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

Tiemen Rhebergen[a,b,*], Thomas Fairhurst[c], Anthony Whitbread[d,e], Ken E. Giller[b], Shamie Zingore[a]

[a] International Plant Nutrition Institute Sub-Saharan Africa Program (IPNI SSAP), ICIPE Complex, Duduville, Kasarani, Box 30772, Nairobi, Kenya
[b] Plant Production Systems group, Wageningen University, P.O. Box 430, 6700 AK, Wageningen, the Netherlands
[c] Tropical Crop Consultants Ltd, 26 Oxenturn Road, Wye, Kent TN25 5BE, United Kingdom
[d] Tropical Plant Production and Agricultural Systems Modelling (TROPAGS), George-August-Universität, Göttingen, Grisebachstraße 6, 37077 Göttingen, Germany
[e] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502324, Telangana, India

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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 $> 20\ \mathrm{t\ ha^{-1}\ yr^{-1}}$ are achievable, average FB yields in Ghana are only $7\ \mathrm{t\ ha^{-1}\ yr^{-1}}$. 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 $21\ \mathrm{t\ ha^{-1}\ yr^{-1}}$ FB, with yield gaps of $15.4\ \mathrm{t\ ha^{-1}\ yr^{-1}}$ FB at smallholder farms and $9.8\ \mathrm{t\ ha^{-1}\ yr^{-1}}$ 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 $3\ \mathrm{t\ ha^{-1}\ yr^{-1}}$ 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$.

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 (≥ 1000 ha) with large-scale processing mills (processing capacity $> 15\ \mathrm{t\ hr^{-1}}$ fruit bunches (FB)) (ii) smallholder farms of up to 100 ha and (iii) small-scale processors using semi-mechanized mills (processing capacities of $< 1\ \mathrm{t\ hr^{-1}}$ FB) (Adjei-Nsiah et al., 2012a). In this paper, 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

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[*] Corresponding author at: International Plant Nutrition Institute Sub-Saharan Africa Program (IPNI SSAP), ICIPE Complex, Duduville, Kasarani, Box 30772, Nairobi, Kenya.
E-mail address: trhebergen@ipni.net (T. Rhebergen).

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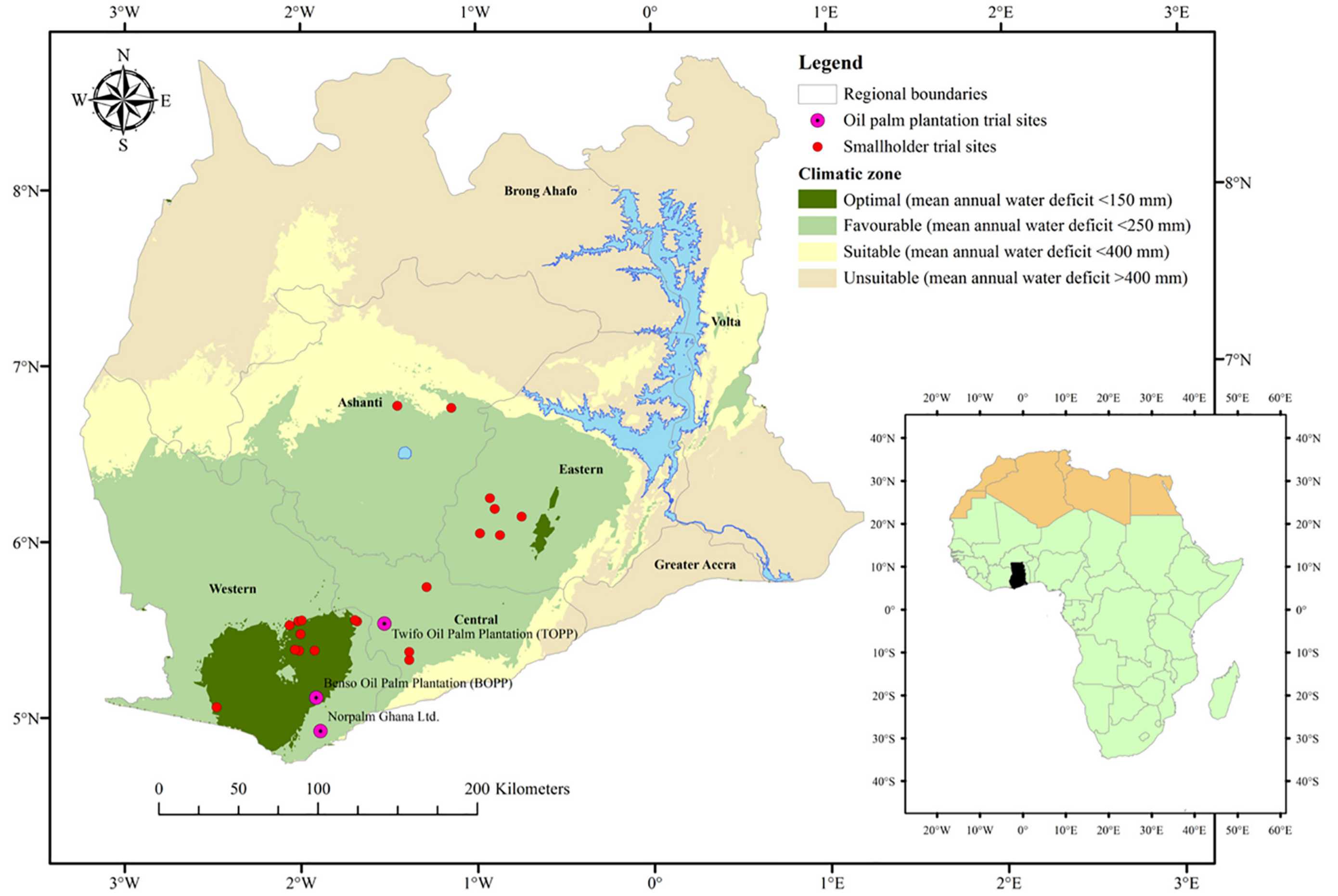

Fig. 1. Map showing location of oil palm plantation and smallholder trial sites and suitability zones for oil palm cultivation in the southern regions of Ghana.

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 and 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. 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.

2. Methods

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. 1).

Rainfall distribution is bimodal in southern Ghana. Mean annual precipitation is greatest at sites in the southwest (with annual average rainfall of 2400 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 (Rhebergen et al., 2016; 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. 1).

2.2. Agronomic trials

Each commercial oil palm plantation consisted of several administrative areas called 'divisions' (± 1000 to 2500 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.

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 will be reported elsewhere.

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 h. 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 and Chew (1997) respectively.

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 to 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. 2).

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):

$$y_1 = \frac{y_w}{1 + (K\ exp(-Rx))}$$

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.

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. Results

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 (2017). The difference between the estimate of Gyasi (1992) and FAO (2017) 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 1).

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

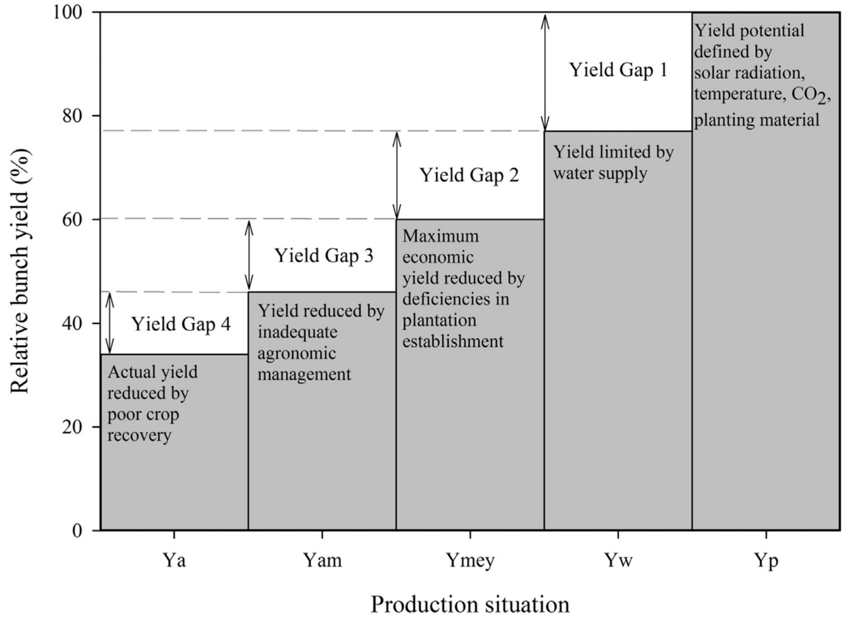

Fig. 2. Modified yield gap model for perennial crops used to partition potential yield (Yp) and actual yield (Ya) into four gaps with the size of each gap depending on site specific factors.

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). 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). Ya was less than Yw at all smallholder and plantation sites (Fig. 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 ($P \leq .05$) 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 ($n = 8$).

3.3. Factors contributing to oil palm yield gaps

3.3.1. 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,

Table 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 (2017), MASDAR (2011) and Ofosu-Budu and Sarpong (2013).

							Mill capacity			
Sector	Area under harvest		Fruit bunch production		Smallholder fruit purchases	Fruit bunch yield	Installed capacity	Operating capacity	Oil extraction rate	CPO yield
	ha	%	t	%	t	$t\,ha^{-1}\,yr^{-1}$	$t\,hr^{-1}$		%	$t\,ha^{-1}\,yr^{-1}$
Oil palm plantations										
TOPP	3250	1	41,300	4	37,600	12.7	30	30	19.8	2.5
BOPP	4890	2	42,300	4	54,700	8.7	20	16	20.8	1.8
Norpalm	3760	1	42,000	4	39,000	11.2	30	25	21.0	2.3
GOPDC	4700	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 (> 10 ha)	3000	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				
FAO (2017)	349,040		2,443,270			7.0				

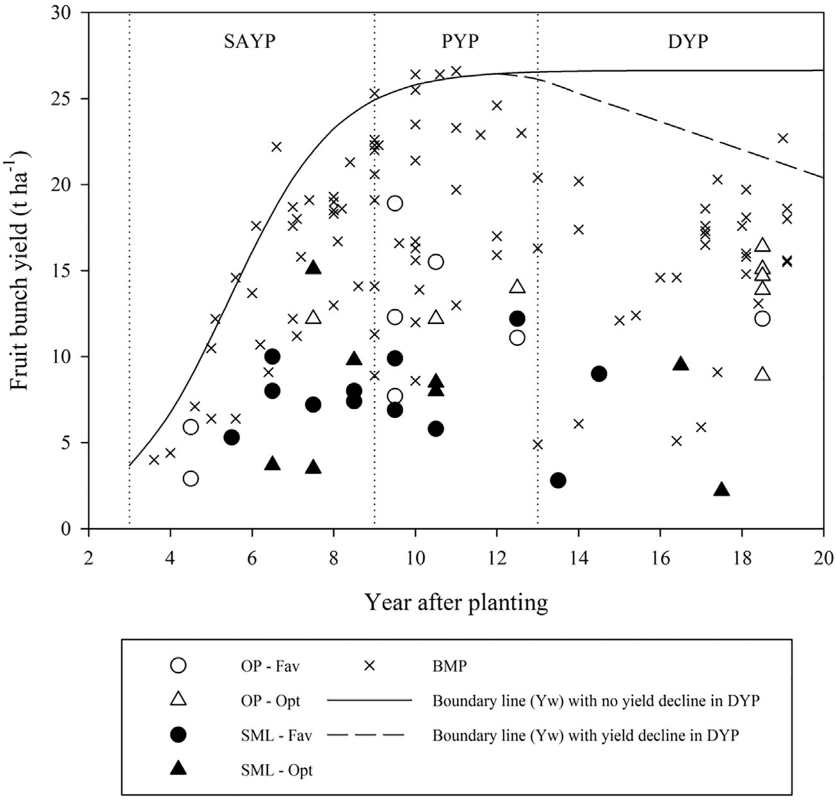

Fig. 3. Actual yields (Ya) plotted against year after planting for oil palm plantations (OP) and smallholder farms (SML) in the optimal (Opt) and favourable (Fav) climatic zones in southern Ghana. Vertical dotted lines indicate the boundaries between production phases (steep ascent yield phase (SAYP), 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 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 and Chew (1997). * Indicates a significant difference of the mean between oil palm plantations and smallholders at $P \le .05$.

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	0.280	
Inter-row	4.9*	1.22*	0.12*	13*	0.73	0.200*	44
Standard deviation (σ)	0.49	0.34	0.03	10	0.52	0.139	
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)	0.51	0.46	0.05	7	0.50	0.071	
Inter-row	5.2	1.43	0.13	5	0.91	0.133	52
Standard deviation (σ)	0.39	0.53	0.05	2	0.56	0.093	
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	

The italics show the average in soil chemical properties from the circle and inter-row.

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 ($P \le .05$), probably due to acidification caused by the repeated application of ammonia-based N fertilizers (Table 2, Table 4) (Goh and Härdter, 2003). By contrast, the average soil pH was higher ($P \le .05$) 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 ($P \le .05$)) (Table 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}) ($P \le .05$), with a larger ($P \le .05$) concentration of available P in soils beneath weeded circles (Table 2), due to application of P fertilizers within this zone. Similarly, the concentration of exchangeable potassium (K) was greater ($P \le .05$) in plantation soils (0.296 cmol(+) kg^{-1}), and deficient in smallholder soils (0.125 cmol(+) kg^{-1}). Exchangeable K was significantly larger ($P \le .05$) in the soil beneath weeded circles than in the frond stack at plantation sites (Table 2), again explained by past application of K fertilizers. By contrast, the average amount of exchangeable magnesium (Mg) was significantly smaller ($P \le .05$) and less variable in plantation soils (0.58 cmol(+) kg^{-1}) compared with smallholder soils (0.86 cmol(+) kg^{-1}) ($P \le .05$), and also significantly smaller ($P \le .05$) 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 off-take in fruit bunches and insufficient replenishment of soil Mg with either crop residues or mineral fertilizer (Table 2, Table 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). Leaf K concentration was adequate in the plantations but deficient in smallholder sites. Leaf Mg concentration was significantly smaller at the

Table 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 $P \le .05$.

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	3.7	5.7	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	0.06	0.21	1.9	6.8	4.9	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 ($\sigma = 0.006$) and 0.16 ($\sigma = 0.008$) respectively.

[b] Taken from Fairhurst et al. (2004).

plantations ($P \le .05$), 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 ($P \le .05$) due to past application of B fertilizer at some sites.

3.3.2. *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 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.

Table 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. (2012a, 2012b).

* Indicates a significant difference of the mean between oil palm plantations and smallholders at $P \le .05$.

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}) ($P \leq .05$). 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.

3.3.3. 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 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-day^{-1} yr^{-1} FB) (in terms of crop recovery) as well as more ground covered by harvesters (ha man-day^{-1} yr^{-1}) (Table 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 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 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 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.

4. Discussion

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. 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.

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. 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. 5). Whilst plantations apply moderate amounts of mineral fertilizers and occasionally recycle small amounts of crop residues (Table 4), most smallholder farmers apply little if any mineral fertilizer and do not recycle crop residues, resulting in a larger Yield Gap 3 (Fig. 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.

At plantation sites an average total leaf cation (TLC) of 85 cmol kg^{-1} was reported (Table 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. 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

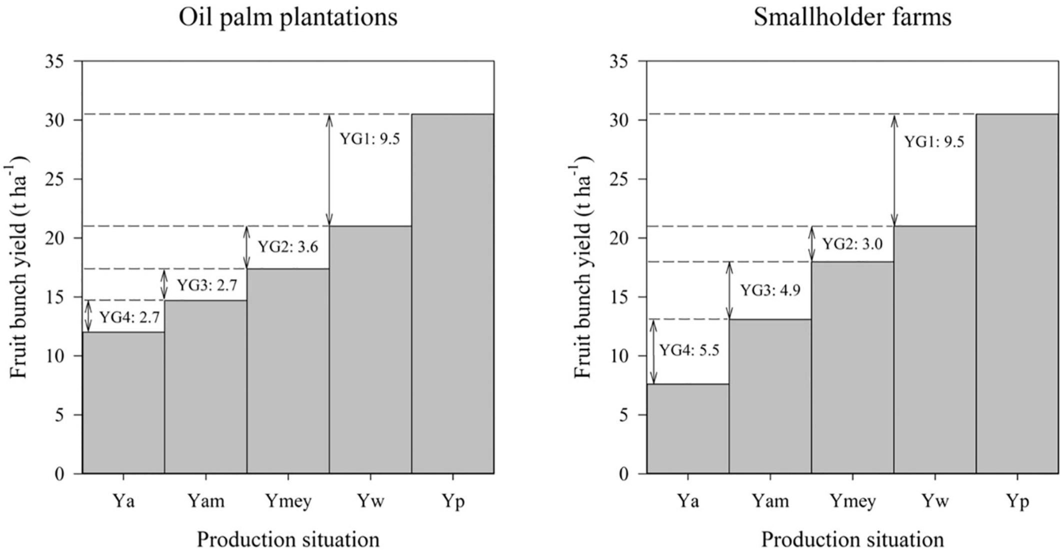

Fig. 4. Partitioning yield gaps at oil palm plantations and smallholder farms. Estimates for Yp and Yw were taken from Rhebergen et al. (2014) and the boundary line approach respectively. Ymey was estimated by adjusting Yw based on the relationship between the stand per hectare and the planting density (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.

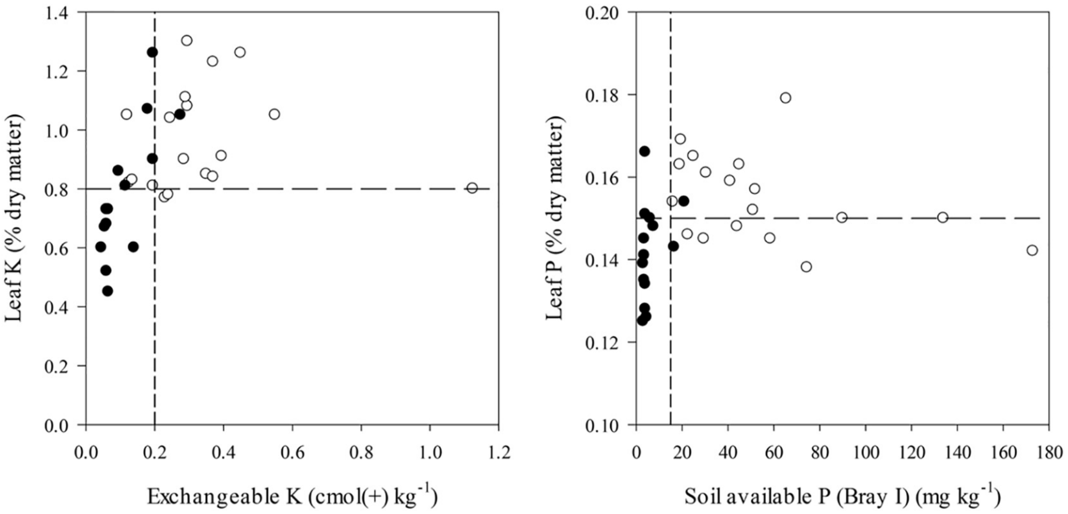

Fig. 5. Relationship between leaf K and P concentrations and the amount of exchangeable K and available P in soil beneath weeded palm circles in smallholder (black circles) and plantation sites open circles. The leaf and soil critical values for K and P are represented by horizontal (long dash), respectively, vertical (short dash) lines.

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. 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.

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. 6). Therefore, to improve oil yields, both FB yields and milling efficiency must be improved.

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 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 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

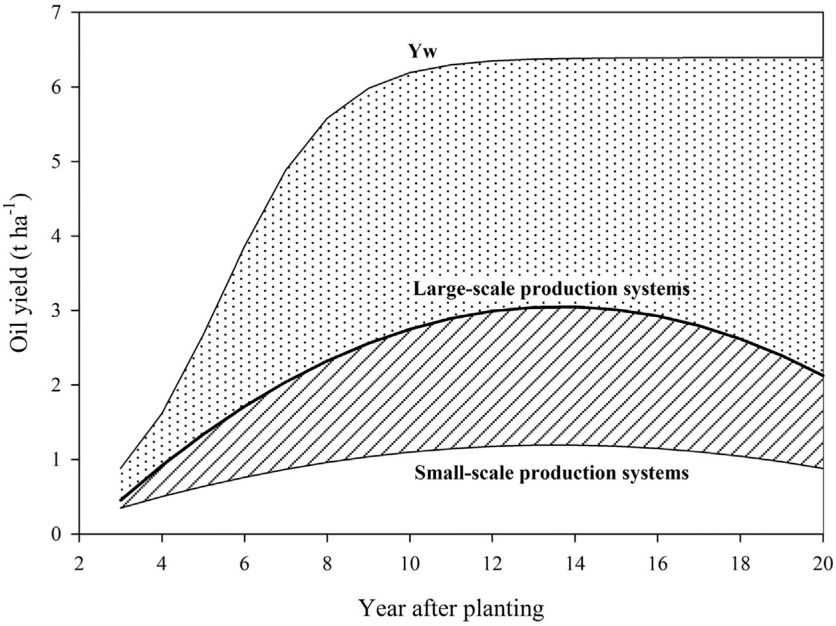

Fig. 6. Estimated CPO yield (t ha^{-1}) at large-scale and small-scale production systems. Yw was calculated as the product of the boundary line from Fig. 2 and an oil extraction rate (OER) of 24%, whilst the curves for large-scale and small-scale production systems were estimated with a regression through 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}).

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. 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 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 6).

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).

Table 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	1400
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

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 6). Large-scale mills thus have the capacity to process the current total national FB production (including smallholder production), but

Table 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

additional investments in mills would be required were significant yield improvement achieved across all sectors.

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 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ FB and large average yield gaps estimated at 15.4 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ FB for smallholder farms and 9.8 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ 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.

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