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

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ABSTRACT

The area under oil palm in Ghana has expanded but average fruit bunch yields remained low, resulting in large yield gaps. This study assessed the potential for increasing yield with 'Best Management Practices (BMP)' on plantations and smallholder farms in southern Ghana, compared with current standard practices, i.e. reference (REF) yield. We evaluated short-term ($\leq$1 year) yield increases with 'yield taking' (improved crop recovery), and long-term increases (> 1 year) with 'yield making' (better agronomy) practices and identified the factors that contributed most to yield improvements. Average fruit bunch 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 smallholder farms respectively. Short-term yield improvements were achieved with more frequent harvesting events and improved field access, which can help finance inputs needed for the yield making phase. Our analysis suggests more balanced palm nutrition could contribute considerably to yield making, particularly on smallholder farms. Improved fertilizer recommendations are therefore essential for sustainable oil palm production in Ghana. Increasing yields to 21.0 t ha^{-1} on land already planted to oil palm, can increase national fruit bunch production from 2.5 Mt to 6.9 Mt, sparing 600,000 ha of land. However, labour constraints on plantations and lack of access to credit and agricultural inputs on smallholder farms are major hurdles that need to be overcome to increase production.

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 palm oil 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

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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 between the potential (*potential yield* for irrigated systems or environments with adequate water supply to avoid water deficits, or *water-limited yield* under rainfed conditions where water is sparse) and actual yield 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 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 economically important 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 (Rhebergen et al., 2018, 2016; Rhebergen et al., 2014). With an estimated water-limited yield over a planting cycle of 21.0 t ha^{-1} fruit bunches averaged across favourable areas (with a mean annual water deficit < 250 mm) and optimal areas (with a mean annual water deficit < 150 mm) in Ghana (Rhebergen et al., 2016)), and an actual fruit bunch yield of ~11.0 t ha^{-1} on large commercial plantations and ~6.0 t ha^{-1} on smallholder farms, it is clear that large yield gaps exist in Ghana (Rhebergen et al., 2018).

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) (Fairhurst and Griffiths, 2014).

In this paper, 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.

2. Methodology

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 bi-modal. Mean annual precipitation is highest in the southwest ~2400 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 predominantly 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.

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 Rhebergen et al. (2018), Fig. 1). At each plantation, three to five paired management blocks were selected. The paired blocks (n = 12) were representative of a plantation and

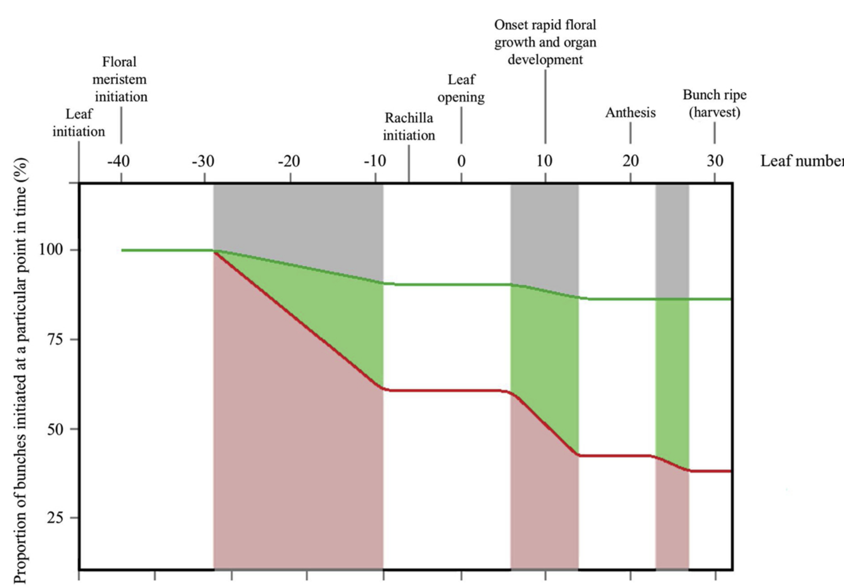

Fig. 1. Diagram on the effect of stress (shaded periods; sex determination (left), inflorescence abortion (middle), bunch failure (right)) and elimination of stress on bunch number in oil palm (after Woittiez et al. (2017)). The green line shows a well-managed plot and the red line shows a poorly managed plot.

comparable in size, topography, soil type, year of planting, and planting material (Table A1). 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 (Fig. A1). On 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.

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 (Rhebergen et al. (2018), Fig. 2). Once this was accomplished, additional yield making activities such as nutrient management to achieve the water-limited yield potential were implemented at each site and to close or minimize Yield Gaps 2 and 3 (Rhebergen et al., 2018). 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.

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 Table A2 (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 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 palm stand per hectare 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

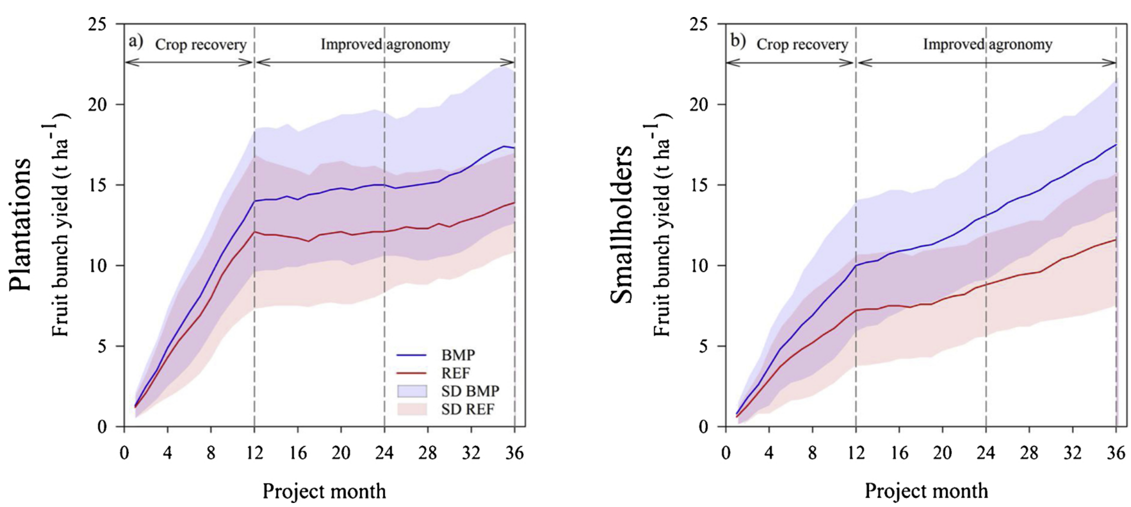

Fig. 2. Average cumulative monthly yield for the first 12 project months and twelve-month rolling averages for fruit bunch yields for project months 12–36 on a) plantation blocks and b) smallholder farms. Average yields are uncorrected and include standard deviations (SD)) for BMP and REF treatments. The dashed vertical lines indicate 12 month periods.

2.3.1. 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, (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

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.

2.3.2. 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. 1).

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 ratio of female to total inflorescences, inhibit floral initiation, or induce abortion of flowers or fruit (Corley and Tinker, 2016; Jones, 1997). 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 fruit bunch 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 to 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 not be realised due to periods of unfavourable climatic conditions (e.g. large water deficits and reduced photosynthetic active radiation 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. 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. 1) have become harvestable. In this research, we intended to determine 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 timeframe 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 were:

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’ (on the ground) per bunch 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 by removing dead and unproductive fronds,
vi Harvested crop delivered to the mill within 24 h of harvest, to reduce the amount of free fatty acids in the crude palm oil produced.

Yield making BMPs were:

i Maintenance pruning, which involved 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 improve water availability during the dry season, e.g. by blocking the drains with sand bags before the end of the rains,
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 maximum*), woody plants (e.g. *Baphia nitida*)) and replacement with soft weeds and grasses to control erosion during heavy rains,
vii Application of fertilizer and crop residues (e.g. empty fruit bunches and pruned fronds) at timing and rates 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 fertilizer application is ineffective if the area is not properly drained, or if woody weeds are not first fully eradicated.

2.4. Measurements

2.4.1. Crop production

Number of bunches, fruit bunch weight, loose fruit weight, 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. Yield and its components (number of bunches, average individual bunch weight, loose fruit weight), harvester productivity (t man-day^{-1} fruit bunches, bunches man-day^{-1}, ha man-day^{-1}), harvesting labour (man-days ha^{-1} cycle^{-1}) and the average harvest cycle (cycles yr^{-1}) were derived from the crop production data.

2.4.2. 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}).

2.4.3. Leaf analysis

Permanent datum palm points were established at each site for leaf sampling. Datum palms 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 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, 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 (solution of ash in concentrated hydrochloric acid) by inductively coupled plasma analyser (ICP). Leaf tissue samples were taken annually.

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 published information from fertilizer trials carried out in West Africa (e.g. Danso et al., 2010; van der Vossen, 1970) and Southeast Asia, as well as grey literature. 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) (Table A3). 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. Nutrient application recommendations for the BMP plots (per annum) were 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 plots respectively, and 0.08–0.16 palm^{-1} Mg for plantation plots (Mg fertilizer was not applied in smallholder BMP plots). The general recommendation for smallholder BMP plots 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 our 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). To optimise nutrient recovery, urea, TSP, RP, and KCl were applied in two applications per year and compound fertilizers in three applications per year.
- Right place. All fertilizers were applied over the edge of the weeded circles and the frond stack. Compared with palm circles, root development in this area 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 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™) 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 in plantations, mulching with empty fruit bunches was recommended at 30–40 t ha^{-1}, and repeated once fully decomposed (i.e. every two years). If there was a shortage of empty fruit bunches, we focused 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.

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 variables analysed by UNIANOVA were (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*:

$$y = \text{Production system} + \text{Site(Production system)} + \text{Treatment} + \text{Production system x Treatment}$$

Production system had two levels: i) plantations and ii) smallholder farms, each production system had several sites (BOPP, Norpalm, TOPP for plantations, and SWAPP East and SWAPP West for smallholder farms), and each site had two treatments (BMP and REF). 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 ha^{-1} fruit bunches) 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, harvesting labour and field upkeep labour, and for yield making practices we investigated leaf nutrient concentrations, the number of pruning rounds and palm stand. 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 whether the model could be improved by including squared variables and interactions. All statistics were performed using IBM SPSS Statistics Version 24.

3. Results

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 of smallholders at project start was estimated to be about 5.3 t ha^{-1}.

The average fruit bunch yield with BMP at plantation sites increased by 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. 2, Table 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 by 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, where 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 1–3 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 (Fig. A2).

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 similar effects on both treatments. However, plantation management and farmers improved the management of REF plots as their knowledge of better practices increased. While BMP yields increase, yields of REF plots often increased as well, even if fertilizer was not applied and implementation of BMPs was less rigorous than in BMP plots.

Across smallholder sites, average fruit bunch yield differed significantly between treatments ($P \leq 0.05$) in all years, and the differences were larger than on plantations. Average fruit bunch yields with BMP increased by 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 ($P \leq 0.05$) by 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 ($P \leq 0.05$) compared with year 2. BMP yields increased by 4.5 t ha^{-1} (+34 %), and averaged 17.6 t ha^{-1}, whilst REF yields increased by 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. 2, Table 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.

Differences in yield between treatments were largest in the plateau (PYP) and declining yield phase (DYP) on plantations and in the steep ascending (SAYP) and plateau yield phase (PYP) on smallholder plots (Fig. 3). However, more samples are required for each treatment and growth phase to understand the underlying causes. Furthermore, yields were still in a strongly upward mode at the end of the project (Fig. 2), suggesting that yields in the plateau phase are greater than reported, especially in the smallholder fields (Fig. 3).

Table 1

Mean yield and its 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 Table A4 for model parameters). A post-hoc test (LSD) shows where significant differences occur in the interaction effect; the letters $^{a–d}$ indicate significant differences (at $P \leq 0.05$) between treatment means *within* each project year, while ^{e,f} indicate significant differences (at $P \leq 0.05$) *between* project years for the BMP treatment, and ^{g,h} for the REF treatment. Where no letters appear, there are no significant differences.

Parameter	Units	Yr	Oil palm plantation blocks		Yr	Smallholder farms		Interaction
			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} fruit bunches	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

** Sum of loose fruits and bunches.

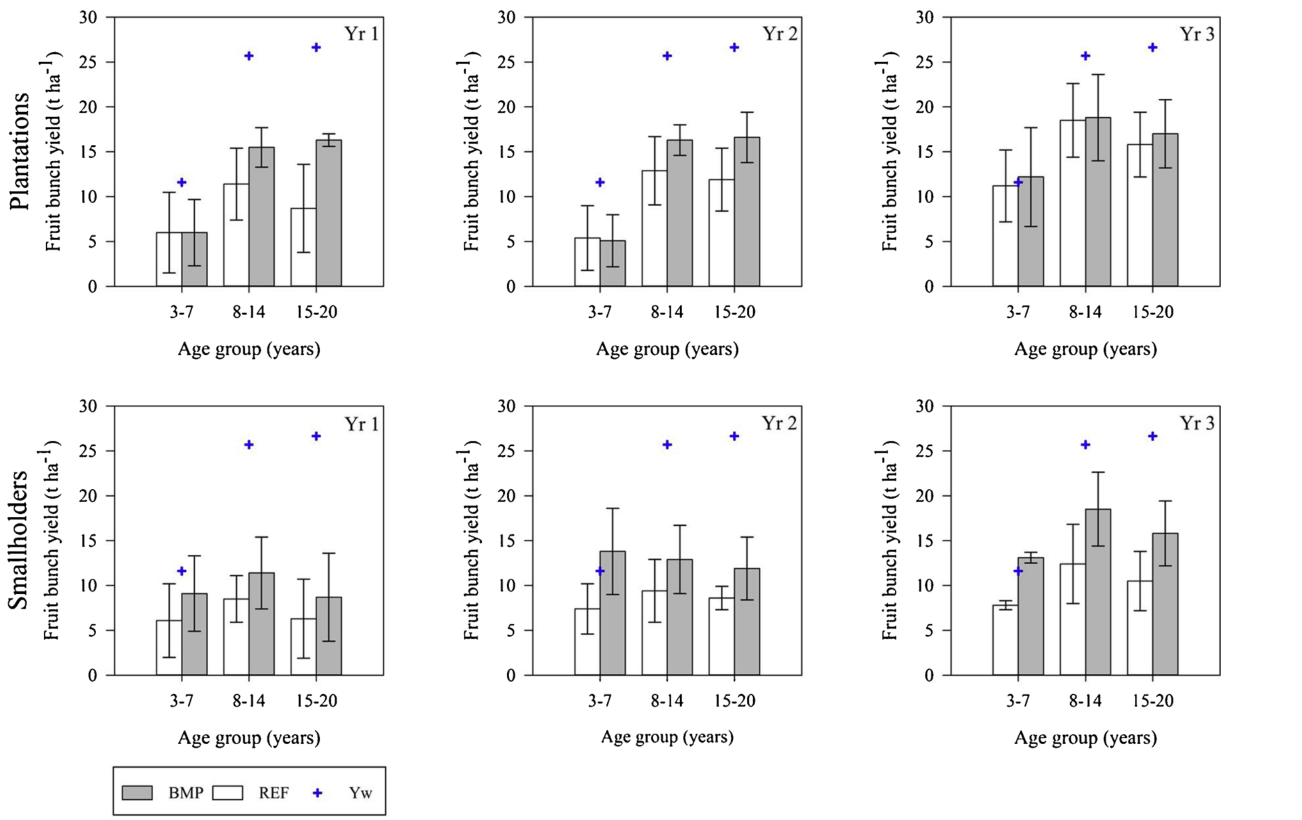

Fig. 3. Average BMP and REF yields with standard deviations (SD) for plantation blocks and smallholder farms according to age group (3–7, 8–14, 15–20) for project years (Yr) 1, 2 and 3. The blue crosshairs show the average potential rain-fed yield of oil palm in Ghana for each age group, averaged across production areas with mean annual water deficit < 250 mm (Rhebergen et al., 2016, 2018).

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 were significantly more ($P \le 0.05$) frequent on BMP plots compared with REF for all years, whilst on smallholder sites the difference in harvesting events was smaller with each consecutive year (Table 2). Improved crop recovery resulted in a greater number of harvested bunches and larger average bunch weight at BMP plots (except on plantations in year 1, where average bunch weight was higher at REF plots), particularly at smallholder sites where access with BMP was better than in the REF plots (Table 1).

Table 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 $P \le 0.05$, NS for not significant; see Table A4 for model parameters). A post-hoc test (LSD) shows where significant differences occur in the interaction effect; the letters $^{a–d}$ indicate significant differences (at $P \le 0.05$) between treatment means *within* each project year, while ^{e,f} indicate significant differences (at $P \le 0.05$) *between* project years for the BMP treatment, and ^{g,h} for the REF treatment. Where no letters appear, there are no significant differences.

Parameter	Units	Yr	Oil palm plantation blocks		Yr	Smallholder farms		Interaction
			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 $man\text{-}day^{-1}$ fruit bunches	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.

3.2. Harvester productivity and harvesting labour

At plantation sites, harvesters' output in terms of weight and number of bunches per man-day was lower on BMP plots for all years. On average, harvesters also significantly ($P \leq 0.05$) covered less area (ha man-day^{-1}) in BMP plots, compared with REF (Table 2). This is most likely related to shorter harvesting intervals on 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} fruit bunches and bunches man-day^{-1}) was slightly higher on 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 (Tables 1 and 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 did not differ between treatments at plantation and smallholder sites. However, harvesting labour increased significantly ($P \leq 0.05$) from year 1–2 at smallholder sites for BMP and REF treatments, which was a result of an increase in yield (Tables 1 and 2).

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 2). However, significantly more ($P \leq 0.05$) labour was spent on 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

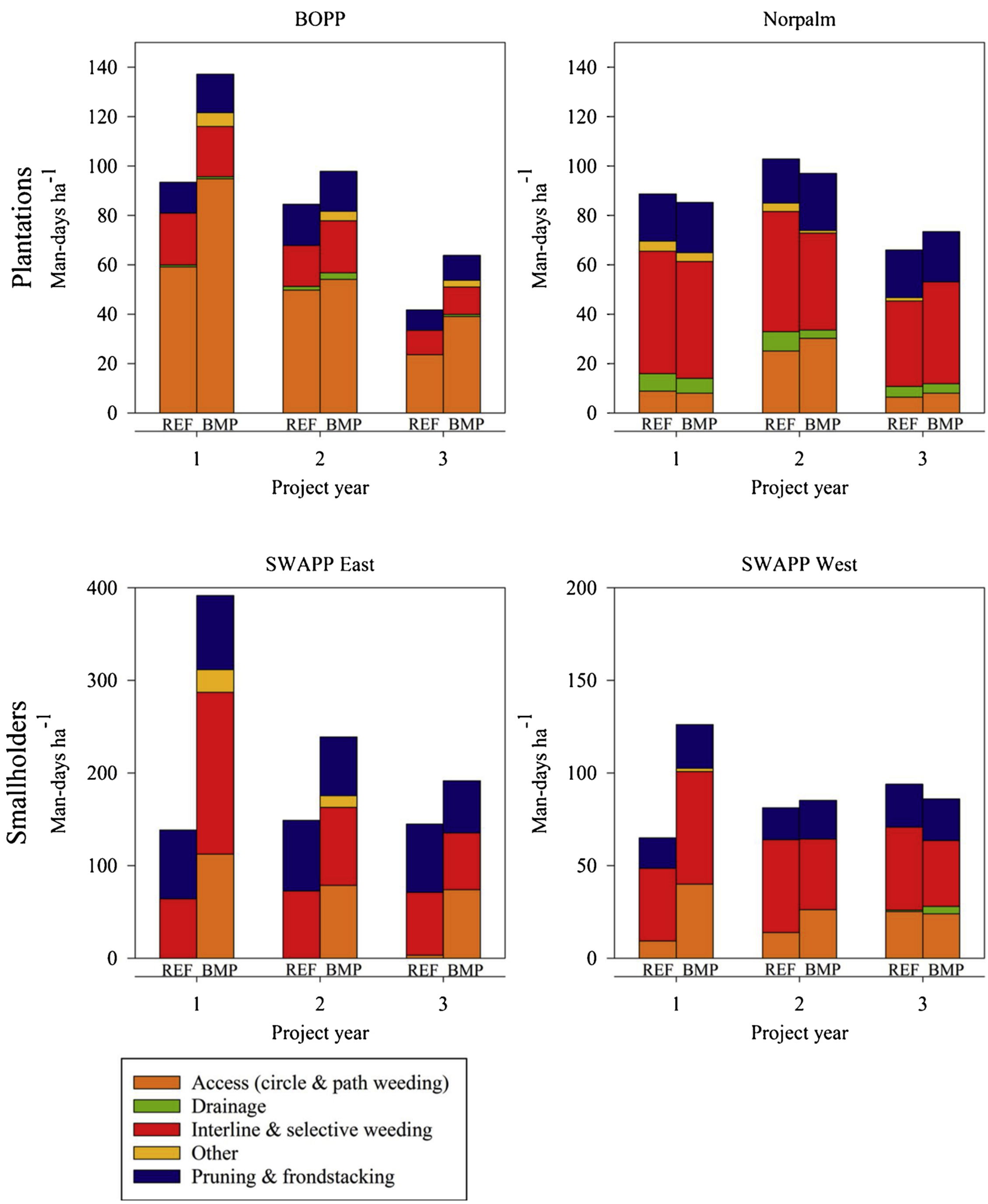

Fig. 4. Total labour (man-days ha^{-1}) spent on field upkeep activities on plantation and smallholder sites for project years 1, 2 and 3.

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). 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). Total field upkeep labour activities decreased with each year at smallholder sites.

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.

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. 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 in both treatments (Fig. 5), even though B fertilizer was applied only to BMP plots (Fig. 6).

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. 6). Failure to

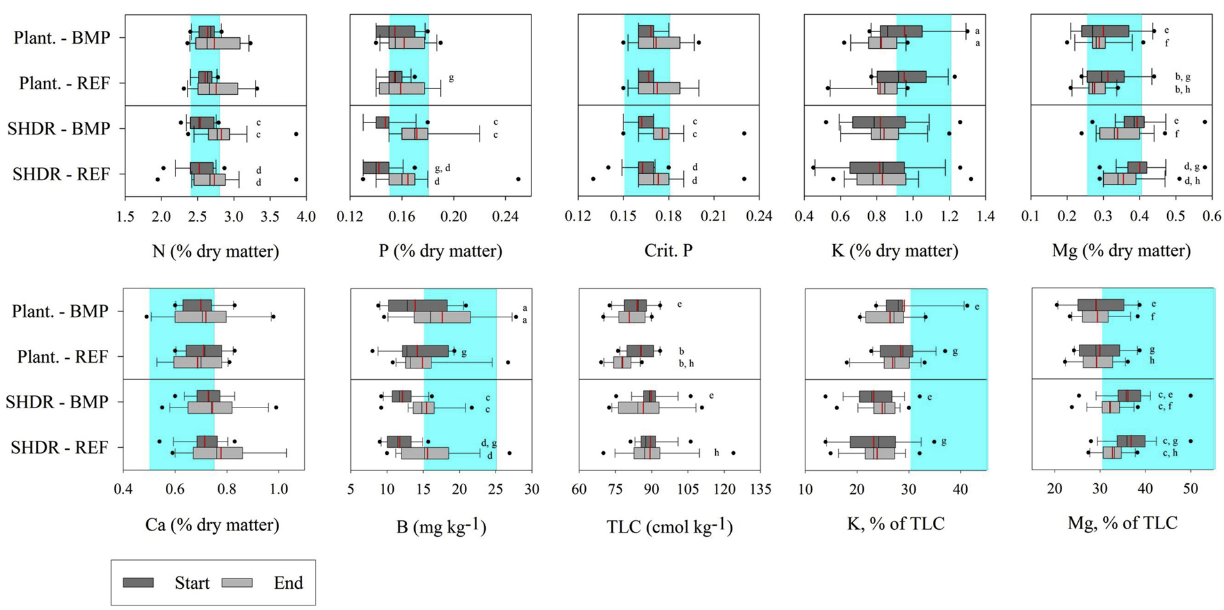

Fig. 5. Leaf nutrient concentrations at oil palm plantations (n = 11 for BMP and n = 11 REF) and smallholder farms (n = 18 for BMP and n = 18 REF) at project start and end. Box plots show the median, lower (25th percentile) and upper quartile (75th percentile). The whiskers represent the 10th and 90th percentiles, whilst outliers are plotted as individual points. 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. Significant differences (at $P \leq 0.05$) between treatment means and years are indicated with a, b, c, d, e, f, g, h.

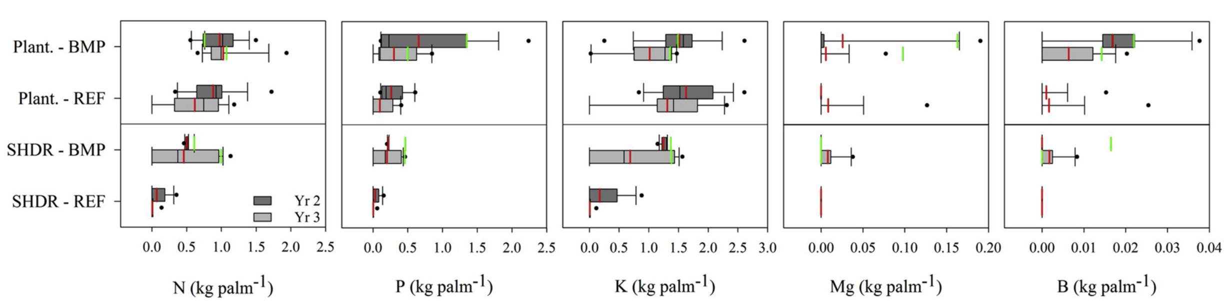

Fig. 6. Box plots showing fertilizer nutrients (elements) N, P, K, Mg, B applied at oil palm plantations (n = 15 for BMP and n = 15 REF) and smallholder farms (n = 18 for BMP and n = 18 REF) in project years (Yr) 2 and 3. Average applied rates of application are indicated with a red vertical line, and average recommended rates of application for BMP plots are indicated with a green vertical line. Outliers are plotted as individual points.

implement fertilizer recommendations partly explains the large variability in leaf nutrient concentrations (Fig. 5).

3.5. Palm stand

At plantation sites the average number of productive palms (i.e. mature, immature and supply palms) was significantly less ($P \le 0.05$) than the initial planting density for both treatments in all years, whilst at smallholder sites no significant differences were found (Fig. 7). Between treatments, no significant differences ($P \le 0.05$) 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. 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.

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 fruit bunches 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 fruit bunches 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

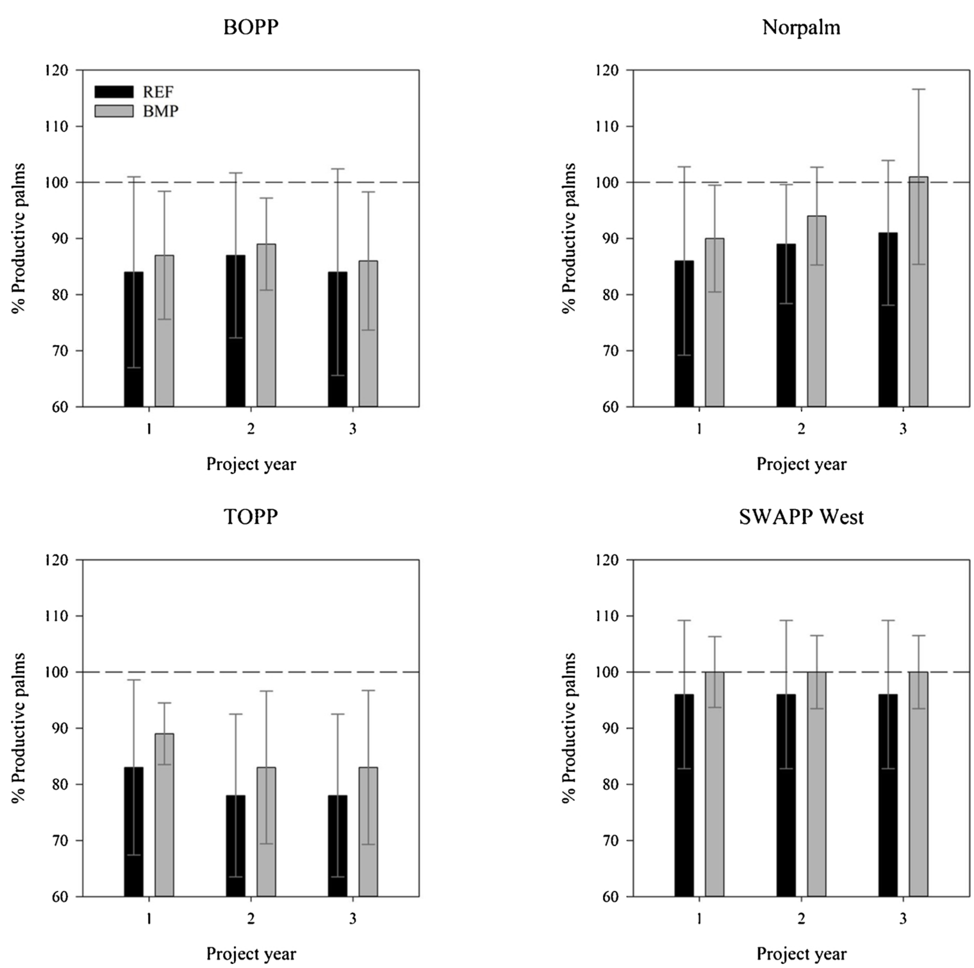

Fig. 7. Palm census results expressed as proportion of productive palms (palms ha^{-1}) in relation to the initial planting density (palms ha^{-1}, see Table A1 for initial planting densities) for BMP and REF treatments at plantation blocks and smallholder farms for project year 1, 2 and 3. Error bars represent standard deviations.

weight harvested and less area covered per harvester) on both plantations and smallholders, and the larger importance of improved nutrition on smallholder farms.

4. Discussion

Best Management Practices (BMP) were successfully applied and improved oil palm yields in Ghana. The BMP approach provided the means for systematic identification and reduction 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 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.

4.1. 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. 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.

The larger yield response on smallholder farms was largely due to the very poor initial field conditions, where the benefits from yield taking BMPs where greater than on 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 (Figs. 5 and 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 were still in a strong upwards mode, indicating that the site yield potential had likely not yet been reached at the project sites (Fig. 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). 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 yield response to fertilizer inhibits fertilizer use by smallholders and is a major reason for low yields on 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 of 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 who 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 on 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 further depleting the fertility of 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.

On 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.

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 competition from other employment opportunities might also play a role in labour shortages. A possible solution is to reduce labour requirements and workload through mechanization of certain field operations, such as fruit bunch collection, to make the work more attractive. Whilst mechanization offers potential 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 plantation managers approach 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.

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.

4.2. Yield intensification versus area expansion

Most of the increases in the production of palm oil in Ghana have been achieved through area expansion (Rhebergen et al., 2018). 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 fruit bunch yields (11.4 t ha^{-1} at plantations and 7.3 t ha^{-1} at smallholders) resulting in fruit bunch production of 189,240 t and 2,270,300 t at plantations and smallholders respectively. With moderate BMP implementation (increasing fruit bunch yields to 17.9 t ha^{-1} and 17.6 t ha^{-1} at plantations and smallholders respectively), fruit bunch production would increase to 5801,840 t, thus avoiding 452,533 ha area expansion at present yields. However, at potential production levels (i.e. increasing fruit bunch 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 of 21 %, approximately 1.3 Mt crude palm oil can be produced (worth almost 1 billion US$ at US$750 t^{-1} crude palm oil). This is more than enough to meet Ghana's current annual demand of 106,000 t crude palm oil, and does not require the need to plant additional land (Rhebergen et al., 2018).

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).

4.3. Opportunities for increasing production and scaling BMPs

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 (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), most smallholders in Ghana are completely self-reliant (Fold and Whitfield, 2012). 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).

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, suggest that with a strong institutional arrangement, smallholder farmers can participate in supply chains on advantageous conditions and substantially increase their productivity. In addition, organizing smallholder farmers in large concessions (akin to smallholder schemes as in e.g. Malaysia and Indonesia), could potentially facilitate biodiversity conservation as well, but would require good supporting policies and a significant restructuring of land allocated to oil palm and conservation in Ghana.

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. Access to, and adoption of, modern agricultural technologies, such as the implementation of BMPs, is essential to yield intensification. 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 *dura* x *pisifera* hybrid 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 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.

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.

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, 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 labour, and budget provision and resources (particularly in the first year) to implement BMPs diligently and on time.

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Intellectual property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

CRediT authorship contribution statement

Tiemen Rhebergen: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Visualization, Project administration. **Shamie Zingore:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Ken E. Giller:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Charles Adu Frimpong:** Investigation, Resources, Project administration. **Kwame Acheampong:** Investigation, Resources, Project administration. **Francis Tetteh Ohipeni:** Investigation, Resources, Project administration. **Edward Kofi Panyin:** Investigation, Resources, Project administration. **Victor Zutah:** Investigation, Resources, Project administration. **Thomas Fairhurst:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of Competing Interest

No conflict of interest exists.

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Appendix A

See Fig. A3.

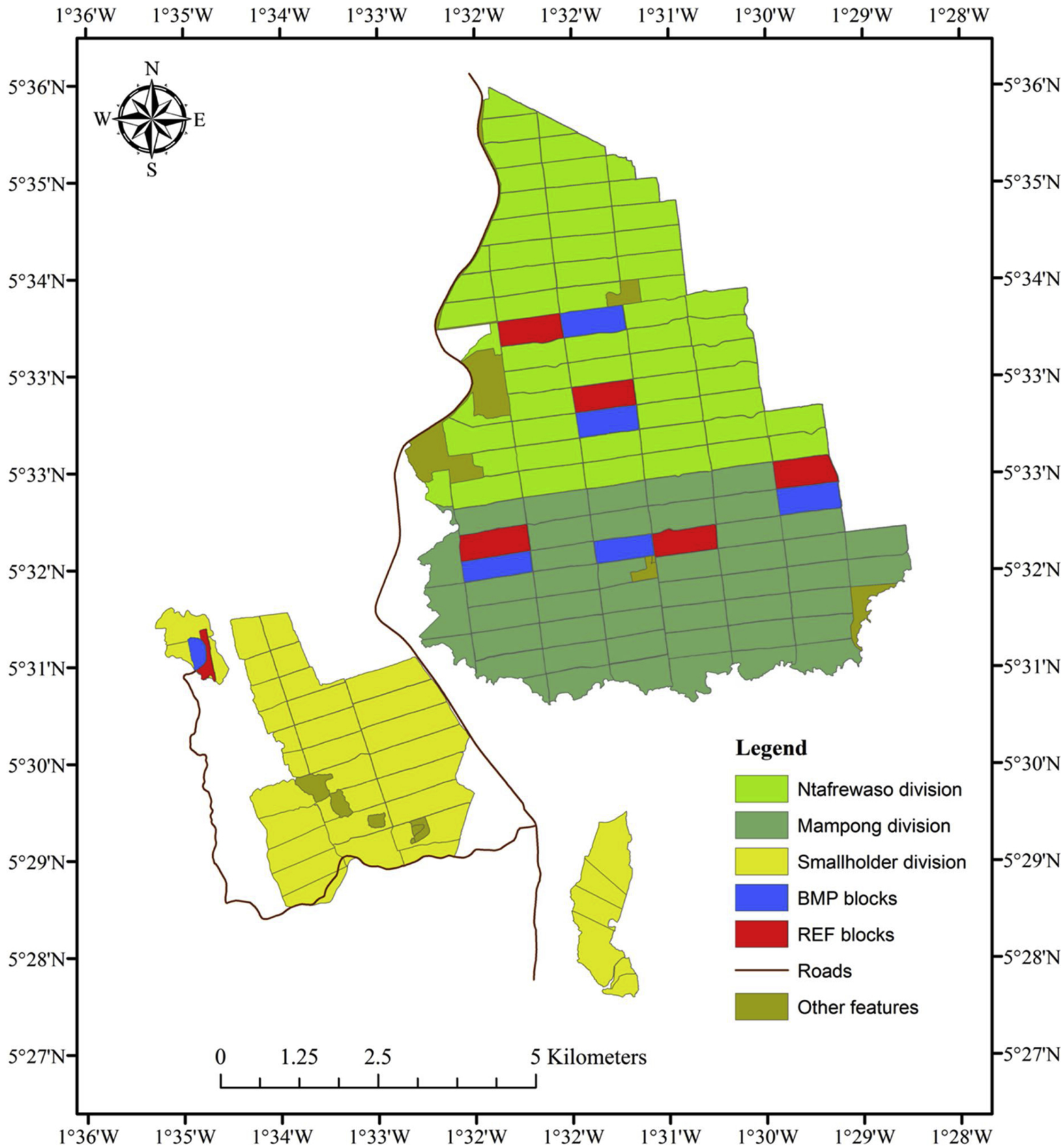

Fig. A1. Example of the experimental design including paired BMP (blue) and REF (red) blocks at the nucleus plantation of Twifo Oil Palm Plantation (TOPP).

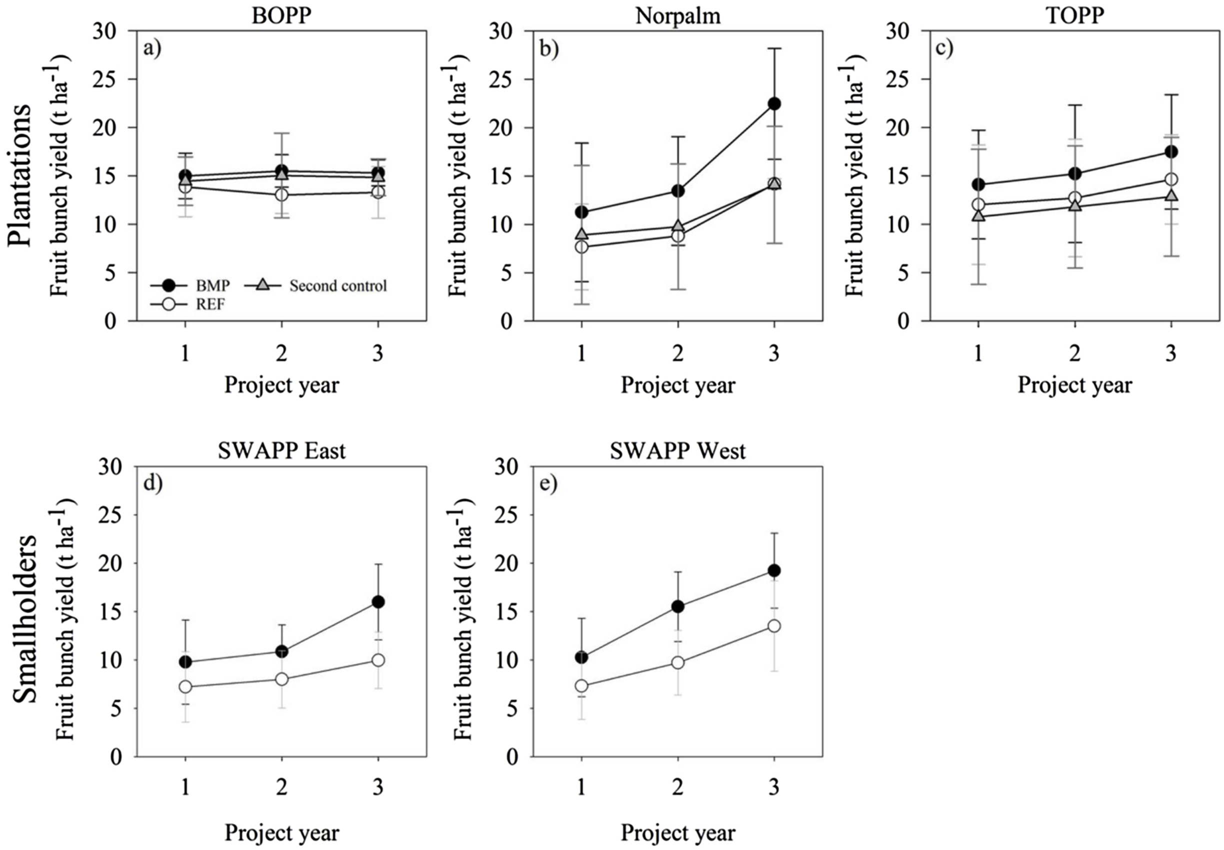

Fig. A2. Average yields + SD for each project year for BMP and REF treatments on plantation (BOPP, Norpalm, TOPP) and smallholder sites (SWAPP East, SWAPP West). The grey triangles for plantation sites show average yields for the second control plots which serve as an absolute reference for plantation performance, since REF treatments were also undergoing improvement.

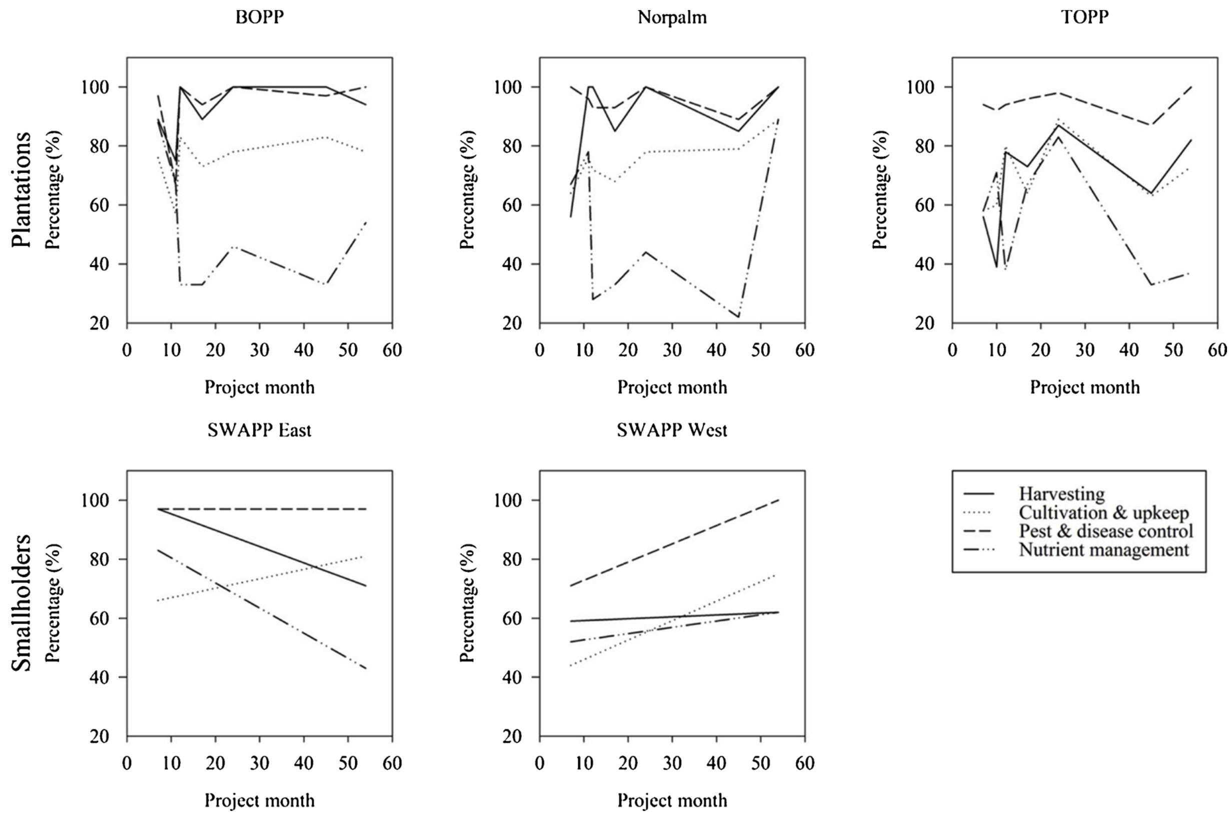

Fig. A3. Field audit results summarized according to category (harvesting practices, cultivation and upkeep, pests & diseases and nutrient management) for oil palm plantation and smallholder BMP plots. Percentages were calculated as the total score across all BMP plots at each site relative to the total 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.

Table A1
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	
	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

(*continued on next page*)

Table A1 (*continued*)

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
	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.

Table A2
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 5–20° (10–36 %)
		Terraces or contour harvest paths installed at slopes > 20° (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
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

(*continued on next page*)

Table A2 (*continued*)

Category	Parameter	Auditing criteria
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
	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 empty fruit bunches, prioritize application on the slopes

Table A3
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.

Table A4
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} fruit bunches	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 $man\text{-}day^{-1}$ fruit bunches	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 $man\text{-}day^{-1}$	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 $man\text{-}day^{-1}$	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

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