Agricultural Systems 224 (2025) 104269

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Improving yield and profit in smallholder oil palm fields through better agronomy

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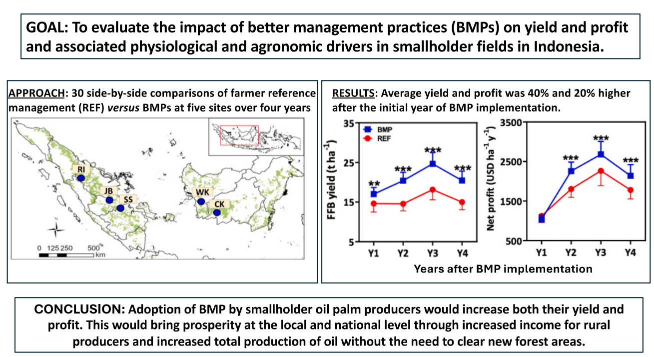
HIGHLIGHTS

- There is a large gap between attainable yields and smallholders oil palm yields.
- We evaluated impact of better management practices (BMP) on yield, profit, and labor.
- The BMPs led to 40 % and 20 % higher yield and profit, with same labor requirement.
- Yield increase was larger at sites with low initial yield and higher BMP adoption.
- Yield intensification is essential to meet palm oil goal on existing plantation area.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Oil palm
Better management practices
Yield
Smallholders
Profit

ABSTRACT

CONTEXT: Palm oil production is a major source of income for millions of smallholders in Indonesia, the main palm oil producing country in the world. However, smallholders' yield is low in relation to the attainable yield. Adoption of better management practices (BMPs) as an approach to increase yield and profit has received less attention than certification and replanting programs.
OBJECTIVE: To evaluate the impact of BMP on yield and profit and associated physiological and agronomic drivers in smallholder fields in Indonesia.
METHODS: We evaluated BMP against the farmer reference management (REF) on 30 paired fields over four years in five provinces in Indonesia. The BMP treatment included improved harvest, weed, soil, and nutrient management practices. Besides fresh fruit bunch (FFB) and crude palm oil (CPO) yields, and associated profit, we

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https://doi.org/10.1016/j.agsy.2025.104269
Received 15 September 2024; Received in revised form 23 December 2024; Accepted 25 January 2025
Available online 2 February 2025
0308-521X/

measured plant growth, nutrient accumulation, and radiation capture over time to understand the physiological factors associated with variation in yield.

RESULTS AND CONCLUSIONS: Implementation of BMP led to increased annual FFB yield by *ca.* 40 % with 1.2 t ha^{-1} more CPO yield. Profit was 20 % greater in BMP than in REF fields. Higher yield in BMPs was associated with higher nutrient accumulation, dry matter production, and partitioning to fruit bunches. The magnitude of FFB yield increase due to BMP depended upon initial yield and degree of BMP adoption, but not the planting material.

SIGNIFICANCE: Adoption of BMPs by smallholder oil palm producers in Indonesia would increase both their yield and profit. This would bring prosperity at the local and national level through increased income for rural producers and increased total production of oil without the need to clear new forest areas.

1. Introduction

Oil palm is the most important source of vegetable oil in the world, accounting for 40 % of global production (USDA, 2022). Indonesia is the largest oil palm producer in the world, with *ca.* 60 % of global crude palm oil (CPO) production (USDA, 2022). Palm oil production over the past 20 years has increased impressively in Indonesia, from 7 MMT CPO in 2000 to 48 MMT CPO in year 2020 (Directorate General of Estate Crops, 2022). However, the increase in CPO production was driven almost exclusively by oil palm area expansion with yield stagnating at *ca.* 18 t ha^{-1} of fresh fruit bunches (FFB) (Monzon et al., 2021). Current average yield is well below the estimated yield potential for oil palm of *ca.* 30.6 tons FFB ha^{-1} (Monzon et al., 2021). The large yield gap suggests that there is an opportunity to increase CPO production on existing plantation area *via* better agronomic management, which, in turn, can reduce the pressure to clear forest for oil palm cultivation.

Nearly 60 % of the oil palm area in Indonesia is managed by large plantations owned by private and state companies. The other 40 % is managed by smallholders, who manage around 2 ha each. There are two types of smallholders in Indonesia: "plasma" farmers who are attached to plantation companies and receive support for establishment, fertilization, harvesting, and field upkeep; and independent smallholders, who are not tied to large plantations (Molenaar et al., 2013; Jelsma and Schonevelg, 2016). Independent smallholders account for *ca.* two thirds of the smallholder oil palm area in Indonesia (Molenaar et al., 2013; Hidayat, 2017). Average FFB yield in independent smallholders at *ca.* 14 t FFB ha^{-1} (Monzon et al., 2021), is 25 % less than that of large plantations (20 t FFB ha^{-1}) and 60 % less than the attainable FFB yield (29 t ha^{-1}) estimated by crop modelling and data from well-managed plantations in Indonesia (Monzon et al., 2021).

Large yield gaps in independent smallholder fields are associated with imbalanced nutrient input and poor field upkeep, including weed control, harvest, pruning, and soil management (Molenaar et al., 2013; Lee et al., 2014; Euler et al., 2016; Monzon et al., 2023; Sugianto et al., 2023; Lim et al., 2023). Additionally, widespread use of uncertified planting material with a high dura frequency in smallholder fields is associated with low oil extraction rates (OER), which reduce CPO yields (Sugianto et al., 2023). We suggest that adoption of better management practices (BMPs) could increase yield in both current plantations and newly replanted fields that use certified planting material, leading to higher CPO yields and profits in both cases. Such an approach can potentially bring prosperity to farmers, local communities, mills, and the whole country *via* higher incomes, productivity, and CPO exports (Monzon et al., 2021, 2023). However, at present, most efforts to increase smallholder profit focus on promoting adoption of certified planting material and participation in certification programs such as RSPO (Roundtable on Sustainable Palm Oil) or ISPO (Indonesia Sustainable Palm Oil), with relatively little attention paid to yield intensification and increased profitability (Zen et al., 2005; Molenaar et al., 2013; Coordinating Ministry for Economic Affairs Republic of Indonesia, 2023; Indonesian Oil Palm Association, 2023).

Previous studies aiming to increase oil palm yields in Indonesia and elsewhere have focused on large plantations (Griffiths and Fairhurst, 2003; Fairhurst et al., 2006; Donough et al., 2006, 2009, 2011; Oberthür et al., 2012; Tao et al., 2017, 2018; Rhebergen et al., 2020). Overall, these studies showed consistent yield increases due to BMP implementation from improved harvest, weed, ground cover, and nutrient management practices. FFB yields increased two or three years after BMP implementation by 3.2 to 5.7 t FFB ha^{-1} across the studies when compared with the reference farmer management. Much less effort has been devoted to improving yield in smallholder oil palm fields. Only two studies have aimed to increase smallholder yields. Working with smallholders in Ghana, Rhebergen et al. (2020) showed that BMP adoption led to a yield increase (+7.6 t FFB ha^{-1}) in relation to the typical farmer management. However, this study reported neither the impact of BMPs on farmer income nor the physiological drivers of higher FFB yields. In another study, Woittiez (2019) reported lack of yield improvement after three years of BMP implementation in independent smallholder fields in Indonesia, leading to a negative impact on farmer income. However, careful examination of this study revealed problems with BMP implementation and yield determination. Hence, their study cannot be taken as conclusive evidence of BMP failure to increase yield and profit for independent smallholders. Finally, previous studies on BMPs in large plantations and smallholder fields have not explored the drivers of yield response to BMPs. Lack of information on the drivers of variation makes it difficult to provide recommendations with confidence as we do not know which factors are of greatest importance (Hoffmann et al., 2020). Furthermore, extrapolation from the sites of the original studies is fraught with uncertainty.

There is a knowledge gap in relation to the impact of BMPs on smallholder yield and profit and associated drivers. Here we filled this gap by quantifying the impact of BMPs on FFB, CPO yield, profit and identifying the physiological and agronomic drivers of yield variation for independent smallholder oil palm fields in Indonesia. To do so, we compared yield and profit in fields with BMPs *versus* those following typical current farmer management across 30 fields located in the main producing areas of Indonesia over four years. Our hypothesis was that BMPs would lead to higher yield and profit. We quantified radiation interception and nutrient uptake to understand the physiological drivers explaining the yield response to BMPs. We also assessed factors explaining variation in yield response to BMPs across on-farm experiments. Finally, implications for agronomists and policy makers were discussed.

2. Materials and methods

2.1. Study sites, field selection, and treatments

On-farm experiments were conducted from Jan 2020 until Dec 2023 in five sites: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK) (Fig. 1). The sites were in climate-soil domains that collectively account for two thirds of total oil palm area in Indonesia (Agus et al., 2024). Our study focused exclusively on independent smallholders' fields located in mineral soils, since *ca.* 80 % of total oil palm area in Indonesia is in mineral soils (MoEF, 2016). Local NGOs helped us identify farmers willing to participate in our field trials. We prioritized farmers who were motivated in the study, and willing to keep records and implement our recommendations. Only productive fields were selected, with palm age at the beginning of the trials ranging from 8 to 16 years (average: 12 years). At each site, we worked with local NGOs who assisted with BMP implementation, monitoring, and data collection. We conducted a total of 30 field trials across five provinces, with the number of trials per province ranging from five (WK) to seven (RI). Field trials were initiated on Jan 1, 2020, and stopped on Dec 31, 2023. For simplicity, we referred to each year as Y1 (2020), Y2 (2021), Y3 (2022), and Y4 (2023). Two field trials were stopped during early 2023 because fields were sold and, hence, were not included for the analysis in Y4. Description of soil, weather, and topography for each site are shown in Table 1. To answer the question of how representative our selected fields were in relation to the population of smallholder fields in Indonesia, we surveyed yield and management practices in 837 fields (*ca.* 175 in each site) in the areas located around our trial fields (see Monzon et al., 2023), hereafter referred to as 'non-field trials' (NFT) (Supplementary Table S1).

Each field trial consisted of two pairs of fields ($>$ 1 ha each), managed by the same farmer, and with comparable field size, palm age, plant density, planting material, soil, and topography. In each pair, one field was designated for farmers to implement BMPs, while the other field was managed using the farmers' typical practices, referred to as the 'reference' (REF). Hence, the 30 trials included a total of 60 fields, with 30 fields assigned to BMPs and another 30 to the REF treatment. The size of each field and the areas that corresponded to each treatment were measured with a GPS device and validated with drone imagery data. Farmers did not have yield records from previous years, so we were neither able to estimate the initial yield level nor to assess differences between BMP and REF fields before the beginning of the trials. To evaluate the similarity of BMP and REF fields before applying the BMPs, we evaluated soil properties. In addition, we conducted a black bunch census (BBC) for 20 palms per field, including all bunches and bloomed (receptive) female inflorescences and evaluated vegetative dry matter, N, P, and K concentration in leaves, rachis, and trunk, and dura frequency at the start of the trials.

Our BMP treatment included better management of nutrients, weeds and beneficial vegetation, harvest, and soil cover (Table 2). The positive impact of individual BMPs on FFB yield has been documented elsewhere (*e.g.*, Fairhurst and Härdter, 2003 and references cited therein). The goal of the present study was to evaluate the combined impact of BMPs on FFB yield and profit through a system comparison, rather than evaluation of individual practices (Griffiths and Fairhurst, 2003; Donough et al., 2009; Fairhurst and Griffiths, 2014). Shortening the harvesting interval aims to reduce yield losses and maximize the yield recovery (Donough et al., 2010; Lee et al., 2014; Ng and Southworth, 1973). Field upkeep of BMP fields consisted of eradication of woody weeds in the entire field, while keeping the vegetation that serves as a host for natural pest enemies and protects the soil against erosion (*e.g.*, *Nephrolepis biserrata, Axonopus compressus, Zoysia japonica)*. An exception was harvesting paths and circles, which were always kept clean. Farmers continued their normal weed control practices in the REF fields, which ranged from no control to total spraying out of all weeds, leaving the soil bare and exposed to high temperature and heavy rainfall events. To further improve soil cover and avoid soil erosion and nutrient losses in BMP fields, pruned fronds were spread in the inter-rows and in-between palms in the row with a C shape around each palm (Rankine and Fairhurst, 1998; Gillbanks, 2003). The actual degree of BMP implementation is shown in Section 3.1 of the Results section.

We provided fertilizer recommendations for the BMP fields considering the nutrient removal through FFB and nutrient stored in the trunk and based on a yield target, with further tuning according to plant nutrient status as determined *via* leaf tissue analysis. The target yield for Y1 was estimated based on the number of black bunches and bloomed (receptive) female inflorescence. This census was conducted at the end of 2019 from a total of 20 palms per field. The time from pollination of female inflorescence until a bunch becomes ripe is *ca.* 5 to 6 months (Thomas et al., 1971; Corley and Tinker, 2003; Kasim et al., 2012). Therefore, target yield for Y1 was assumed to be 2× the value of black bunches plus female inflorescences, because it takes *ca.* 6 months for receptive flowers to develop into a ripe bunch (Adam et al., 2011). Following this approach, we determined a yield target for Y1 of 15 t FFB ha^{-1} for JB and 18 t FFB ha^{-1} for the other sites (RI, SS, WK, and CK). For subsequent years, we assumed the yield target in each field to represent 1.3× (Y2) and 1.2× (Y3 and Y4) of the measured yield in previous year, based on expected yield improvement due to BMPs as reported elsewhere (Donough et al., 2011; Rhebergen et al., 2020). To estimate nutrient removal with FFB, we assumed 3.15 kg N, 0.40 kg P, 3.89 kg K, and 0.57 kg Mg per ton of FFB (Lim et al., 2018). Nutrients stored in annual trunk growth were estimated for Y1 using the data from a previous study (Lim et al., 2018) and based on allometric measurement of trunk growth and nutrient concentration in the trunk in each field for subsequent years. In all years, leaf nutrient concentration was used as an indicator of plant nutrient status, and nutrient fertilizer recommendation was further adjusted as needed following Foster (2003). Following this approach, our final fertilizer recommendation ranged from 126 to

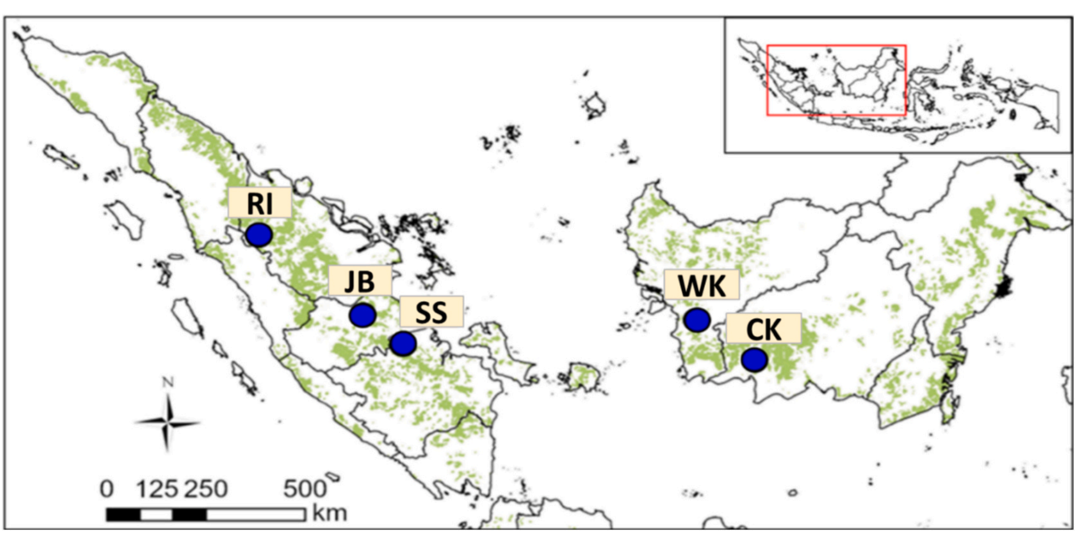

Fig. 1. Map showing the location of the five study sites in Indonesia: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK). Inset shows the study area within Indonesia. Green area shows oil palm area in mineral soils reported by Ministry of Agriculture (2012) and Harris et al. (2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Mean (2020−2023) total annual rainfall, average fresh fruit bunches (FFB) yield in the reference treatment, topographic wetness index (TWI), and selected topsoil (0-20 cm) properties across 30 paired-fields in Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK). Parenthetic values indicate ranges across years (rainfall) and sites (FFB yield, TWI, and soil properties). We only showed here the results for the topsoil (0–20 cm) in the initial sampling, averaging across the two treatments and the two sampling sites (palm circle and below the pruned fronds).

Site	Rainfall (mm)	FFB yield ($t\ ha^{-1}$)	TWI[†]	Texture	pH	SON (%)	SOC (%)	CEC ($cmol\ kg^{-1}$)	K ($cmol\ kg^{-1}$)	Mg ($cmol\ kg^{-1}$)	P Bray I (ppm)
RI	1830 (1384–2183)	16.4 (9.5–20.6)	3.7 (2.6–4.8)	Clay	5.2 (4.6–5.6)	0.21 (0.11–0.36)	2.5 (1.9–3.6)	15 (9–27)	0.18 (0.07–0.48)	0.79 (0.13–1.63)	8 (2–55)
JB	2087 (1812–2417)	8.4 (7.2–12.6)	4.2 (3.2–5.4)	Clay loam	5.2 (4.5–5.7)	0.17 (0.12–0.26)	1.5 (1.1–2.3)	7 (5–13)	0.08 (0.04–0.24)	0.14 (0.06–0.46)	2 (1–4)
SS	1475 (613–2457)	15.2 (11.9–20.4)	4.4 (3.9–5.1)	Clay loam	4.9 (4.3–5.5)	0.20 (0.14–0.45)	2.4 (1.1–5.8)	9 (4–18)	0.12 (0.04–0.36)	0.29 (0.06–0.98)	12 (1–47)
WK	3392 (2820–3942)	17 (8.9–28.1)	4.7 (3.9–5.6)	Sandy clay loam	5.4 (4.3–5.9)	0.24 (0.12–0.32)	2.8 (1.3–4.4)	7 (4–11)	0.07 (0.04–0.11)	0.14 (0.05–0.44)	13 (0.4–96)
CK	2610 (1673–3393)	20.9 (12.1–26.8)	4.6 (4.2–4.9)	Sandy clay loam	4.7 (4.1–5.1)	0.13 (0.06–0.21)	1.5 (0.5–2.4)	5 (3–9)	0.09 (0.04–0.35)	0.08 (0.03–0.17)	14 (1.1–52)

TWI indicates the likelihood of surface runoff (run-on) from (to) an area based on slope and surrounding area, with bottom and upland areas having highest and lowest values, respectively (Moore et al., 1993; Sorensen et al., 2006). The TWI was calculated following Cock et al. (2016). SON: soil organic nitrogen; SOC: soil organic carbon, CEC: cation exchange capacity; K: exchangeable potassium; Mg: exchangeable magnesium; P-Bray I: available phosphorous. Average FFB yield in the reference treatment was calculated as the 4-year average (2020–2023) in each trial.

Table 2
Recommended agronomic practices in the better management practices (BMP) fields and usual farmer practices in the reference fields (REF). See Section 3.1 for degree of BMP implementation across the 30 trials.

Practices	BMP	REF
Harvesting	Two (three) rounds per month during low-(high-) yielding season	Two rounds per month
Nutrients	Site-specific fertilizer recommendation based on expected nutrient removal with fresh fruit bunches, nutrient immobilized in trunk, and leaf nutrient concentration. Fertilizer applied on frond heaps, except for urea which is applied in the circle.	Mostly used “phonska” (15–15-15), urea (46–0-0), dolomite or no fertilizer at all. All fertilizer applied in the circle.
Field upkeep	All woody, grass, and broadleaf weeds removed, harvesting paths and circles cleaned, and beneficial vegetation kept	Blanket spraying or no weed control
Pruned frond arrangement	Spread out in C shape	Piled up in I shape

151 (N), 27 to 36 (P), 217 to 274 (K), and 17 to 33 (Mg) kg ha^{-1} across field-years. Boron was also applied in BMP fields when leaf tissue analysis indicated low levels.

2.2. Data recording and soil and plant measurements

Farmers were requested to keep records for all field activities, including dates and associated labor input (*i.e.*, man-hours), inputs rates, and prices. Data recording was monitored by local NGO collaborators, including a full-time coordinator who was responsible for compiling the data and clarifying any anomalous records. Following this approach, farmers reported the amount of FFB and the number of bunches in each harvest, as well as the associated family and/or hired labor used, and gross revenue from sale of the harvested FFB. Likewise, farmers recorded the cost and labor associated with pruning, weed and pest control, and fertilizer application, as well as the type and amount of the applied products (fertilizer, herbicide, *etc.*) and other agronomic information such as fertilizer placement and application rate, and weed control. Farmers were also asked to take pictures of fertilizer bags and other chemicals so that we could verify which products were applied and their nutrient contents. Finally, a field audit was conducted once to twice per year to monitor BMP implementation. In these visits, we met with farmers to discuss any issue, gave feedback to them about their field conditions, and suggested corrective measures whenever needed. Farmers also communicated *via* WhatsApp whenever there were questions about BMP implementation and data recording.

We collected soil samples from each BMP and REF field at the beginning, middle (Y2), and end of the study period. Separate samples were collected from two management zones (palm circle and below frond heaps), with four sub-samples being collected in each sampling site. Sub-samples were taken from two soil depths (0–20 and 20–40 cm) and a composite sample for each management zone and for each depth per field was sent to the to Asian Agri laboratory (https://www.asianagri.com) to determine pH, texture, organic C and N, cation exchange capacity (CEC), exchangeable cations (K, Ca, Mg), extractable P and K (25 % HCl), and available P (P Bray I). This lab is actively participating in WEPAL (IPE, 2022; https://www.wepal.nl/en/wepal.htm) to evaluate the performance of the laboratory by cross-comparison with those of other laboratories at regular time intervals.

To calculate the annual increase in aboveground dry matter (ADM), we estimated vegetative dry matter increase every *ca.* 12 months, starting at the beginning of the trials, and added the bunch dry matter. In some cases, the sampling occurred at slightly shorter or longer intervals than 12 months. For those cases, we adjusted the values to a 12-month period. The trunk and frond dry matter was determined through allometric measurements following previous studies (Hardon et al., 1969; Corley et al., 1971; Prabowo et al., 2006; Prabowo et al., 2023). These measurements included trunk diameter, plant height, rachis length, petiole cross-section, number of leaflets on frond #17, and the width and length of the six leaflets used for the leaf samples. Additionally, frond production and the total count of green fronds were assessed for a subset of 20 palms per field. Finally, bunch dry matter was calculated based on the farmer-reported FFB yield, assuming a water content of 47 % (Corley et al., 1971).

To determine differences in nutrient uptake between BMP and REF fields, we also collected leaf, rachis, and trunk samples from the same 20 palms: samples were pooled separately for each organ. In the case of leaf samples, we used frond #17 as a reference following the method described in Rhebergen et al. (2018). The rachis was also collected from frond #17, cleaned with a soft towel, and cut into small pieces whereas a trunk sample was taken from the base of frond #41 following Prabowo et al. (2006) using a stainless-steel pipe. The trunk samples were cut into small pieces. All leaf, rachis, and trunk samples were oven-dried and sent to Asian AA-Lab to determine nutrient concentration. We determined nitrogen (N) by Kjeldahl titrimetry, phosphorus (P) and boron (B) by spectrophotometry, potassium (K) by flame photometry, and magnesium (Mg) and calcium (Ca) by atomic absorption spectrophotometry. At the beginning of the trials, we also determined leaf copper (Cu), zinc

(Zn), manganese (Mn) and iron (Fe) in frond #3 by atomic absorption spectrophotometry. Initial results showed no deficiencies for these nutrients, so we did not evaluate them in subsequent samplings. Annual nutrient uptake was calculated based on the annual dry matter increase in each organ and the average nutrient concentration between the two samplings, together with the nutrient removal with FFB. Since we did not measure nutrient concentration in FFB, nutrient removal was estimated based on FFB yield and FFB nutrient concentration reported by Lim et al. (2018).

Dry matter and nutrient partitioning to different organs (FFB, trunk, and fronds) was estimated as the quotient between the annual dry matter and nutrient accumulation in each organ in relation to the total annual ADM increase and nutrient uptake. Different organs have different dry matter composition. For example, FFB is rich in oil whereas trunk and fronds are comparably rich in carbohydrates. To account for these differences in dry matter composition, we performed a separate calculation of dry matter partitioning after converting the dry matter of each organ into glucose equivalents. To do so, we used the conversion factor based on metabolic cost reported by Breure (1998) and Penning de Vries et al. (1983) as follow: 2.29 (bunch), 1.44 (frond), and 1.52 (trunk) CH_2O kg^{-1} dry matter.

Differences in annual plant growth between BMP and REF fields can be attributed to differences in light interception and conversion of light intercepted into ADM (Monteith, 1972). To discern the causes for differences in plant growth, we determined light interception following two independent methods. In the first method, we estimated light interception following Monsi and Saeki (2005) and Romero et al. (2022) based on the leaf area index (LAI) values derived from our allometric measurements:

$$f = 1 - exp^{(-k^{*}LAI)} \quad (1)$$

where f is the fraction of the light intercepted by the canopy and k is the canopy extinction coefficient, which was set at 0.44 based on data from Corley (1976). We complemented this estimation with a semi-quantitative measurement of light interception following a simple approach that consists of counting the number of 'dark' spots on the ground underneath the oil palm canopy. This 'shade index' was estimated based on transects between adjacent palms, one transects within the row and another across the inter-row. A rope was marked at 50-cm intervals and the number of 'dark' spots were counted and expressed as a frequency of the total number of spots that were assessed along the rope, averaging the frequency calculated for the two transects. This procedure was repeated for the subset of 20 sampling palms in each field. In all cases, measurements were conducted between 10 am and 2 pm, avoiding cloudy days and weedy spots. We used linear regression to compare f derived from LAI measurement *versus* shade index. Finally, we estimated radiation-use efficiency (RUE) as the ratio between annual ADM increase and the intercepted photosynthetically active radiation (PAR), the latter derived from the f value derived from Eq. (1) and the incident PAR retrieved from the nearby weather stations.

2.3. Estimation of CPO yields based on OER measurements

We were also interested in analyzing the impact of BMPs on CPO yield. To do so, we measured OER in each of the BMP and REF fields during Y3. Our smallholder fields have a high frequency of dura palms (average: 50 % of total palms per field), which have much lower OER relative to Tenera palms (Sugianto et al., 2023). Hence, we decided to measure OER separately for each palm type (*i.e.*, dura and tenera) in each field, sampling four palms of each type in each field, except for those fields exhibiting a high frequency of either dura or tenera (>75 %) where only the dominant palm type was sampled for OER determination. We repeated the OER measurement in each field twice, with measurements performed four to six months apart. Following this approach, a total of 451 bunches were sampled for OER ($n = 237$ and 214 for dura and tenera, respectively), with an average of eight samples per field with a well-balanced ratio of dura and tenera (*i.e.*, four bunches per field per palm type and only one ripe bunch was sampled per palm). The OER determination was based on the methodology described by Hasibuan et al. (2013) and Hasibuan and Nuryanto (2015).

2.4. Estimation of water-limited yield potential and attainable yield

In the case of rainfed oil palm, the water-limited yield potential (Yw) is determined by solar radiation, temperature, carbon dioxide, age of the plantation, precipitation, and soil properties influencing the crop water balance such as soil texture and depth (van Ittersum et al., 2013). To determine the degree of yield-gap closure due to BMP implementation, we estimated Yw for each of the BMP-REF pairs in each year. To do so, we used the PALMSIM v2.0 crop simulation model (Hoffmann et al., 2014; Hekman et al., 2018) coupled with data on local weather data, and field-specific palm age and soil properties. The PALMSIM model estimates Yw on a field-scale level and simulates plant growth and partitioning in daily time steps (Hoffmann et al., 2014; Hekman et al., 2018). This model has been satisfactorily validated on its ability to reproduce the highest yields obtained in large plantations (Hoffmann et al., 2014; Hekman et al., 2018; Monzon et al., 2021, 2023). The model has been used to benchmark yields in large plantations and smallholder fields in previous studies (Hoffmann et al., 2015; Monzon et al., 2021, 2023). For our simulations, daily rainfall data was recorded on-site, while incident solar radiation, maximum and minimum temperature, and humidity data were retrieved from the nearest weather station (https://www.bmkg.go.id/). The Yw for each field was simulated based on the plantation age and measured soil texture and depth. When simulating Yw, PALMSIM assumes no limitation by nutrients and no yield reduction due to incidence of weeds, pathogens, insect pests or excess water. Achieving Yw is neither feasible nor desirable for smallholders because it is difficult to ensure that crops grow without any nutrient limitation over time and space and without incidence of weeds, pests, and diseases and that harvest losses can be fully avoided. Likewise, it would require copious amounts of nutrients and pesticides to ensure Yw, leading to negative economic and environmental outcomes. Hence, a more realistic goal for farmers with reasonable access to markets, inputs, and technical information is to target 70 % to 80 % of the Yw, hereafter referred to as "attainable yield" (Lobell et al., 2009; van Ittersum et al., 2013). In the case of oil palm, previous studies have used 70 % of Yw as a target, and empirical data shows that this is reasonable (Monzon et al., 2021, 2023).

2.5. Assessing impact of BMPs on farmer profit and labor requirement

We assessed the economic impact of BMPs by comparing the net profit in the BMP *versus* REF fields. To do so, farmers reported all costs associated with field activities, including field upkeep, pruning, harvesting and fertilizer application, and the gross income derived from FFB selling. Reported costs included both inputs (*e.g.*, fertilizer, herbicide, *etc.*) and associated labor (including both family and hired labor) and were calculated based on the actual prices reported by the farmers. In the case of family labor, we computed the associated economic value assuming the minimum wage per man-day in Indonesia (USD 8.6 d^{-1}). Net income was calculated separately for each year as the difference between gross income and total costs. Using prices for specific years can bias the analysis due to episodic high or low prices in agricultural inputs and/or FFB. Thus, we repeated our economic analysis using historical (2005–2020) average prices for agricultural inputs and FFB (Directorate General of Estate Crops, 2022; Lim et al., 2023). Because labor is a key driver for BMP adoption, we also calculated the labor requirement for each treatment as the ratio between total man-hours (including harvesting, field upkeep, pruning, and fertilizer and pesticide application) and FFB yield.

2.6. Data analysis

We performed repeated measures statistical analysis using mixed effects model for plant nutrient concentrations in each organ, FFB yield, annual ADM production, and annual nutrient uptake. For each variable, we fitted a model with the following structure:

$$y_{ijklm} = \mu + TRT_i + T_j + S_k + TRT \times T_{ij} + T \times S_jk + F(S)_{kl} + e_{ijklm} \quad (2)$$

where y_{ijkl} is the m^{th} observation for the i^{th} treatment (TRT; two treatments: BMP and REF) in the j^{th} year of experiment (T) in the k^{th} site (S) for the l^{th} field (F) within the k^{th} S, and assuming: $F(S)_{kl} \sim N(0, \sigma^2_{FS})$; and $e_{ijklm} \sim N(0, \sigma^2_e)$. A linear mixed-effect model was fitted for each variable using the *nlme* package (Pinheiro and Bates, 2000; R Core Team, 2022). Finally, we estimated the mean differences between treatments (BMP *versus* REF) for each year of the experiment using *emmeans* r-package (Lenth, 2022).

We investigated the drivers for BMP-REF yield differences across sites using multiple regression analysis. In oil palm, the effect of management interventions is not immediately apparent given the long period between bunch initiation and ripeness (Thomas et al., 1971; Corley and Tinker, 2003; Ng et al., 2003). Hence, our dependent variable was the annual BMP-REF yield difference, calculated as the average from Y2 and Y3. We selected those independent variables with expected impact on yield, including REF yield in Y1, BMP-REF yield difference during the first six months, fertilizer application in BMP during the first two years (as percentage of the recommended fertilizer application), number of dry months (*i.e.*, < 100 mm) in the prior two years and first year after BMP implementation, palm density, palm age, dura frequency, and BMP-REF differences in key soil properties. The REF yield during Y1 provides a measure of the initial yield level at each site, whereas the BMP-REF yield difference during the first six months can help discern cases in which yield responses were biased because of initial differences in yield between BMP and REF fields within each pair. Likewise, adding the number of dry months, palm age, dura frequency, and palm density can help discern other factors influencing the yield response to BMPs, for example, low yield response due to drought in previous years and/or sub-optimal palm density. Finally, we computed a soil similarity index for each BMP-REF. To do so, we evaluated differences in sand and clay contents, soil organic carbon and N, cation exchange capacity, exchangeable Mg and K, available P and pH between BMP and REF fields using *t*-tests. Our index was estimated as the number of soil properties that were not statistically significant different between REF and BMP treatments ($p > 0.05$), expressed as a fraction of the evaluated soil variables. To evaluate the overall adoption of BMPs, we used a semi-quantitative index based on their degree of adoption in BMP fields. To do that, we summed four sub-indexes related with BMP adoption, including (i) harvest interval (1 if <12.5 d; 0.5 if between 12.5 and 14 d; 0 if >14 d), (ii) frond arrangement (1: spread in C shape; 0: piled up in I shape), (iii) weed management (1: good, 0.5: fair; 0: poor), and (iv) actual fertilizer application (as a fraction of the recommended fertilizer). Thus, the degree of BMP implementation can range from zero (nil implementation) to four (full implementation).

3. Results

3.1. Evaluation of field trial selection, initial conditions, and treatment implementation

Similarity in agronomic and socio-economic variables between trial fields and 837 non-field trials indicated that our 30 trial fields can be considered a representative sample (Supplementary Table S1). Likewise, the REF plots received similar amounts of N, P, and K fertilizer as the non-field trial farmers and no differences in plant nutrient status, based on measured leaf nutrient concentration, were detected. Moreover, there was no statistically significant difference in FFB yield between REF and NFT ($p = 0.55$). Thus, the REF fields can be considered representative of the FFB yield achieved by smallholders in Indonesia. In relation to the initial conditions in BMP and REF fields, there was no statistically significant differences in soil properties between treatments at the beginning of the trials, including clay content, organic N and carbon, cation exchange capacity, exchangeable Ca, Mg, and K, and extractable P and K ($p > 0.15$). Therefore, we concluded the soil properties were similar in the BMP and REF fields at the beginning of the trials. Likewise, there were no significant differences between treatments in BBC, vegetative dry matter, N, P, and K concentration in leaves, rachis, and trunk, and dura frequency ($p > 0.55$). Finally, there was no difference in FFB yield between BMP and REF during the first six months of the trials ($p = 0.60$) (Supplementary Fig. S1-S2). Overall, these findings indicate that the REF and BMP fields had similar biophysical backgrounds and yields at the beginning of the trials.

On average, BMP fields were harvested every 10–15 days depending upon availability of bunches to harvest, whereas the REF fields were typically harvested every two to three weeks (average: 12 and 16 d, respectively). About two thirds of the BMP fields adopted shorter harvest interval relative to the REF fields; the main constraint for adoption of this practice was the reluctance of the middle men, who purchase FFB, to visit fields more often to collect a relatively smaller amount of FFB in each visit (de Vos et al., 2023). Implementation of our fertilizer recommedation in the BMP fields was close to the recommended rates, with BMP fields representing 85 % (N and K), 83 % (P) and 77 % (Mg) of the recommended rates (Supplementary Fig. S3). Conversely, REF fields followed farmer fertilizer practices, ranging from no fertilizer application at all (JB) to relatively large applications of subsidized fertilizers (CK). In general, farmers tended to apply low amounts of fertilizer in REF fields, especially for K and N, and rarely applied any Mg or B. Finally, there was no evidence that management of the REF fields changed over time. For example, there was no statistically significant difference in applied N, P, K, and Mg fertilizer over time in REF fields (Supplementary Fig. S3). According to our field audits, all BMP fields adopted a C shape pruned frond arrangement, whereas pruned fronds were typically stocked in piles in the REF fields and arranged following an I shape in the inter-rows only (75 % of REF fields). Likewise, recommendations on field upkeep were properly implemented in 70 % of BMP fields. Conversely, 75 % of the REF fields exhibited poor field upkeep, including severe weed infestation.

3.2. Plant nutrient status and uptake as influenced by better management practices

Nutrient concentration in various plant organs was similar in the BMP and REF treatments at the beginning of the trials (Fig. 2). However, from that point onwards, nutrient concentration was higher in BMP *versus* REF fields, except for Mg. Among nutrients, the large increase in K concentration in the BMP fields was notable, with K concentration increasing, on average, +18 % (leaf), +53 % (rachis), and + 38 % (trunk) over Y1 to Y4 ($p < 0.001$). Annual N, P, K, and Mg accumulation in ADM was higher in BMP *versus* REF fields in all years (Fig. 3). Nutrient uptake increased over time in the BMP treatment ($p = 0.02$) but not in REF ($p = 0.83$). Thus, differences in annual nutrient uptake between BMP and REF fields increased over time, ranging from 5 % (Mg) to 26 % (K) in Y1, from 15 % (Mg) to 48 % (K) in Y2, from 19 % (Mg) to 40 % (K) in Y3, and from 18 % (Mg) to 49 % (K) in Y4. After the four years, accumulated N 126 kg ha^{-1}, P 14 kg ha^{-1}, K 221 kg ha^{-1}, and Mg 15 kg ha^{-1} in BMP fields was higher than in REF fields ($p < 0.001$). In contrast, soil nutrient concentration as well as soil properties (*e.g.*, CEC, SOM, SON) did not change over time, except for two sites (RI & JB) where pH was significantly lower in Y4 relative to Y1 ($p < 0.05$).

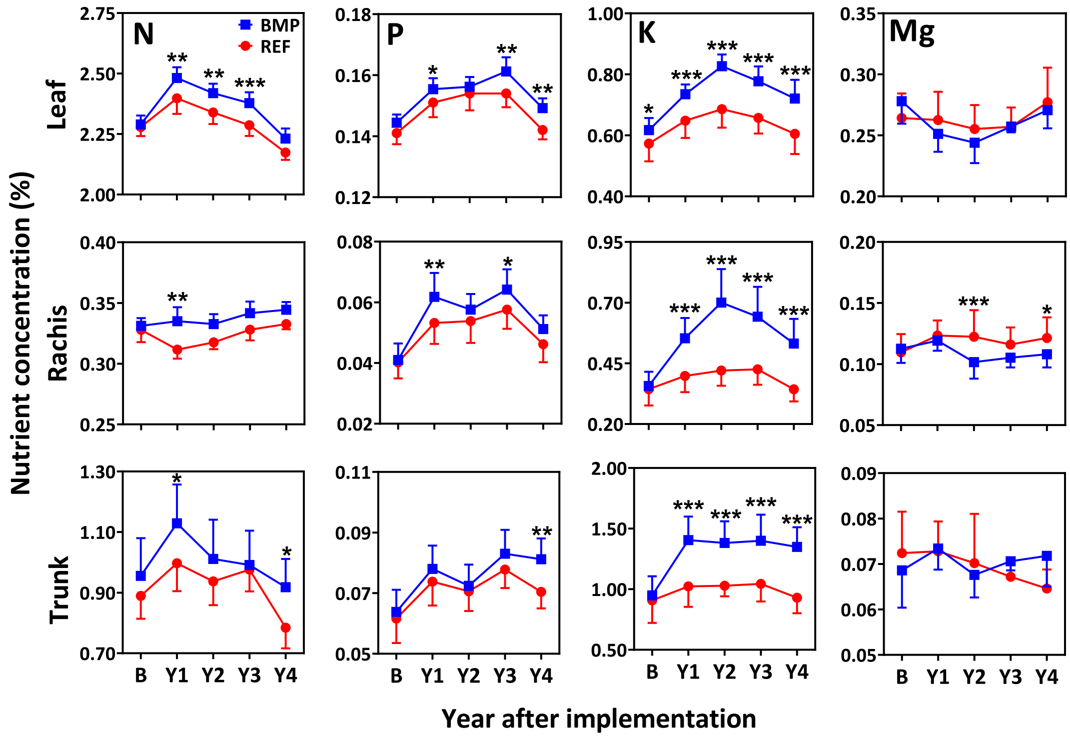

Fig. 2. Nitrogen (N), phosphorous (P), potassium (K), and magnesium (Mg) concentration in leaf, rachis, and trunk at the beginning of the trials (baseline, B) and after one (Y1), two (Y2), three (Y3) and four years (Y4) for two treatments: better management practices (BMP) and reference farmer management (REF). Asterisks indicate statistically significant differences at $^{*}p \leq 0.05$, $^{**}p \leq 0.01$ and $^{***}p \leq 0.001$ as evaluated using Tukey's test. Each point represents the mean for each treatment and year, while vertical bars indicate the standard error of the mean. To avoid overlapping, only downward and upward error bars are shown for REF and for BMP, respectively.

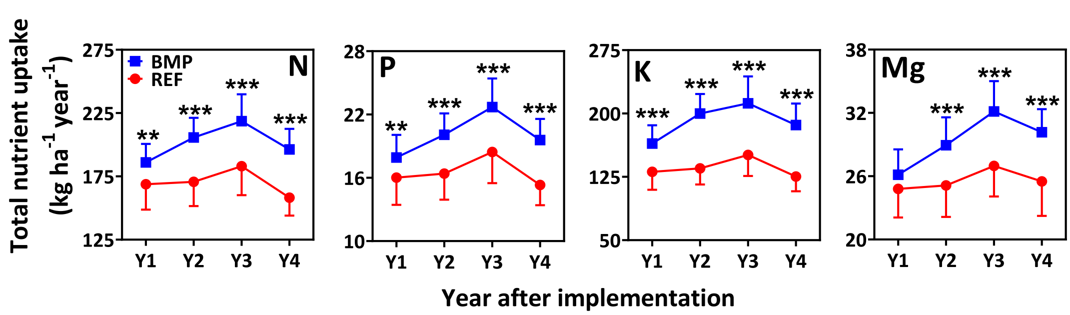

Fig. 3. Plant nitrogen (N), phosphorous (P), potassium (K), and magnesium (Mg) uptake during the first (Y1), second (Y2), third (Y3) and fourth year (Y4) after beginning of the trials. Data were collected from 30 paired fields that included two treatments: better management practices (BMP) and reference farmer management (REF). Asterisks indicate statistically significant differences at $^{*}p \leq 0.05$, $^{**}p \leq 0.01$ and $^{***}p \leq 0.001$ as evaluated using Tukey's test. Each point represents the mean for each treatment and year, while vertical bars indicate the standard error of the mean. To avoid overlapping, only downward and upward error bars are shown for REF and for BMP, respectively.

3.3. Influence of better management on dry matter production and partitioning

Average (Y2-Y4) annual ADM production, was 21 % higher in the BMP *versus* REF fields ($p < 0.001$) (Fig. 4). This difference can be partly attributed to differences in intercepted solar radiation, as we found that the shade index was 14 % higher in the BMP than REF fields in Y3 ($p < 0.001$). This finding was consistent with differences in LAI (+8 %) and fraction of intercepted solar radiation (+3 %) in the BMP *versus* REF fields. However, the magnitude of these differences was not sufficient to explain alone the observed differences in annual plant growth between treatments. Consistent with this observation, average (Y2- Y4) RUE, estimated based on annual crop growth and intercepted PAR, was +18 % higher in the BMP than REF fields. Variation in RUE across field-years was associated with differences in leaf N, P, and K concentrations ($p < 0.001$, $r^2 = 0.22$–0.40).

Average (Y2-Y4) partitioning to bunches was higher in BMP than REF fields, averaging 47 % and 42 %, respectively ($p < 0.001$) (Fig. 4). Correcting dry matter of each organ by dry matter composition led to higher partitioning to bunches and lower for fronds and trunk (Supplementary Fig. S4). For example, average (Y2-Y4) dry-matter corrected partitioning to bunches was 57 % (BMP) and 52 % (REF). Nutrient partitioning to the different organs followed the same trend as dry matter, except for K, which was similar in BMP and REF fields (Fig. 5). Results on nutrient partitioning needs to be taken with caution since we did not measure nutrient concentration in FFB.

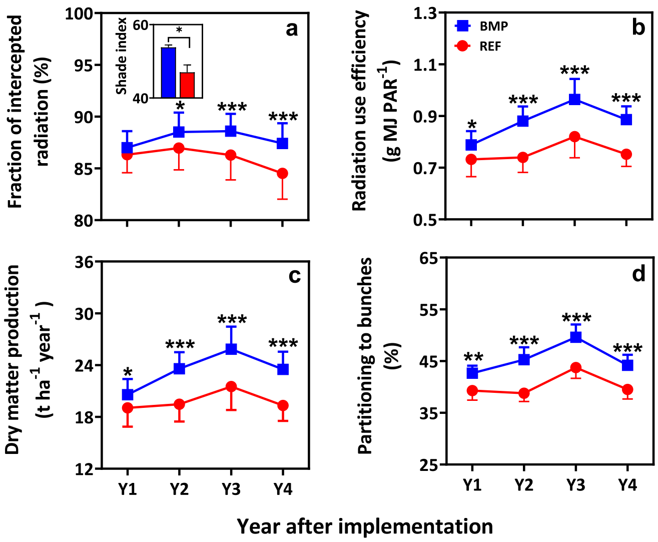

Fig. 4. Fraction of intercepted radiation (a), radiation use efficiency (b), aboveground dry matter production (c), and partitioning to bunch (d) in fields following better management practices (BMP) and farmer practices (REF) from year 1 (Y1) through year 4 (Y4). Inset in (a) shows average shade index in BMP and REF fields. Asterisks indicate differences at $^{*}p \leq 0.05$, $^{**}p \leq 0.01$ and $^{***}p \leq 0.001$ as evaluated using Tukey's test. Each point represents the mean for each treatment and year, while vertical bars indicate standard error. To avoid overlapping, only downward and upward error bars are shown for REF and for BMP, respectively. Trends in (b), (c), and (d) after correction by dry matter composition are shown in Supplementary Fig. S4. Relationship between shade index and leaf area index is shown in Supplementary Fig. S5.

3.4. Effect of better management on yield components and FFB and CPO yields

Accumulated FFB yield in BMP and REF fields were similar during the first six months after initiation of trials ($p = 0.60$) (Supplementary Figs. S1-S2). Differences in FFB yield started to become apparent after six months and were initially closely associated with the increase in bunch number, leading to a BMP-REF yield difference of 2.4 t ha^{-1} at the end of Y1 (Fig. 6). The BMP-REF yield difference increased in subsequent years, averaging 5.8 t ha^{-1} (Y2), 6.5 t ha^{-1} (Y3) and 5.5 t ha^{-1} (Y4). The yield increase (Y2-Y4) was associated with an average increase in both bunch number (+23 %) and weight (+8 %) in BMP *versus* REF fields. The average (Y1-Y4) FFB yield in the REF fields (15.6 t ha^{-1}) was 47 % of the attainable yield (33.5 t ha^{-1}). Implementation of BMPs increased actual yield from 46 % of the attainable yield in Y1 to 71 % in Y2-Y4. Except for Y3, there was no difference in average FFB yield across years in the REF fields, suggesting that farmers did not adopt BMPs in their REF fields.

Deriving OER for each field based on a small number of palms was not possible given the high spatial variation that exists in OER among palms within a field, with coefficients of variation >20 %. However, there was no statistically significant difference in OER between BMP and REF fields ($p = 0.66$) (Supplementary Table S2). Similarly, no statistically significant difference was found for the interaction between site and palm type ($p = 0.43$), site and treatment ($p = 0.62$), palm type and treatment ($p = 0.94$), and among site, palm type, and treatment ($p = 0.97$). Conversely, there were statistically significant differences for OER between palm types and between sites ($p < 0.001$). Thus, we pooled the BMP and REF data to derive OER averages for tenera and dura, separately for each site (Supplementary Fig. S7). Subsequently, we estimated the CPO yield for each field by multiplying the annual FFB yield during Y3 by the average OER expected for that field given the measured frequencies of dura and tenera types and the associated site-average OER for each palm type. Following this approach, we found that average CPO yield was 1.5 t ha^{-1} higher in BMP than in REF fields in Y3 (Fig. 6). The BMP-REF CPO yield difference was related to differences in FFB yield since OER was not different (p = 0.66) between treatments (Supplementary Table S2).

The BMP-REF FFB yield difference varied from 3.2 to 10.5 t ha^{-1} (Y2), 4.3 to 10 t ha^{-1} (Y3), and 3.6 to 7.5 t ha^{-1} (Y4) across trials.

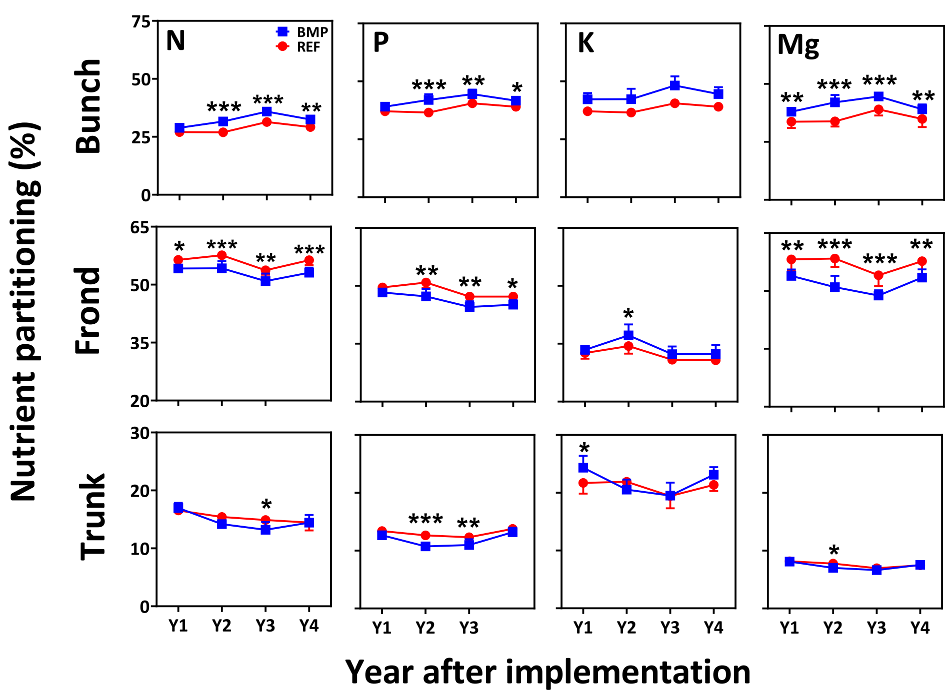

Fig. 5. Nutrient partitioning (as percentage of total nutrient uptake) to bunch, frond, and trunk under better management practices (BMP) and standard farmer practices (REF) for year 1 (Y1), year 2 (Y2), year 3 (Y3) and year 4 (Y4). Asterisks indicate statistically significant differences at $^{*}p \leq 0.05$, $^{**}p \leq 0.01$ and $^{***}p \leq 0.001$ as evaluated using Tukey's test. Each point represents the mean for each treatment and year, while vertical bars indicate the standard error of the mean. To avoid overlapping, only downward and upward error bars are shown for REF and for BMP, respectively.

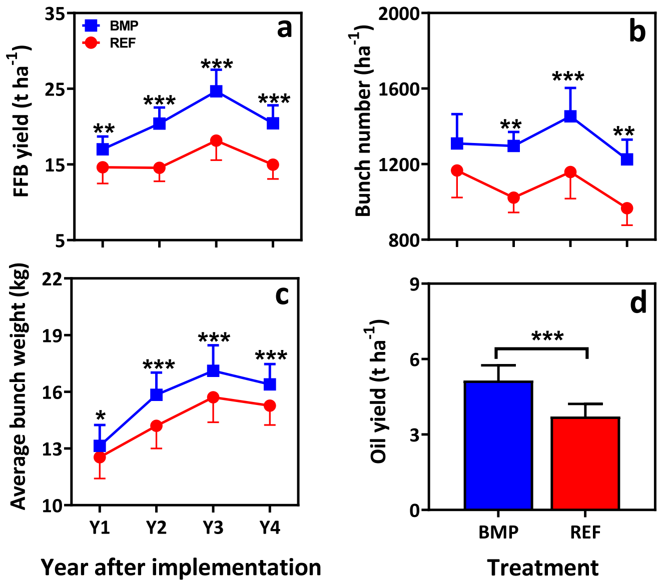

Fig. 6. Annual average (± standard error) fresh fruit bunch (FFB) yield (a), bunch number (b), and bunch weight (c) weight during the first (Y1), second (Y2), third (Y3), and fourth year (Y4) after beginning of the trials. Also shown are average crude palm oil (CPO) yield based on measured oil extraction rates during Y3 (d). Data were collected from 30 paired fields that included two treatments: better management practices (BMP) and reference farmer management (REF). Asterisks indicate statistically significant differences between treatments at *p ≤ 0.05, **p ≤ 0.01 and ***p ≤ 0.001 as evaluated using Tukey's test. Vertical bars indicate the standard error of the mean. To avoid overlapping, only downward and upward error bars are shown for REF and for BMP, respectively.

Largest and smallest absolute BMP-REF yield differences were observed in SS and CK, respectively (Supplementary Figs. S8-S12). About 70 % of the spatial variation in yield response across sites was associated with the initial yield level (*i.e.*, FFB yield in the REF treatment in Y1), degree of BMPs implementation (*i.e.*, fraction of applied fertilizer relative to recommended), and initial yield differences between BMP and REF fields (*i.e.*, BMP-REF yield difference during the first six months after trial initiation) (Table 3). For example, the yield response to BMPs was greater in fields exhibiting low initial yield and high BMP implementation. Likewise, those BMP-REF fields exhibiting positive (negative) yield differences during the first six months tended to have larger (smaller) yield differences later. However, average FFB yield during the first six months was not significantly different between BMP and REF fields (Supplementary Figs. S1-S2). Thus, these initial BMP-REF yield differences did not influence the overall FFB yield difference that we found between treatments.

3.5. Impact of better management practices on farmer profit and labor

Implementation of BMPs led to lower (−8 %) profit than REF in Y1 due to higher costs (Fig. 7). However, by Y2 greater yields more than compensated for higher costs and net profit was greater in the BMP fields, Y2 (+26 %), Y3 (+18 %), and Y4 (+19 %). The analysis was based on actual prices of FFB and inputs over Y1-Y4. Economic outcomes were similar when based on historical prices (Supplementary Fig. S6). Labor requirement per ton of FFB was slightly higher in BMP than in REF fields during the initial two years but similar afterwards.

4. Discussion

The combination of field measurements, monitoring of trials and farmer practices, surveys across an independent population of 837 smallholders located adjacent to our field trials, and use of crop models

Table 3
Assessment of drivers for spatial variation in BMP-REF yield difference across the 30 sites using multiple regression analysis. Dependent variable is the 2-year (Y2-Y3) average FFB yield (t ha^{-1}). Also shown are the associated parameters and their standard error (s.e.) and statistical significance (n = 30; adjusted R^2 = 0.67). See Methods.

Coefficients	Estimate	s.e.	*p*-value
Intercept	−3.371	6.259	0.597
REF FFB Y1 (t ha^{-1}) [a]	−0.318	0.090	0.002
Accumulated 6-month BMP-REF yield difference [b]	1.025	0.306	0.004
BBC diff BMP-REF (BNO ha^{-1}) [c]	−0.005	0.008	0.538
Average dura frequency (%) [d]	0.004	0.021	0.861
BMP-REF palm density difference (ha^{-1})	0.003	0.034	0.935
Average palm age (Y1)	−0.239	0.275	0.396
Average palm density (ha)	0.029	0.031	0.363
BMP implementation [e]	3.005	0.743	0.001
BMP-REF soil similarity index [f]	0.464	3.004	0.879
Number of dry months [g]	0.418	0.252	0.114
BMP-REF TWI difference [h]	−0.630	0.717	0.391

Yn: year number after initiation of trials: year 1 (Y1), year 2 (Y2), year 3 (Y3), and year 4 (Y4).
[a] The REF yield in Y1 is taken as a reference of the initial yield level.
[b] The BMP-REF yield difference in the first six months after trial initiation is taken as an indicator of possible initial differences in yield level between paired BMP-REF fields.
[c] Differences in black bunch count (BBC) as determined *via* field survey.
[d] Dura frequency is used as an indicator for use of non-certified planting material.
[e] Semi-quantitative measure of BMP implementation, ranging from zero (no implementation) to four (full) (see Material and Methods).
[f] Similarity in soil parameters between BMP and REF fields (see Material and Methods).
[g] Number of dry months (total rain <100 mm) during the three years prior to start of trials and during Y1.
[h] TWI indicates the likelihood of surface runoff (run-on) from (to) an area based on slope and surrounding area, with bottom and upland areas having highest and lowest values, respectively (Moore et al., 1993; Sorensen et al., 2006). The TWI was calculated following Cock et al. (2016).

demonstrated that the paired fields represented well the biophysical, agronomic and socio-economic situation of most independent smallholder oil palm producers on mineral soils in Indonesia (Supplementary Table S1). Likewise, we observed that the BMP and REF conditions were similar at the beginning of the trials and, hence, that later differences were due to the implementation of BMPs with yield and nutrient fertilizer application in the REF fields not changing over time (Fig. 6; Supplementary Fig. S1-S2; Supplementary Fig. S8-S12). Crop models objectively evaluated measured yield improvements relative to the attainable yield as influenced by local weather and soil. For example, we showed that the average yield in the BMP fields increased from 46 % of the attainable yield (Y1) to 71 % in subsequent years. Conversely, average yield in the REF fields remained low over the four years, averaging 46 % of the attainable yield.

Our study shows that improvements in agronomic practices increased FFB and CPO yields by 40 % and profit by 20 % (Fig. 6). The yield difference between BMP and REF fields stabilized at *ca.* 0.5 t FFB ha^{-1} per month one and a half years after initiation of the improved management practices (Figure Supplementary Fig. S2). Increased profits from BMPs were only perceived from the second year when the higher costs were compensated for by higher yields (Fig. 7). This delay before obtaining benefits from investing in improved practices may be an impediment to their adoption, especially when agricultural credit is limited to one year before repayment is due. On the other hand, we found no trade-off between BMP adoption and labor requirements after the initial BMP implementation. Labor has largely been neglected by agricultural research agencies, despite the role increased labor productivity can play to provide farmers and farm laborers with greater prosperity (Cock et al., 2022). As far as we know, this is the first study

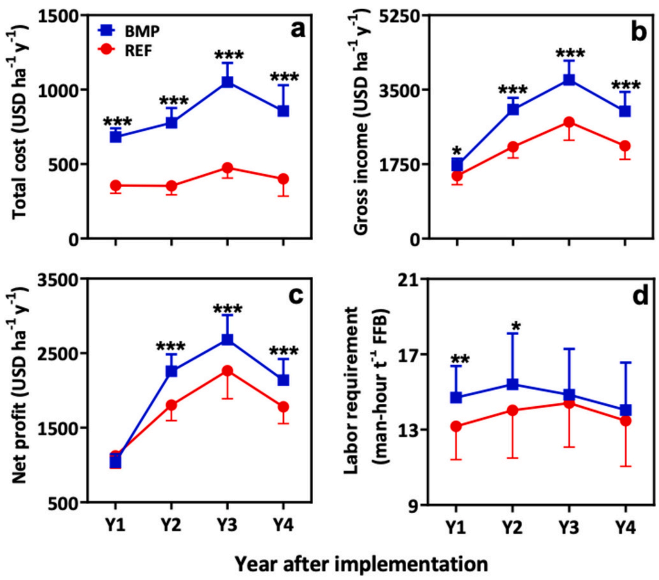

Fig. 7. (a) Total production cost, (b) gross income from FFB selling, (c) net profit, and (d) labor requirement per ton of FFB during the first (Y1), second (Y2), third (Y3), and fourth (Y4) year after beginning of the trials based on actual prices during the trial period. Data were collected from 30 paired fields that included two treatments: better management practices (BMP) and reference farmer management (REF). Asterisks indicate statistically significant differences between treatments at $*p \leq 0.05$, $**p \leq 0.01$ and $***p \leq 0.001$ as evaluated using Tukey's test in (a), (c) and (d). Vertical bars indicate the standard error of the mean. To avoid overlapping, only downward and upward error bars are shown for REF and for BMP, respectively. See similar trends based on historical prices (2005–2020) in Supplementary Fig. S6.

documenting not only the impacts of BMPs on productivity measured as yield but also on profitability and labor requirements on smallholder fields in Indonesia.

This study, unlike most of this type, evaluated drivers of yield variation including light interception and conversion, and biomass partitioning. We developed and tested a simple, robust, *in situ* measurement of light interception based on sun flecks as suggested by Tooming (1967). There was a reasonable relationship between results from the sun flecks method and the more traditional estimates based on estimates of leaf area index (Supplementary Fig. S5). Furthermore, there is no reason, except its common acceptance, to affirm that the LAI method is more precise than the sun fleck method. Hence, we suggest that the simpler and less time-consuming sun fleck method could be a useful tool for future analysis of the drivers of yield variation. We still acknowledge a few limitations and disadvantages of this method, including the need for sunny days and consistency in the time of the day to perform measurements and some subjectivity when determining whether a spot is dark or not.

Evaluating the impact of each BMP separately was not possible given the high degree of correlation among them. In other words, farmers who followed the fertilizer recommendation also tended to have shorter harvest intervals, proper frond arrangement, and good weed management. Ultimately, the combined effect of the BMPs led to a remarkable increase in nutrient uptake in BMP *versus* REF fields, with the former accumulating 18 %, 21 %, 40 %, and 14 % more N, P, K, and Mg by end of Y4 (Fig. 3). Nutrient accumulation was larger than ADM increases, especially for K, leading to higher concentrations of these nutrients (Fig. 2). Associated with the larger nutrient uptake, there was greater ADM production in BMP than in REF fields due to both the higher LAI and the associated fraction of light intercepted and the increased RUE (Figs. 3 and 4, and Supplementary Fig. S4). The increase in ADM associated with increased RUE was large and consistent with the expected impact of higher leaf N, P, and K concentration on photosynthetic rates (Corley and Tinker, 2003; Kamal and Manan, 2020) and the statistically significant relationships found between RUE and leaf nutrient concentrations based on our experimental data (Section 3.3). Nevertheless, earlier studies showed a small increase in the somewhat similar measure of net assimilation rate (NAR) with increased levels of nutrient applications, with the authors commenting that nutrient application increases ADM accumulation or crop growth rate primarily by increasing LAI, rather than NAR (Corley and Mok, 1972). This, as far as we are aware, is the first time that field studies show a large increase in RUE due to higher concentrations of nutrients in the leaves with this increased RUE making a major contribution to the increase in ADM accumulation.

Besides larger ADM production, we found higher ADM partitioning to bunches in the BMP *versus* REF fields. In many crops with simultaneous development of the leaf canopy and storage organs such as fruits and trunk, excess biomass above the need for production and maintenance of the leaf canopy and support structures spills over into the storage organ. This spillover tends to increase the harvest index or biomass partitioning. This spillover frequently accumulates in the storage organs increasing the partitioning to the storage organs and hence the harvest index (*e.g.*, Cock and Connor, 2021.) Oil palm appears to follow this pattern and partitioning to bunches was higher in the BMP *versus* REF fields (Fig. 4). Tao et al. (2017) have reported similar changes in partitioning to bunch in response to BMPs. In terms of yield components, both bunch number and weight were higher in the BMP *versus* REF treatment (Fig. 6), which is consistent with Griffiths and Fairhurst (2003), Donough et al. (2010), Oberthür et al. (2012), and Rhebergen et al. (2020). There was no difference in bunch number in Y1, whereas bunch weight is determined in the final six months before harvest. Bunch weight was greater in Y1 and all subsequent years in BMP fields. We presume the bunch number in Y1 had been largely determined before the treatments were implemented.

Our detailed description of the fields and monitoring provided information on those circumstances where the impact of BMPs was greatest and smallest (Table 3). The largest yield gains due to BMPs were in fields with low initial yield level and well implemented BMPs. Few other studies have attempted to identify where BMPs are likely to have most impact, and which of the many practices are the most important. Our analysis indicates that implementation of BMPs will generate a comparatively large FFB yield response where current yields are low and the socio-economic context allows full implementation of BMPs, with emphasis on optimal fertilizer applications. Dura frequency did not influence the yield response to BMPs. Our study reported mainly FFB yields, however, the industry is interested in CPO yields. The only significant effects on OER, which is necessary to convert FFB yields to CPO yields, were the frequency of dura and tenera palms (plant type) and site, while BMPs had no effect of OER (Supplementary Table S2 and Supplementary Fig. S7). Higher FFB yields, with no changes in OER, due to BMP adoption were also reported by Oberthür et al. (2012).

Our trials were conducted across a range of environments that portray well the variation in climate and soils across the oil palm area in Indonesia (Agus et al., 2024; see Section 2.1), with average REF yields comparable to those retrieved from a larger population of smallholders (Supplementary Table S1). Furthermore, we observed a positive impact of BMPs on FFB yield across the five provinces (Supplementary Figs. S8-S12). Altogether, this gives confidence that our results can be extrapolated to the rest of the oil palm area located in mineral soils in Indonesia, which is mostly located in Sumatra and Kalimantan. If BMPs were adopted nationwide, considering the same relative yield increase (+40 %) as in our trials and a total mature area of independent smallholder 3.1 M ha in mineral soils (Molenaar et al., 2013; Hidayat, 2017; Directorate General of Estate Crops, 2022), we estimated, using an average OER of 21 % and no impact of BMPs on OER, that Indonesia could produce 3.6 MMT more CPO. This is equivalent to 8 % of the national 2020 CPO production, representing *ca.* 3 billion USD at current prices (Directorate General of Estate Crops, 2022). Furthermore, BMPs can amplify the potential impact of replanting programs that promote planting certified tenera material with higher OER (Zen et al., 2005; Molenaar et al., 2013; Coordinating Ministry for Economic Affairs Republic of Indonesia, 2023; Indonesian Oil Palm Association, 2023). For example, implementation of BMPs, together with replanting of current independent smallholder fields (at the end of their plantation cycles) with certified planting material, would produce +5.4 MMT CPO, which would increase current national CPO production of Indonesia by 12 %. Thus, BMP adoption complements current efforts to replant fields with planting material with higher OER. However, to induce a change to higher oil content planting material changes to the supply chain are required so that smallholders receive higher prices for the higher OER in certified planting material. Currently this is not the case (Monzon et al., 2023). An essential feature for implementation of these changes in the supply chain is a means to determine the OER of bunches arriving at the extraction plants (Cock et al., 2014). Such methodologies are now being implemented on commercial plantations in Colombia (Caballero et al., 2022) and would appear to be an interesting option for Indonesia.

There are environmental benefits associated with yield intensification. The potential extra production from BMP adoption by small holders (+5.4 MMT) from land already planted to palm is equivalent to establishing *ca.* 2 million ha of new plantings at current average yield. However, these benefits will only accrue if adequate institutional and policy support are provided to ensure that the gains translate into reducing the clearing of new forest land. However, with this proviso, yield intensification *via* BMPs can complement on-going efforts to minimize deforestation such as certification, moratoria, and EUDR import restrictions providing smallholders with a pathway to become more prosperous by producing more oil without need to clear new land for oil palm cultivation.

5. Conclusions

Better management practices can increase FFB and CPO yields (+40 %) and improve farmer profit (+20 %), without increasing labor requirement per ton of FFB produced. The yield increase, when compared to current management practices, was largest in fields with low initial yield level and when most of the better management practices were applied. The single most important practice was improved plant nutrient management. Better nutrient management increased total leaf area, and hence light interception. This coupled with improved RUE increased total biomass production, of which a greater proportion was distributed to the fruit bunches. The yield with farmer practices was 46 % of attainable yield whereas that of fields with BMPs was 71 % of attainable yield from the second year after their implementation. The BMPs only increased farmer profits after the first year, which suggests that, for farmers to adopt BMPs, credit schemes may need to be extended beyond one year. Nevertheless, yield intensification is shown to be an effective approach to increase farmer yield and profit, complementing current efforts to increase CPO yield *via* replanting programs. Widespread adoption of BMPs can provide smallholders a means to prosper and produce more oil without need to clear land for cultivation.

CRediT authorship contribution statement

Hendra Sugianto: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christopher R. Donough:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Juan P. Monzon:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation. **Sunawan:** Writing – review & editing, Investigation. **Iput Pradiko:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Ya Li Lim:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Fatima A. Tenorio:** Writing – review & editing, Methodology, Investigation, Data curation. **Gonzalo Rizzo:** Writing – review & editing, Formal analysis. **Suroso Rahutomo:** Writing – review & editing, Conceptualization. **Fahmuddin Agus:** Writing – review & editing, Investigation. **Setiari Marwanto:** Writing – review & editing, Investigation. **Maja Slingerland:** Writing – review & editing, Investigation. **James Cock:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Patricio Grassini:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest. The paper contents have not been previously published nor are under consideration for publication elsewhere. All co-authors have contributed to the paper and have agreed to be listed as co-authors.

Acknowledgments

This project was supported by the Norwegian Ministry of Foreign Affairs (grant INS-19/0008 to P.G.), with some additional funding from the Global Engagement Office at the Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln (UNL). We also thank the following collaborators: Antonius P. Tito, Denni Nurdwiansyah, and Asmadi (Bentang Kalimantan), Dhimas Wiratmoko, Heri Santoso, Muhdan Syarovy, Rana Farrasati, Sumaryanto, and Nuzul H. Darlan (Indonesian Oil Palm Research Institute), Mink Zijlstra and Rosa de Vos (Wageningen University), Nadia A. Mulani, Nurul Mahmudah, Nadib Ulfaria, and Puguh (Posyantek), Nurbaya Zulhakim, Pandu Sulistiawan, Sandri Palupi, Muhammad Koirul, and Ridho Iskandar (Setara Jambi), and Nurul Winarni and Asri A. Dwiyahreni (Research Center for Climate Change, Universitas Indonesia). We are grateful to the Indonesian Coordinating Ministry of Economic Affairs, famer associations, large plantations, and provincial plantations offices and district and village authorities for facilitating project activities. We also thank Thomas Farrell (former senior advisor at University of Nebraska-Lincoln) and Dr Thomas Oberthür (former director at the International Plant Nutrition Institute regional office in Southeast Asia) for their encouragement to initiate our research program in Indonesia and the many independent smallholder farmers in Indonesia who participated in this project. Results from this study have been shared with stakeholders through a Fertilizer Roundtable held in Jakarta in January 2023. The associated final document with the consensus points is available at https://agronomy.unl.edu/sites/unl.edu.ianr.agronomy-horticulture/files/media/file/Grassini-Jakarta-Roundtable-Points-of-Consensus-bilingual.pdf.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2025.104269.

Data availability

Data will be made available on request.

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