making’, in het bijzonder bij de kleine boeren. Daarom is er behoefte aan het ontwikkelen van verbeterde aanbevelingen met betrekking tot kunstmestgebruik, om zo de opbrengsten verder te verhogen en om de oliepalmproductie duurzaam te intensiveren in Ghana.

In hoofdstuk 5 lag de focus op het bepalen van de interactie van nutriënten en water op de oliepalmopbrengst op een oliepalmplantage in Western region, Ghana. De gemiddelde opbrengsten van ongeveer 32.6 ton per ha werden bereikt met een combinatie van irrigatie en kunstmest. Yield gaps die veroorzaakt werden door nutriënten, werden geschat op 4.1 ton per ha en door water 4.7 ton per ha. De respons op irrigatie alleen zonder kunstmest was 0.6 ton per ha. Deze resultaten opperden dat kunstmest essentieel was voor de toename in opbrengsten met irrigatie, maar informatie over de hoeveelheid aan vereiste specifieke nutriënten kon niet bevestigd worden en vereist verder onderzoek. Ondanks het gebruik van irrigatie bleven opbrengstcycli in oliepalm bestaan. Dit kan leiden tot onregelmatige spreiding van de productie en een tekort aan verwerkingscapaciteit en onvoldoende oogsters in de piek gewasmaanden. In de literatuur zijn veel factoren naar voren gebracht die deze fluctuaties veroorzaken, maar de processen achter deze opbrengstcycli zijn nog steeds onduidelijk.

Het onderzoek, dat in deze thesis beschreven is, toont aan dat er grote yield gaps te vinden zijn in de productiesystemen van plantages en kleine boeren in Ghana. De oorzaak daarvan is te vinden in de suboptimale klimaatomstandigheden (bijv. water) en slechte managementpraktijken (bijv. crop recovery, nutriëntenmanagement). De potentie om met BMP de productiviteit te verhogen is echter aanzienlijk. Door BMPs toe te passen zijn er significante verbeteringen in de opbrengst bereikt op locaties die representatief waren voor de Ghanese oliepalmindustrie. Deze resultaten bieden de mogelijkheid om te voldoen aan de toenemende vraag naar palmolie, zonder het areaal aan oliepalm verder uit te breiden. Het vergroten van de gemiddelde nationale opbrengsten tot bijvoorbeeld 21.0 ton per ha zou kunnen leiden tot het uitsparen van bijna 600,000 hectare land. Bovendien heeft het sluiten van de yield gaps in Ghana op het huidige landareaal (327,000 ha) al een potentieel om de productie te verhogen met een factor 3, van 2.5 megaton tot 6.9 megaton palmvruchten. Als de hele oogst wordt verwerkt bij een OER van 21% dan kan ongeveer 1.4 megaton CPO worden geproduceerd. Dit is meer dan genoeg om te voldoen aan de jaarlijkse vraag in Ghana van 106,000 ton CPO en dan is het niet nodig om meer land aan oliepalm aan te planten. Intensivering van opbrengststrategieën met bijhorend landbeleid is daarom een belangrijke strategie voor duurzame oliepalmontwikkeling in Ghana en West-Afrika.

LIST OF PUBLICATIONS

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Rhebergen, T., Fairhurst, T., Whitbread, A., Giller, K.E. and Zingore, S., 2018. Yield gap analysis and entry points for improving productivity on large oil palm plantations and smallholder farms in Ghana. Agricultural Systems, 165: 14–25, https://doi.org/10.1016/j.agsy.2018.05.012.

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CURRICULUM VITAE

Tiemen Rhebergen was born on 13 June 1983 in Heerenveen, the Netherlands, but spent most of his youth in the Lowveld of Swaziland. He has therefore always had a passion for the natural environment, particularly in Africa. In 2006, he graduated with a BSc, and in 2008 with an MSc in Forest and Nature Conservation, specialisation Ecology at Wageningen University (WU). In 2010, he decided to pursue a career in agriculture instead. He enrolled in an MSc in Plant Sciences (WU), which he completed in 2012. For his MSc Thesis, he worked on Best Management Practices in Oil Palm Plantations in Indonesia, from which he developed interest in oil palm and plantation agriculture in general. In 2013, he joined the International Plant Nutrition Institute, Sub-Saharan Africa Program (IPNI SSA) as project manager on an oil palm yield intensification program in Ghana. Under the framework of this project, he started his PhD program at Wageningen University in 2014, in collaboration with IPNI. Tiemen is currently based in Nairobi, Kenya, where he continues his work on oil palm in Africa.

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PE&RC Training and Education Certificate

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 (4.5 ECTS)

- Yield gap analysis in oil palm production systems in Ghana; presented at Göttingen University (2014)

Writing of project proposal (4.5 ECTS)

- Yield gap analysis in oil palm production systems in Ghana

Post-graduate courses (6.6 ECTS)

- Training on vegetative growth measurements in mature oil palm stands; IJM Plantations Sabah, Malaysia (2013)
- Multivariate analysis; WUR (2015)
- Introduction to R; WUR (2015)
- Geostatistics; WUR (2015)
- Spring school ISRIC WSA; ISRIC (2016)

Invited review of (unpublished) journal manuscript (1 ECTS)

- Geoderma: changes in variability and spatial structure of soil organic carbon under tree plantations in Okomu forest southern Nigeria (2016)

Deficiency, Refresh, Brush-up courses (6 ECTS)

- Nutrient management; WUR (2015)

Competence strengthening / skills courses (5 ECTS)

- Philosophy of science and ethics; WUR (2003)
- Mentoring process on scientific writing; IPNI (2015)

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

- PE&RC First years weekend (2015)
- PE&RC Day (2015)

Discussion groups / local seminars / other scientific meetings (6.6 ECTS)

- Oil palm workshop with Thomas Fairhurst and Lotte Woittiez; Wye, UK (2014)

- Seminar: trade-offs and synergies in climate change adaptation and mitigation in coffee and cocoa systems; Göttingen, Germany (2014)
- Meeting and scientific discussion on implementing fertilizer trials in oil palm at K+S; Kassel, Germany (2014)
- Seminars attended, and given at Göttingen, Germany (2014, 2015)
- Lunch-break meetings; WUR (2015-2018)
- Attendance of PhD defences (2015-2018)
- Regular scientific discussions with oil palm professionals, Thomas Fairhurst, Herbert van der Vossen, Rob Verdooren (2015-2018)
- Regular discussions with Petra Rietberg & Gerrie van de Ven on the development of an oil palm economic model; PPS-WUR (2016)

International symposia, workshops and conferences (12 ECTS)

- International Oil Palm Conference (IOPC); Bali, Indonesia (2014)
- Annual oil palm project review and planning meeting; Takoradi, Ghana (2014-2017)
- IPNI Staff meeting; Naivasha, Kenya (2015)
- CocoaSoils research committee meeting; Utrecht, the Netherlands (2017)

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