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Improving Yield and Profit in Smallholder Oil Palm Fields through Better Agronomy

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IMPROVING YIELD AND PROFIT IN SMALLHOLDER OIL PALM FIELDS THROUGH BETTER AGRONOMY

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Oil palm accounts for 40% of global vegetable oil production and Indonesia contributed 59% of the total production, with total planted area nearly 15 M ha in 2020. About 40% of the planted area is managed and owned by smallholders, and two thirds of them are independent, they are not bounded to a large plantation. Current efforts to increase yield of independent smallholder (ISH) fields focus on replanting programs promoting use of certified planting material, with little attention to improve management practices, in particular, plant nutrition. Here we investigated the degree to which poor nutrition can explain large yield gaps in ISH and how the yield gap can be narrowed down *via* better management practices (BMPs). We assessed nutrient deficiencies in 973 ISH fields using robust protocols for leaf sampling, and the impact of nutrient status on yield as influenced by planting material in 30 trials across five provinces. Each trial included two paired fields: one followed farmer management (‘reference’ fields) and the other receiving BMPs, including better harvest, nutrient, pruning, and weed management. There were widespread nutrient deficiencies, 88% (K), 65% (N & B) and 52% (P) and 34% (Mg). NPK-sufficient fields yielded 5.6 t ha^{-1} (+47%) than deficient fields, and planting material has a little effect on FFB yields, but a substantial effect on oil content.

Implementation of BMPs led to higher (+40%) FFB yield and +20% net profit compared with REF during the second and third year after the trials started. Scaled out to the entire ISH area in Indonesia, BMPs can lead to an additional 3.4 MMT CPO (+8% of current national production), generating an additional revenue of +3.0 billion dollars. Such production increase via yield improvement is equivalent to 1.2 M ha at current yield level. We conclude that intensification provides an effective pathway to independent smallholders to increase their yields and profit, generating an economic benefit from local to national level, while relieving pressure on land conversion for oil palm cultivation.

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CHAPTER 1. GENERAL INTRODUCTION

Oil palm (*Elaeis guineensis*) is native from Africa (Zeven, 1964). Four seeds were brought to Indonesia by D.T. Pryce and planted in the Bogor Botanical Gardens in 1848. Later on, some of the harvested fruits were distributed by J.E. Teijsmann to Java, Sumatra, Kalimantan, Sulawesi, Maluku and Nusa Tenggara. Between 1859 and 1875, trials were carried out in Central Java, South Sumatra, and North Sumatra (GAPKI, 2017). Nearly 170 years after its introduction to Indonesia, oil palm is now cultivated in 15 million hectares (Directorate General of Estate Crops, 2022). Large plantations account for 60% of current oil palm, while the rest is managed by smallholders (Directorate General of Estate Crops, 2022). According to the legal definition, oil palm smallholders are those who manage < 25 ha of land (Ministry of Agriculture, 2013). In practice, the average oil palm area managed by smallholders is ca. 2 ha (Monzon et al., 2023). There are two types of smallholders: plasma and independent. Plasma smallholders manage a plantation established and developed by large plantations (nucleus plantation) and receive technical assistance from them, while independent smallholders managed their field without any assistance from large plantation companies (Jelsma and Schonevelg, 2016). Independent smallholders account for two thirds of total smallholder oil palm area in Indonesia, totalling *ca.* 3.1 million ha (Molenaar et al., 2013; Hidayat, 2017; Directorate General of Estate Crops, 2022).

Production of crude palm oil (CPO) in Indonesia reached 45.7 million tons in 2020 (BPS, 2022), accounting for 59% of global production (USDA, 2022). The CPO production over the last 20 years (2000 to 2022) has been driven by expansion of the plantation area (+9.8 M ha) (Figure 1) and one third of the expansion has occurred at expense of fragile natural ecosystems such as rainforests and peatlands (Gaveau et al., 2022). Conversely, little CPO yield improvement has been observed over the same time period, with annual yield averaging 3.4 t CPO ha^{-1} over the past 20 years, which is equivalent to ca. 16.9 t fresh fruit bunch (FFB) ha^{-1} y^{-1} (Directorate General of Estate Crops, 2022). Increasing yield on existing cropland area can help Indonesia to produce more CPO and alleviate the pressure that exists to convert new land for oil palm cultivation.

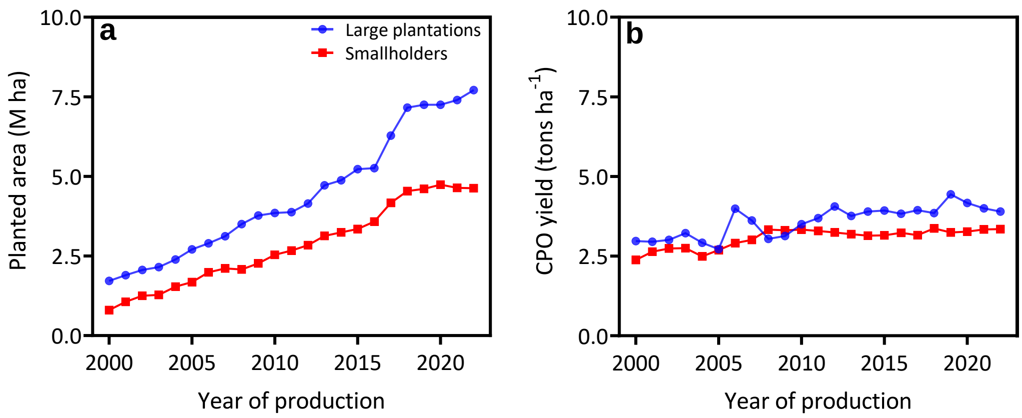

Figure 1-1. *Trends of crude palm oil (CPO) planted area (a) and yield (b) for large plantations (blue) and smallholders (red) between 2000 and 2022. Source: Directorate General of Estate Crops, 2022.*

Yield potential (Yp) is the yield of a well-adapted crop variety, without limitations by water and nutrients, and in absence of biotic stresses (Evans and Fischer, 1999; van Ittersum and Rabbinge, 1997, Cassman et al., 2003; van Ittersum et al., 2013). Hence, Yp is primarily influence by solar radiation, temperature, atmospheric CO_2 levels, and genetics characteristics. In the case of rainfed crops, in addition to the previous factors, water supply and soil properties influencing crop water balance, such as plant-available water holding capacity and rootable soil depth, also determined the water-limited yield potential (Yw). Since oil palm is grown in rainfed conditions in Indonesia, we used Yw as the proper benchmark to evaluate current productivity. Achieving Yw for oil palm is almost impossible because of the difficulty to achieve perfection in management practices, so that all yield-reducing factors are eliminated, and crops grow without any nutrient limitations over time and space. Likewise, it would require copious amounts of nutrient and pesticides, leading to negative economic and environmental impacts. 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 there is empirical data showing that this is a reasonable attainable yield for this crop (Monzon et al., 2021, 2023).

Only one study (Monzon et al. 2021) has estimated the Yw for oil palm in Indonesia using a robust protocol for crop modelling and use of local weather, soil, and yield databases. In this study, Yw was estimated for 22 sites using long-term weather data, dominant soil types at each site, and the average age of the plantations. The Yw was estimated using PALMSIM v2.0 crop simulation model, which has been validated previously on its capacity to reproduce the highest yields observed in oil palm plantations (Hoffmann et al., 2014; Hekman et al., 2018; Monzon et al., 2021, 2023). The attainable yield was calculated as 70% of the simulated Yw and exploitable yield gap was estimated as the difference between average yield and attainable yield. These authors found that average current yield represent 62% (large plantations) and 53% (smallholders) of the attainable yield, the latter estimated to be 30.6 t FFB ha^{-1}. Therefore, Indonesia has a low average yield in relation to the attainable yield, especially in the case of smallholder farmers. However, this study did not estimate the yield gaps separately for plasma and independent smallholders. On a subsequent study, Monzon et al. (2023) assessed exploitable yield gaps for independent smallholders using data collected over four years from 977 fields located in six provinces in Indonesia. The Yw for each field was estimated using the PALMSIM model coupled with local weather and field-specific soil type and age. These authors found that the average FFB yield in independent smallholder fields was 13.9 tons FFB ha^{-1} year^{-1}, which, in turn, represented only 42% of the attainable yield (33.4 tons FFB ha^{-1}) (Figure 2). Altogether, this set of studies indicates a substantial exploitable yield gap in independent smallholder fields, which averaged 19.5 tons FFB ha^{-1}. Considering the total oil palm area managed by independent smallholder oil palm farmers in Indonesia (3.1 million ha), an assuming an average extraction rate of 21%, there is a potential to increase production by 12.6 MMT CPO on existing cropland by closing the current exploitable yield gap in independent smallholder fields. In turn, this represents an opportunity for the country to reconcile production and environmental goal by increasing CPO without need to expand oil palm into natural ecosystems.

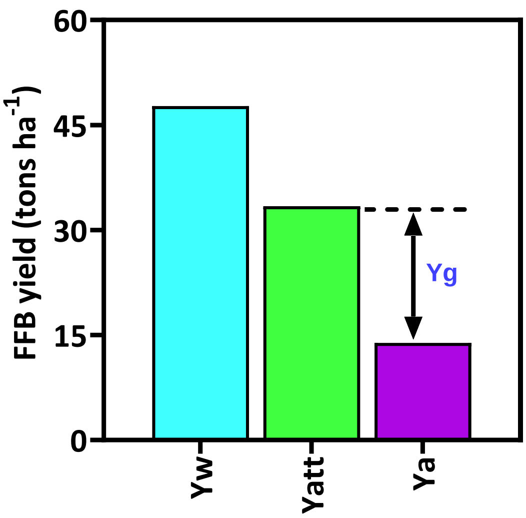

Figure 1-2. *Water-limited yield potential (Yw), attainable yield (Yatt), average yield (Ya), and exploitable yield gap (Yg) in independent smallholder oil palm fields in Indonesia. The attainable yield was estimated as 70% of the Yw. Adapted from Monzon et al. (2023).*

Previous studies focussing on independent smallholders have reported agronomic management as the cause for the yield gap, including poor nutrient, harvest, weed, and pruning management (Jelsma et al., 2019; Woittiez et al., 2018a, 2018b; Monzon et al., 2021). In particular, current nutrient inputs seem insufficient in relation to plant nutrient requirements (Monzon et al., 2021; Lim et al., 2023; Woittiez et al., 2018b; Jelsma et al., 2019). For example, Lim et al (2023) used data collected from 977 independent smallholder field over two years to evaluate current nutrient management. The fields were located across six oil palm producing areas in Indonesia. These authors found the average nutrient fertilizer averaged 20 kg N, 5 kg P, 15 kg K, and 2 kg Mg per ha per year (Table 1). These nutrient fertilizer inputs represented only 13% (N,) 26% (P), 8% (K), and 9% (Mg) of the nutrient requirements needed to achieve the attainable yield. Thus, current fertilizer use is clearly insufficient to close the exploitable yield gap in independent smallholder farmers. Unfortunately, current agricultural research and development programs in Indonesia focussed on promoting replanting programs with certified planting material as the only approach to increase productivity in smallholder fields (Molenaar et al., 2013; Zen et al., 2005; Coordinating Ministry for Economic Affairs, 2023; Indonesia Oil Palm Association, 2023), paying little, if any, attention to improving agronomic management as a pathway to increase yield and profit.

Table 1-1. *Nutrient requirements associated with the attainable yield in independent smallholder fields in Indonesia. Also shown are the current nutrient fertilizer application, nutrient gap (difference between required and applied fertilizer), and the applied fertilizer as percentage of the requirement. All values are in elemental nutrients. Adapted from Lim et al. (2023).*

Nutrients	Nutrient requirement [a] (kg ha-1)	Applied nutrient (kg ha^{-1}) fertilizer	Nutrient gap (kg ha^{-1})	Applied (% of requirement)
N	150	20	130	13%
P	19	5	14	26%
K	195	15	180	8%
Mg	23	2	21	9%

[a] Nutrients requirement was estimated based on the relationship between removed nutrients in FFB plus immobilized nutrients in trunk.

Despite the evidence of low nutrient use in independent smallholder fields, there has been no systematic assessment of nutrient deficiencies in independent smallholder fields and its influence on oil palm yields. In oil palm, nutrient deficiencies are usually diagnosed from leaf nutrient levels (Foster, 2003). To determine if the leaf analysis results are deficient, leaf nutrient concentrations are compared to the range of nutrient sufficiency proposed by Von Uexküll and Fairhurst

(1991). Unfortunately, leaf sampling protocols are not available for smallholders, especially when it comes to the number of palms that must be sampled. For example, the protocols available for large plantations recommend to sample one percent (1%) of the palms within a block. Considering that most smallholder field size range from one to two hectares, if this guide is applied, most likely one to two palms to be sampled, which may or not may not be representative of the palms planted in that field. Furthermore, the heterogeneity in independent smallholder field is greater compared with large plantation due to use of non-certified planting material and/or poor seedling culling. Because plant sampling protocols do not exist for smallholder fields, previous researchers took leaf samples using arbitrary sample sizes. For example, Woittiez et al. (2018b) took leaf samples for their study: at site one, they took three palms per field randomly avoiding “sick” or “unrepresentative” palms, while at another site, they took four palms per field in the four corners of the field. Meanwhile Jelsma et al. (2019) sampled “a minimum of four non-randomly selected palms per field was compounded into one sample per field at least two rows away from the road and preferably at least five palms away from other sampled palms”. Meanwhile Rhebergen et al. (2019, 2020) sampled “every fifth palm in every fifth row to provide a sampling density of three to six percent (5-9 palms per ha)”. Thus, a research priority should be to develop proper protocols for sampling smallholder fields to diagnose nutrient deficiencies.

Most previous studies evaluating the influence of better management practices (BMP) on oil pam yield have focussed on large plantations in South-east Asia. These studies generally showed a positive impact of BMPs on FFB yield (Fairhurst et al., 2006; Donough et al., 2009; Griffiths and Fairhurst, 2003; Rhebergen et al., 2019; Oberthür et al., 2012). Only a handful of studies have aimed to implement BMPs in independent smallholder fields and evaluate their impact on yield and profit. One of these studies was carried out by Woittiez et al. (2018b) at two sites in Indonesia (Jambi and Sintang). This study was conducted across 14 smallholder fields over three years, focusing on improving harvesting, weeding, pruning, and nutrient application. These authors reported that there was no yield difference between fields receiving BMPs versus those following farmer practices, resulting in a negative economic return on BMP investment. These researchers argued that the lack of yield improvement in the BMP fields was related to a high baseline yield at the beginning of the trials (average: 17.5 t FFB ha^{-1}), increase in frond size leading to inter-palm competition, and environmental constraints such as excess water (Woittiez, 2019). On a separate study, Rhebergen et al. (2020) carried out a similar study in Ghana, where the focus of the BMP treatment was to improve canopy management via pruning, elimination of non-productive palms, efficient water management, effective management of pests and diseases, eradication of woody plants, enhancement of nutrient management, and utilization of empty fruit bunches to improve soil quality. This study included both large plantations and smallholder fields. Three years after implementing BMPs, the annual FFB yield in smallholder fields following BMPs plots was 5.9 t FFB ha^{-1} higher than that in the fields following farmer management. Unfortunately, this previous study did not analyse the impact of BMP implementation on farmer profit and the drivers for the observed variation across sites. To summarize, evidence that BMPs can help increase yield and profit of independent oil palm smallholders in Southeast Asia is lacking as well as knowledge on the factors that explain differences in yield response to BMPs across farmer fields.

There is a dearth of knowledge in relation to the extent and severity of nutrient deficiencies in independent smallholder fields in Indonesia and the management practices to narrow the large yield gap. The objectives of the present study are:

(i) Assess the extent and severity of nutrient deficiencies, and its influence on crop yields as influenced by planting material, using robust sampling protocols **(see Chapter 2)**.

Hypothesis: We hypothesize that there are widespread and severe nutrient deficiencies in independent smallholder fields in Indonesia, which override the influence of planting material on FFB yield.

(ii) Provide evidence about the potential to increase smallholder yield and profit *via* implementation of better management practices (BMPs) and understand associated physiological drivers and factors influencing variations across sites **(see Chapter 3)**.

Hypothesis: We hypothesize that implementation of BMPs would lead to higher yield and profit as a results of better crop growth and nutrient uptake, with variation across sites according to the level of BMP implementation and biophysical factors, such as rainfall and soil type.

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CHAPTER 2. FIRST THINGS FIRST: WIDESPREAD NUTRIENT DEFICIENCIES LIMIT YIELDS IN SMALLHOLDER OIL PALM FIELDS

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Abstract

CONTEXT: Indonesia is the most important oil palm producing country. Nearly 40% of planted area is managed by smallholders, with yields well below the potential. Efforts to increase productivity have focused on the source of planting material, with little attention paid to plant nutrition.

OBJECTIVE: To assess the degree to which current productivity in smallholder oil palm fields is limited by nutrients in scenarios with distinct sources of planting material.

METHODS: We collected detailed data on leaf nutrient concentration from 30 fields to derive minimum sampling size needed to diagnose nutrient status. Subsequently, we collected data on yield and palm type from 973 smallholder fields to assess the importance of nutrient status and planting material in the determination of yield.

RESULTS AND CONCLUSIONS: Potassium (K) deficiency was widespread (88% of fields) and often severe. Nearly two thirds of fields were also deficient for nitrogen (N) and boron (B), half were phosphorous (P) deficient, and one third were magnesium (Mg) deficient. Nutrient imbalances, especially between K and N, were also common. Fields with sufficient N, P, and K levels yielded 47% more (equivalent to 1.2 t oil ha^{-1}) than deficient fields across the entire range of planting materials. We conclude that improved plant nutrition increases fresh fruit yields in smallholder fields irrespective of the source of planting material. The advantage of certified planting material is reflected in the higher oil extraction rates.

SIGNIFICANCE: Increased smallholder oil palm yields on existing plantations through improved plant nutrition offers the opportunity to improve smallholder profits and livelihoods, whilst at the same time increasing total oil production without bringing new areas into cultivation.

Keywords: oil palm; nutrients; smallholders; yield; planting material

2.1. Introduction

Oil palm is the main global source of vegetable oil in the world, accounting for *ca*. 40% of global production. Indonesia, the main palm oil producing country with *ca*. 15 M ha planted in 2020 (BPS, 2021), produces 59% of global palm oil (USDA, 2022). Large plantations account for *ca*. 60% of oil palm area in Indonesia. The remaining 40% of the area is managed by smallholders. Some of these smallholders (*ca*. one third) are bound to sell their fruit to the core plantation which provides them with financial and technical assistance ("plasma" smallholders), whilst others (*ca*. two third), hereafter referred to as ‘independent smallholders’, establish their own plantations and get no technical assistance directly from the core plantation (Molenaar et al., 2013; Jelsma and Schonevelg, 2016). In contrast to large plantations, where field size ranges from 25 to 40 ha, independent smallholder fields are small, typically ranging between 1.2 and 2.1 ha (Monzon et al., 2023). Despite the small field size, the income of *ca.* 2.6 million households depends directly on revenue from selling fresh fruit bunches (FFB) (Directorate General of Estate Crops, 2020). The average yield in independent smallholder fields is 13.9 t ha^{-1}; this yield level represents 42% of the attainable yield and is considered low (Monzon et al., 2023). Hence, identification and correction of causes for the yield gap, defined as the difference between actual and attainable yield, could not only improve farmers` livelihoods but also increase total oil production on existing planted area, without need to clear new land for cultivation (Monzon et al., 2021).

Current efforts to improve the FFB yield of independent smallholders focus on promoting replanting fields with certified planting material (Molenaar et al., 2013; Zen et al., 2005; Coordinating Ministry for Economic Affairs, 2023; Indonesia Oil Palm Association, 2023). In Indonesia, certified planting material has a high frequency (>98%) of tenera palm type (SNI, 2015). In contrast, non-certified planting material typically exhibits a higher frequency of dura palms. Oil extraction rate (OER) is generally greater in tenera palms, with OER decreasing 0.35-0.50 percent points per 10% increase in dura frequency (Donough et al., 1993; Ho et al., 1996; Oberthür et al. 2012). Certified planting material has been massively adopted by large plantations whereas independent smallholders typically use non-certified planting material (Molenaar et al. 2013; De Vos et al., 2021; Monzon et al., 2023). Adopting certified planting material is only possible at planting time or replanting, which usually occurs when plantations reach *ca*. 25 years. Hence, ways to rapidly increase yield of existing smallholder plantations *via* improved agronomic practices are vital for increased current smallholder yields and income (Woittiez et al., 2018a; Rhebergen et al., 2019, De Vos et al., 2021; Monzon et al., 2023).

Adequate plant nutrition is essential to reach attainable yields in mature oil palm plantations (Goh et al., 1994, 2003; Foster, 2003; Sidhu et al., 2001). Inadequate plant nutrition has been postulated as a major cause of low productivity in smallholder fields (Woittiez et al., 2018a; Jelsma et al., 2019). Furthermore, according to Monzon et al. (2023), closing yield gaps through yield-improving technologies also leads to higher farmer net profit. Hence, if plant nutrition can be improved through better use of fertilizers, it can provide a cost-effective, fast approach to increase smallholders yield and profit from the 4 million ha of palm they manage. Moreover, local communities and mills will also perceive benefits leading to a large positive economic impact at the country level. We hypothesized that an evaluation of plant nutrition on existing smallholders' plantations could rapidly provide guidelines on the expected FFB and oil yield increases from improved nutrient management.

Suitable diagnostic tools are required to evaluate the nutrient status of smallholder fields. We have not been able to find any guidelines that were established specifically to determine the nutrient status of smallholder oil palm fields. The standard diagnostic for nutrient deficiencies in oil palm measures leaf nutrient concentration of a standard reference frond (Chapman and Gray, 1949;

Broeshart, 1955; Smilde and Chapas, 1963), and compares the concentration of each nutrient with a range of previously established critical values (Von Uexküll and Fairhurst, 1991). Reliable data on the nutrient status, based on leaf nutrient content of leaves, is extremely scarce in independent smallholder fields over the oil palm producing areas in Indonesia. For a robust diagnosis of the status of a field, several palms need to be sampled per field. Available recommendations on sample size for leaf nutrient were developed from fertilizer experiments and uniformity trials performed in large, commercial plantations or in research centers (Chapman and Gray, 1949; Broeshart, 1955; Smilde and Chapas, 1963; Smilde and Leyritz, 1965; Ward, 1966; Ng and Walters, 1969; Poon et al., 1970). For example, Ward (1966) indicated that sampling 1% of the palm population provides adequate precision to determine leaf N, P, and K concentration for a 30-ha field. Following this recommendation, many large plantations use a fixed grid sampling scheme to sample 1% of total palms per field. Unfortunately, these guidelines are not appropriate for smallholder fields, with much smaller size (*ca*. 2 ha) and potentially greater heterogeneity than that found in large plantations due to use of non-certified planting material and poor seedling selection. For example, application of the sampling protocol developed for large plantations to a typical smallholder field of 2 ha would sample only one or two palms per field.

There is a dearth of knowledge in relation to the degree and severity of nutrient limitations in smallholder oil palm fields and its impact on yield. Here, robust guidelines for determination of nutrient status in smallholder fields were used to diagnose nutrient status of palms across 973 smallholder fields located across the oil palm producing area in Indonesia. From this diagnosis, the relationship between yield and plant nutrient status was appraised for fields with a range of dura frequencies. Implications for agronomists and agricultural research and development (AR&D) programs are then discussed. Management drivers explaining the nutrient deficiencies reported here are assessed in a separate study (Lim et al., 2023).

2.2. Materials and Methods

2.2.1. Study sites

Our study focused on six sites located within the oil palm producing area in Sumatra and Kalimantan islands in Indonesia (Figure 2-1, Table 2-1). The sites correspond with climate-soil domains that account for 87% of current oil palm area in Indonesia (Agus et al., 2024). Sites were selected based upon availability of local partners to collect the data and included only independent smallholder fields with mineral soils (Monzon et al., 2023). We excluded fields where oil palm was intercropped with other crops (*e.g.*, banana, cassava, *etc*.), home gardens (<0.1 ha), and immature (< 3 years) or very old plantations (> 25 years). Following these criteria, we selected 200 independent smallholders at each site, totaling 1,200 farmers across sites. We only considered the largest field for each farmer (average: 2 ha). After quality control (see below), a total of 973 fields were used for the analysis. The data generated from these fields was used to determine the extent of nutrient limitations and their impact on smallholder fresh fruit bunch yield. An additional 30 fields at all sites (except for East Kalimantan (EK) were selected for the detailed sampling size analysis. In both cases, fields were sampled between January and October 2021 and the mean sampling time was 16 days per site. Description of weather, soil, and management at each site is provided elsewhere (Monzon et al., 2023).

2.2.2. Minimum sample size to determine nutrient status in smallholder fields

We measured leaf nutrient concentration for individual palms in independent smallholder fields at five production regions located across Sumatra and Kalimantan islands in Indonesia (Figure 2-1). For simplicity, we referred to each site using the name of the associated province: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK). We sampled six independent smallholder fields per site; hence, a total of 30 fields were used to determine an adequate sample size for leaf sampling per field (Table 2-1). The fields were selected to portray the observed range in nutrient status based on preliminary leaf nutrient concentration data collected in the previous year. The fields were also selected to provide a good representation of the variation in field size, palm age, soil properties, FFB yield, and dura frequency in the five sites (Supplementary Tables S2-1; S2-2).

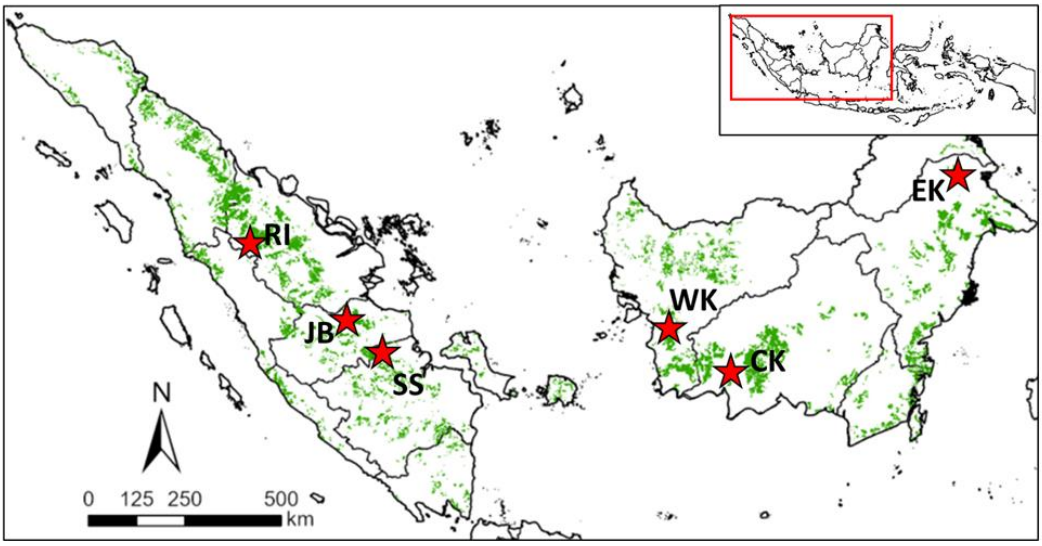

Figure 2-1. *Map showing the location of the six study sites in Indonesia: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), Central Kalimantan (CK), and East Kalimantan (EK). Inset shows the study area within Indonesia. Green area shows oil palm area in mineral soils (Ministry of Agriculture, 2012; Harris et al., 2015). See Table 2-1 for description of data collected at each site.*

Table 2-1. *Description of databases used in the present study to assess nutrient status in smallholder oil palm fields in Indonesia.*

Objective	Sites (and field per site)	Sampled palms per field	Leaf nutrient sampling	Other measured variables
Determine sample size needed to assess nutrient status	5[a] (6)	20	An individual sample per sampled palm	none
Evaluate extent of nutrient deficiencies across fields	6 (120-194)	10	Composited sample from 10 palms per field	FFB yield, dura frequency

[a] All provinces but East Kalimantan.

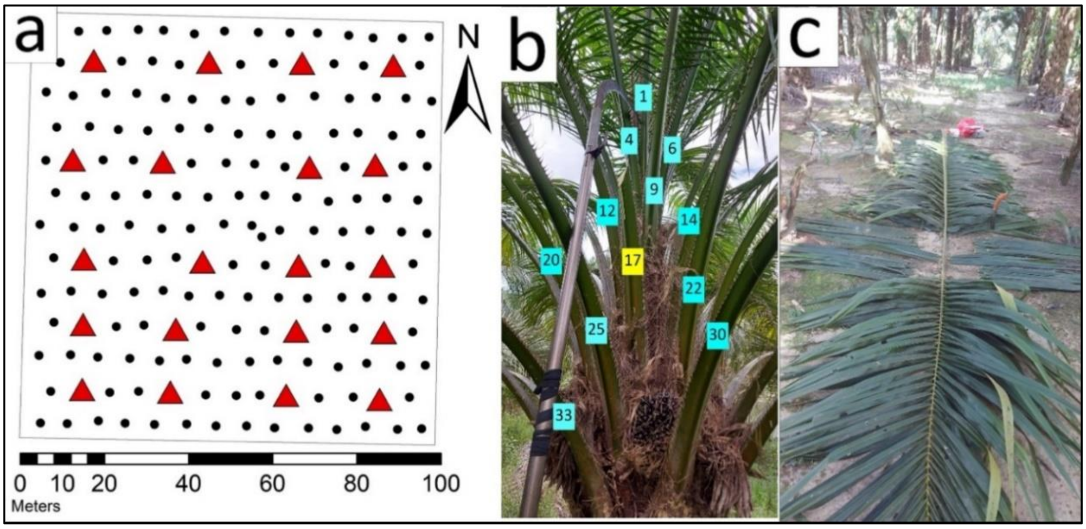

Figure 2-2. *(a) Map showing an example of the 20 sampled palms (triangles) in one of the selected fields. (b, c) Pictures showing the frond #17 being sampled and collection of associated leaflets.*

In each selected field, 20 palms located along a two-row harvesting path were selected for this study, totaling 600 palms (Table 2-1). Contiguous palms and field edges were avoided (Figure 2-2a). We also excluded abnormal palms (*e.g.*, infertile) and those severely affected by diseases (*e.g.*, Ganoderma). Following Rhebergen et al. (2018), we sampled frond #17 in each selected palm, collecting the leaflets located within the middle portion of the frond (Figure 2-2b, c). A total of 30 leaflets were sampled from each frond, with 15 leaflets collected from each side of the rachis. We note that this is more than the usual six leaflets per frond because we needed to ensure that there was enough plant material from each palm for the chemical analysis. Leaflets were gently wiped with a soft towel (previously immersed in distilled water) to remove dust. The mid-ribs of the leaflets were removed, and the remaining lamina was cut into small pieces (*ca.* 1-1.5 cm), oven-dried, and packed and labelled separately for each individual palm. Samples were sent to the Asian Agri (AA) laboratory in North Sumatra (https://www.asianagri.com) to determine 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. The AA laboratory is actively participating in WEPAL (Wageningen Evaluating Programs for Analytical Laboratories, International plant-analytical exchange IPE, 2022) for objectively evaluating the performance of the laboratory by cross-comparison with those of other laboratories at regular time intervals. Based on the latest report, the Z-score for the AA laboratory is 0.35 (N), -0.08 (P), -0.25 (K), -0.88 (Mg), 0.95 (Ca) and 0.14 (B), indicating a high accuracy on their tests.

We followed two approaches to estimate the minimum number of palms needed for a robust estimation of nutrient concentration: *power analysis* and *bootstrapping*. Power analysis was performed as described by Desu and Raghavarao (1990) using the sample mean and standard deviation derived for each field based on the measured values from individual palms for each variable, assuming normality in the data distribution. *Bootstrapping* uses computer intensive resampling to make inferences rather than assuming a parametric form for the data distribution. A bootstrap sample is formed by selecting samples from a given statistical dataset by random resampling with replacement, which means that any sample may occur no times, one time, or many times in each bootstrap sample (Simpson and Mayer-Hasselwander, 1985). For each nutrient (N, P, K, Mg, Ca, and B), we estimated the average value using different numbers of palms (*n*, from 1 to 20 palms) with 200 subsets of palms of size *n* re-sampled from the 20 oil palms. The resulting range gives an indication of uncertainty due to field-to-field variability for each variable. Following both approaches (*i.e.*, power analysis and bootstrapping), we estimated the minimum number of palms needed to achieve different levels of precision (5%, 10%, and 15%) based on a 95% confidence interval. Palm-to-palm variation in leaf nutrient concentration was quantified for each field and each nutrient using the coefficient of variation (CV, %).

2.2.3. Assessing nutrient deficiencies in independent smallholder fields

We diagnosed nutrient status in 973 smallholder fields in the five sites previously described (*i.e.*, RI, JB, SS, WK, and CK) and we included an additional site in East Kalimantan (EK) (Table 2-1, Figure 2-1). Samples from total of 182 (RI), 162 (JB), 147 (SS), 168 (WK), 194 (CK), and 120 fields (EK) were collected. The 30 fields that were used to derive the guidelines on sample size were not included in this assessment. Sample size was determined based on the results from our previous analysis, following a similar approach to select the palms to be sampled in each field. From each palm, we collected six leaflets from frond #17 following the approach described in Section 2.2 and a single composite sample for each field was prepared to determine leaf nutrient concentration on a field basis. Comparison of actual nutrient concentration *versus* the lower level of the sufficiency range reported in the literature (Von Uexküll and Fairhurst, 1991), was used to establish the frequency of deficient fields for each site and nutrient. In the case of K and Mg, it has been suggested that expressing these cations as percentage of the total leaf cations (TLC) provide a more accurate representation of their status (Foster and Chang, 1977; Foster et al., 1988). In our case, TLC-K and TLC-Mg were highly correlated with K and Mg concentrations (r^2>0.90, p<0.001) leading to identical findings and interpretations. For simplicity, we only showed the results for leaf K and Mg concentrations without any correction by TLC. Finally, we evaluated ratios between nutrients as suggested by Ng (2002) and Goh and Härdter (2003). Balanced N:K and P:K ratios were estimated as the quotients between the lower end of the optimum range of leaf concentration reported for each nutrient (Von Uexküll and Fairhurst, 1991), the balanced N:P ratio was derived from the leaf N concentration following the equation reported by Ollagnier and Ochs (1981). Subsequently the nutrient ratios derived from each field were compared with the balanced ratios, considering nutrients to be balanced for a given combination of nutrients when the associated ratio was within ±25% from the balanced ratio.

2.2.4. Assessing relationships between nutrient status and yield as influenced by dura frequency

Data on FFB yield data were collected over two years (2020-2021) in the same fields that were sampled across the six sites. Quality control measures were implemented to detect erroneous yield data entries and outliers. For example, yields exceeded 35 t FFB ha^{-1} in a few fields, which, after field validation, were found to be associated with FFB pooling across adjacent fields. In other cases, yield was extremely low (<3 t FFB ha^{-1}) and/or average harvest interval was too long (>45 days) because fields were quasi-abandoned and/or subjected to prolonged flooding. These fields were excluded from the database. For all our analyses, we used the average annual FFB yield calculated as the average over the two years (2020-2021). Detailed description of database and quality control is provided elsewhere (Monzon et al., 2023). In the case of planting material, qualified personnel from the Indonesian Oil Palm Research Institute (PPKS) checked the frequency of dura palms in each field based on a sub-sample of 25 palms selected to portray the field variability. As a first approach to assess the link between FFB yield and plant nutrition, taking into account dura frequency, we performed a multiple regression analysis including FFB yield (dependent variable) and leaf nutrient concentration, dura frequency, and their interactions (independent variables). Quadratic terms were not significant (p>0.10) and thus excluded from the model. Analysis of variance (ANOVA) was used to test the statistically significance of each term using F tests. Given the lack of a formal experimental design underpinning our database, we used sequential type-I sum of squares for our multiple-regression analysis. To further assess relationships between FFB yield and leaf nutrient concentration and planting material background, we created two groups of fields based on their measured leaf nutrient status: NPK-sufficient (*i.e.*, fields sufficient for *all* three nutrients) and NPK-deficient (*i.e.*, fields deficient for *all* three nutrients). The FFB yields were plotted against dura frequency and linear-regression analysis was used to evaluate the overall regression and differences between sufficient and deficient fields over the range of dura frequency. Finally, to account for the influence of dura frequency on OER, we calculated oil yield for each field based on FFB yield and frequency of each palm type, assuming that average (OER) of 18% for dura and 24% for tenera palms. These values were derived from our own measurement of OER in 446 individual palms performed across a subset of 30 fields between Aug 2022 and Feb 2023 following the method proposed by Hasibuan et al. (2013) and Hasibuan and Nuryanto (2015). Our average OER for dura and tenera are consistent with those reported in the literature (Donough et al., 1993; Ho et al., 1996; Oberthür et al., 2012).

2.3. Results

2.3.1. Minimum sampling size for estimation of leaf nutrient concentration

Our subset of 30 fields portrayed a wide range of leaf nutrient concentration values (Supplementary Figure S2-1). Palm-to-palm variation in nutrient concentration, quantified using the average CV across fields, was relatively low for N (6%) and P (7%), intermediate for Ca (16%), B (17%), and K (19%), and high for Mg (28%) (Supplementary Figure S2-1). The two approaches (*i.e.*, power analysis and bootstrapping) used to estimate the minimum sampling size delivered similar results (Figure 2-3). Considering 10% as a reasonable level of precision, our analysis showed that three palms per field were sufficient to estimate N and P concentration at field level, which was consistent with the small palm-to-palm CV observed for these nutrients. However, a larger sample size would be needed for other nutrients to achieve a similar level of precision. Assuming that 15% is still a reasonable level of precision, 10 palms per field were generally sufficient for robust estimation of K, Ca, and B in smallholder fields. In contrast, the required sampling size was larger for Mg, in some cases requiring up to 30 palms to reach a precision level of 15%.

2.3.2. Extent and type of nutrient deficiencies across smallholder fields

Extensive sampling was performed across six sites spread out across the Indonesian archipelago, including a total of 973 smallholder fields. In each field, 10 palms were sampled, and leaf nutrient concentration was determined from a composite sample collected from each field. Comparison of the nutrient concentration in each field *versus* the sufficiency ranges reported in the literature allowed us to determine the extent and severity of nutrient deficiencies across smallholder fields (Figure 2-4). Leaf nutrient concentration varied across sites and across fields within each site. In the case of N and P, leaf nutrient concentration was relatively stable across sites and fields (average CVs=8% and 10%). In contrast, other nutrients (K, Mg, Ca, and B) exhibited larger spatial variation (average CVs=27%, 31%, 22%, and 28%, respectively).

Deficient nutrient levels were found in a large proportion of smallholder fields (Figure 2-4; Supplementary Figure S2-2). The K deficiency was widespread (88% of fields), while N and P were deficient in *ca*. two thirds of the fields. Deficiencies of these nutrients were more frequent and severe in JB and less frequent in CK. Also, B and Mg deficiencies were apparent in about half and one third of the fields, respectively, especially in RI and JB (B) and CK (Mg). In contrast, Ca deficiency was rare and, indeed, values well above the sufficiency threshold in a large proportion of fields, especially in WK, CK, and RI. There were large deviations from the balanced nutrient ratios, especially in the case of K (Figure 2-5). While 58% of the fields had a balanced N:P ratio (*i.e.*, within ±25% from the balanced ratio derived from the literature), only 22% and 20% of the fields had balanced N:K and

P:K ratios. When nutrients were sufficient and in balanced ratios, yields were consistently greater.

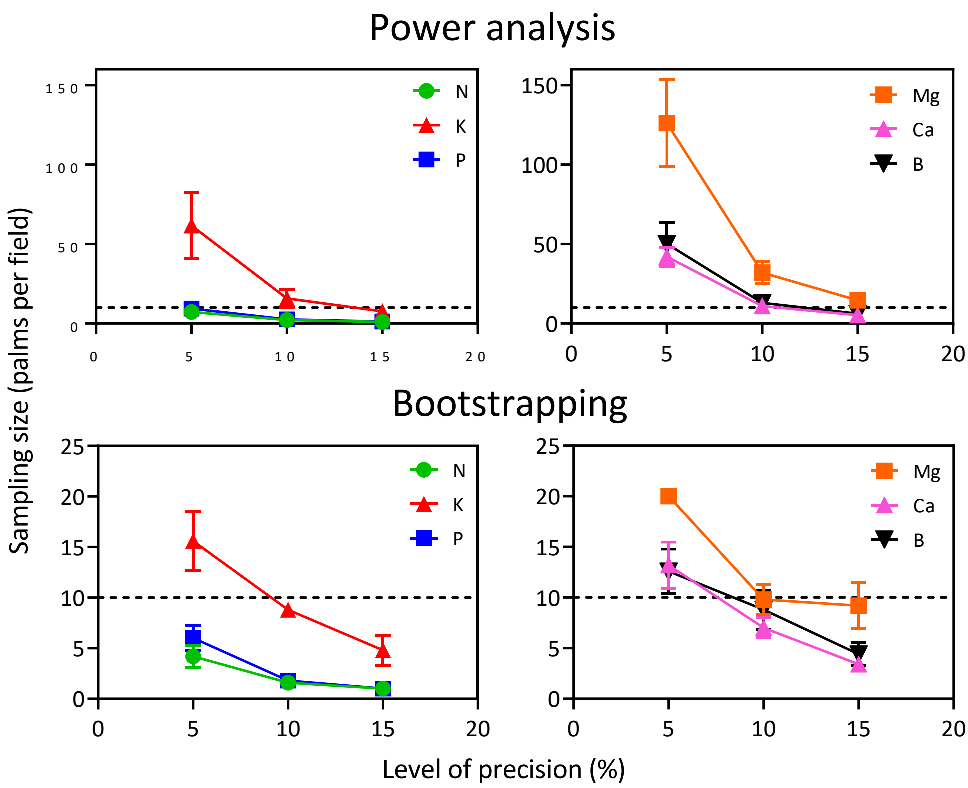

Figure 2-3. *Sampling size for estimation of nutrient concentration for different levels of precision (5%, 10%, and 15%) as determined using power analysis (upper panels) and bootstrapping (lower panels) for each nutrient: nitrogen (N), phosphorous (P), potassium (K), magnesium (Mg), calcium (Ca), and boron (B). Values are averages (± standard deviation) across all 30 sampled fields. Dashed line, in all panels, shows a sampling size of 10 palms.*

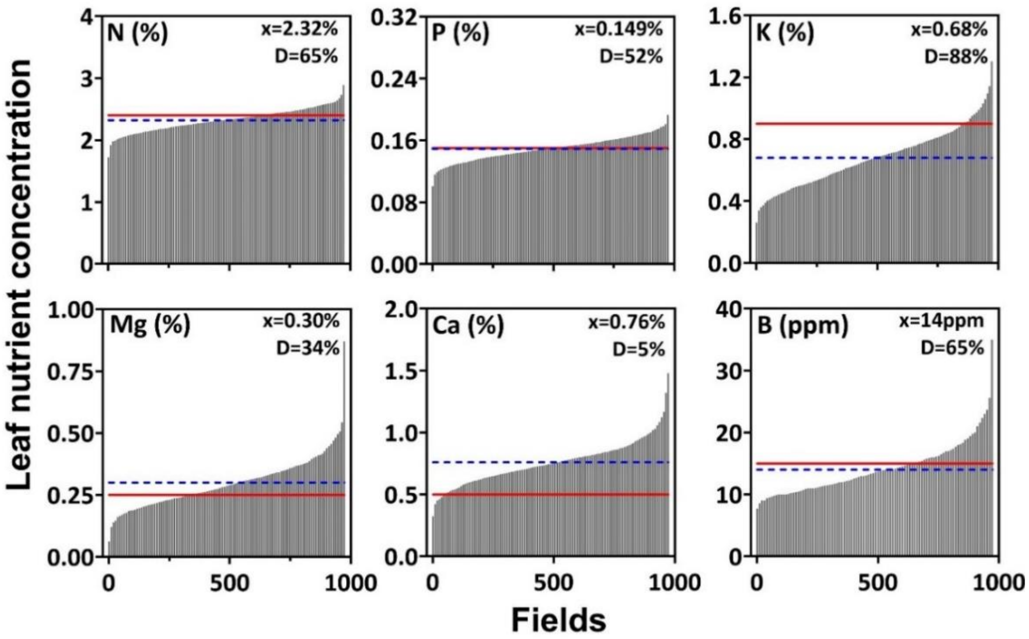

Figure 2-4. *Leaf nitrogen (N), phosphorous (P), potassium (K), magnesium (Mg), calcium (Ca), and boron (B) concentration based on data collected from 973 smallholder fields in Indonesia. Each bar corresponds to a farmer field; the fields are sorted from lowest to highest nutrient concentration. Horizontal lines indicate averages nutrient concentration (dashed blue) and the lower end of the sufficiency level for each nutrient (solid red) as reported by von Uexküll and Fairhurst (1991). Also shown are means (x) and percentage of deficient fields (D). Extremely low and high leaf nutrition concentrations shown for a few fields should be taken with caution as they probably reflect human error in sample collection and/or processing.*

2.3.3. Effect of leaf nutrients status on FFB yield as influenced by dura frequency

A multiple regression model including N, P, K, dura frequency, and their interactions, explained close to 20% of observed variation in yield ($p<0.01$). Statistically significant ($p<0.05$) positive effects of leaf N, P, and K concentration, and P × K and N × P × K interactions, on FFB yield were detected (Table 2-2). In contrast, dura frequency and interactions with nutrients had no statistically significant effect on FFB yield, although the analysis suggested a possible dura × P interaction ($p=0.06$).

***Table 2-2**. Multiple-regression analysis for annual FFB yield (t ha^{-1}). Independent variables included leaf nitrogen (N), phosphorous (P), and potassium (K) concentration (in %), dura frequency (D, %), and their interactions.*

Source of variation	d.f.	Coefficient (±s.e.)	SS	*F*-test	*p*-value
Intercept	15	2.46(±16.44)			
N	1	0.74(±8.07)	547	28	<0.001
P	1	124.3(±94)	2489	126	<0.001
K	1	4.58(±20.43)	624	32	<0.001
D	1	0.02(±0.21)	0.30	0.02	0.90
N × P	1	-32.59(±40.12)	4.4	0.22	0.64
N × K	1	-10.1(±10.62)	59	3.0	0.09
P × K	1	32.51(±47.96)	123	6.2	0.01
D × N	1	0.05(±0.11)	1.4	0.07	0.79
D × P	1	-0.38(±0.48)	71	3.6	0.06
D × K	1	-0.19(±0.3)	5.0	0.25	0.61
N × P × K	1	51.78(±30.75)	74	3.7	0.05
D × N × P	1	-0.27(±0.3)	8.3	0.42	0.52
D × N × K	1	0.06(±0.15)	5.7	0.29	0.59
D × P × K	1	0.73(±0.48)	46	2.30	0.12
D × N × P × K	1	-0.12(±0.38)	1.8	0.09	0.76
Error	957		18939		
Total	972		22997		

d.f.: degrees of freedom; s.e.: standard error, SS: type-I sum of squares

We further investigated the influence of nutrient status and dura contamination on yield by comparing NPK-deficient fields *versus* sufficient fields across the range of dura frequency (Figure 2-6a). On average, NPK-sufficient fields yielded 5.6 t FFB ha^{-1} (+47%) more than NPK deficient fields (p<0.001). The yield difference between the two groups of fields was consistent over the entire range of dura frequency, as indicated by the lack of statistical significance for the interaction term (p=0.17). Only fields sufficient in N, P, and K yielded >25 t ha^{-1}, with some approaching 30 t ha^{-1}, while most NPK-deficient fields (82%) yielded <15 t ha^{-1}.

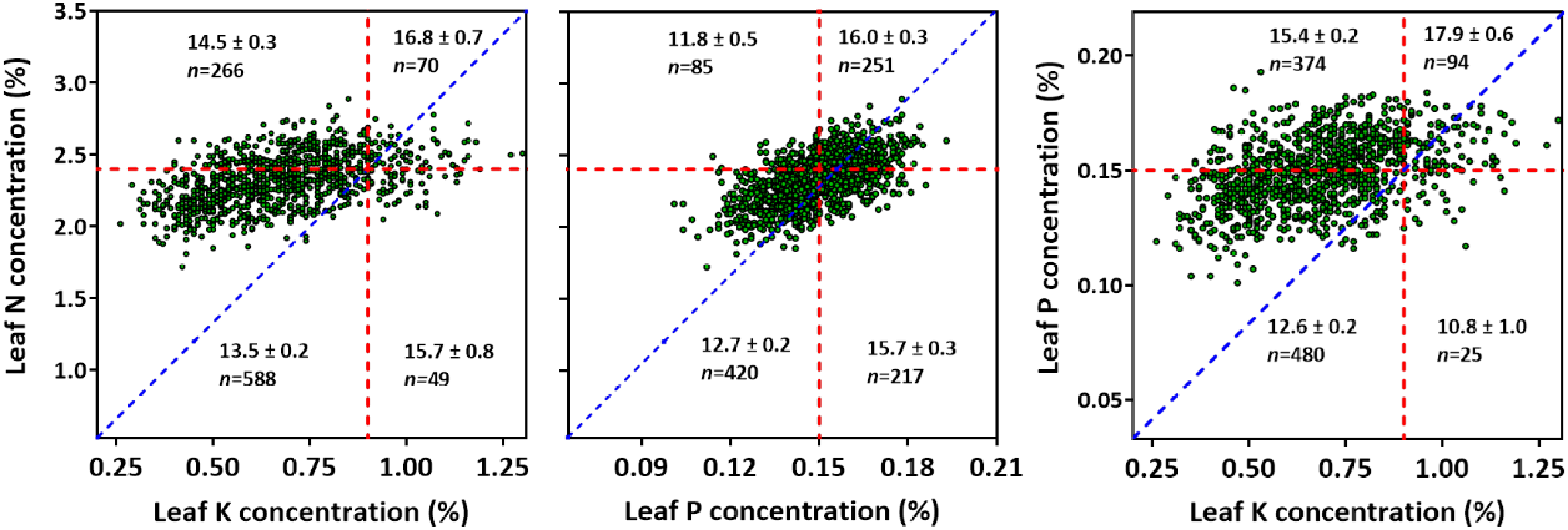

Figure 2-5. *Comparison between leaf nitrogen (N), phosphorous (P), and potassium (K) concentration based on data collected from 973 smallholder fields. Red dashed lines show the lower end of the sufficiency range for each nutrient. Average yield (± standard error) and number of fields (n) are shown for each quadrant. Also shown are the balanced ratios for each combination of nutrients with the blue dashed lines (see Material and Methods).*

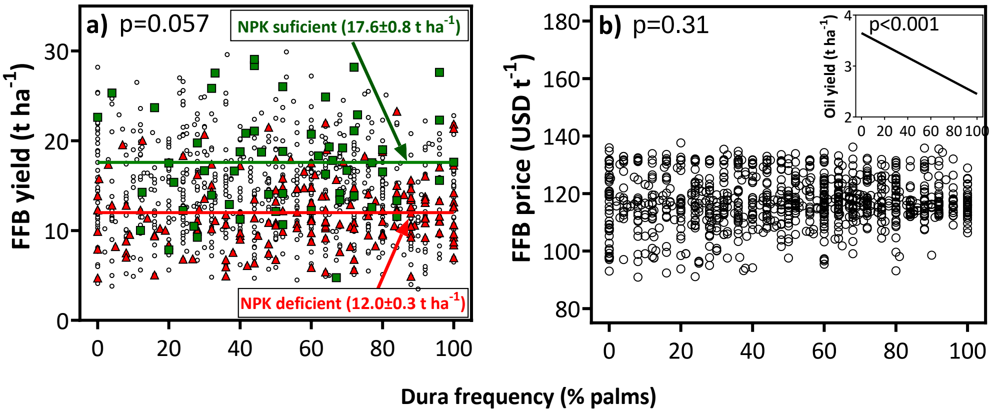

Figure 2-6*. Influence of dura frequency on (a) fresh fruit bunch (FFB) yield and (b) FFB price received by farmers based on data collected from 973 smallholder fields. Statistical significance of the linear regression model fitted to the pooled data is shown. Each data point represents a field. Red triangles and green squares in (a) show fields categorized into deficient and sufficient (n=178 and 57, respectively), according to their leaf nitrogen (N), phosphorous (P), and potassium (K) concentration; horizontal lines and values indicate means (± standard error) for each group. Inset in (b) shows oil yield as a function of dura frequency.*

The magnitude of fresh fruit yield change due to dura frequency was relatively small, with FFB yield decreasing by 7% as dura frequency went from zero to 100% (p=0.057). However, our measurement of OER for a subset of fields showed that OER is greater in tenera than in dura palms (Figure 2-7), and consequently oil yield is likely to be greater as dura frequency decrease. When we accounted for the impact of dura frequency on OER, the oil yield decreased by 30% as dura frequency increased from 0 to 100% (p<0.001) (Figure 2-6b, inset). Despite these differences in oil yields, the price received by farmers remained stable over the range of dura frequencies (Figure 2-6b).

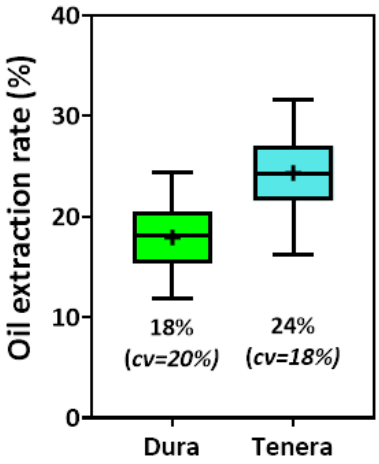

Figure 2-7*. Box plots for oil extraction rates (OER) measured individual dura (n=235) and tenera palms (n=211) across a subset 30 smallholder fields located in Riau, Jambi, South Sumatra, West Kalimantan, and Central Kalimantan. Upper and lower boundaries of boxes indicate 75th and 25th percentile, respectively. Vertical bars indicate 5th and 95th percentile values. Horizontal lines and crosses within boxes are the median and mean values, respectively. Also shown are the mean and the coefficient of variation (cv, in %) for each palm type.*

2.4. Discussion

To our knowledge, this is the first time that a detailed and extensive leaf sampling scheme, explicitly developed for smallholders, has been used to diagnose nutrient deficiencies in smallholder fields (Table 2-1). Recent studies that included leaf analysis to diagnose nutrient status in smallholder oil palm fields in Indonesia (Woittiez et al., 2018b; Jelsma et al., 2019) and Ghana (Rhebergen et al., 2019, 2020) used arbitrary sample sizes. For example, Woittiez et al. (2018b) sampled smallholder fields to determine leaf nutrient concentration at two study sites: at one site, they selected three palms per field "*randomly*" avoiding "*sic*k" or "*unrepresentative*" palms, while, at the second site, they selected four palms "*in the four corners of the field, three palms away from the edge*". Jelsma et al. (2019)

sampled "*a minimum of four non-randomly selected palms*" per field "*at least two rows away from the road and preferably at least five palms away from other sampled palms"*, avoiding palms with any "visual abnormalities". In Ghana, Rhebergen et al. (2019, 2020) selected "*every fifth palm in every fifth row to provide a sampling density of 3–6% at each trial plot (5–9 palms per ha)*" to "*produce sufficient leaf sample material for each treatment plot*".

Ten palms per field provided a reasonable compromise between precision and labor, providing an average precision level of 3% (N), 4% (P), 10% (K), 14% (Mg), 8% (Ca), and 9% (B) as calculated *via* power analysis (Figure 2-3). This sampling size is higher than in previous studies diagnosing nutrient deficiencies in smallholder oil palm fields in Indonesia (Woittiez *et al*., 2018b; Jelsma *et al*. 2019). We also found that palm-to-palm variation in nutrient concentration was low-to-intermediate for N, P, K, Ca, and B, but comparably higher for Mg, confirming results of previous studies in large plantations (Ng and Walters, 1969; Smilde and Leyritz, 1965). This similarity suggests that palm-to-palm variation in smallholder fields is not necessarily higher than that in large plantations and that the trends for greater variability in some nutrients is similar in both circumstances, smallholders and larger plantations. Thus, we concluded that 10 palms per field is sufficient for robust diagnosis of nutrient deficiencies in smallholder fields. In our study, sampling size guidelines were derived from fields ranging in size from 0.6 to 2.2 ha. The sampling size depends on the desirable level of accuracy and the expected spatial variation. Hence, sample size would not be expected to be greater for larger smallholder fields unless the spatial variation is larger. However, as the spatial variation is unknown a priori in most cases, ten palms may not be sufficient to portray the spatial variation in larger fields.

Hence, we suggest, it would be prudent to increase the sampling size in larger fields (>10 ha) to allow for greater accuracy, where a reasonable compromise would be to follow the recommendation of sampling 1% of the palm population made for large plantations (Ward, 1966; Ng and Walter, 1969). Sampling time also influences the nutrient content of leaves. In oil palm, it is recommended to collect leaf samples around the same time of the year to avoid the confounding effect of seasonal changes in nutrient contents (Foster and Chang, 1977; Martineau et al., 1969; Foster, 2003). In our study, it took around 16 days to complete the sampling at each site, both for the sampling size study as well as for assessing the extent of nutrient limitations (Table 2-1). As one can imagine, it was logistically impossible to sample all sites at the same time. However, seasonal fluctuations in nutrient concentrations reported in previous studies (Foster and Chang, 1977; Martineau et al., 1969; Ng and Thamboo, 1969; Foster, 2003) are small when compared to the wide range of concentrations between fields in this study (Figure 2-4). Hence, seasonal fluctuations were deemed unlikely to affect the overall results and conclusions from the study.

Oil palm FFB yield was significantly associated with leaf nutrient concentration (Figure 2-5 and 2-6; Table 2-2). This finding confirms the conclusion from previous local studies based on a small number of fields (Woittiez et al., 2018b; Jelsma et al., 2019) that nutrient deficiency is a major yield constraint in independent smallholder oil palm fields in Indonesia. Most fields were deficient in K and a large proportion were also deficient in N, P, Mg, and B. The concentration of leaf N, P, K, and Mg in many samples was well below those reported in treatments receiving adequate nutrient amounts to reach or exceed yields of 30 t ha^{-1} indicating that deficiencies are both common and severe (Sidhu et al., 2001, 2009, 2014;

Prabowo et al., 2006; Lee et al., 2019). Severe K deficiencies are most prevalent, with many fields with less than half the level considered to be sufficient (Figure 2-5). Indeed, many K leaf nutrient concentrations are comparable to or even lower than those reported in long-term fertilizer-omission trials in Indonesia and elsewhere (Sidhu et al., 2001, 2009, 2014; Prabowo et al., 2006; Lee et al., 2019). On the other hand, high leaf Ca concentration (>1%) was found on 8% of fields: this is likely due to the smallholder practice of applying dolomite (Lim et al., 2023). However, we note that Ca excess can interfere with K and Mg absorption and exacerbate the deficiencies of these nutrients (Xie et al., 2021; Von Uexküll and Fairhurst., 1991). We could not find statistically significant relationships between soil parameters (nutrient concentration, pH, soil organic matter) and leaf nutrient concentration, indicating that soil variables should not be used to diagnose nutrient deficiencies in oil palm.

The large number of fields that are distant from the balanced nutrient ratios suggests a high frequency of fields with nutrient imbalance (Figure 2-5). However, care is needed in interpreting this lack of nutrient balance. A point close to the blue line in Figure 2-5 in the lower left quadrant might suggest a good nutrient balance, however the plants would clearly be deficient in both the nutrients in question. The optimum point for yield is likely to be close to the intersection of the dotted red lines, with all points in the upper right quadrant deficient in neither of the two nutrients. Foster (2003) points out that in commercial practice only the most deficient nutrients can be accurately diagnosed from leaf nutrient levels as the levels of all the other nutrients are distorted. We suggest that, while nutrient ratios may have value when only one nutrient is deficient, they should be treated with care when one or more of the other nutrients are deficient. Nevertheless, the frequent cases of extreme K deficiency, when compared with the much smaller range of nutrient values for N and P (Figure 2-4), in conjunction with the many points in the lower left quadrants (Figure 2-5), indicates that not only is nutrient deficiency common on smallholder fields, but also that there is a lack of balance in the nutrient supply. The large number of points well to the left of the dotted red line in the case of K concentration is indicative of a generalized imbalance in nutrient supply with insufficient use of K fertilizers, as documented by Lim et al. (2023).

Inadequate nutrient management was identified as the most important single factor contributing to the large yield gap on smallholder fields (Monzon et. al., 2023). Our survey data which diagnoses nutrient deficiency in individual fields, and shows relationships between deficiencies with yield, validates the conclusion that nutrient management is critical to closing yield gaps. We estimated here that improving the nutrient supply to achieve nutrient sufficiency on currently nutrient deficient fields would increase the yields of deficient fields by 47%, equivalent to 5.6 t FFB ha^{-1} (Figure 2-6a). This increase is equivalent to 1.2 t ha^{-1} of crude palm oil (CPO) and has the potential to massively impact productivity and return to investment on millions of hectares of oil palm managed by independent smallholders. Although we focus here on nutrient deficiencies, there are many other management factors besides nutrients (*e.g.*, harvest, pruning, weed management) that have been identified as yield constrains (Monzon et al., 2023). Hence, the estimate of yield gain due to improved plant nutrition is conservative as it would likely be larger if complemented by improved overall management. Indeed, the yields of many NPK-sufficient fields were similar to those of deficient fields

(<15 t ha^{-1}), probably reflecting the incidence of other yield constraints. Although fresh fruit yield and the response to nutrients was similar for high and low dura frequencies, the oil yields are greater with low dura frequency due to the positive effect on the oil extraction rate (OER) and thus oil yield (Figure 2-6b, Figure 2-7). Hence, improved plant nutrition has the potential to increase oil yield during the current plantation cycle and amplify the positive impact of certified planting material with low dura frequency when fields are replanted. For example, with the average FFB yield in NPK-sufficient fields in our study, we estimate that a reduction of dura frequency from 50%, which is commonly found in smallholder fields (Monzon et al., 2023), to close to zero would increase the average oil yield by 0.6 t CPO ha^{-1}, from 3.7 to 4.3 t ha^{-1}. We note that this estimate is based on actual OER measurements performed for a subset of fields (Figure 2-7). In contrast, the absolute impact of adopting planting material with low dura frequency would be smaller in a context of nutrient deficiencies. In the case of NPK-deficient fields, the increase in oil yield would be 0.4 t CPO ha^{-1}, from 2.5 to 2.9 t ha^{-1}.

Current efforts to increase smallholder yield heavily focus on a replanting program promoting use of certified planting material with low dura frequency. Over the long term, there are evident advantages to the Indonesian oil palm industry of reducing the dura contamination from the current high levels we observed. However, this advantage is not picked up by the independent smallholder as the industry does not measure oil yield at the field level and the price received by farmers does not depend on the dura frequency (Figure 2-6b). Hence, farmers managing fields with lower dura frequency do not capture the economic benefit associated with higher OER and, thus, will have little incentive to use certified planting material when fields are replanted. To be paid according to OER, farmers would need to produce sufficient volume and collectively sell directly to a mill which would grade their feedstock and pay accordingly (Molenaar et al, 2013). However, the industry does not, at present, measure oil yield at the field level and farmers sell FFB to the mill through intermediaries. Hence, improving traceability and OER measurement seem key factors to incentivize adoption of certified material in smallholder fields. Over the shorter term, given the extent and severity of nutrient deficiencies, improved fertilization (Lim et al., 2023) offers the opportunity to increase the FFB yield over the range of dura frequencies. This will complement the programs directed to reducing dura frequency and planting of improved planting material with greater total oil yield. Such an approach would further increase the impact of replanting programs and help smallholders to increase both FFB and oil yields on existing and newly replanted plantations, improving farmer profit and providing Indonesia with a pathway to increase CPO production on existing plantation area, avoiding further conversion of fragile ecosystems for oil palm cultivation.

2.5. Conclusions

Following criteria for sampling size that were explicitly developed for smallholders, we identified widespread nutrient deficiencies across independent smallholder fields in Indonesia, with N and P deficiencies common and severe K deficiency prevalent across fields. The FFB yield of fields that were sufficient for N, P, and K were 47% greater (equivalent to about 1.2 t CPO ha^{-1}) than the yields in deficient fields. Dura frequency did not influence relationships between FFB yield and nutrient status. We conclude that better plant nutrition has the potential to rapidly improve yield of existing plantations and complement the impact of better planting material on oil yield when fields are replanted. Such an approach would improve farmer livelihood and simultaneously increase palm oil production on existing plantation area.

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Supplementary Table S2-1. *Means (and ranges) for field size, palm density and age, frequency of Dura palms, and average (2020-2021) annual fresh fruit bunches (FFB) yield across 30 fields selected for the intensive sampling in Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK). Values were derived from in-situ field measurements and farmer-reported FFB yield.*

Site	Field size (ha)	Palm density (palm ha^{-1})	Palm age (YAP)	Dura (% palms)†	FFB yield (t ha^{-1})
RI	0.98 (0.83-1.11)	144 (118-168)	14 (9-18)	52 (30-75)	16.7 (8.8-24.6)
JB	0.92 (0.62-1.31)	144 (125-172)	13 (10-16)	55 (0-90)	10.5 (6.7-17.9)
SS	1.24 (0.73-2.18)	147 (137-165)	12 (10-13)	58 (33-76)	18.1 (10.4-25.9)
WK	1.11 (0.93-1.62)	153 (131-176)	10 (9-11)	40 (15-90)	17.1 (7.6-29.5)
CK	0.95 (0.66-1.21)	170 (153-220)	14 (11-17)	72 (60-80)	20.9 (9.9-30.5)
Pooled	1.03 (0.62-2.18)	152 (118-220)	13 (9-18)	55 (0-90)	16.6(6.7-30.5)

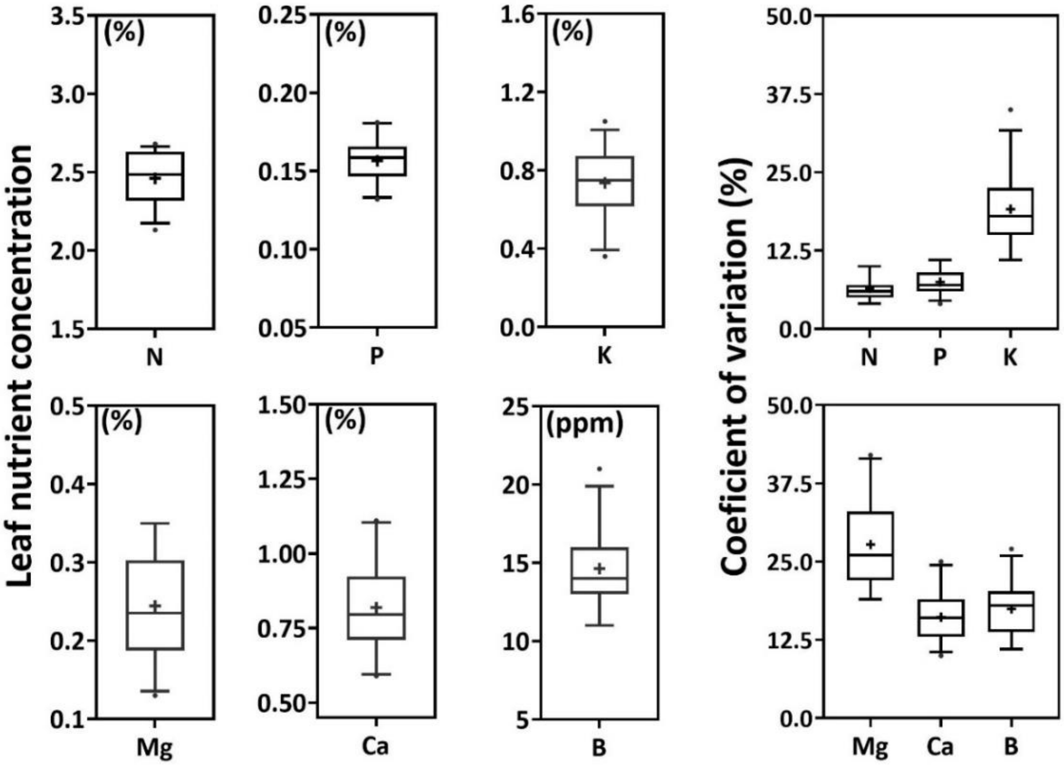
†Percentage of Dura palms in relation to total number of palms based on a subset of 25 palms per field.
YAP: years after planting.

Supplementary Table S2-2. *Mean (2020-2021) total annual rainfall, topographic wetness index (TWI), and selected topsoil (0-20cm) properties across 30 fields in Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK). Parenthetic values indicate ranges.*

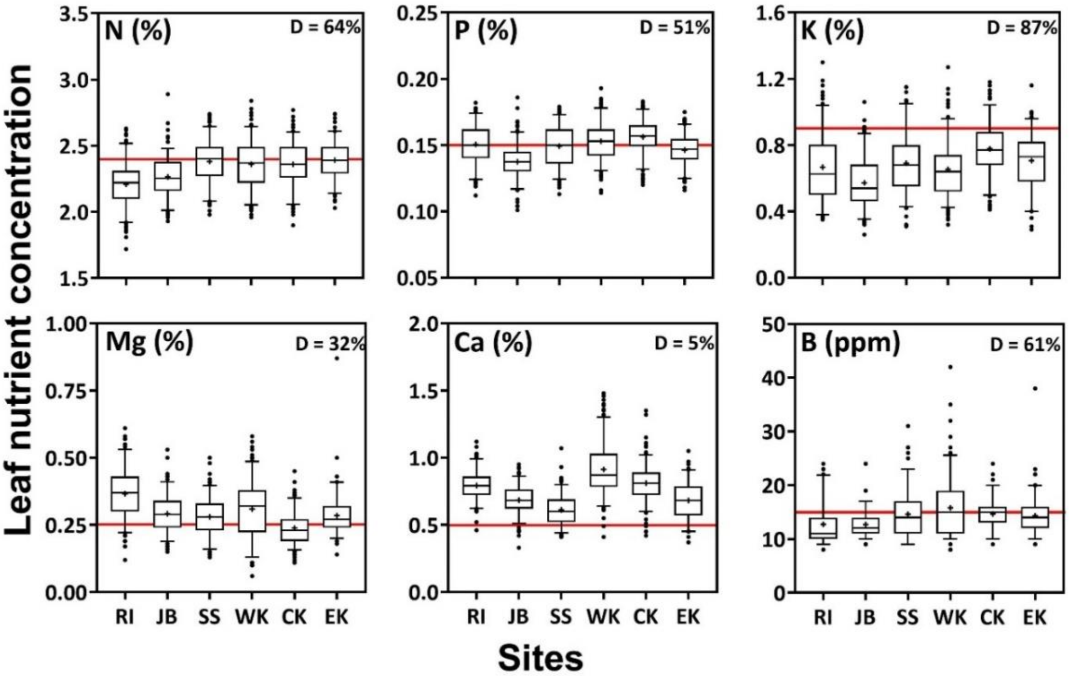
Site	Rainfall (mm)	TWI†	Texture	pH	SON (%)	SOC (%)	CEC (cmol kg^{-1})	K (cmol kg^{-1})	Mg (cmol kg^{-1})	P (ppm)
RI	1876	3.2 (2.3-4.2)	Clay	5.2 (4.9-5.5)	0.20 (0.11-0.34)	2.4 (2-2.8)	16 (14-20)	0.2 (0.17-0.24)	0.81 (0.52-1.32)	4 (2-7)
JB	2285	4.3 (3.6-5.3)	Clay loam	5.1 (4.6-5.4)	0.18 (0.13-0.18)	1.4 (1.2-1.6)	6 (6-7)	0.06 (0.06-0.07)	0.08 (0.07-0.09)	2 (1-3)
SS	2121	3.8 (2.9-4.3)	Clay loam	4.9 (4.3-5.5)	0.16 (0.14-0.18)	1.3 (1.1-1.6)	7 (5-10)	0.11 (0.06-0.22)	0.2 (0.10-0.25)	5 (2-9)
WK	3506	4.1 (2.7-5.3)	Sandy clay loam	5.4 (4.9-5.9)	0.25 (0.18-0.32)	2.9 (2.1-4.2)	5 (4-6)	0.05 (0.05-0.07)	0.15 (0.08-0.26)	17 (2-43)
CK	2688	4.2 (3.8-4.6)	Clay loam	4.8 (4.3-5.1)	0.13 (0.12-0.14)	1.5 (1.4-1.8)	5 (4-7)	0.12 (0.08-0.21)	0.09 (0.07-0.13)	6 (4-7)

†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.

SON: soil organic nitrogen; SOC: soil organic carbon, CEC: cation exchange capacity; K: exchangeable potassium; Mg: exchangeable magnesium (Mg); P-Bray: Bray-extractable phosphorous



Supplementary Figure S2-1. *Box plots for leaf nutrient concentration (left) and coefficient of variation (right) based on samples collected from 30 smallholder fields in five sites: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK). A total of 120 palms were sampled in each site. Upper and lower boundaries of boxes indicate 75th and 25th percentile, respectively. Vertical bars indicate 5th and 95th percentile values. Horizontal lines and crosses within boxes are the median and mean values, respectively.*



Supplementary Figure S2-2. *Box plots showing field average leaf nitrogen (N), phosphorous (P), potassium (K), magnesium (Mg), calcium (Ca), and boron (B) concentration based on data collected from smallholder fields located in six sites across six provinces in Indonesia. Upper and lower boundaries of boxes indicate 75th and 25th percentiles, respectively. Vertical bars indicate 5th and 95th percentile values. Horizontal lines and crosses within boxes are the median and mean values, respectively. Red line shows the lower end of the sufficiency level for each nutrient as reported by von Uexküll and Fairhurst (1991). Also shown is the frequency of deficient) fields (D) per site and nutrient.*

CHAPTER 3. IMPROVING YIELD AND PROFIT IN SMALLHOLDER OIL PALM FIELDS THROUGH BETTER AGRONOMY

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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, actual yield in smallholder fields remains low in relation to the attainable yield. Adoption of better management practices (BMP) as an approach to increase yield and profit has received less attention compared with certification programs and replanting programs.

OBJECTIVE: To evaluate the impact of BMP on yield and profit in smallholder fields in Indonesia and associated physiological and agronomic drivers.

METHODS: We evaluated BMP against the farmer reference management (REF) in 30 paired fields located in five provinces in Indonesia over three years. The BMP treatment included better harvest, weeds, soil, and nutrients management. Besides yield and profit, we estimated plant growth and nutrient accumulation over time, to understand the physiological factors explaining the variation in yield between treatments.

RESULTS AND CONCLUSIONS: Implementation of BMP led to +40% increase in FFB yield and +1.2 t ha^{-1} higher oil yield. Higher yield in BMPs was associated with larger nutrient accumulation, higher dry matter production, and greater partitioning to fruit bunches. Yield increases due to BMPs led to +20% increase in net profit compared with REF fields.

SIGNIFICANCE: Adoption of BMP can increase yield and profit of smallholder farmers, leading to a positive impact at local and national level by increasing overall palm oil production and reducing the need to bring new areas into cultivation.

Keywords: oil palm; better management practices; yield; smallholders; profit

3.1. 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 main oil palm producing country in the world, accounting for ca. 60% of global crude palm oil (CPO) production (USDA, 2022). Increase in palm oil production over the past 20 years has been impressive, from 7 MMT CPO in 2000 to 45.7 MMT CPO in year 2020 (Directorate General of Estate Crops, 2022). However, all the increase in CPO production was driven by oil palm area expansion rather than yield improvement. Indeed, average FFB yield has remained relatively stable at around 15.3 t FFB ha^{-1} (Monzon et al., 2021). Current average yield is well below the yield potential for oil palm, which has been estimated to be around 33.4 tons FFB ha^{-1} (Monzon et al., 2023). This large yield gap represents an opportunity to increase CPO production on existing plantation area while reducing conversion of fragile ecosystems, such as rainforests and peatlands, 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 managed 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 bounded 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). Productivity of smallholders' fields was well below the large plantations, especially in the case of independent smallholders, who achieve average yields of ca. 13.9 t FFB ha^{-1} (Monzon et al., 2023), while the average for large plantations was 19.7 t FFB ha^{-1} (Monzon et al., 2021; Directorate General of Estate Crops, 2022). This yield level is 23% below the large plantations' yield and represents only 42% of the attainable yield[1] of ca. 33.4 t FFB ha^{-1} that can be achieved in Indonesia with good agronomic management (Monzon et al., 2023).

Underlying causes for large yield gaps in independent smallholder fields are associated with insufficient and 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 in

[1] Attainable yield is typically estimated as 70% to 80% of the simulated water-limited yield potential (Lobell et., 2009, van Ittersum et al., 2003). The attainable yield is a realistic yield goal for farmers who have reasonable access to markets, inputs and technical information.

smallholder fields leads to lower oil extraction rates (OER), which further reduces CPO yields (Sugianto et al., 2023). As the contributing factors identified (above) for the low yields in such smallholders' fields are related to agronomy and related field practices, adoption of better management practices (BMP) should help increase yield in the current plantation cycle and also that of newly replanted fields with certified planting material, leading to higher CPO yields in both cases. Such approach would lead to higher farmer income, as shown by Monzon et al. (2023), and also benefit local communities and mills, and the whole country *via* higher CPO exports. Most efforts to increase smallholder yields at present focus on promoting certified planting material, with little (if any) attention on improving the management of existing and future (Molenaar et al., 2013; Zen et al., 2005; Coordinating Ministry for Economic Affairs, 2023; Indonesia Oil Palm Association, 2023).

Previous studies aiming to increase oil palm yields in Indonesia and elsewhere have focussed 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 show consistent yield improvement as a result of BMP implementation, with the latter including appropriate harvest protocols, weed control, ground cover, and nutrient management. These studies have reported FFB yield increases after two or three years of BMP implementation in relation to the baseline yield, ranging from 3.2 to 5.7 t FFB ha^{-1} across studies. Much less effort has been devoted to improving yield in smallholder oil palm fields. Only two previous studies have aimed to increase smallholder yields. Rhebergen et al. (2020) assessed implementation of BMP in smallholder fields (and plantations) in Ghana. They reported BMP's yield was 5.9 t

FFB ha^{-1} higher compared with REF's yield in the third year after BMP implementation. However, this study did not report neither the impact of yield improvement on farmer income nor the physiological drivers leading to higher yields. Analysis of the impact of BMPs on farmer profit is crucial, where income from FFB production represents a high fraction of the household income for smallholders (Monzon et al., 2023). In another study, Woittiez et al. (2019) reported lack of yield improvement after three years of BMP implementation in independent smallholder fields in Indonesia, leading to a negative economic impact on farmer income. However, careful examination of this study revealed problems with BMP implementation and yield determination. Hence, this study cannot be taken as a conclusive evidence of BMP failure at increasing yield and profit in independent smallholder fields. Finally, studies in both large plantations and smallholders did not explore the drivers for variation in yield response to BMPs across fields, which is vital to understand under which circumstances BMPs can deliver largest yield increases.

We have attempted to fill the gaps in our knowledge on their impact of BMPs on FFB and oil yield and economic performance of independent smallholder oil palm fields in Indonesia. To do so, we compared yield and profit in fields following BMPs versus those following farmer management across 30 fields located in the main producing areas of Indonesia over four years. Our testing hypothesis is that BMPs would lead to higher yield and profit. We evaluated the role of light interception and efficiency of use as well as nutrient uptake as drivers of yield and assessed factors explaining variation in yield response to BMPs across sites. Finally, implications for agronomists and policy makers were discussed.

3.2. Materials and methods

3.2.1. Study sites, field selection, and treatments

On-farm experiments were initiated in Jan 2020 and will end in Dec 2023. The present study shows results from the first three years, that is, from Jan 2020 to Dec 2022. Research sites were located in five provinces of Indonesia: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK) (Figure 3-1), representing 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, which account for ca. 80% of total oil palm area in Indonesia (Directorate General of Estate Crops, 2022). Local NGOs helped us identify farmers willing to participate in our field trials. 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. Experiments were conducted in a total of 30 fields across five provinces, with the number of trials per province ranging from five (WK) to seven (RI). Description of soil, weather, and topography of the experimental sites are shown in Table 3-1.

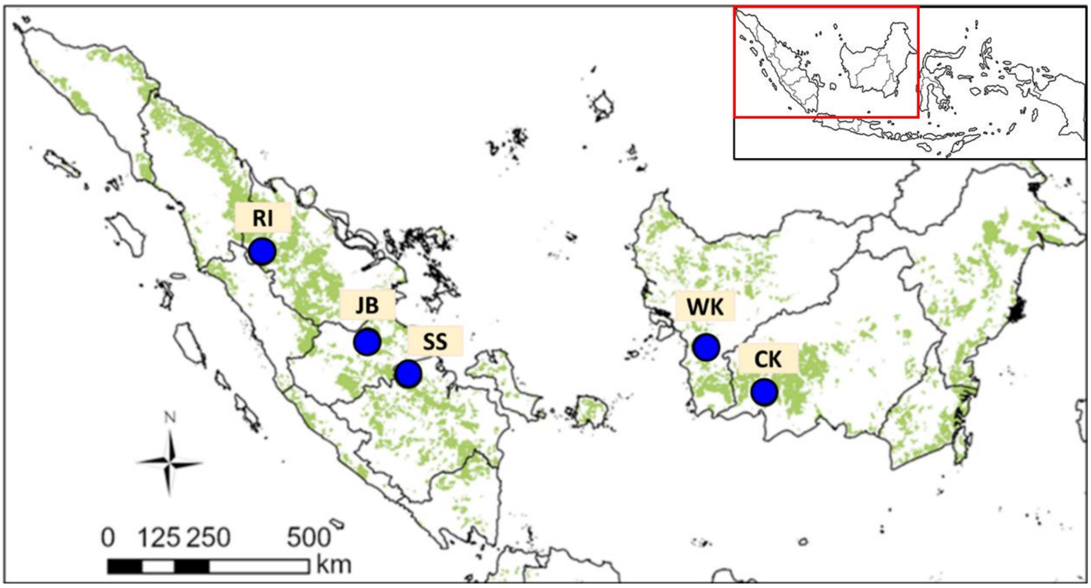

Figure 3-1. *Map showing the location of the five study sites in Indonesia: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK). Inset shows the study area within Indonesia***.** *Green area shows oil palm area in mineral soils (Ministry of Agriculture, 2012; Harris et al., 2015).*

Each trial consisted of two 'paired' fields. In cases where farmer fields were reasonably large (>2 ha), we divided the fields into halves. In other cases, splitting the fields was not possible as farmer fields were too small (< 2 ha). For those cases, we selected two fields managed by the same farmer and with comparable field size, palm age, plant density, planting material, soil, and topography. Following this procedure, a total of 30 paired fields were selected. Size of each field was measured with a GPS device and validated with drone imagery data. For each pair, one field was selected for farmers to implement BMPs whereas farmers were requested to continue with their typical management in the other field, hereafter referred to as 'reference' (REF).

We collected soil samples from each BMP and REF field at the beginning 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 Asian Agri lab to determine pH, soil texture, organic C and N, cation exchange capacity (CEC), exchangeable cations (K, Ca, Mg), extractable P and K (25% HCl), as well as available P (P Bray I). Since the final soil sampling has not been completed yet, 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 (Table 3-1).

Table 3-1. *Mean (2020-2022) total annual rainfall, topographic wetness index (TWI), and selected topsoil (0-20cm) properties across 30 paired-fields in Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), and Central Kalimantan (CK). Parenthetic values indicate ranges.*

Site	Rainfall (mm)	TWI[†]	Texture	pH	SON (%)	Org. C (%)	CEC (cmol kg^{-1})	K (cmol kg^{-1})	Mg (cmol kg^{-1})	P Bray I (ppm)
RI	1978	3.7 (2.6-4.8)	Clay	5.2 (4.8-5.3)	0.21 (0.17-0.25)	2.5 (2.2-3.2)	15 (10-20)	0.18 (0.12-0.29)	0.79 (0.41-1.28)	8 (3-27)
JB	2178	4.2 (3.2-5.4)	Clay loam	5.2 (4.9-5.4)	0.17 (0.14-0.24)	1.5 (1.2-2.1)	7 (5-13)	0.08 (0.05-0.11)	0.14 (0.07-0.39)	2 (2-3)
SS	1762	4.4 (3.9-5.1)	Clay loam	4.9 (4.6-5.3)	0.20 (0.15-0.28)	2.4 (1.5-4.5)	9 (5-15)	0.12 (0.06-0.17)	0.29 (0.11-0.44)	12 (2-24)
WK	3517	4.7 (3.9-5.6)	Sandy clay loam	5.4 (4.8-5.7)	0.25 (0.17-0.30)	2.9 (2.0-3.7)	7 (5-9)	0.07 (0.05-0.09)	0.11 (0.06-0.19)	11 (1-48)
CK	2923	4.6 (4.2-4.9)	Clay loam	4.7 (4.5-4.9)	0.13 (0.11-0.16)	1.5 (1.1-2.0)	5 (4-6)	0.09 (0.07-0.13)	0.08 (0.05-0.13)	14 (4-25)

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. SON: soil organic nitrogen; Org. C: organic carbon, CEC: cation exchange capacity; K: exchangeable potassium; Mg: exchangeable magnesium (Mg); P-Bray I: available phosphorous

Unfortunately, farmers did not have yield records from previous years to calculate the initial yield level, and to assess differences between BMP and REF fields before the beginning of the trials. However, there was no statistically significant differences in soil properties, including clay content, total N, organic carbon, cation exchange capacity, exchangeable Ca, Mg, and K, and extractable P and K ($p>0.15$). Therefore, we concluded the soil properties were not significantly different between BMP and REF fields. We also conducted a black bunch census (BBC) for 20 palms per field, including all bunches and bloomed (receptive) female inflorescences. The BBC was not statistically different ($p=0.58$) between BMP fields and REF fields. Likewise, there was no difference between BMP and REF fields in vegetative dry matter, N, P, and K concentration in leaves, rachis, and trunk, and dura frequency ($p>0.70$). Furthermore, there was no difference in FFB yield between BMP and REF during the first six months of the trials ($p=0.60$). Altogether, these findings indicate that the REF and BMP paired fields have similar biophysical background and yield level at the beginning of the trials.

At question is how representative our selected fields were in relation to the population of smallholder fields in Indonesia. To do so, we collected data on yield and management practices via surveys from ca. 200 fields in the area located our trial fields in each site (see Monzon et al., 2023). Similarity in yield levels and agronomic and socio-economic variables between our trial fields and the surrounding 200 farmer fields indicate that our 30 trial fields can be considered a representative sample (Supplementary Table S3-1).

Our BMP treatment included better management of nutrients, weeds and beneficial vegetation, harvest, and soil cover (Table 3-2). While the BMP fields were harvested every 10-15 days depending upon availability of bunches to harvest, the REF fields were typically harvested every two weeks (or more) regardless of productivity level. We provided fertilizer recommendations for the BMP fields based on nutrient removal through FFB and nutrient stored in the trunk based on a yield target, with further nutrient application 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 become a ripe bunch is about 5 to 6 months (Thomas et al., 1971; Corley and Tinker, 2003; Kasim et al., 2012). Therefore, the target yield for Y1 assumed to be 2x the value of black bunches plus female inflorescences. Following this approach, we determined a yield target for Y1 of 15 t FFB ha^{-1} for JA and 18 t FFB ha^{-1} for the other sites (RI, SS, WK, and CK). For subsequent years (Y2 and Y3), we assumed the yield target in each field to represent 1.3x (Y2) and 1.2x (Y3) of the measured yield in the previous year (Y1 and Y2, respectively), based on the expected yield improvement due to BMPs as reported in previous studies Donough et al. (2011) and Rhebergen et al. (2020). To estimate nutrient removal with FFB, we assumed as 3.15 kg N, 0.40 kg P, 3.89 kg K, and 0.57 kg Mg per FFB ton (Lim et al., 2018). In the case of nutrient (N, P, K, Mg) stored in annual trunk growth, we used the data from a previous study (Lim et al. 2018) for Y1 whereas it was estimated for Y2 and Y3 based on allometric measurement of trunk growth and nutrient concentration in trunk in each field. 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 151 (N), 27 to 36 (P), 217 to 274 (K), and 17 to 33 (Mg) kg ha^{-1} across field-years. Implementation of our the fertilizer recommedation in the BMP fields was satisfactory, with actual fertilizer rates in BMP fields representing 85% (N and K), 83% (P) and 77% (Mg) of the recommendation.

Conversely, REF fields followed farmers' fertilizer practices, ranging from no fertilizer application at all for farmers in JB to relatively large applications of cheaper subsidised fertilizers in CK. Field upkeep of BMP fields consisted of eradication of woody weeds in the entire field, while we kept the vegetation that serves as a host for natural pest enemies and helps to protect the soil against erosion (e.g., *Nephrolepis biserrata*, *Axonopus compressus, Zoysia japonica)*, except for the harvesting paths and circles, which were 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 like a "U" or "C" shape around each palm. Conversely, the pruned fronds were stocked in piles and arranged following an "I" shape in the inter-rows only in the REF fields. Finally, there was no evidence that the 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 Figure S3-2).

Table 3-2. *Recommended agronomic practices in the better management practices (BMP) fields and usual farmer practices in the reference fields (REF).*

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 in the palm 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, grasses and broadleaf weeds removed and harvesting paths and circles completely cleaned and keep beneficial vegetation	Blanket spraying or no weed control
Pruned frond arrangement	“U” or “C”-shaped	“I”-shaped

3.2.2. Data recording and soil and plant measurements

Farmers were requested to keep records for all field activities, including the date(s) and associated labour input (i.e., man-hours), inputs rates and prices. Data recording was monitored by local collaborators, including a full-time experiment coordinator who was responsible for collect the data and clarify any anomalous records. Following this approach, farmers reported the amount of FFB in each harvest i.e., total number and weight, as well as the associated family and/or hired labour used, and gross revenue from sale of the harvested FFB. Likewise, farmers recorded the cost and labour 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 place of fertilizer application 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 meet with farmers to discuss any issues, give feedback to them about their field conditions, and advise corrective measures whenever needed. They could also communicate with us via WhatsApp at any time.

To calculate the annual increase in aboveground dry matter (ADM), we estimated vegetative dry matter every *ca.* 12 months, starting at the beginning of the trials, and added the calculated bunch dry matter during that period. In some cases, the sampling occurred at slight 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 Hardon et al. (1969); Corley et al. (1971), Prabowo and Foster (2006), and 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 for leaf sample. Additionally, frond production and the total count of green fronds were assessed for a subset of 20 palms per field. Finally, the bunch dry matter was calculated based on the farmer-reported FFB yield, assuming a water content of 470 g kg^{-1} FFB (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 20 palms and 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 and Foster (2006) using a stainless-steel pipe and cut into small pieces. All leaf, rachis, and trunk samples were oven-dried and sent to Asian Agri laboratory (AA-Lab, https://www.asianagri.com) to determine nutrient concentration. This lab is actively participating in WEPAL (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. 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 but results showed no deficiencies for these nutrients, so we did not evaluate again 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 the 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 trunks 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, 1.44, and 1.52 CH_2O kg^{-1} dry matter, for bunch, fronds, and trunk, respectively.

Differences in annual plant growth between BMP and REF fields can be attributed to differences in light interception and/or conversion of light intercepted into dry matter (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 LAI values derived according to the Beer-Lambert law from our allometric measurements:

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

where *f* is the fraction of the light intercepted by the canopy, 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 shady 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 shady 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 dry matter increased and the intercepted photosynthetically active radiation. The latter was estimated based on the measured LAI and the incident solar radiation retrieved from nearby weather stations (https://www.bmkg.go.id/).

3.2.3. Estimation of oil yields based on OER measurements and economic analysis

We were also interested to analyse the impact of BMPs on oil yield. To do so, we measured OER in each of the BMP and REF fields during the third year of the trials. Our smallholder fields have a high frequency of dura type palms (average: 50%) (Monzon, 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 and only one ripe bunch was sample per palm. The OER determination was based on the methodology described by Hasibuan et al. (2013) and Hasibuan and Nuryanto (2015).

Deriving OER for each field based on a small number of palms is not possible given the high spatial variation that exists in OER among palms within a field, with coefficients of variation above 20%. Thus, we calculated average OER for each palm type, separately for each site, pooling the data across all fields. There was no statistically significant difference in OER between BMP and REF fields (p=0.66) (Supplementary Table S3-2). 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). However, there was statistically significant differences for OER between palm type, i.e., dura and tenera, and among sites (p<0.001). Thus, we pooled the BMP and REF data to derive OER averages for tenera and dura per site. 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 average OER for each field at each site.

3.2.4. Estimation of water-limited yield potential

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., 2003). 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 provides estimates of Yw on a field-scale level and simulates plant growth and partitioning at a daily time step (Hoffmann et al., 2014; Hekman et al., 2018). This model has been satisfactorily validated on its ability to reproduce highest yields measured 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 plantation and smallholder fields in previous studies (Hoffman et al., 2015; Monzon et al., 2021, 2023). For our simulations, daily rainfall data was recorded on-site, while 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 of the difficulty 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 nutrient and pesticides, 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 there is empirical data showing that this is a reasonable attainable yield for this crop (Monzon et al., 2021, 2023).

3.2.5. Assessing impact of BMPs on farmer profit

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 labour (including both family and hired labour) and were calculated based on the actual prices reported by the farmers. In the case of family labour, we compute 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. Return on investment (ROI) was calculated as the quotient between the BMP-REF difference in net income and the BMP-REF difference in total cost. Using prices from a specific year 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 average prices for agricultural inputs and FFB (Directorate General of Estate Crops, 2022; Lim et al., 2023).

3.2.6. Data analysis

We performed repeated measures statistical analysis using mixed effects model for plant tissue (leaf, rachis and trunk) nutrient concentrations, FFB yield, annual dry matter production, and annual nutrient uptake. For each variable, we fitted a model with the following structure:

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

where y_{ijkl} is the m^{th} observation for the i^{th} treatment (TRT) 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: $F(S)_{kl} \sim N(0, \sigma_{FS}^2)$; and $e_{ijklm} \sim N(0, \sigma_e^2)$. A linear mixed-effect model was fitted for each variable using the *nlme* package (Pinheiro, and Bates, 2020; 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 time period between bunch initiation and ripeness (Thomas et al., 1971; Ng et al., 2003; Corley and Tinker, 2003). Hence, our dependent variable was the annual BMP-REF yield difference, calculated as the average from years 2 and 3. We selected those independent variables with expected impact on yield, including REF yield during Y1, BMP-REF yield difference during the first six months, fertilizer application in BMP field 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 soil differences. 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 differences in initial yield level between BMP and REF fields within each pair. The level of fertilizer application, in relation to the recommendation, gives insight on the overall adoption of the BMPs. 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 too low palm density. Finally, we computed a soil similarity index for each BMP-REF. To do, we evaluated differences in sand and clay contents, soil organic carbon and N, cation exchange capacity, exchangeable magnesium & potassium, available P and pH between BMP and REF using t-tests. Our index was estimates as the number of soil properties that were not statistically significant different ($p>0.05$), expressed as a fraction of the total number of evaluated soil variables.

3.3. Results

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

Nutrient concentration in various plant organs was similar between the BMP and REF treatments at the beginning of the trials and mostly below the sufficiency range reported in the published literature (Figure 3-2). However, from that point onwards, nutrient concentration was higher in BMP versus REF fields, except for Mg. Among nutrients, it was notable the large increase in K concentration in the BMP fields, not only in leaves as for N and P, but also in trunk and rachis, with K concentration increasing, on average, +19% (leaf), +59% (rachis), and +34% (trunk) over Y2 and Y3 ($p<0.001$).

Annual N, P, K, and Mg accumulation in aboveground dry matter was higher in BMP versus REF fields in all years (Figure 3-3). 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 between 5% (Mg) and 26% (K) in Y1 and from 19% (N and Mg) to 39% (K) in Y3. After the three years, the BMP fields have accumulated 87 kg N, 10 kg P, 158 kg K and 10 kg Mg more than the REF fields.

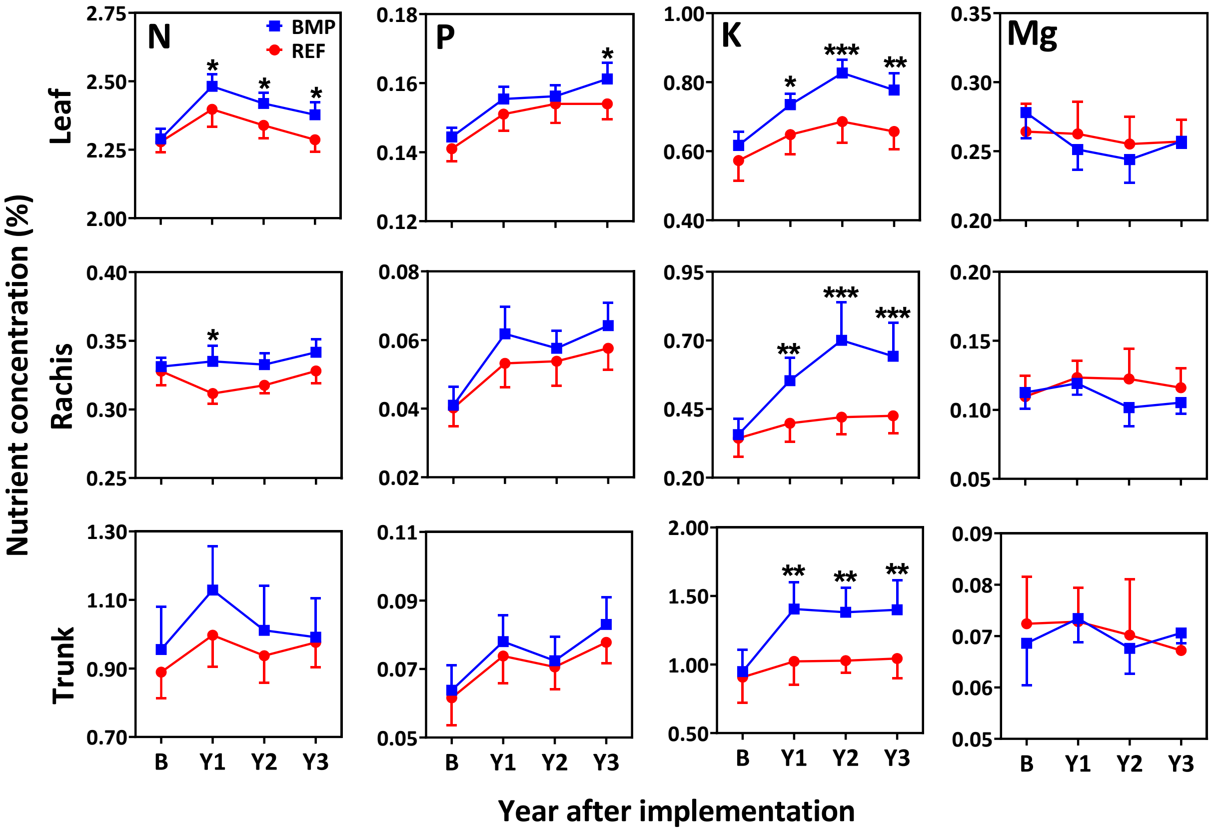

Figure 3-2. *Average nitrogen (N), phosphorous (P), potassium (K), and magnesium (Mg) concentration in leaf, rachis and trunk at the beginning of the trials (baseline, B) and after one (Y1), two (Y2), and three years (Y3) for two treatments: better management practices (BMP) and reference farmer management (REF). Asterisks indicate statistically significant differences 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.*

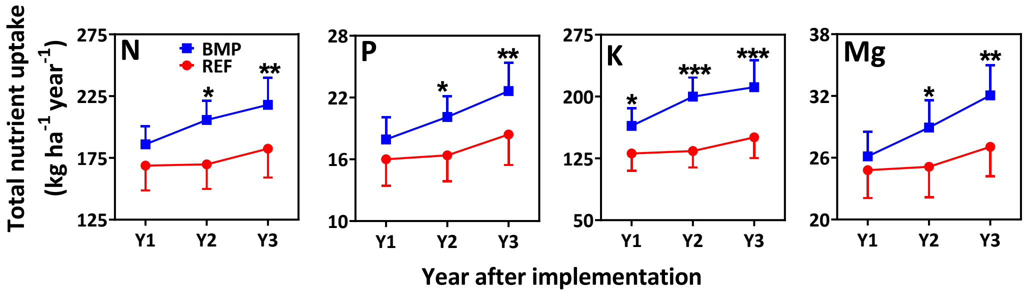

Figure 3-3. *Average plant nitrogen (N), phosphorous (P), potassium (K), and magnesium (Mg) uptake during the first (Y1), second (Y2), and third year (Y3) after beginning of the trials. Data were collected from 30 paired fields that included two treatments: better management practices (BMP) and reference 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. Vertical bars indicate the standard error of the mean.*

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

Annual dry matter production was 21% higher in the BMP *versus* REF fields during Y2 and Y3 ($p<0.001$) (Figure 3-4). 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 field 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. Estimated RUE, based on the annual crop growth and associated intercepted PAR, was +20% higher in the BMP than REF fields in Y2 and Y3.

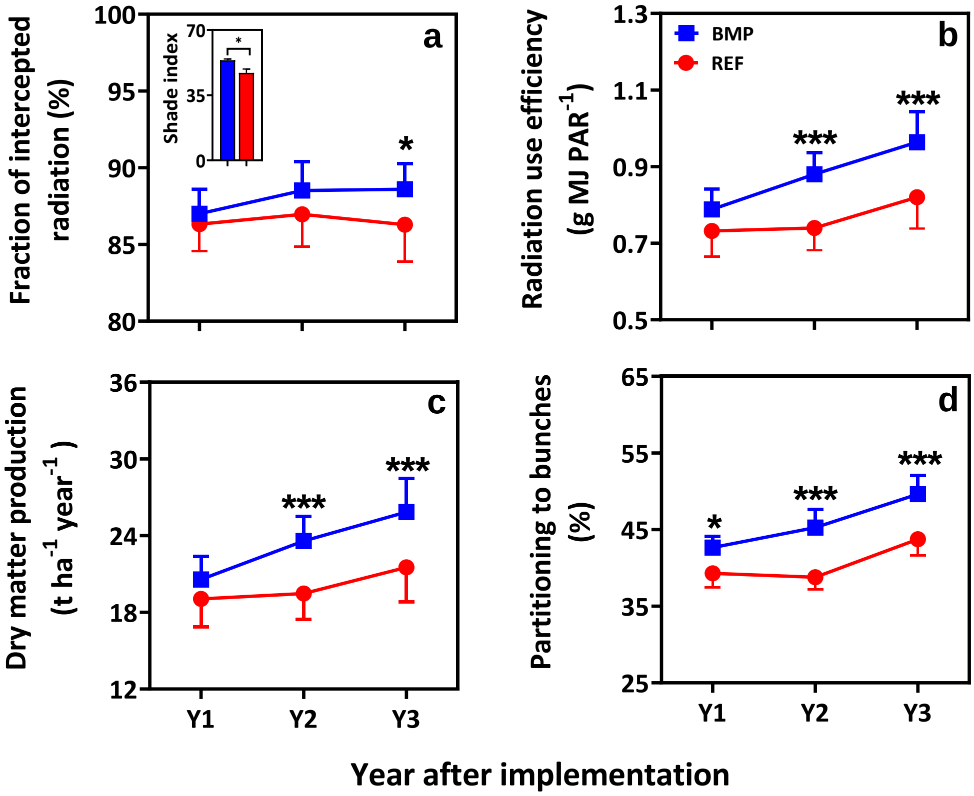

***Figure 3-4**. Annual average (± standard error) of fraction of intercepted radiation (a), radiation use efficiency (b), dry matter production (c) and partitioning to bunch (d) under better management practices (BMP) and standard farmer practices (REF) for year 1 (Y1), year 2 (Y2) and year 3 (Y3). The inset graph (panel a) shows the comparison of shade index between BMP and REF fields. The values were averaged across five sites. Asterisks indicate statistically significant differences at *p≤0.05, **p≤0.01 and ***p≤0.001 as evaluated using Tukey's test.*

Partitioning to bunches during Y2 and Y3 was higher in BMP than REF fields, averaging 47% and 41%, respectively (p<0.001). However, partitioning to fronds was lower during the same period in BMP than REF fields (40% versus 45% p=0.002), and also was the case for trunk (12% versus 14%; p=0.001) (Figure 3-4). Correcting dry matter of each organ by dry matter composition led to higher values of partitioning to bunches and lower for fronds and trunk (Supplementary Figure S3-3). For example, average (Y2-Y3) dry-matter corrected partitioning was 58% (bunch), 32%

(frond), 10% (trunk) in the BMP fields and respective 52%, 36%, and 12% for the REF fields. Nutrient partitioning to the distinct organs followed the same trend as dry matter, except for K, which did not exhibit statistically significant differences between BMP and REF fields (Figure 3-5).

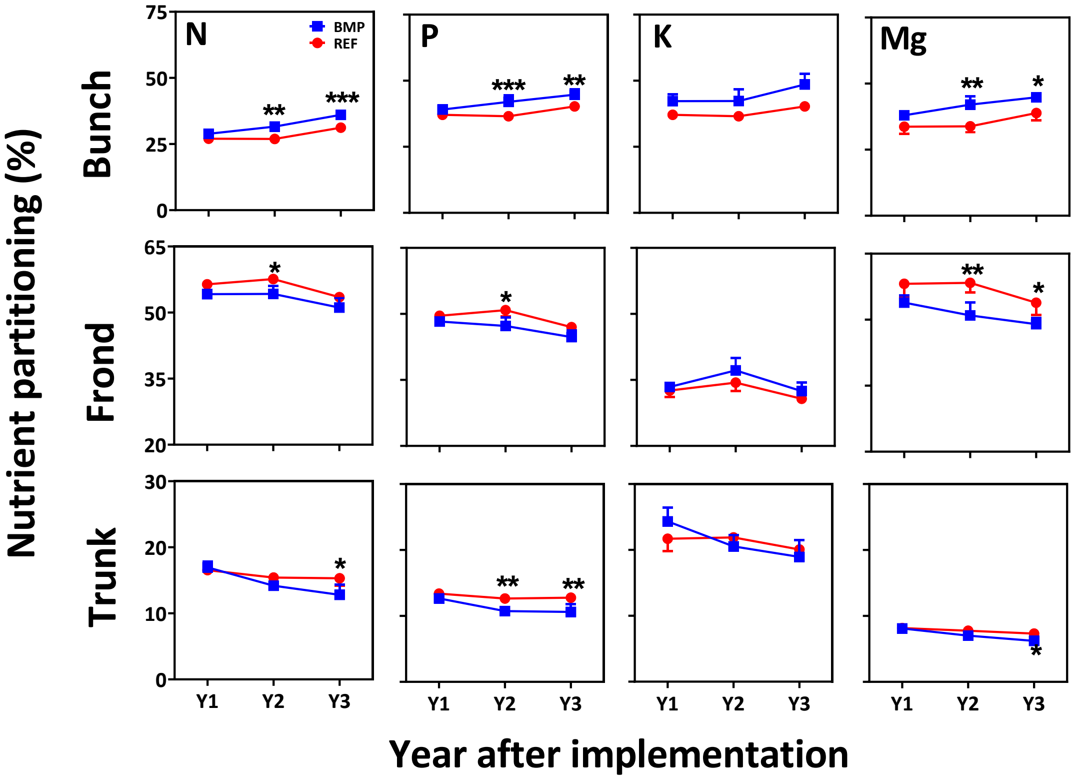

Figure 3-5. *Annual average (± standard error) of total nutrient uptake partitioning (%) to bunch, frond, and trunk under better management practices (BMP) and standard farmer practices (REF) for year 1 (Y1), year 2 (Y2) and year 3 (Y3). The values were averaged across five sites. Asterisks indicate statistically significant differences at *p≤0.05, **p≤0.01 and ***p≤0.001 as evaluated using Tukey's test.*

3.3.3. Effect of better management on yield components and FFB and oil yields

Accumulated FFB yield in BMP and REF fields were similar during the first six months after initiation of trials (p= 0.60) (Supplementary Figure S3-1). Differences in FFB yield started to become apparent afterwards, mostly related to an increase in bunch number, leading to a BMP-REF yield difference of 2.4 t ha^{-1} at the end of Y1 (Figure 3-6). The BMP-REF yield difference increased in subsequent years, averaging 5.8 t ha^{-1} (Y2) and 6.5 t ha^{-1} (Y3), which were associated with an increase in both bunch number (+27%) and weight (+11%) in BMP *versus* REF fields. Average FFB yield did not differ across years in REF fields (p=0.44). In relation to the magnitude of the yield gap, the average FFB yield over the three years (15.8 t ha^{-1}) in the REF fields represented 46% of the attainable yield. Implementation of BMP led to a substantial closure of the yield gap, with average BMP yield representing 76% of the attainable yield in Y3 (Figure 3-6a). Higher FFB yield led to higher CPO yield in Y3, which was 1.5 t ha^{-1} higher in BMP than REF fields. The BMP-REF oil yield difference was related to differences in FFB yield since OER was not different (p=0.66) between BMP and REF fields (Supplementary Table S3-2).

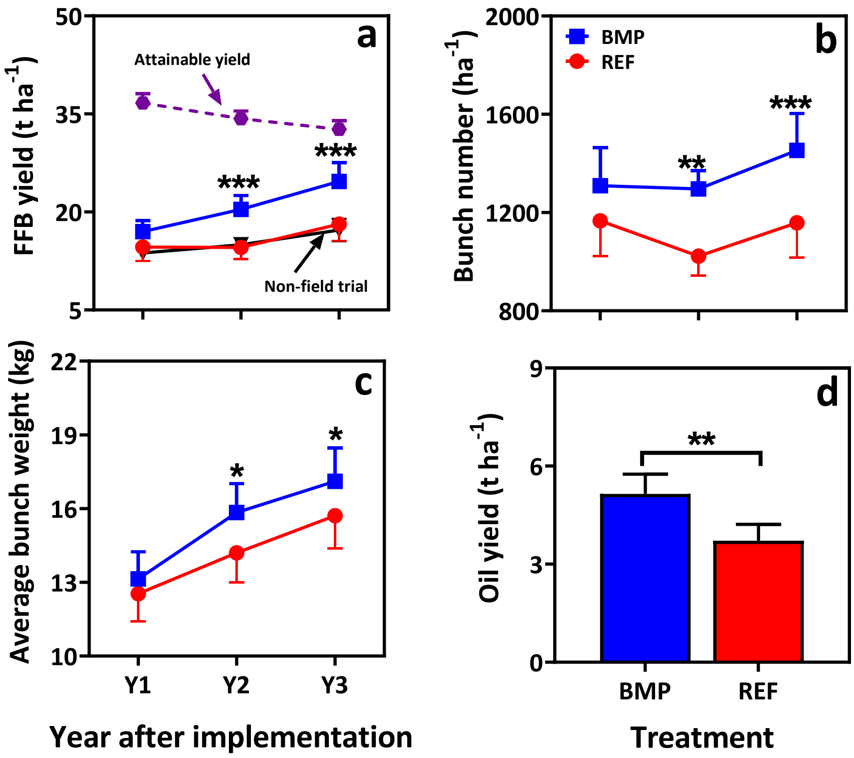

Figure 3-6. *Annual average (± standard error) fresh fruit bunch (FFB) yield ha^{-1} (a), bunch number (b), and bunch weight (c) weight during the first (Y1), second (Y2), and third year (Y3) after beginning of the trials. Also shown are average oil yield based on measured oil extraction rates during Y3 (d). Data were collected from 30 paired fields that included two treatments: better management practices (BMP) and reference farmer management (REF). Also shown in (a) is the average annual FFB yield estimated based on data for 837 independent smallholder non-trial fields (NTF) and the attainable yield (Yatt) estimated as 70% of the simulated water-limited yield potential. Asterisks indicate statistically significant differences at *p≤0.05, **p≤0.01 and ***p≤0.001 as evaluated using Tukey's test.*

The BMP-REF FFB yield response varied from 3.2 to 10.5 t ha^{-1} (Y2) and 4.3 to 10 t ha^{-1} (Y3) across trials. Our analysis revealed that the initial yield level, initial yield differences between BMP and REF fields, and degree of BMPs implementation explained ca. 70% of the BMP-REF yield variation observed during the Y2 and Y3 (Table 3-3). Yield response with BMP was greater in fields with both a low initial yield and a high implementation of BMPs. Likewise, those BMP-REF fields exhibiting positive (negative) yield differences during the first six months, exhibited larger (smaller) yield differences later on. We note, however, that the average FFB yield during the first six months was not significantly different between BMP and REF fields. Hence, while the initial BMP-REF yield differences explain part of the variation in yield differences across fields, it does not influence the overall yield difference between treatments.

Table 3-3. *Multiple regression model for the average yield difference (t* ha^{-1} y^{-1}*) during the first (Y1) and second year (Y2) between fields following better management practices (BMPs) versus those following the reference farmer management (REF). Also shown are the associated parameters and their standard error (s.e.) and statistical significance (n=30; adjusted* R^2*= 0.69).*

Coefficients	Estimate	s.e.	*p*-value
Intercept	-1.689	7.621	0.827
REF FFB Y1 (t/ha) [a]	-0.324	0.119	0.014
Accumulated first 6-month BMP-REF yield different [b]	1.000	0.388	0.019
BBC diff BMP-REF (BNO ha^{-1}) [c]	-0.005	0.010	0.642
Average dura frequency (%) [d]	-0.013	0.026	0.624
Diff palm density (/ha)	-0.013	0.041	0.760
Average palm age (Y1)	-0.016	0.323	0.962
Average palm density (ha)	0.024	0.038	0.537
Fertilizer applied Y1-Y2 (% of recommendation) [e]	0.093	0.041	0.036
BMP-REF soil similarity index [f]	1.915	3.761	0.617
Number of dry months [g]	0.273	0.350	0.445
BMP-REF TWI	-0.726	0.892	0.427

[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] Applied fertilizer as percentage of recommendation. [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.

3.3.4. Impact of better management practices on farmer profit

Implementation of BMP led to lower (-8%) profit than REF in Y1 (Figure 3-7). However, higher yields led to higher net profit in Y2 (+25%) and Y3 (+18%) because the increase in gross income was proportionally higher than the increase in costs. The economic analysis was similar when based on historical prices (Supplementary Figure S3-5).

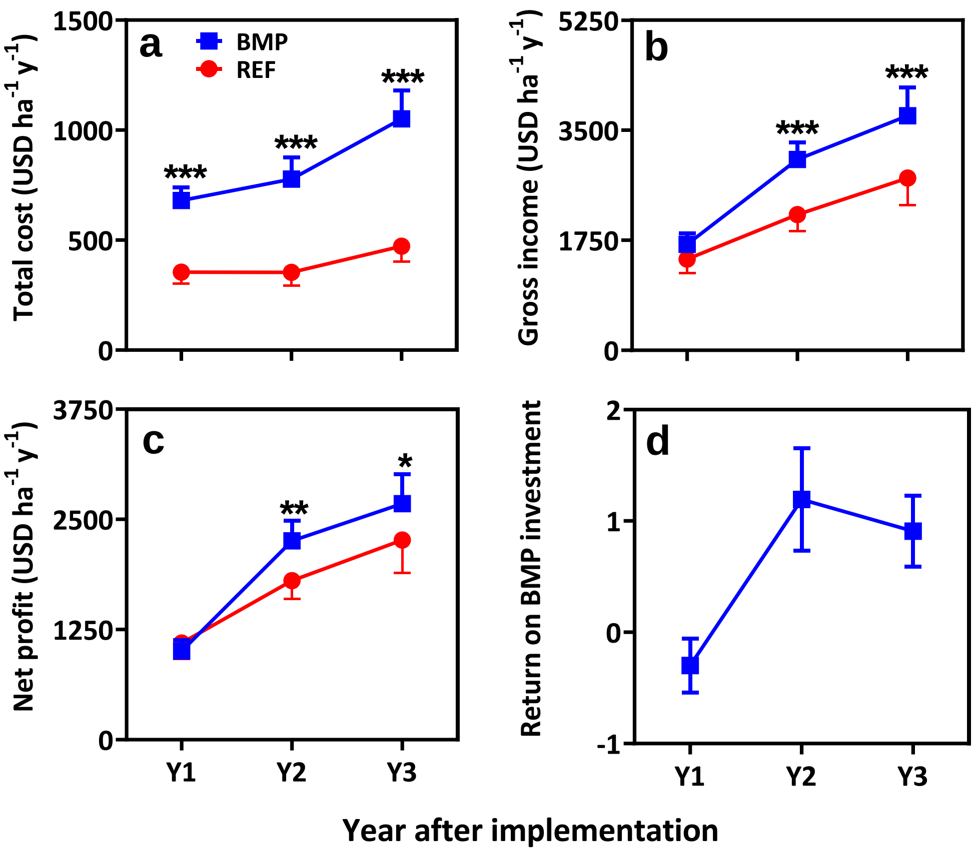

Figure 3-7. *(a) Total production cost, (b) gross income from FFB selling, (c) net profit, and (d) return on BMP investment (ROI) based on actual cost and FFB price during the first (Y1), second (Y2), and third (Y3) year after beginning of the trials. Data were collected from 30 paired fields that included two treatments: better management practices (BMP) and reference farmer management (REF). Asterisks indicate statistically significant differences at *p≤0.05, **p≤0.01 and ***p≤0.001 as evaluated using Tukey's test in (a), (c) and (d). Vertical bars indicate the standard error of the mean.*

3.4. Discussion

The combination of field measurements, monitoring of trials and farmer practices, surveys across an independent population of smallholders located adjacent to our field trials, and use of crop models allowed us to avoid confounding factors and ensure the representativeness of the fields chosen for the BMP implementation. For example, we showed that biophysical, agronomic, and socio-economic background of our REF fields were representative to that of an independent group of 837 smallholders fields located at the same sites (Supplementary Table S3-1). Likewise, we showed the BMP and REF showed similar conditions at the beginning of the trials and that the REF yield did not increase over time and that the use of nutrient fertilizer in these fields also remained relatively constant over the study period (Supplementary Figure S3-2). On the other hand, use of crop models to estimate the attainable yield allowed us to remove the confounding effect of changing weather and measure yield improvements in terms of yield gap closure, rather than in absolute terms. For example, we showed that the yield gap in the BMP fields was narrowed down by ca. half, from 54% (Y1) to 24% of the attainable yield in Y3 (Figure 3-6). In contrast, the average yield gap in the REF fields remained large over the three years, averaging 54% of the attainable yield, which is consistent with that reported by Monzon et al. (2023) for independent smallholders in Indonesia (58% of attainable yield). Finally, our study measured the yield drivers in terms on light interception, conversion, and partitioning. We cross-validated our estimates of with in-situ measurement of light interception using a simple, yet robust, experimental approach based on a shade index, showing a reasonable agreement

(Figure 3-4). Our estimated intercepted radiation, radiation use efficiency, and partitioning were comparable with those reported in Corley (2003), Tao et al (2017), and Romero et al. (2022).

We showed here that improvements in agronomic practices, especially regarding nutrient management, led to +40% increase in FFB and oil yields and +20% increase in farmer net profit (Figures 3-6 and 3-7). The economic benefit is expected to increase as BMPs are extended over time and the financial loss of the first year gets diluted. As far as we know, this is the first study documenting the positive productivity and economic impacts of BMP implementation in smallholder fields in Indonesia. We showed that differences in annual dry matter production between BMP and REF fields is attributable to higher nutrient uptake, LAI, intercepted solar radiation (f) and RUE (Figure 3-3, Figure 3-4, and Supplementary Figure S3-1). In relation to nutrient uptake, it was remarkable the increase for all nutrients: +19% (N), +22% (P), 43% (K), and +16% (Mg) (Figure 3-2). The observed increase in RUE is consistent with the higher leaf N, P, and K concentration and the expected impact on photosynthetic rates (Corley and Tinker, 2008; Kamal and Manan, 2020). In addition to changes in light interception and conversion, partitioning to bunch was higher in the BMP versus REF fields (Figure 3-4). Tao et al (2017) has reported similar changes in partitioning to bunches in response to BMPs. In terms of yield components, both bunch number and weight were higher in the BMP versus REF treatment (Figure 3-6). These findings are consistent with those reported by Griffiths and Fairhurst (2003), Donough et al. (2010), Oberthür et al. (2012), and Rhebergen et al. (2020).

Our detailed description of the fields and monitoring allowed us to determine drivers for variation in yield responses across trials (Table 3-3). For example, we found larger yield gains due to BMPs in fields with low initial yield level and proper BMP implementation, especially in relation to fertilizer use. While there has been effort to understand the drivers for variation in yield response to BMPs for other perennial crops (Hoffmann et al., 2020), our study is the first one addressing this important topic for oil palm. This information can be used to determine areas where BMPs are expected to deliver largest yield gains, based on current yield level and expected farmer adoption of recommendations. For example, implementation of BMPs is expected to generate a comparably large FFB yield response when current yields are low and the socio-economic context allowed full implementation of BMPs.

Our study on smallholders consistently documented large increases in FFB and oil yields after the first year of BMP implementation, with +40% higher yield in BMP versus REF fields. Because OER was not different between BMP and REF fields, the yield increase translated into similar increases in oil yields (Supplementary Figure S3-6). This finding was consistent with a previous study (Oberthür et al., 2012). If this BMP is adopted to the nationwide, and considering the same relative yield increase (+40%) as in our trial and a total mature area of independent smallholder 3.1 M ha (Molenaar et al., 2013; Hidayat, 2017; Directorate General of Estate Crops, 2022), we estimated that Indonesia could produce 3.6 MMT CPO. This is equivalent to a +8% increase in national CPO production in year 2020 (Directorate General of Estate Crops, 2022), generating extra 2.9 billion USD for the country level. This calculation assumes an average OER of 21% and no impact of BMPs on OER as we found in our study. Thus, better agronomic practices can also complement the potential impact of replanting programs promoting use of certified planting material with higher OER (Molenaar et al., 2013; Zen et al., 2005; Coordinating Ministry for Economic Affairs, 2023; Indonesia Oil Palm Association, 2023). For example, implementation of BMPs, together with replanting current independent smallholder fields (at the end of their plantation cycles) with certified planting material, can lead together to an increase of +5.4 MMT CPO, which would increase current national CPO production of Indonesia by 12%. Thus, BMP adoption can complement current efforts to replant fields with planting material with higher OER. There are also potential benefits for nature, as this production increase is equivalent to 1.9 M ha of new land brought into cultivation given current yield level, assuming that proper institutions and policy are on place so that intensification gains translate into land sparing for nature. Hence, yield intensification via BMPs can provide current efforts to avoid deforestation, such as certification and moratoriums, a means to compensate for the opportunity cost derived from not allowing conversion of natural ecosystems for oil palm cultivation.

3.5. Conclusions

Implementation of better management practices led to an increase in FFB and oil yields (+40%) and improved farmer profit (+20%) compared with farmer current management. The yield increase was largest in fields with low initial yield level and high degree of BMP implementation, and driven by increases of nutrient uptake, light interception, and RUE, together with greater dry matter partitioning to bunches. Overall, the average yield gap in BMP fields was narrowed down substantially from 54% in Y1 to 24% in Y3. Yield intensification through BMPs is an effective approach to increase farmer yield and profit and can complement current efforts to increase oil yield via replanting programs promoting use of certified planting material with higher OER, as well as conservation efforts to protect fragile ecosystems.

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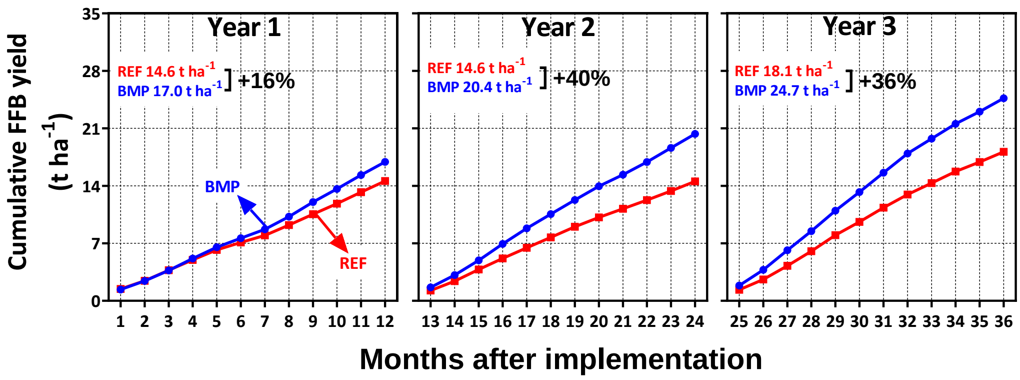
Supplementary Table S3-1. *Means, 25th (P_{25}) and 75th (P75) percentiles of the baseline data for socio-economic, soil and agronomy variables collected at the beginning of the trials and also for 1200 independent fields located near the trials (non-field trials). P25 and P75 are not show for categorical variables.*

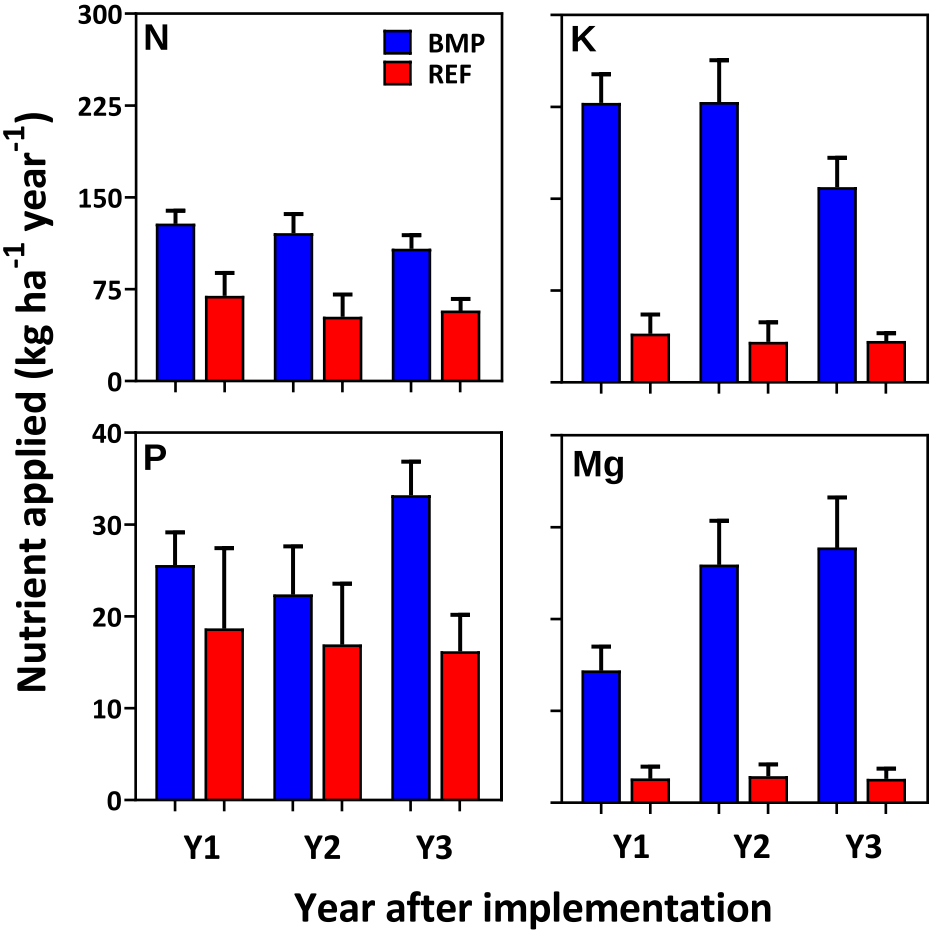
	Field trial			Non-field trials		
Variables	$P_{25\%}$	Mean	$P_{75\%}$	$P_{25\%}$	Mean	$P_{75\%}$
Socio-economic						
Total oil palm area (ha)	1.76	2.08	2.25	1	2.49	2.82
Middle school or higher education (% farmers)		73%			54%	
Adequate access to fertilizer (% farmers)		79%			69%	
Management based on own experience or neighbours (% farmers)		61%			86%	
Agronomy variables						
FFB yield (t ha^{-1})	9.1	14.5	19.4	9.8	13.8	17.1
Palm age (years)	9	11	13	10	13	16
N applied (kg ha^{-1})	52	115	175	0	21	33
P applied (kg ha^{-1})	12	27	38	0	5	7
K applied (kg ha^{-1})	19	51	102	0	15	23
Mg applied (kg ha^{-1})	0	0	4	0	2	0
Leaf N (%)	2.17	2.28	2.37	2.18	2.31	2.45
Leaf P (%)	0.135	0.142	0.152	0.139	0.150	0.161
Leaf K (%)	0.46	0.59	0.71	0.53	0.67	0.79
Leaf Mg (%)	0.21	0.27	0.34	0.23	0.30	0.36
Harvesting interval (days)		15		15	19	22
Planting density (palms ha^{-1})	139	152	163	127	145	157
Dura frequency (% palms)	46%	58%	75%	25%	50%	73%
Severe weed infestation (% fields)		85%			91%	

Supplementary Table S3-2. *Analysis of variance for oil extraction rate (OER, in %) as influenced by site, palm type (frequency of dura palms) and treatment. Data were measured in individual dura (n=237) and tenera palms (n=214) across the 30 paired-fields.*

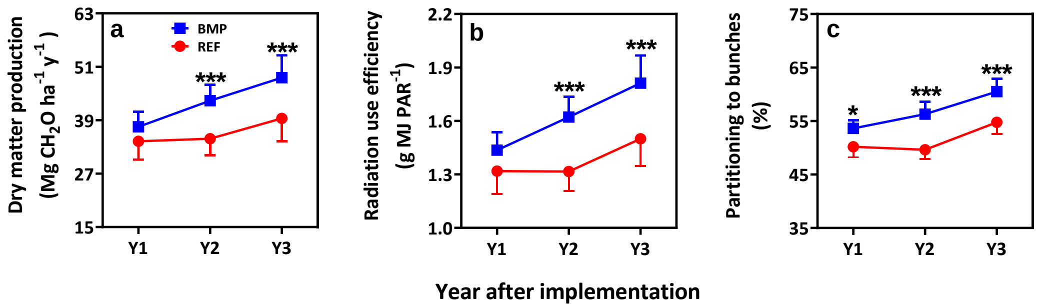
S.V.	SS	df	MS	F	p-value
Model	4981.17	19	262.17	16.14	<0.0001
Site (S)	221.54	4	55.39	3.41	0.0093
Palm type (P)	4355.74	1	4355.74	268.09	<0.0001
Treatment (T)	3.18	1	3.18	0.20	0.6583
S*P	62.64	4	15.66	0.96	0.4271
S*T	42.71	4	10.68	0.66	0.6221
P*T	0.09	1	0.09	0.01	0.9412
S*P*T	8.76	4	2.19	0.13	0.9695
Error	7002.48	431	16.25		
Total	11983.65	450			



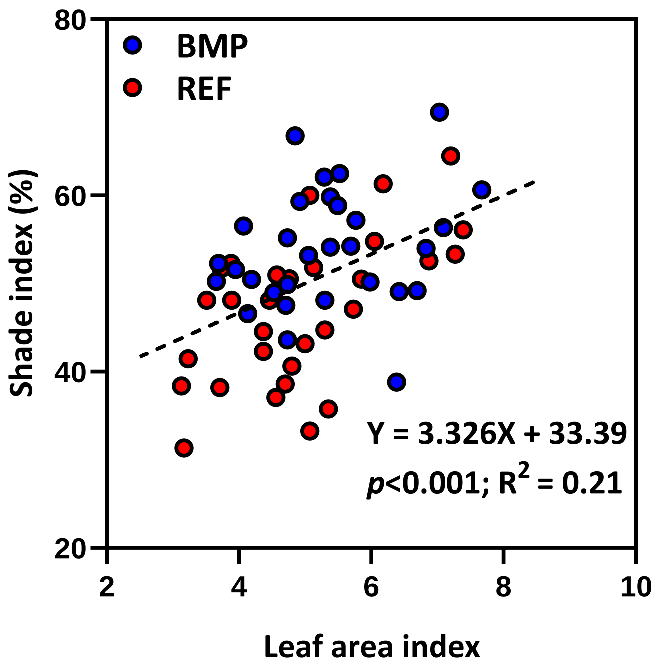
Supplementary Figure S3-1. *Cumulative fresh fruit bunches (FFB) yield for better management practices (BMP) and reference farmer management (REF). Values are averages across 30 paired fields.*



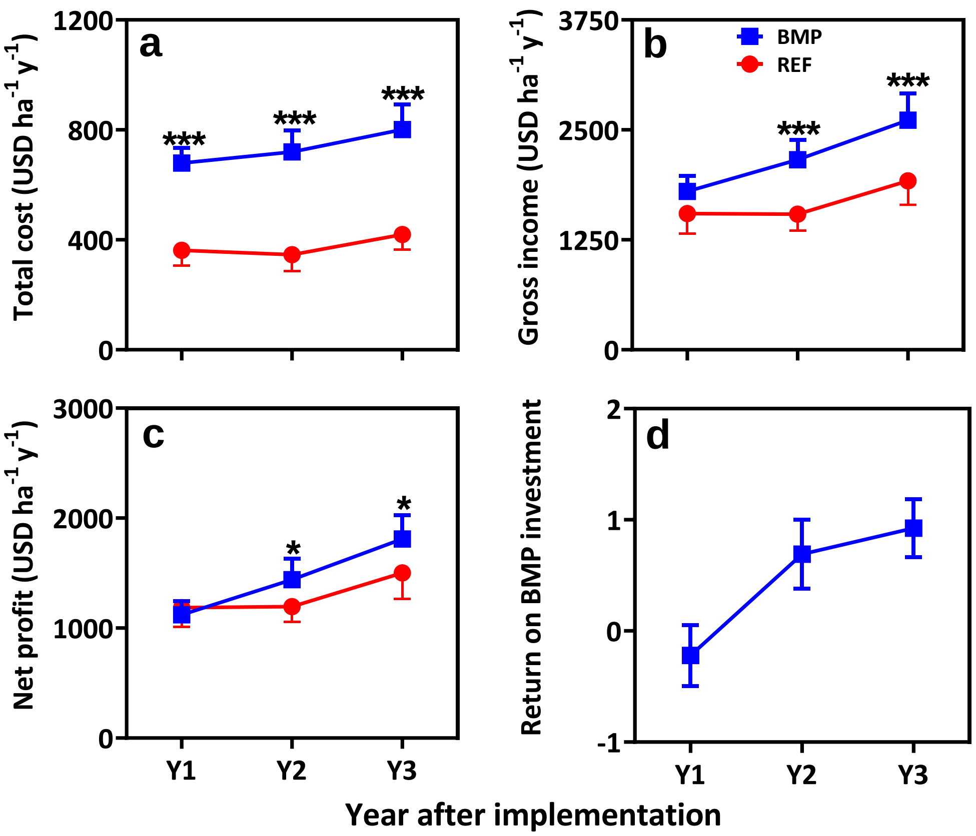
Supplementary Figure S3-2. *Annual average (± standard error) fertilizer nutrient applied across 30 paired fields including two treatments: better management practices (BMP) and reference farmer management (REF).*



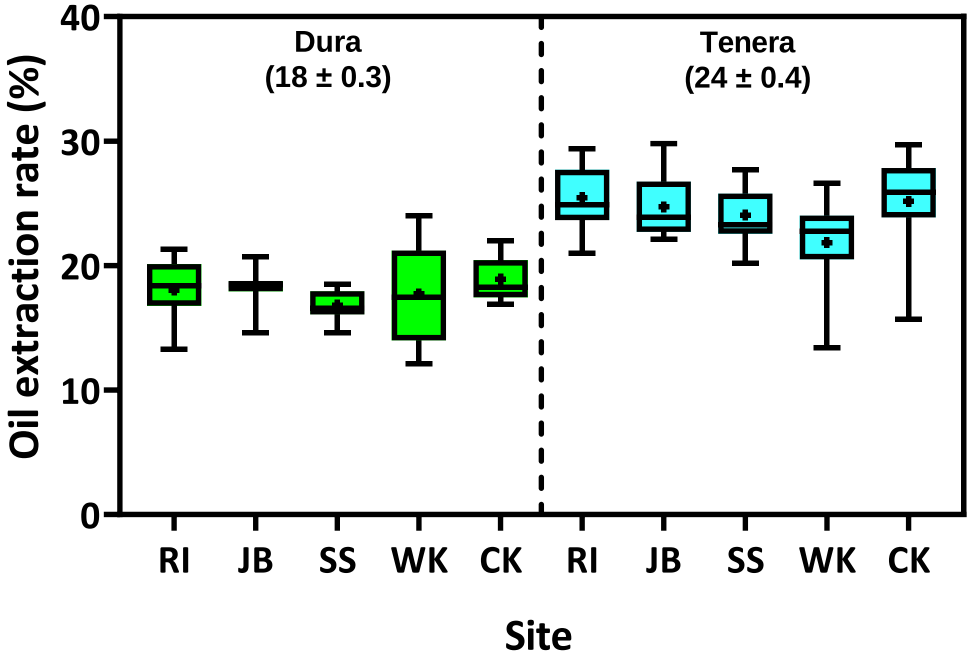
Supplementary Figure S3-3. *Annual average (± standard error) of corrected dry matter production (a), radiation-use efficiency (b) and d partitioning to bunch (c). All values were corrected by metabolic costs as proposed by Breure (1998). Asterisks indicate statistically significant differences at *p≤0.05, **p≤0.01 and ***p≤0.001 as evaluated using Tukey's test.*



Supplementary Figure S3-4*. Relationship between the shade index derived from field measurements and the fraction of intercepted solar radiation derived from the estimated leaf area index during Y3 across 30 paired fields including two treatments: better management practices (BMP) and reference farmer management (REF). Each datapoint represents a BMP or REF field. Also shown is the fitted linear regression model and associated parameters, coefficient of determination (r^2), and statistical significance.*



Supplementary Figure S3-5. *(a) total cost, (b) gross income, (c) net profit and (d) return on investment (ROI) based on historical cost and FFB price during the first (Y1), second (Y2), and third (Y3) year 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≤0.05, **p≤0.01 and ***p≤0.001 as evaluated using Tukey's test. Vertical bars indicate the standard error of the mean*



Supplementary Figure S3-6. *Box plots for Oil extraction rate (OER, %) measured in individual dura palms and tenera palms across five sites, Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK) and Central Kalimantan (CK) including two treatments: better management practices (BMP) and reference farmer management (REF). Vertical bar indicate 5th and 95th percentile values. Horizontal lines and crosses within boxes are the median and mean, respectively. Also shown are the means (± standard error) across five sites for each palm type.*

CHAPTER 4. GENERAL DISCUSSION, IMPLICATIONS FOR RESEARCH & POLICY, AND DISSEMINATION ACTIVITIES

4.1. General Discussion

Over the past two decades, cropland has expanded by 70 million hectares, reaching a total of 1.56 billion hectares by 2020 (FAO, 2022a). However, due to the substantial increase in global population, there has been a 18% reduction in cropland per capita, from 0.24 in 2000 to 0.20 ha per capita by 2020 (FAO, 2022b). This trend is expected to persist as population keeps increasing, peaking 9.7 billion by 2050 (United Nations, 2021). The ongoing decline in cropland per capita highlights the need to increase crop yields on current cropland, that is via crop intensification, to meet current and future demand for food, fibre, and feed on existing cropland while minimizing the negative environmental impact (Cassman et al., 2010; Cassman & Grassini, 2020).

Our study supports the view that improved management could increase the yields and profits of smallholder palm growers in Indonesia. Plant nutrition plays a key role in explaining yield gaps in current smallholder fields. Knowing the status of plant nutrients is important for tuning nutrient management. The commonly used approach to diagnose the nutrient status of oil palm is through leaf nutrient content, comparing it with the nutrient range proposed by Von Uexküll and Fairhurst (1991). However, there were no specific guidelines on sample size to obtain reliable estimates of leaf nutrient concentration in smallholder fields until now. Our approach to diagnose nutrient deficiency included developing guidelines for sampling size in smallholder fields. Overall, it appears that 10 palms per field would provide a good representation of the nutrient status, with an average precision level of 3% (N), 4% (P), 10% (K), 8% (Ca), and 9% (B), although uncertainty is larger for specific nutrients such as magnesium (Mg). The sampling size guidelines we developed here were used to diagnose nutrient status across 977 farmer fields and assess its relationship to the FFB yield, as influenced by planting material (Chapter 2).

As mentioned previously, current agricultural research and development programs in Indonesia mostly focus on replanting programs that promote the use of certified planting material. While new planting material has the potential to increase oil yield via higher oil extraction rates (OER), we show that, at present, smallholders do not get paid by oil but rather by the amount of harvested fresh fruit bunches (FFB). Currently, the price of FFB is determined based on palm age, which is a proxy for OER. For example, a 4-year-old palm has an oil content of 20.69%, while a 7-year-old palm has an oil content of 21.03% (Ministry of Agriculture, 2018), without considering fruit type (dura or tenera). According to our field measurements, dura and tenera had OER of 18% and 24%, respectively. Due to the fact that this pricing system does not consider fruit type, farmers will not be motivated to plant certified planting material containing >98% tenera. Thus, we believe that FFB should be priced based on oil content, using dura frequency as a proxy reduction factor. Since OER is reduced by 0.6% units for a 10%-unit increase in dura frequency, the FFB price should be reduced by 2.5%. For example, if the dura contamination is 40%, then the OER is 21.6%, so the FFB price should be reduced by 10%. Unless the FFB price is adjusted according to fruit type, there will be little motivation from smallholders to adopt planting material with higher OER.

In the meantime, the most effective approach to increase smallholder yield and profit for existing plantations is to promote the adoption of better management practices that are effective at increasing FFB yield. Our study showed that improving the current plant nutrition status can lead to substantial increases in FFB and oil yields. We showed that fields that were sufficient in nitrogen (N), phosphorus (P), and potassium produced FFB yields that were, on average, 5.6 tons FFB ha-1 (+47%) higher than fields that were deficient in these nutrients. Meanwhile, palm type (dura) had a very small effect on FFB yield, with the latter decreasing only -7% as dura frequency went from zero to 100%. In contrast, palm type has a strong effect on OER and, thus, oil yield. Farmers are paid according to bunch weight with no incentive for higher oil content associated with lower dura frequency. In this context, smallholders will benefit little from adopting certified planting material compared to the expected impact derived from improving plant nutrition via better fertilizer management.

Our field study across five provinces in Indonesia conclusively showed that smallholders can increase their yield and profit by following better management practices (BMPs), especially in regards with nutrient management (Chapter 3). After the first year of BMP implementation, yield increased by 35-40% compared with those fields following farmer management, resulting in a +20% increase in net profit. Better nutrient management led to increases in nutrient uptake and greater leaf area index and greater RUE. With more radiation intercepted and greater efficiency of photosynthesis, reflected in greater RUE, total dry matter increased significantly and higher partitioning to bunches.

Our study shows that the annual yield response, averaged over the second and third year after BMP implementation, varied across the 30 trials, ranging from 3.8 to 10.3 to FFB ha^{-1}. In relation the causes for such variation, we found that the yield response was positively associated with the degree of BMPs implementation (measured as the percentage of fertilizer applied in relation to that recommended) and negatively related with the initial yield level. In other words, BMPs are expected to deliver the largest yield response when the recommendations are fully implemented and the initial yield level is low.

4.2. Implications of BMPs

Intensification of FFB production is a sound approach to increase production and farmers' income without need to expand oil palm cultivation into new land. Average yield in BMP fields was ca. 40% higher than the reference fields managed by farmers during year 2 and 3 after BMP implementation. At question is what will be the production increase IF the BMPs are scaled out to all independent smallholder farmers in Indonesia (Table 4-1). Considering the same relative yield increase (+40%) as in our trial and a total mature area of 3.1 M ha cultivated with oil palm by smallholders (Molenaar et al., 2013; Hidayat, 2017; Directorate General of Estate Crops, 2022), we estimate that Indonesia could produce an extra 3.6 MMT CPO. This calculation assumes an average OER of 21% and no impact of BMPs on OER as we found in our study (Chapter 3). Thus, considering a national CPO production year 2020 was 45.7 MMT, which includes both large plantations and smallholders (Directorate General of Estate Crops, 2022), Indonesia could produce 8% more CPO by implementing BMPs in independent smallholder fields, generating an extra 2.9 billion USD for the country and replacing 1.2 M ha that would otherwise be converted to oil palm cultivation. For the latter, we assumed the current oil yield of 2.91 t ha^{-1} in smallholder fields (based on average FFB yield of 13.9 t ha^{-1} and OER of 21%). If this is complemented by replanting programs promoting use of certified planting material with higher OER, the overall impact of BMPs on oil yields and CPO production will be larger due to higher OER. For example, assuming that OER will change from current 21% to one close to 24%, the extra CPO production in smallholder fields derived from BMP implementation *and* use of certified planting material will be 5.4 MMT, which is equivalent to 12% of current national CPO production of 45.7 MMT. In turn, this approach will generate an extra 4.3 billion USD for the country, which is equivalent to 1.9 M ha of land converted for oil palm cultivation. Thus, we see BMPs as a complementary approach to replanting efforts in Indonesia to promote use of certified planting material with higher OER.

Table 4-1. *Ex-ante impact assessment of the impact of adopting BMPs and/or replanting programs with certified planting material in independent smallholder (ISH) fields on oil yield, oil extraction rate (OER), national crude palm oil (CPO) production, potential land savings, and national oil palm gross value.*

Variable	Baseline	BMPs approach	BMPs & replanting
ISH oil yield (t ha^{-1}) [a]	2.9	4.1	4.7
ISH OER (%) [b]	21%	21%	24%
National CPO production (MMT) [c]	45.7	49.3	51.1
Potential land savings (M ha) [d]		1.2	1.9
National gross value (billion USD) [e]	36.5	39.3	40.8

[a] *Average oil yield for independent smallholder derived from FFB yield and OER data collected across provinces (Monzon et al., 2023; Chapter 3)*
[b] *Oil extraction rate (%) in independent smallholder yields based on field measurements (Chapter 3).*
[c] *National CPO production for year 2020 (Directorate General of Estate Crops, 2022) including both smallholders and large plantations.*
[d] *Potential land savings was estimated based on the potential additional CPO production derived from BMP implementation in IS fields, divided by the current oil yield in IS fields.*
[e] *Aggregated gross value was calculated based on total CPO production multiplied by current CPO price (https://mpoc.org.my/daily-palm-oil-price/ accessed: Oct, 18th 2023) including both smallholders and large plantations.*

At question is how to foster large scale dissemination of BMPs across independent smallholder fields in Indonesia. Several options can be considered.

1. Providing fertilizer subsidies that are appropriate for oil palm. So far, oil palm has not been included in the fertilizer subsidy program as stated in the Minister of Agriculture Decree No. 10 year 2022.
2. Improve fertilizer distribution system, as many independent smallholder fields are located in remote areas, where there are no local fertilizers or not offering proper fertilizers sources.

3. Improve currently ill-organized and poorly trained agricultural extension programs in oil palm so that they can provide better guidance to the independent farmers.
4. Collaborate with plantation companies to provide training. Plantation companies have corporate social responsibility (CSR) which can be empowered by the Indonesian government to provide training to independent oil palm farmers where they operate.
5. Combating the distribution of fake fertilizer. This fake fertilizer is very detrimental to independent farmers who use it in terms of nutrient content that does not meet expectations and waste time.
6. Farmers can improve their bargaining through farmer groups that serve as "farmer discussion groups", joint sales (FFB), or purchasing (fertilizer and input materials).

In relation to areas of research that (we believe) warrant further research, we can list the following ones:

1. Investigate intercropping strategies that allow smallholders to diversify their income sources, especially in the first years after replanting.
2. Analyse benefits and challenges for smallholder cooperatives to pool resources, share knowledge, and collectively market their oil palm products.
    a. Smallholder cooperatives can play a crucial role in addressing the financial constraints faced by smallholders and in researching innovative financing models, microcredit options, or subsidies to

support their oil palm cultivation in the following ways: (i) collective financial resources: smallholder cooperatives allow farmers to pool their financial resources. This collective savings can be used to provide loans or grants to members in need, reducing the individual financial burden on smallholders; (ii) access to credit: cooperatives can negotiate with financial institutions and government agencies to secure better credit terms for their members. This can result in more favourable interest rates, longer repayment periods, and easier access to credit for agricultural investments.

b. Cooperatives can leverage their collective bargaining power to secure better prices for their products and favourable terms for loans or subsidies. This is especially important for smallholders who may be at a disadvantage when dealing with larger stakeholders (palm oil mill).

3. Develop and disseminate tools that can help smallholders to make better nutrient management decisions, for example:

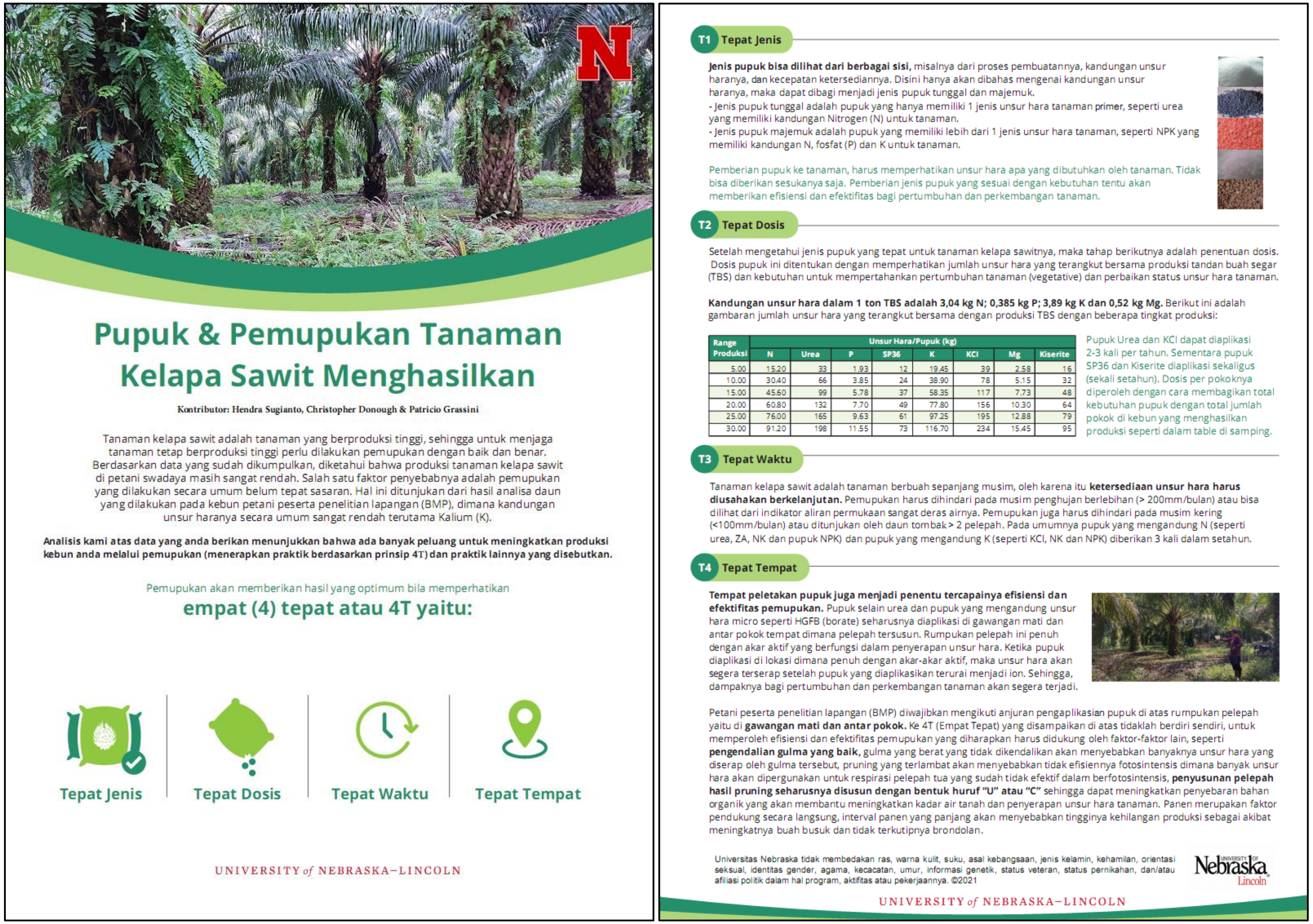
   a. Develop oil palm nutrient colour charts. Leaf nutrient analysis plays a crucial role in diagnosing nutrient deficiencies, yet obtaining and preparing samples for analysis can be a challenging task for farmers. To address this issue and provide a more accessible solution for farmers, we propose the development of nutrient colour charts, similar to those developed for rice by researchers from the International Rice Research Institute (Witt et al., 2005; Buresh & Witt, 2007). This will allow farmers to easily determine the nutrient status of their oil palm fields and help them inform fertilizer decisions.

b. Fertilizer calculator. A simple calculation based on a target yield level, also considering the expected nutrient amount stored in the trunk, can allow farmers to determine fertilizer requirements

4.3. Dissemination activities

Besides our research activities, we have disseminated the results of this study across 1,200 farmers in six provinces, which were involved in the research that served as basis for this dissertation. Our dissemination strategy included:

#1. Flyers: we prepared three flyers providing technical information on: (i) nutrient management for mature oil palm fields; (ii) better harvest practices; (iii) pruning and cut-front arrangement (Figure 4.1-4.3).



Pupuk & Pemupukan Tanaman Kelapa Sawit Menghasilkan

Kontributor: Hendra Sugianto, Christopher Donough & Patricio Grassini

Tanaman kelapa sawit adalah tanaman yang berproduksi tinggi, sehingga untuk menjaga tanaman tetap berproduksi tinggi perlu dilakukan pemupukan dengan baik dan benar. Berdasarkan data yang sudah dikumpulkan, diketahui bahwa produksi tanaman kelapa sawit di petani swadaya masih sangat rendah. Salah satu faktor penyebabnya adalah pemupukan yang dilakukan secara umum belum tepat sasaran. Hal ini ditunjukan dari hasil analisa daun yang dilakukan pada kebun petani peserta penelitian lapangan (BMP), dimana kandungan unsur haranya secara umum sangat rendah terutama Kalium (K).

Analisis kami atas data yang anda berikan menunjukkan bahwa ada banyak peluang untuk meningkatkan produksi kebun anda melalui pemupukan (menerapkan praktik berdasarkan prinsip 4T) dan praktik lainnya yang disebutkan.

Pemupukan akan memberikan hasil yang optimum bila memperhatikan

empat (4) tepat atau 4T yaitu:

Tepat Jenis | Tepat Dosis | Tepat Waktu | Tepat Tempat

UNIVERSITY of NEBRASKA–LINCOLN

T1 Tepat Jenis

Jenis pupuk bisa dilihat dari berbagai sisi, misalnya dari proses pembuatannya, kandungan unsur haranya, dan kecepatan ketersediannya. Disini hanya akan dibahas mengenai kandungan unsur haranya, maka dapat dibagi menjadi jenis pupuk tunggal dan majemuk.

- Jenis pupuk tunggal adalah pupuk yang hanya memiliki 1 jenis unsur hara tanaman primer, seperti urea yang memiliki kandungan Nitrogen (N) untuk tanaman.
- Jenis pupuk majemuk adalah pupuk yang memiliki lebih dari 1 jenis unsur hara tanaman, seperti NPK yang memiliki kandungan N, fosfat (P) dan K untuk tanaman.

Pemberian pupuk ke tanaman, harus memperhatikan unsur hara apa yang dibutuhkan oleh tanaman. Tidak bisa diberikan sesukanya saja. Pemberian jenis pupuk yang sesuai dengan kebutuhan tentu akan memberikan efisiensi dan efektifitas bagi pertumbuhan dan perkembangan tanaman.

T2 Tepat Dosis

Setelah mengetahui jenis pupuk yang tepat untuk tanaman kelapa sawitnya, maka tahap berikutnya adalah penentuan dosis. Dosis pupuk ini ditentukan dengan memperhatikan jumlah unsur hara yang terangkut bersama produksi tandan buah segar (TBS) dan kebutuhan untuk mempertahankan pertumbuhan tanaman (vegetative) dan perbaikan status unsur hara tanaman.

Kandungan unsur hara dalam 1 ton TBS adalah 3,04 kg N; 0,385 kg P; 3,89 kg K dan 0,52 kg Mg. Berikut ini adalah gambaran jumlah unsur hara yang terangkut bersama dengan produksi TBS dengan beberapa tingkat produksi:

Range Produksi	Unsur Hara/Pupuk (kg)							
	N	Urea	P	SP36	K	KCl	Mg	Kiserite
5.00	15.20	33	1.93	12	19.45	39	2.58	16
10.00	30.40	66	3.85	24	38.90	78	5.15	32
15.00	45.60	99	5.78	37	58.35	117	7.73	48
20.00	60.80	132	7.70	49	77.80	156	10.30	64
25.00	76.00	165	9.63	61	97.25	195	12.88	79
30.00	91.20	198	11.55	73	116.70	234	15.45	95

Pupuk Urea dan KCl dapat diaplikasi 2-3 kali per tahun. Sementara pupuk SP36 dan Kiserite diaplikasi sekaligus (sekali setahun). Dosis per pokoknya diperoleh dengan cara membagikan total kebutuhan pupuk dengan total jumlah pokok di kebun yang menghasilkan produksi seperti dalam table di samping.

T3 Tepat Waktu

Tanaman kelapa sawit adalah tanaman berbuah sepanjang musim, oleh karena itu **ketersediaan unsur hara harus diusahakan berkelanjutan.** Pemupukan harus dihindari pada musim penghujan berlebihan (> 200mm/bulan) atau bisa dilihat dari indikator aliran permukaan sangat deras airnya. Pemupukan juga harus dihindari pada musim kering (<100mm/bulan) atau ditunjukan oleh daun tombak > 2 pelepah. Pada umumnya pupuk yang mengandung N (seperti urea, ZA, NK dan pupuk NPK) dan pupuk yang mengandung K (seperti KCl, NK dan NPK) diberikan 3 kali dalam setahun.

T4 Tepat Tempat

Tempat peletakan pupuk juga menjadi penentu tercapainya efisiensi dan efektifitas pemupukan. Pupuk selain urea dan pupuk yang mengandung unsur hara micro seperti HGFB (borate) seharusnya diaplikasi di gawangan mati dan antar pokok tempat dimana pelepah tersusun. Rumpukan pelepah ini penuh dengan akar aktif yang berfungsi dalam penyerapan unsur hara. Ketika pupuk diaplikasi di lokasi dimana penuh dengan akar-akar aktif, maka unsur hara akan segera terserap setelah pupuk yang diaplikasikan terurai menjadi ion. Sehingga, dampaknya bagi pertumbuhan dan perkembangan tanaman akan segera terjadi.

Petani peserta penelitian lapangan (BMP) diwajibkan mengikuti anjuran pengaplikasian pupuk di atas rumpukan pelepah yaitu di **gawangan mati dan antar pokok.** Ke 4T (Empat Tepat) yang disampaikan di atas tidaklah berdiri sendiri, untuk memperoleh efisiensi dan efektifitas pemupukan yang diharapkan harus didukung oleh faktor-faktor lain, seperti **pengendalian gulma yang baik,** gulma yang berat yang tidak dikendalikan akan menyebabkan banyaknya unsur hara yang diserap oleh gulma tersebut, pruning yang terlambat akan menyebabkan tidak efisiennya fotosintensis dimana banyak unsur hara akan dipergunakan untuk respirasi pelepah tua yang sudah tidak efektif dalam berfotosintensis, **penyusunan pelepah hasil pruning seharusnya disusun dengan bentuk huruf "U" atau "C"** sehingga dapat meningkatkan penyebaran bahan organik yang akan membantu meningkatkan kadar air tanah dan penyerapan unsur hara tanaman. Panen merupakan faktor pendukung secara langsung, interval panen yang panjang akan menyebabkan tingginya kehilangan produksi sebagai akibat meningkatnya buah busuk dan tidak terkutipnya brondolan.

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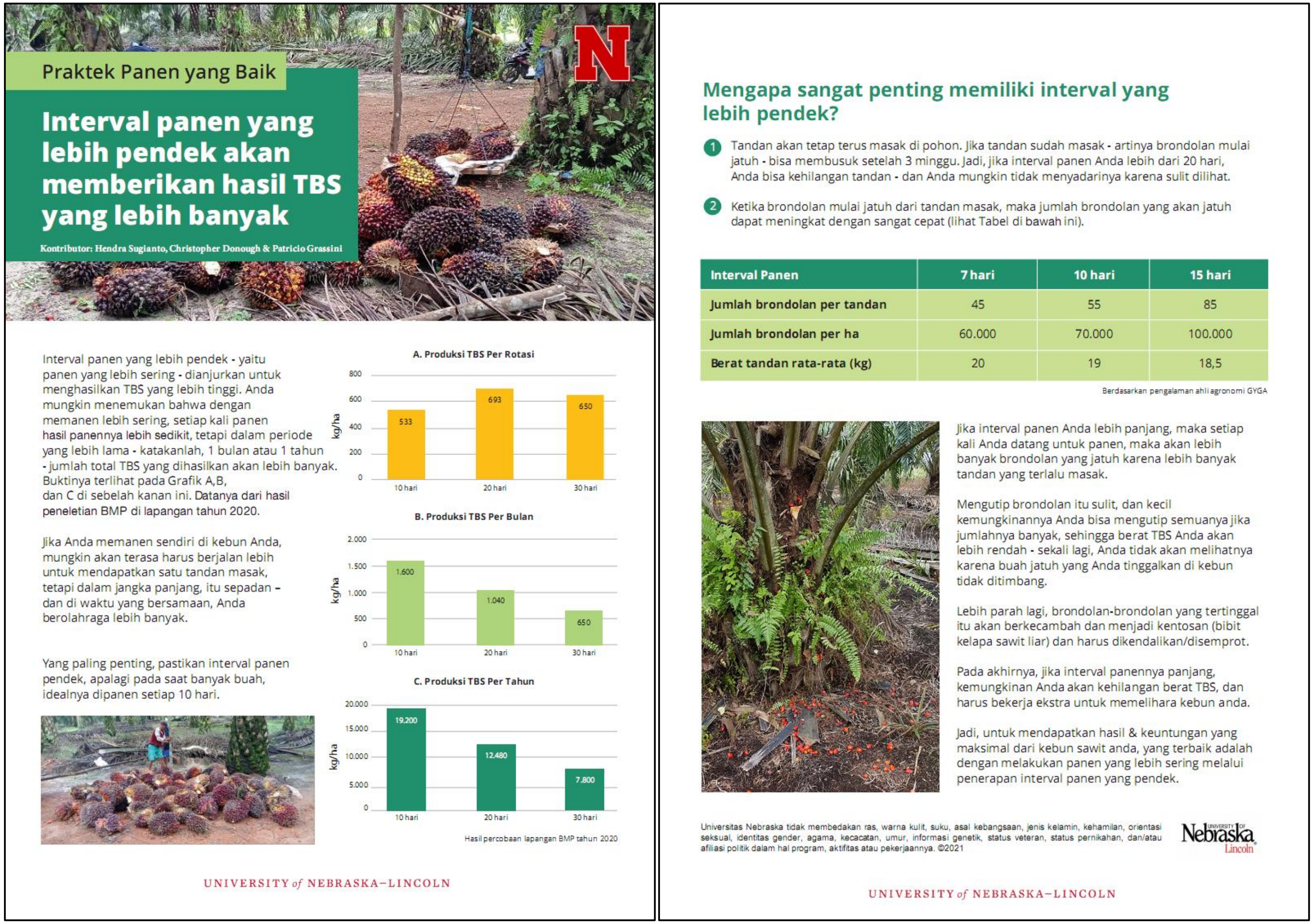
***Figure 4-1**. Flyer on fertilizer management for mature oil pam fields.*



Praktek Panen yang Baik

Interval panen yang lebih pendek akan memberikan hasil TBS yang lebih banyak

Kontributor: Hendra Sugianto, Christopher Donough & Patricio Grassini

Interval panen yang lebih pendek - yaitu panen yang lebih sering - dianjurkan untuk menghasilkan TBS yang lebih tinggi. Anda mungkin menemukan bahwa dengan memanen lebih sering, setiap kali panen hasil panennya lebih sedikit, tetapi dalam periode yang lebih lama - katakanlah, 1 bulan atau 1 tahun - jumlah total TBS yang dihasilkan akan lebih banyak. Buktinya terlihat pada Grafik A,B, dan C di sebelah kanan ini. Datanya dari hasil peneletian BMP di lapangan tahun 2020.

Jika Anda memanen sendiri di kebun Anda, mungkin akan terasa harus berjalan lebih untuk mendapatkan satu tandan masak, tetapi dalam jangka panjang, itu sepadan – dan di waktu yang bersamaan, Anda berolahraga lebih banyak.

Yang paling penting, pastikan interval panen pendek, apalagi pada saat banyak buah, idealnya dipanen setiap 10 hari.

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Mengapa sangat penting memiliki interval yang lebih pendek?

1. Tandan akan tetap terus masak di pohon. Jika tandan sudah masak - artinya brondolan mulai jatuh - bisa membusuk setelah 3 minggu. Jadi, jika interval panen Anda lebih dari 20 hari, Anda bisa kehilangan tandan - dan Anda mungkin tidak menyadarinya karena sulit dilihat.
2. Ketika brondolan mulai jatuh dari tandan masak, maka jumlah brondolan yang akan jatuh dapat meningkat dengan sangat cepat (lihat Tabel di bawah ini).

Interval Panen	7 hari	10 hari	15 hari
Jumlah brondolan per tandan	45	55	85
Jumlah brondolan per ha	60.000	70.000	100.000
Berat tandan rata-rata (kg)	20	19	18,5

Berdasarkan pengalaman ahli agronomi GYGA

Jika interval panen Anda lebih panjang, maka setiap kali Anda datang untuk panen, maka akan lebih banyak brondolan yang jatuh karena lebih banyak tandan yang terlalu masak.

Mengutip brondolan itu sulit, dan kecil kemungkinannya Anda bisa mengutip semuanya jika jumlahnya banyak, sehingga berat TBS Anda akan lebih rendah - sekali lagi, Anda tidak akan melihatnya karena buah jatuh yang Anda tinggalkan di kebun tidak ditimbang.

Lebih parah lagi, brondolan-brondolan yang tertinggal itu akan berkecambah dan menjadi kentosan (bibit kelapa sawit liar) dan harus dikendalikan/disemprot.

Pada akhirnya, jika interval panennya panjang, kemungkinan Anda akan kehilangan berat TBS, dan harus bekerja ekstra untuk memelihara kebun anda.

Jadi, untuk mendapatkan hasil & keuntungan yang maksimal dari kebun sawit anda, yang terbaik adalah dengan melakukan panen yang lebih sering melalui penerapan interval panen yang pendek.

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Figure 4-2. *Flyer on harvesting management.*

Pruning & Penyusunan Pelepah

Kontributor: Hendra Sugianto, Christopher Donough & Patricio Grassini

A. PRUNING

Pruning atau pemangkasan adalah proses pemotongan pelepah- pelepah yang sudah tidak produktif dan atau pelepah kering pada tanaman kelapa sawit. Pemotongan pelepah ini harus dilakukan serapat mungkin ke batang sawit, dengan tidak menyisakan pangkal pelepah yang bisa menyebabkan tersangkutnya brondolan.

Setidaknya ada 2 tujuan utama dari pruning, yaitu:

1. Mempertahankan jumlah pelepah yang optimal agar tanaman bisa berproduksi maksimal.
   a. Tanaman muda (<8 tahun) harus mempertahankan jumlah pelepah 48-56 pelepah (songgoh 3) atau 6-7 pelepah per spiral.
   b. Tanaman tua (≥ 8 tahun) jumlah pelepah yang harus dipertahankan adalah 32-48 (songgoh 2).
2. Memberikan akses agar panen bisa dilakukan dengan lebih efisien.
   a. Agar penglihatan pemanen tidak terhalang oleh pelepah-pelepah yang berlebihan dalam identifikasi tandan masak.
   b. Agar brondolan tidak tersangkut di pelepah-pelepah.

Foto 01. Penyusunan Pelepah Hasil Pruningan

Pruning bisa dilakukan bersamaan dengan panen, yang dikenal dengan istilah *progressive pruning*, atau dilakukan dengan tempo waktu tertentu misalnya 6 bulan atau setahun sekali. Pruning dengan tempo waktu tertentu lebih umum dilakukan setahun sekali.

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B. PENYUSUNAN PELEPAH HASIL PRUNING

Pelepah hasil pruningan seharusnya diperlakukan sebagai sumber bahan organik yang dapat dipergunakan untuk meningkatkan kesuburan tanah. Oleh karena itu, pelepah hasil pruningan ini harus disusun sedemikian rupa, agar dapat memberikan hasil yang maksimal bagi tanaman kelapa sawit.

1. Pelepah-pelepah ini disusun membentuk huruf "U" atau "C", sehingga hampir seluruh permukaan lahan dapat ditutupi dengan menyisakan pasar pikul dan piringan.
   - Lebar pasar pikul yang umum dipergunakan adalah 1,50 m demikian juga dengan jari-jari piringan, namun apabila tanaman sudah sangat tinggi maka lebar piringan yang tidak disusun dengan pelepah bisa lebih lebar agar proses panen bisa lebih mudah.
2. Bagian pangkal pelepah harus diletakan ke gawangan mati yaitu bagian ujung pelepah diarahkan ke pasar pikul.

Foto 02. (Kiri) Kondisi tanah terbuka (akar kering dan mati), (kanan) Kondisi akar dibawah rumpukan pelepah, segar, dan aktif.

Ada beberapa keuntungan yang diperoleh dengan melakukan penyusunan pelepah huruf "U" atau "C" ini antara lain:

1. Konservasi tanah dan air, dengan pemerataan penyusunan pelepah ini maka permukaan tanah yang tertutupi akan semakin banyak.

Sehingga benturan butiran air hujan yang sampai ke permukaan yang dapat menghancurkan agregat tanah menjadi berkurang pula.
- Volume air yang akan masuk ke dalam tanah akan meningkat, itu berarti aliran permukaan akan menurun sehingga pengikisan tanah lapisan atas juga menurun.
- *Ilustrasi (foto 02), coba perhatikan tanah yang tidak tertutupi, tanah menjadi rusak dan akar terlihat (kering dan mati), sementara tanah yang dibawah permukaan rumpukan pelepah terlihat lebih basah dan akar-akar sangat segar (hidup).*
  - *Tentu dengan jumlah akar sehat yang makin banyak, maka penyerapan unsur hara (pupuk) akan lebih baik.*

2. Membantu menekan pertumbuhan gulma, itu berarti menghemat biaya pengendalian gulma juga.

Berdasarkan informasi dari data yang diberikan, diketahui bahwa kebanyakan petani menyusun pelepah hasil pruning seperti huruf "I" lurus di gawangan mati. Tentu pola penyusunan ini tidak memanfaatkan bahan organik dari pelepah secara maksimal.

Petani peserta penelitian lapangan (BMP) wajib menyusun pelepah hasil pruning dengan pola huruf "U" atau "C" ini, agar manfaat bahan organik dari pelepah ini dapat membantu meningkatkan produksi.

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Figure 4-3. *Flyer on pruning and cut-fronds arrangement.*

#2. Field days (Figure 4.4-4.5) A total of 17 fields days were organized, around three topics (yield formation, nutrient management, and yield benchmarking). Each field day was attended, on average, by ca. 200 farmers. On what follows there is a brief description of what was covered under each topic:

(i) Yield formation. We dissected a palm in situ to give farmers an idea on the process of yield formation, from inflorescences to ripped bunches, and the impact of agronomic factors at different stages. This way, we hope farmers would understand that what they do today will have an impact later on.

(ii) Nutrient management. We provided fertilizer information regarding the contents as stated on the fertilizer bag, followed by demonstrations on how to select appropriate sources (right source), how to calculate fertilizer requirement based on FFB yield (right rate), where to place the fertilizer (right place) and time of the application (right time).

(iii) Yield benchmarking. We generated a scorecard for each farmer, showing his/her field yield in relation to that from other 200 farmer fields at each site. The goal was to show farmer the importance to keep track of yield (and learn how to estimate it), farmers must measure their field activities, in order to be able to diagnose their productivity level and eventually, try to understand what are the management practices that other farmers are following to attain higher yields under comparable climate and soil conditions.

Figure 4-4. *Some pictures of the field days organized in our study.*

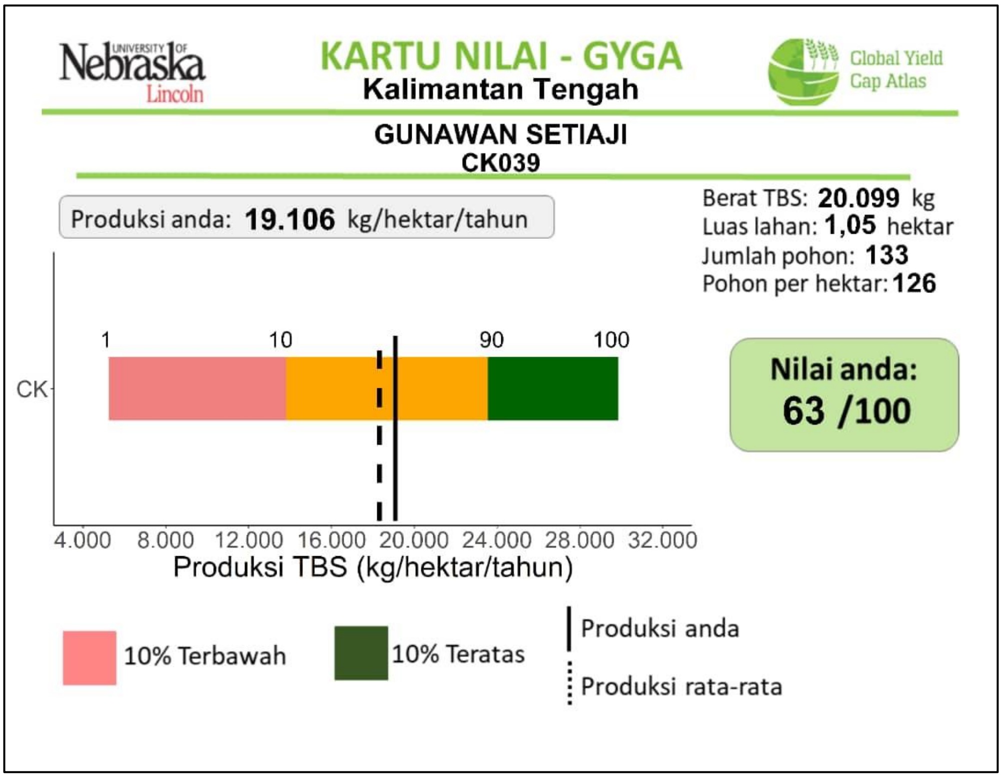

Figure 4-5. *Score card for farmer's yield performance within the GYGA-club farmers yield performance.*

#3. Basic agronomy training for NGOs' agronomists: We have conducted five sessions of the events, namely (i) better management practices; (ii) weed management; (iii) fertilizer and nutrient management; (iv) determination of fertilizer rate; (v) management of pests and diseases.

#4. Frequently asked questions (FAQs): We provided an opportunity for farmers who may have special issues in their fields, so they could ask us any kind of questions regarding the oil palm management following a process involving NGOs and the UNL core team (Figure 4.6). There was a total of 193 questions, the most common ones were on fertilization, followed by pests & diseases and production.

Figure 4-6. *The process for Frequently asked questions (FAQs) by GYGA club farmers. The questions were collected by NGO (non-government organization) enumerators then compiled by the NGO FAQ team, then submitted to the UNL team to get response on the questions. The response would be received by the NGO FAQ team and then distributed by the NGO's enumerators to all the GYGA club farmers.*

#5. Pocket guide (Figure 4.7): We put together a pocket guide on BMPs for smallholder oil palm farmers in collaboration with the Indonesian Oil Palm Research Institute (IOPRI). The topics included in the pocket guide are: better management practices (harvesting, pruning, cut-fronds arrangement, fertilization following 4Rs approach: type, rate, place and time, nutrients deficiency symptoms, organic matter for field application, ground management, pest and diseases management, and field activities recording).

Figure 4-7. *Cover of pocket guide (Bahasa version), containing 17 chapters (topics) discussing better management practices for oil palm, including harvesting, fertilization, pruning and cut-fronds arrangement, field upkeep, nutrient deficiencies, pest and disease management and data recording.*

Finally, throughout the four years of dissemination activities with farmers, we have derived a number of conclusions in relation to their capacity to learn and implement BMPs:

1. Farmers do not have or very little access to any reliable source of technical information.
2. Farmers do not know how to diagnose nutrient deficient or make fertilizer recommendations (not even how to choose fertilizer).
3. Most farmers do not know how to recognize/interpret the nutrient composition of fertilizers
4. Many farmers do not know basic principles for proper weed management, and many of them simply sprayed completely and leave the land without protection.
5. Some farmers may lack the necessary capital for investing in improved farming practices, technology, or accessing credit to expand their operations. However, this is not the main constraint for most of them.
6. Technology on its own does not necessarily resolve problems, we need the correct socio-economic context. Available options are to promote record keeping, joint selling and farmer discussion groups.

The following changes have occurred in the non-field trial fields:

1. Nutrient management. Some farmers have replaced NPK15-15-15 (NPK15) fertilizer with NPK13-6-27-4 (NPK13) fertilizer that is more suitable for oil palm, even though NPK13 is about twice as expensive as NPK15. Farmers

who participated in this study recognize that better nutritional management would increase their plantation's FFB yield.

2. Blanket spraying. Several farmers have stopped spraying their entire fields, so the soil now has vegetation to provide protection from soil erosion.
3. Cut-frond arrangement. Some farmers have changed their cut-frond arrangement from “I” pattern to “C/U” pattern that cover more area and better organic distribution. In this way, soil and water conservation were improved.

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