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RESEARCH ARTICLE

Oil palm smallholder's management practices and yield: a case study in Krabi, Southern Thailand

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Summary

In recent years, Southern Thailand has witnessed an increase in surface planted with oil palm, driven primarily by smallholders who contribute over 90% of Thailand's oil palm output. Despite their significant contribution, oil palm smallholders have consistently achieved lower yields compared to agro-industries, and limited research has been conducted to understand the limiting factors, such as management practices. Structured interviews were conducted to gather information about management practices and estimate the fresh fruit bunch yield in a network of 18 plantations in Krabi province, Thailand. A clustering approach, combining principal component analysis and hierarchical cluster analysis, was used to characterise the diversity of smallholder management practices. Four clusters of management practices were highlighted, characterised by varying intensities of fertiliser application (nitrogen, phosphorus, and potassium), mechanical versus chemical weeding, and harvest intervals. Notably, the farmers in our study applied less fertiliser, on average, than the recommendations of Thai Good Agricultural Practices. A significant portion of plots in the area (12 out of 18 plots) achieved good yields compared to attainable yields. A clear relationship between management practices and yield could however not be established. The large diversity of oil palm smallholders' management practices and their performances highlighted in this study need to be better taken into account and understood in order to improve sustainability and foster certification schemes such as Roundtable on Sustainable Palm Oil (RSPO).

Keywords: agronomy; production; farmer practices; cluster analysis

Introduction

During the last 10 years, palm oil has emerged as the leading vegetable oil on a global scale, surpassing its counterparts. Approximately 35% of all vegetable oils consumed worldwide are derived from oil palm. Oil palm production has efficient land utilisation, requiring less than 10% of the total land allocated to oilseed crops (OECD-FAO, 2022). The demand for palm oil is increasing rapidly globally, and the supply market is dominated by Indonesia and Malaysia, the two major producing countries, which contribute 80% of global oil palm production (OECD-FAO, 2022). Oil palm is linked to multiple concerns worldwide over increasing plantation surfaces, which is a key cause of deforestation, large emissions of greenhouse gases, biodiversity loss, land conflicts, and/or labour abuses (Ogahara *et al.*, 2022). The adoption of new regulations that aim at monitoring the impacts of the supply chain, such as the European Union Deforestation-Free Regulation, may put even more pressure on governments in the major oil palm producing countries in the coming years (Leijten *et al.*, 2023; Marín Durán and Scott, 2022). Given the benefits of oil palm land utilisation, improving existing oil palm productivity is thus of prime importance.

The global demand for oil palm opens opportunities for Thailand, which was the world's third largest oil palm producer in 2023. As of 2020, Thailand had 6.2 million ha planted with oil palms and produced 16.2 million tonnes of fresh fruit bunches (FFBs) (OAE, 2022). According to governmental statistics, the production of FFBs in the oil palm sector is projected to reach around 23 million tonnes by 2031, alongside an expected increase in the plantation area of up to 9 million hectares by the same year, facilitated by supportive policies aiming for an average annual growth rate of 1.04% (OAE, 2022). The oil palm industry has become one of the major sources of income and employment, particularly in Southern Thailand (Somnuek *et al.*, 2016). In this region, farmers have gradually shifted from perennial crops, paddy rice, orchards, and rubber to growing oil palm. According to the Office of Agricultural Economics, the number of oil palm growers in Thailand increased by around 30% between 2013 and 2019. The drivers of land use change are numerous, such as national policies, agricultural prices, and economic growth (Jayathilake *et al.*, 2023; Nualnoom *et al.*, 2016; Wicke *et al.*, 2011). Particularly, the subsidies given for conversion from rubber or abandoned paddy fields to oil palms are favouring the farmers to turn to oil palm in Thailand (Keson *et al.*, 2015; Somnuek *et al.*, 2016).

Smallholder plantations account for 40% of the oil palm production in Malaysia and Indonesia (Nagiah and Azmi, 2013; Rahman, 2020). In contrast, Thai smallholders are the main actors in the oil palm production system, where they contribute more than 90% of the nation's oil palm production (Efeca, 2018). As of 2019, the number of smallholders growing oil palm was 364 864, with a 1% annual growth rate (OAE, 2022). While there have been numerous studies on management practices and oil palm performance in other countries, such as Indonesia and Malaysia, there has been limited research conducted in Thailand, especially concerning smallholder plantations. Understanding these practices is critical for informing policies and interventions aimed at enhancing the sustainability and efficiency of the oil palm industry in Thailand.

Most smallholder FFB yields fall well below attainable yield (Euler *et al.*, 2016; Lee *et al.*, 2014; Woittiez *et al.*, 2017). This was attributed to several factors, such as choice of planting material, soil and climate, pests and diseases, and management practices (Monzon *et al.*, 2023; Ab Rahman *et al.*, 2008; Woittiez *et al.*, 2017). Monzon *et al.* (2023) recently highlighted that agronomic practices are critical drivers to fill the yield gap. Among the agronomic practices, nutrient management, harvest interval, weed control, and pruning were observed as those most significantly influencing yield in a smallholder network in Indonesia (Monzon *et al.*, 2023). Smallholders who follow recommended best management practices, particularly in terms of fertilisation, tend to achieve higher yields in various contexts, such as in Indonesia (Monzon *et al.*, 2023; Sugianto *et al.*, 2023; Thoumazeau *et al.*, 2024) and Ghana (Atta-Ankomah and Danso-Mensah, 2022; Rhebergen *et al.*, 2020). These studies collectively emphasise the crucial link between effective management practices and production performance (yield), as improved management can help smallholders increase yield and profit on existing plantations (Mettauer *et al.*, 2021).

This research aims to characterise the smallholders' management practices and test their relationship with the yield of oil palm plantations in Southern Thailand. We first describe the management practices implemented by the farmers in the area. Then, a farmer typology is implemented to collect a gradient of the diversity of practices at the plot scale that was linked to plot yield. We hypothesise that optimised management practices could contribute to the reduction of the yield gap among smallholders. Identifying these practices could help smallholder farmers optimise their performance.

Material and methods

Study site and plot selection

The study was implemented on a study area of 9 km^2 in Plai Phraya district, Krabi province (8.5073 °N, 98.86732 °E) from May 2023 to July 2023. Krabi is one of the provinces in Thailand where more than 50% (1568 km^2) of the province's farmland is under oil palm cultivation (OAE, 2022). The villages in Plai Phraya district had diverse land uses before cultivating oil palm plantations, including a first generation of oil palm, rice, and rubber. The annual average temperature and precipitation for Krabi from 1991 to 2020 are described in Supplementary Material Figure S1. The region typically receives an average monthly rainfall of more than 230 mm from May to November. During the dry season (December to April), the average monthly rainfall is below 140 mm. The lowest rainfall (~35 mm) can be expected in February. The mean temperature stands between 27 °C and 29 °C. In all the study areas, soils are Ultisols. However, they slightly differed according to the Thai soil series (Figure S2). The soil series that were observed are classified as Pac chan (Pac), Sai Buri (Bu), Rueso (Ro), Lamphu la (Ll), and Phato (Pto).

We selected 18 oil palm (*Elaeis guineensis Jacq.*) plots in the Plai Phraya district. The plots had different previous land use types (rubber, rice, or oil palm) and differed in terms of age (6–25 years). We had a well-distributed number of plots for these two factors (previous land use and oil palm age) to cover a variety of cropping conditions. We did not have any selection criteria on the management practices, as it was one of the factors tested. The area of the smallholders' plots ranged from 0.3 Ha to 3 Ha.

Data collection

To understand current farm management practices as well as production-related practices, a structured questionnaire was prepared, which focused on management practices at the plot scale (Figure S3). The interviewee was the manager of the plot's activities on each plot. The questionnaire consisted of five parts: Farm characteristics, previous crop management, current practices (irrigation, pest monitoring, weeding, fertilising, pruning, and harvesting), plot economics, and social aspects. For this paper, we excluded the data collected on plot economics and social aspects. The interviews were conducted with the help of simultaneous translation (Thai-English) by a native and local speaker. The help of local experts and some data triangulation based on selling point records provided some safeguards regarding uncertainty embedded in farmers' interviews due to the lack of a systematic tracking of practices and yield.

Data on management practices were collected over 3 years (2020–21 to 2022–23) to integrate potential variations over time. Details related to planting material, such as seed variety and location of purchase, were gathered. If farmers irrigated their plots, data on irrigation frequency and area were collected. In addition, to understand the drainage capability, information about the flooded area and the number of days flooded was noted. Information about fertiliser applications, such as fertiliser composition, period of application, quantity applied per palm, frequency per year, and location of application, was also collected. We did not integrate the oil palm density for fertiliser application rate and considered the standard density to be 143 palms per hectare. Preliminary analysis showed a strong correlation between standard density and actual oil palm density observed in the plot (Figure S4). We did not convert the values of organic amendments (OA) into N, P, and K

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equivalents due to the lack of robust information provided by the farmer in terms of OA characteristics and application rate over the past 3 years. Disease and pest observations in the plantations and control measures were also collected. For pruning, we asked about the number of times pruning was performed per year, the pruning period, and the frond placement zones. For the weeding activity, frequency, period of the year, herbicide name, and quantity of application were collected. In addition, information on weeding zones was also gathered during interviews. The chemical treatment frequency index (TFI) was calculated based on equation (1).

$$\text{TFI}: \sum n * \frac{Va * As}{Dr} \tag{1}$$

where n is the frequency of chemical weeding performed for a given commercial herbicide in a year, Va is the volume of applied herbicide, As is the quantity of active product for the given commercial herbicide (mg ha^{-1}), and Dr is the recommended dose of active product for the given herbicide for oil palm plantations (mg ha^{-1}).

The density of oil palms (palms per hectare) was assessed by manually counting the number of palms in the field, with the plot boundary and area information provided by the landowner.

For data related to harvesting, we collected data for one year (June 2022– May 2023). Annual yield data were challenging to collect as most farmers did not record their production, and the collecting point mixed the harvests of the different farmers' plots. We asked farmers about the months in which the production quantity of FFB was at its peak and when it was low in their plots. Furthermore, farmers were requested to share the highest frequency and second highest quantities produced during peak and off-peak seasons. They were also asked to provide the quantity produced during these specific periods and the number of harvests that occurred during these periods. Finally, equation (2) was used to calculate the estimated annual yield for all the plots.

$$Yield_{est} = Q_p M_p \left(\frac{H}{12}\right) + Q_l M_l \left(\frac{H}{12}\right) + 2 \times avg(Q_p, Q_l)\left(\frac{H}{12}\right) \tag{2}$$

where Q_p and Q_l are the mean quantities produced during the peak months M_p and off-peak months $M_{l.}$ The number of off-peak months M_l is calculated by 10-M_p. H is the number of harvests calculated based on the harvesting interval.

To validate equation (2), we compared the output of the equation (Yield$_{\text{est}}$) with real data that we could collect at the collecting point from two farmers who only had one plot of oil palm. We observed similar values for the estimated and observed yield (Figure S5).

Statistical analysis

All statistical analysis was performed using R software (R Development Core Team, 2008). To analyse diversity in management practices, we built a typology of technical operations following the first step of the Typ-iti method (Akakpo *et al.*, 2021; Renaud-Gentié *et al.*, 2014). This method allowed us to group farmers with similar practices and distinguish them from other groups. We implemented this procedure on a yearly basis for technical operations, integrating 3 years: 2020–21, 2021–22, and 2022–23. This resulted in 54 individuals (18 plots × 3 years).

As a first step, variables linked to management practices were transformed into quantitative variables and modalities. The initial list of 20 variables and modalities is shown in the table (Table S1a). For variables that had a continuous range of values, we divided them into quartiles and defined four modalities. If one modality was represented by more than 80% of individuals, the associated variable was not included for further analysis (Akakpo *et al.*, 2021; Renaud-Gentié *et al.*, 2014). A set of 13 variables was obtained (Table S1b). This set of variables included the oil palm density, quantity, and application frequency of nitrogen (N), phosphorus (P), and potassium (K)

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fertilisers, chemical and mechanical weeding counts, pruning frequency, and the harvesting interval (Table S1b). Missing values, representing less than 2% of the global data set, were imputed using the missMDA package. Subsequently, we conducted a Multiple Correspondence Analysis (MCA) using the FactoMineR package (Husson *et al*., 2013). The MCA results provided insights into the clustering patterns of individuals and the significance of variables in explaining the observed variations. Following this, we performed an Ascending Hierarchical Correspondences analysis to identify distinct clusters within the dataset, employing dendrograms, cluster visualisations, and statistical tests for validation. The optimal number of clusters was determined through the Elbow method. Finally, we identified the significant variables ($n = 8$) and modalities, along with the most representative individuals.

The link between management practices and yield was addressed through a visual representation of the association between clusters and yield groups.

Results

Management practices description

All the plots were planted with Tenera oil palm seedlings. Most of these seedling sources can be traced back to the 'Golden Tenera' or 'Univanich' company (Table S2). Other farmers have less common sources of seedlings, such as 'Thaksin palm', 'Nong ped', and 'Surat thani 7' from Department of Agriculture (DOA). The oil palm density of the plantations varied from 109 to 170 palms per hectare. The observed planting pattern of oil palms was predominantly triangular, except for one plot where the palms were planted in a square pattern.

Water canals run throughout the study area, and there is no sign of water scarcity. Among the 18 farmers, three chose to irrigate their plots. This was performed only during the dry season (Dec–May), when rainfall was low. Irrigation was done by directing the canal waters into the plot through a large pipe controlled by the farmer. This was done two times per season, and a single irrigation time varied between 48 and 96 hours. Three farmers mentioned that more than 80% of their plot was submerged during heavy rains, which happen during July–November. The rainwater usually logs from a few days to weeks, indicating poor drainage capability. Other three farmers shared similar experiences of having their plots flooded for 1–2 days after heavy rains. All these six plantations have 'Bu' and 'Ro' soil series, which are lowland terrains.

The list of mineral fertilisers used by farmers is presented in Figure S6. Although numerous fertiliser compositions were used, these were actually a mix of three commonly used fertilisers in various proportions, which were ammonium sulphate (21-0-0), Muriate of potash (0-0-60), and di-ammonium phosphate (18-46-0). The average application rate of macronutrients through mineral fertilisation (N, P, and K) per ha per year over 3 years varied between the study plots (Figure 1). The average N application rate was 82.68 kg ha^{-1} yr^{-1} with a coefficient of variance (CV) of 50%. The average P application rate was 18.41 kg ha^{-1} yr^{-1} with a CV of 76%. The application rate for K was 150.6 with a CV of 69%. High variance was observed for K values, which was relatively higher than N or P. Farmers applied similar amounts of mineral fertilisers regardless of whether they also applied organic fertilisers. They even tended to increase the quantity of mineral fertiliser application when incorporating organic inputs (Figure 1a,b). Regarding the application zones, 10 farmers applied fertiliser around each palm, and 4 farmers applied it in windrows. Three farmers broadcast fertiliser further from the palms, that is, between the palms. One farmer stopped applying fertiliser in 2022, as he intends to cut the palms and replant with new ones in the subsequent year. The period of fertiliser application varied significantly among farmers and also within each year.

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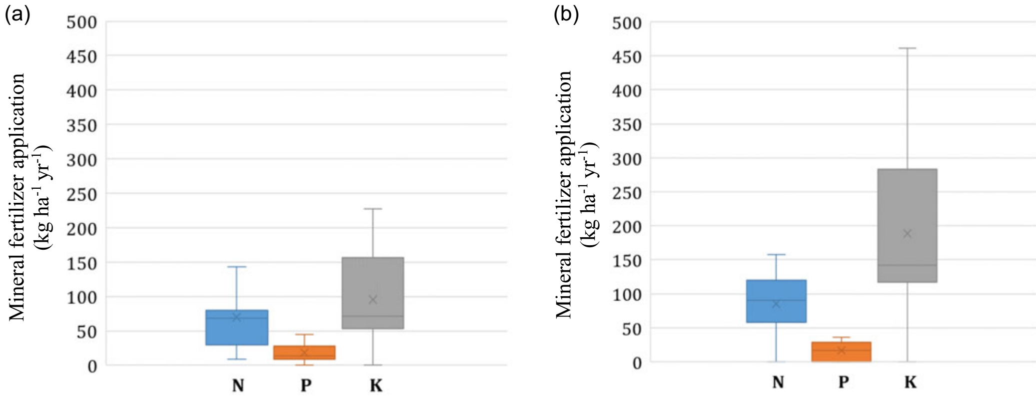

Figure 1. (a) Box plot of mean N, P, and K application rate from mineral fertilisation over the last 3 years of farmers who applied mineral fertilisers only ($n = 9$). (b) Box plot of mean N, P, and K application rate from mineral fertilisation over the last 3 years of farmers who applied mineral fertilisers and organic amendments ($n = 9$).

Another micronutrient, boron, was applied separately by 12 farmers, and among these, 8 of them applied it regularly every year. The quantity applied was highly variable among farmers and ranged from 1 to 2 tablespoons to 200 g. Magnesium was applied once in the last three years by two farmers; between them, one farmer applied only to the palms that showed deficiency in leaves.

In addition to mineral fertilisation, a diverse range of OA was used, including animal manure (chicken, goat, cow, and pigs) and recycled materials such as empty fruit bunches (EFB), palm kernel cake, and vegetable compost. One farmer had also started to use nano-bio-fertilisers (seaweed based). Around 50% of the interviewed plots incorporated one or more OA mentioned in their plots. Three out of the 18 plots applied at least one type of OA in their plot every year. The application zone for OA is mostly near windrows. The quantity, type, and frequency of using OA vary largely among the farmers and were linked to the availability of animal manure and/or the purchase price for palm kernel cake, or EFB.

Pruning was done once a year in 15 plots and twice a year in 2 plots. It was mainly considered a separate activity rather than something that was done during harvesting. In only one plot, the pruning was done only during harvesting activities. The period of pruning for three years was consistent among all the farmers in the study and was conducted during April–July. More than 80% of the farmers placed fronds in windrows. Among these, four farmers stacked fronds in alternating rows, making harvesting easier. Three farmers spread fronds in a U-shaped pattern around the palms.

The farmers did not implement any measures to control or monitor rat infestations, despite the fact that damage had occurred. None of the farmers implemented control measures to prevent pests such as the rhinoceros beetle (*Oryctes rhinoceros*). However, five farmers monitored their plots; these were farmers who had replanted oil palms in their plots.

The weed control was either mechanical only or both mechanical and chemical (herbicide application). All farmers performed mechanical weeding over the last 3 years; however, chemical weeding was done by 10 farmers. The mechanical weeding was performed either using hand-held grass cutters or mowing tractors. Mechanical weeding was performed more or less regularly every year and done in either of the four seasons (Mar–May, Jun–Aug, Sept–Nov, or Dec–Feb) (Table 1). Among the 10 farmers who applied herbicide, half of them applied it during the

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Table 1. Timeline of the weeding activities implemented in the 19 oil palm plots

	Weeding period											
Plot code	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Plot 1							M					
Plot 2							M					
Plot 3										M		
Plot 4									M,C*,†			M
Plot 5	C‡			M			C†					M
Plot 6					M						M	
Plot 7											M	
Plot 8					M							M
Plot 9				M,C‡	C*,†		M		C†			
Plot 10				M			M					
Plot 11	M,C‡					M						
Plot 12						M	C†			M		
Plot 13	M			M,C*,†			M			M		
Plot 14				M								M
Plot 15	M			C‡			M					
Plot 16			C*,†	M								
Plot 17		M		C*						M		
Plot 18				M				M				M,C*

M = mechanical weeding carried out by farmers every year, at approximately the same time; C = chemical weeding performed based on necessity between 2020 and 2023.*Chemical weeding in 2020–21.
†Chemical weeding in 2021–22.
‡Chemical weeding in 2022–23.

Mar-May period, depending on weed growth and density (Table 1). The rest of them chose Jul–Sept or Dec–Jan as the preferred period of herbicide application (Table 1). The herbicide doses applied ranged from 0.5 to 2.5 times the minimum recommended effective dosage, with an average of 1.5 among the 18 plots.

Most of the smallholders (66%) organise their harvests by contacting a harvesting team, usually gathering family members and other groups of labourers. Four farmers managed the FFB harvest by themselves, while two other farmers hired relatives. The harvesting interval among the smallholders varied between 2 and 3 weeks. Thirteen farmers responded that their usual harvesting interval is 18 or 19 days.

Typology

The significant variables that defined clusters were (i) oil palm planting density (OP density), (ii) frequency of chemical fertiliser application, (iii) quantity of chemical fertiliser (N, P, and K) applied, (iv) frequency of chemical and mechanical weeding, and (v) harvesting interval (Table S1c). Four clusters were defined for 54 individuals on the 2 main dimensions that constitute 26.3% of the dataset variation (Figure 2a). Cluster 1 (C1) consists of 15 individuals; cluster 2 (C2) represents 12 individuals. Clusters C3 and C4 consist of 12 and 15 individuals, respectively. Clusters C1 and C2 in the dendrogram merge at the same level (Figure 2b), which indicates that they have a moderate level of similarity compared to other clusters, which is also observed with individuals overlapping in Figure 2a. Most of the plots were assigned to the same cluster each year for the last 3 years, suggesting that the farmers did not change management practices over time

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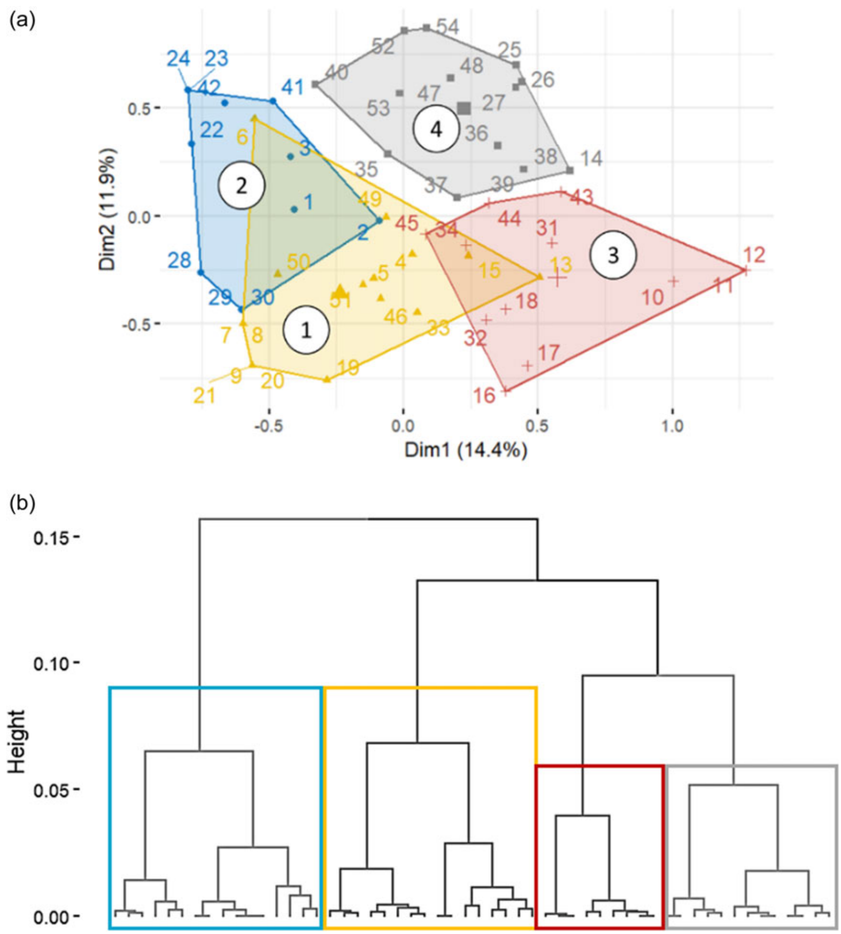

Figure 2. (a) Factor map of individuals and clusters plotted on dimensions 1 and 2. (b) Cluster dendrogram of individuals.

(Table S3). Only five plots were assigned to two different clusters. These plots were reassigned to clusters, which majorly represented them.

Figure 3 shows the variables and modalities of management practices that characterise the different clusters. Individuals in C1 represent farmers who apply low quantities of fertiliser and do not perform mechanical weeding more than once per year. These farmers also tend to have shorter harvesting intervals and, thus, more harvests per year. On the other hand, C2 farmers' plots have a medium planting density (126–140 palms ha^{-1}), which stands below the recommended 143 palms ha^{-1}. Another significant variable that characterised this C2 cluster was the mechanical weeding intensity, which was higher (>1) than that of C1 farmers. Optimal (N) and moderate use (K) were observed for C3 farmers. The application rate of K was in the range of 80–160 kg ha^{-1} yr^{-1} for C3 farmers, which was less than C2 farmers. For the C4 cluster, fewer variables were representative. Farmers applied chemical fertilisers more frequently (3–4 times per year) and higher amounts of N (>114 kg ha^{-1} year^{-1}) than other clusters. Furthermore, C4 farmers performed chemical weeding on their plots more often.

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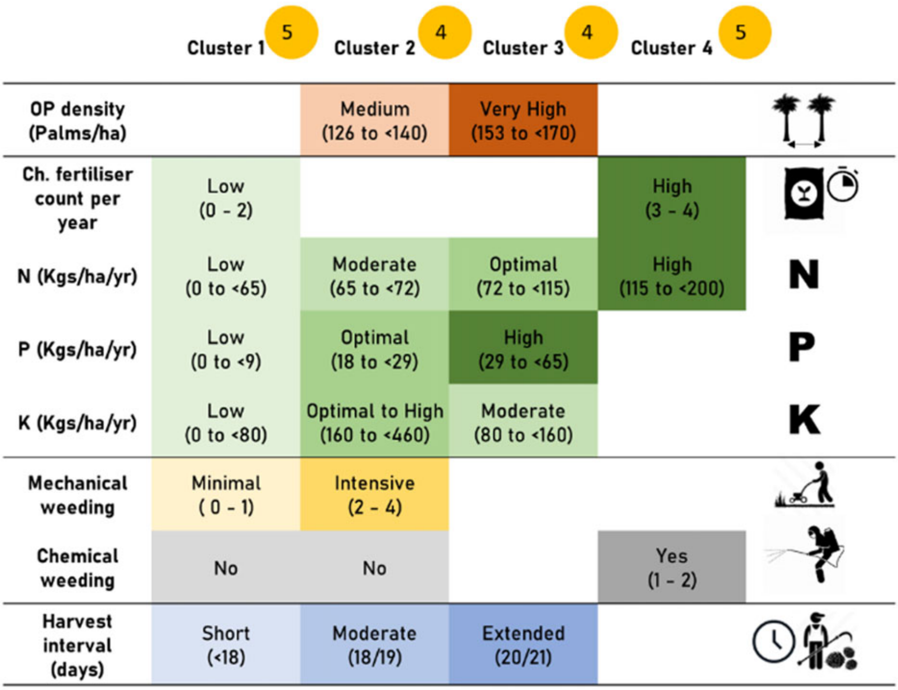

Figure 3. Representation of the four clusters and their characteristics with variables and modalities linked to management practices. The number of farmers per cluster is shown in the yellow sphere.

Yield assessment

On average, the yield achieved by smallholders in Plai Phraya is 20.61 tonnes FFB ha^{-1} yr^{-1}, while a high variability was observed between them (min = 12.54 tonnes FFB ha^{-1} yr^{-1}; max = 28.63 tonnes FFB ha^{-1} yr^{-1}; CV = 24.64%). The yield plotted for various plantation ages is compared with the attainable yield (Yatt) and yield data from large plantations in Indonesia (Yind) in Figure 4. Three groups (S1, S2, and S3) were identified. The S1 group consists of six plantations with a stand age of less than 6 years. The S1 farmers' yields show a large variance but are rather close to Yatt. The group S3 contains five plots with yield ranging between 25.3 and 28.6 FFB tonnes ha^{-1} yr^{-1}. S3 farmers achieve a yield close to the attainable yield as well (Figure 4). On the other hand, the S2 group consists of seven plantations (about 40%) aged from 6 to 25 years with yields between 12.5 and 19.6 FFB tonnes ha^{-1} yr^{-1}, which is below the Yatt curve. The yield of S2 farmers falls below the attainable yield.

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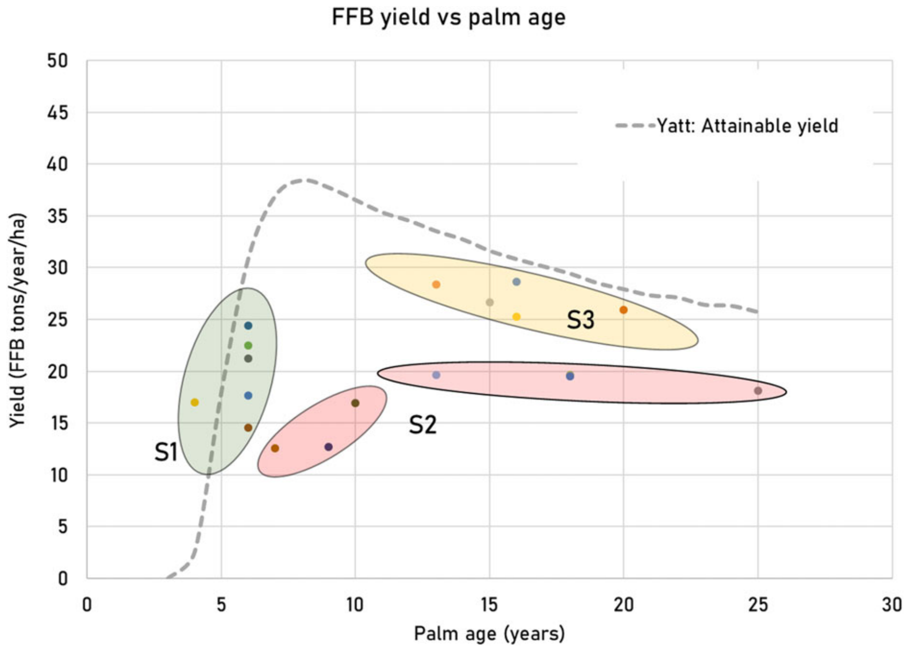

Figure 4. Annual estimated yield of smallholders (scatter points) compared with Yatt: attainable yield (grey line) obtained from www.yieldgap.org.

Linkages between management practice and yield

On one side, Farmers in the C1 cluster who applied lower N and K quantities are present both in high-yielding groups (S1 and S3) and in the relatively lower yield group (S2) (Figure 5). On another side, the farmers with more optimal fertilisation practices (C2–C3) were also observed in high-yielding groups (S1 and S3) but also in the relatively lower yield group (S2) (Figure 5). The low-yielding group (S2) could not be attributed to any specific management practice cluster. The four practices clusters were observed to be linked to S2 (Figure 5).

Discussion

Management practices diversity

The typology of practices implemented provided a good indication of the diversity of plot management, particularly in terms of fertiliser use. The C1 cluster consists of low-intensive farmers, while C2 and C3 clusters had farmers with moderately intensive/optimal use, and C4 cluster consists of relatively more intensive farmers. The average N, P, and K application rates through mineral fertilisation over the past 3 years were 84.38, 19.06, and 154.05 kg ha^{-1} yr^{-1}. This rate stands as lower than the recommended fertilisation rates based on Thai Good Agricultural Practices for an optimal planting density of 143 palms ha^{-1}, which is 151, 5.7, and 284 kg ha^{-1} yr^{-1} for N, P, and K, respectively (Somnuek and Slingerland, 2018). The application rates applied in the village were also mostly lower than other studies on smallholder plots with Ultisols (Goh, 2004; Ng *et al.*, 1999; Rhebergen *et al.*, 2014; Woittiez *et al.*, 2019), signifying a margin to close the gap in fertiliser applications by some farmers in the study area. The farmers interviewed expressed that the prices of fertilisers were higher than usual between December 2021 and March 2023 (Figure S6b), which could explain lower application rates (Sugianto *et al.*, 2023). The N-P-K calculation in this research did not account for nutrient content derived from OA, given that half

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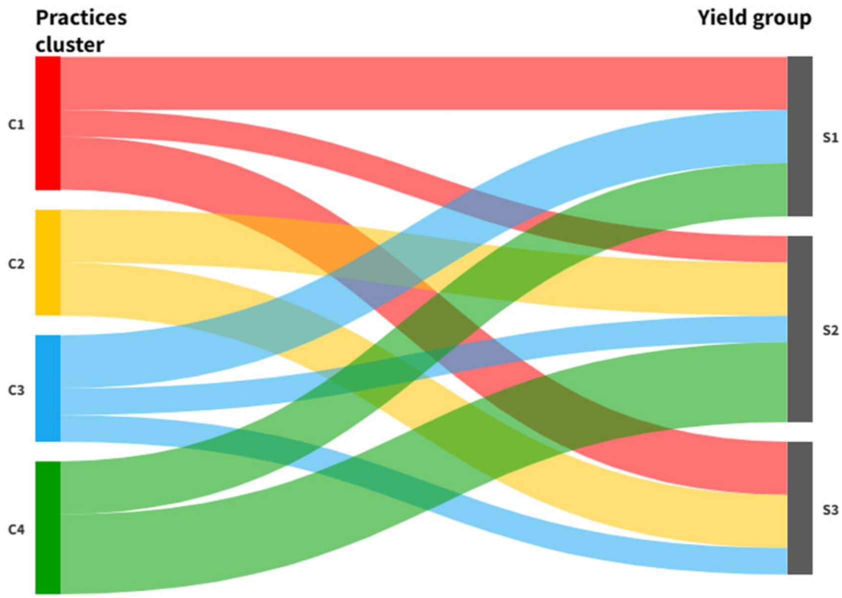

Figure 5. Parallel set graph showing the relationship between management practices clusters (C1, C2, C3, and C4 – see Figure 4) and yield groups (S1, S2, and S3 – see Figure 5).

of the farmers applied them irregularly over the past 3 years. Those OA may reduce the nutrient gap observed on mineral fertilisers for part of the farmers. Price and availability were major drivers for the application of organic materials. Farmers who were well connected with people who managed poultry or livestock were able to procure animal manure when it was available.

On average, the chemical treatment by the 18 farmers was higher than the recommended dosage. TFI values are similar to those of the study by Mettauer *et al.* (2021); however, they report higher variability (0–5) of TFI. Furthermore, on average, the farmers in this study applied 3.9 litres/ha of herbicide, which was lower than the amounts reported in another study on smallholders in Indonesia, where farmers applied 4.8–5.9 litres/ha (Euler *et al.*, 2016). Most of the farmers interviewed were environmentally conscious of the impact of herbicides and tried to avoid their use. This explains why some farmers do not perform chemical weeding and rather opt for mechanical weeding (Table 1). Degli Innocenti and Oosterveer (2020) conducted a comparative study of Thai and Indonesian oil palm growers. The share of Thai and Indonesian farmers among the study participants who applied herbicides in their study was 20% and 70%, respectively, which further emphasises the awareness of environmentally friendly practices by Thai farmers who aim to reduce herbicides. Some of the farmers have adopted sustainable practices such as reduced herbicide application and increased soil cover area, which reflects the impact of Roundtable on Sustainable Palm Oil (RSPO) training performed in the study region.

Yield and management practices

The average yield achieved in our study region was 20.61 FFB tonnes ha^{-1} yr^{-1}, which is higher than independent (12.7 FFB tonnes ha^{-1} yr^{-1}) or supported smallholders (19.5 FFB tonnes ha^{-1} yr^{-1}) in Indonesia, as reported by Euler *et al.* (2016). Similarly, Monzon *et al.* (2021) report an average yield of 15.3 tonnes ha^{-1} yr^{-1} of smallholders across 22 sites in Indonesia. Contrasting results were reported by Moulin *et al.* (2017), who found average yields of 24.92 and 11.44 FFB tonnes ha^{-1} yr^{-1} in Riau and Jambi provinces, respectively. The disparity was attributed to factors such as the

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influence of the palm oil sector and efficient infrastructure facilitating access to high-quality planting materials, particularly in Riau province. The quality of the planting material is the first aspect to fill the yield gap (Rhebergen *et al.*, 2018; Woittiez *et al.*, 2017). In our study, we found zero dura frequency in all the smallholder plots, which is in contrast to the study done by Monzon *et al.* (2023) in Indonesia. This difference could be due to the ease of access to the latest generation of Tenera seedlings in Plai Phraya. Due to the proximity of seedling companies (e.g. Univanish), the latest seed varieties were easily available to farmers. Another management practice that may have affected yield is pruning. In our study, the majority of farmers pruned their oil palms once a year, despite the recommended frequency being twice annually.

To the best of our knowledge, this study represents the first endeavour to include in the analysis the impact of previous land use on current oil palm productivity. Farmers who shifted from rice, rubber, and replanted oil palms have achieved average yields of 21.42, 20.65, and 19.76 FFB tonnes per hectare per year, respectively. Also, no links between the previous and the oil palm yield were identified (Figure S7). Our findings thus suggest that, in our context, the previous land use had a very low influence on oil palm yields.

Out of 18 plots, six had a lower yield compared to the attainable yield and constituted the S2 group. Farmer plots belonging to the four clusters of management practices (C1, C2, C3, C4) were linked to this S2 group. We thus did not observe a specific management practice explaining lower yield, despite a large contrast in management practices between farmers. This is contradictory to other studies that found significant effects of agronomic parameters on oil palm performances (Monzon *et al.*, 2023; Thoumazeau *et al.*, 2024). Those studies had a larger range of management and yield values that could make it easier to link statistically.

Other factors than management practices, such as the diverse variety of seedlings, soil conditions, were difficult to standardise between farmers and could have had high influence on the production. Disentangling the effects of such other factors would have needed to extend the number of plots included in the study. In this study, we limited the number of plots due to constraints in time and resources. As the effect of management takes around 3 years to be detected on oil palm production (Combres *et al.*, 2013; Corley and Tinker, 2015; Lamade and Tcherkez, 2023), we interviewed farmers on their management practices over the 3 years. However, these data collected could be a source of uncertainty. Not all farmers maintained precise records of input purchases, sales of produce, point of sale, and harvesting intervals. For yields, we relied on estimated yield rather than real yield data, which is also a source of uncertainty. Real data would have been more accurate, but these data are very difficult to collect in smallholders perennial cropping systems. We thus handled this uncertainty through the validation of our model with real data from two plots to confirm the relevance of our approach. A recommendation for further study would be to work tightly with farmers and share with them a diary they would fill in with the true data (Monzon *et al.*, 2023). This, however, necessitates an effort of the farmers and may not be easily adapted to all contexts.

Conclusion

Our study provides insights into the management practices and productivity of smallholder oil palm plantations in the Plai Phraya region. Our findings reveal a diverse range of management practices among farmers. Although some of the smallholders achieved substantial yields close to the attainable yield, a notable portion (6 out of 18) of them still produced a relatively low quantity annually. This lower yield could not be attributed to any specific management practices cluster. Future research should expand to consider additional dimensions, such as external factors (rainfall, fertiliser price volatility) and socio-economic factors influencing farmers' decisions on management practices and performance. By integrating these perspectives, a more comprehensive understanding of the challenges and opportunities within smallholder oil palm plantations can be

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achieved, ultimately contributing to the development of more sustainable and equitable agricultural practices.

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