Norwegian University
of Life Sciences

Master's Thesis 2023 30 ECTS
Faculty of Biosciences (BIOVIT)

A multi-criteria assessment of the impact of previous land use and current management practices on the performance of oil palm on smallholders' plots in the southern Thailand.

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Double degree M.Sc. in Agroecology

Author: Charan Krishna Nichenametla **Year: 2023** **Confidential: No**

Topic category:

A MULTI-CRITERIA ASSESSMENT OF THE IMPACT OF PREVIOUS LAND USE AND CURRENT MANAGEMENT PRACTICES ON THE PERFORMANCE OF OIL PALM ON SMALLHOLDERS' PLOTS IN THE SOUTHERN THAILAND.

Key-words- Sustainability assessment, socio-economic, multivariate analysis, yield gap, agronomy

Abstract

In recent years, Southern Thailand has witnessed a surge in oil palm plantation expansion, driven primarily by smallholders who contribute over 90% of Thailand's oil palm output. Despite their significant contribution, Thai smallholders have consistently achieved lower yields compared to counterparts in Indonesia and Malaysia. To address this challenge, the DYNAMOST project (2022-2023) was initiated to investigate land use changes and assess smallholder management practices in Southern Thailand. The project was structured into three work packages (WP). WP1 examined recent changes in oil palm cultivation in Southern Thailand, mapping these changes alongside historical land use dynamics over the past decade. WP2 focused on specific zones to understand smallholders' trajectories and the factors driving these changes. Finally, WP3, which encompasses my thesis, aimed to conduct a comprehensive analysis integrating smallholders' yield gaps and bottlenecks to provide valuable recommendations for implementing best management practices in the region.

Management practices, primarily related to fertilizer application intensity, characterized different groups of farmers in the study area. Notably, an average farmer applied less fertilizer than Thai Good Agricultural Practices (GAP) recommendations. The most optimal fertilizer use is observed for a cluster of farmers, who consistently produced higher quantity than their counterparts, particularly in June. Oil extraction rates varied between 23% to 35%, with the highest mean value achieved in young plantations (< 7 years). Additionally, the study highlights the significant influence of previous land use type on production performance. Replanted oil palms demonstrate relatively higher oil extraction efficiency than other land use changes. The transition from rice to oil palm cultivation has a notable effect on soil quality, influencing palm growth (low K/Mg and Ca/Mg) and production quantity. Therefore, it is crucial to consider balanced soil nutrient levels for plantations with a history of rice cultivation. Our findings further emphasize the need for improving several practices. These include optimal use of fertilizers, maintaining more fronds (>32) per palm during pruning, regular pest monitoring and recording of resource use and sales data for fresh fruit bunches. Furthermore, having good knowledge of the planting material is crucial for production performance.

Total number of volumes: 1
Number of pages of the main document: 63

Host institution: CIRAD

Acknowledgments

I would like to express my deepest gratitude and appreciation to the many individuals and institutions that have contributed to the completion of this master's thesis.

First and foremost, I am grateful to Dr. Aurélie Ferrer and Dr. Anna Marie Nicolaysen for being my academic supervisors. Their mentorship, scholarly insights, and constructive feedback have been helpful in shaping the direction and quality of this thesis.

I am profoundly thankful to my thesis supervisor, Dr. Alexis Thoumazeau, for providing me with an opportunity to work on this thesis topic. His support, guidance, and important insights have been instrumental in shaping this work. I also want to express my appreciation to Dr. Jean Ollivier for accompanying us on field visits and sharing his extensive knowledge of oil palms. Additionally, I am truly fortunate to have had the opportunity to learn from Dr. Bénédicte Chambon-Poveda and Ms. Charlotte Simon, whose experiences and expertise have greatly enriched my research. My heartfelt thanks go out to Ms. Patjima Kongplub, whose assistance with fieldwork and facilitating conversations with people in Plai Phraya were indispensable to this study.

Further, I am thankful to Asst. Prof. Uraiwan Tongkaemkaew for hosting me at Thaksin University and sharing valuable insights. My gratitude also goes to Dr. Orawan Jittham and the staff of Krabi Oil Palm Research Centre for collaborating field work and sharing their experience on oil palm. I am also grateful to have worked with Ms. Phantip Panklang and the staff at the Land Development Department, helping with soil measurements. Moreover, our general conversations helped me gain a deeper understanding of the cultural aspects of the Thai people.

Also, I want to acknowledge the participants of this study, without whom this research would not have been possible. Their willingness to share their knowledge and experiences has been invaluable in advancing our understanding of the subject matter.

My parents, to whom I am indebted, provided their constant support and encouragement throughout this journey. Lastly, completing this master's thesis has been a challenging yet immensely rewarding endeavor, and I want to thank all those whose names may not appear in this acknowledgment but have played a part. This accomplishment would not have been possible without each and every one of you.

Thank you from the bottom of my heart.

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1. Introduction

In the last ten 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 (*Elaeis guineensis*). An interesting aspect of palm oil production is its efficient land utilization, requiring less than 10% of the total land allocated to oilseed crops (OECD-FAO, 2022). The demand for palm oil globally is increasing rapidly, however, the supply and expansion of oil palm areas are expected to slow down in Indonesia and Malaysia, the two major producing countries, which contribute with 80% of global the oil palm production (OECD-FAO, 2022). This is due to the strict environmental policies of palm oil importing countries and the need for sustainable agricultural regulations. There is a huge concern for increasing oil palm productivity, but at the same time, we know that oil palm production is the cause of deforestation, large emissions of greenhouse gas, biodiversity loss, land conflicts and labor abuses (Ogahara et al., 2022). However, increasing productivity of existing oil palm plantation areas alone does not guarantee reduction in deforestation unless coupled with land use related policies and sustainable production practices.

The huge global demand for oil palm opens opportunities for Thailand which is the world's third largest oil palm producer. As of 2020, Thailand has 6.2 million ha of planted area of oil palm and produces 16.2 million tons of fresh fruit bunches (OAE, 2022). It is forecasted that the production will reach around 23 million tons (fresh fruit bunches) by 2031. In addition, the government supports oil palm with policies that aim to increase the plantation area, which can be expected to increase up to 9 million ha by 2031 with an average annual rate of 1.04% (OAE, 2022). In southern Thailand, there has been a gradual shift among farmers from growing perennial crops, paddy, orchards, and rubber to growing oil palm. According to the Office of Agricultural Economics, the oil palm growers in Thailand increased by ~30% from 2013 to 2019. The drivers for the 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., 2008). Particularly, the compensation given for conversion from rubber or abandoned paddy fields to oil palms are favoring the farmers in Thailand.

While there have been numerous studies on management practices and oil palm performance in other countries like Indonesia and Malaysia, there has been limited research conducted in Thailand, especially concerning smallholder plantations[1]. Smallholder plantations account to 40% of the oil palm production in Malaysia and Indonesia (Nagiah & Azmi, 2013; Rahman, 2020). In Thailand, in contrast, smallholders are the main actors in the oil palm production system, where they contribute with 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 (OAE, 2022).

[1]Based on keyword query on dimesions.ai. "Oil palm and smallholder and practices and (Malaysia/Indonesia/Thailand)"

Smallholder farmers have autonomy over the use and management of their land, and use of seed varieties and are not bound to any contracts with private companies (Nagiah & Azmi, 2013). Smallholder oil palm cultivation has the potential to revitalize rural economies by keeping profits and jobs within the local community. In contrast, large-scale plantations often transfer economic benefits to urban shareholders, disregarding welfare of the migrant or local workers (Jelsma et al., 2017; Sinaga, 2013). In addition, compared to large plantations or state oil palm development, smallholder activities make a greater contribution to poverty reduction by expanding farm size (Alwarritzi et al., 2016; Lee et al., 2014). Although oil palm cultivation has brought significant economic improvement, it has also led to destruction of peatlands and mangrove areas in Thailand. An estimation indicates more than 35% of mangrove deforestation was caused by oil palm plantations and paddy cultivation (Efeca, 2018).

The yield of oil palm plantations, expressed in tons/hectare/year, is a non-linear and age-dependent parameter. Fresh fruit bunches (FFB) are produced exponentially until palms attain 8-9 years and decline linearly thereafter. The attainable yield of plantation is shown in (Figure 1). The attainable yield was defined by Fischer et al., (2014) as “the yield attained by a farmer from average natural resources when economically optimal practices and levels of inputs have been adopted while facing the vagaries of weather”.

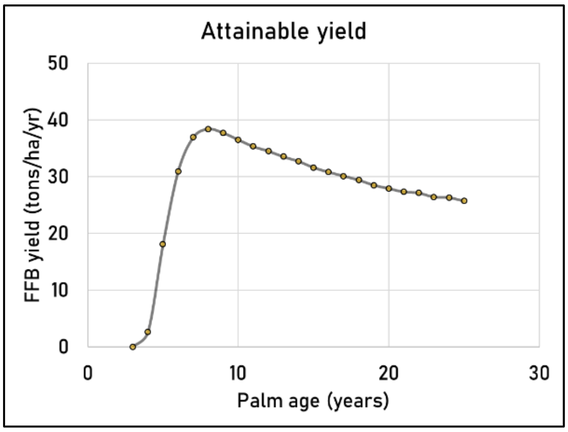


Figure 1: Attainable yield for different palm ages. Data retrieved from www.yieldgap.org

Despite the potential, most smallholder FFB yields fall well below this attainable yield (Woittiez et al., 2017). The average oil palm yield in Thailand has decreased from 20.6 tons/ha in 2013 to 18 tons/ha in 2019 (OAE, 2022). To improve the productivity of existing smallholder plantations is of utmost importance for the Thai government, whose goal is to increase the nation’s average yield. A low FFB yield in smallholder plantations is attributed to several factors such as palm age, palm stand, choice of planting material, soil and terrain, pests and diseases, and management practices (Monzon et al., 2023; Rahman et al., 2008; Woittiez et al., 2017). Agronomic practices that largely influence yield are; insufficient nutrient application of fertilizers, long harvest interval, poor weed control, and sub-optimal palm density (Monzon et al., 2023). To achieve optimal crop yields, it is crucial to apply the right amounts of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and boron (B) at the appropriate times, and considering the soil type. In Thailand, N, P and K application per hectare were reported to be 72, 16 and 69 kg/ha/year. The application rates for N and K were lower than among their counterparts in Indonesia or Malaysia.

The transition from one land use type (LU) leaves a "legacy effect" on soil environment. It is described as the influence of previous land use disturbances on present soil environment and its ecosystem functions (Bürgi et al., 2017). Even subtle agricultural practices may have long-term effects on soil and vegetation that sometimes can be observed after several decades or even centuries. Such practices may affect new LU transitions, such as that into oil palm plantations. To the best of my knowledge, there has been no study conducted that specifically focuses on the relationship between previous land use and the performance of oil palm plantations. Monzon et al. (2023) suggests that previous land use type, soil texture, and soil cover may affect oil palm performance. Hence, it is of utmost importance to conduct research that examines the relationship between past land use and current management practices on oil palm performance.

Cultivation of oil palm have socio-economic impacts, such as improved household living standards and nutrition among smallholder farmers in Indonesia (Euler et al., 2017). Due to lower labor requirements compared to agro-systems such as rubber plantations, oil palm producing smallholders are able to both efficiently manage large areas of plantations and engage more into off-farm activities. The effects of adopting oil palm cultivation have positive and significant impacts on both food and education expenditures, as well as on dietary quality and number of calories consumed. Thus, oil palm cultivation improves the household's living standards and human capital formation (Chrisendo et al., 2022). Notably, a considerable portion of these overall effects were attributed to farmers expanding their farm size rather than solely relying on increased profits per hectare (Euler et al., 2017). Regarding gender role contribution, compared to in other traditional such as rice, women in the household spend less time in oil palm activities and more time on household chores and leisure (Mehraban et al., 2022). This reduction in workload may have positive social effects, however, it may also result in less decision-making power over farm activities and control over income.

In terms of environmental aspects, a study was done by Azhar et al. (2011) examining biodiversity richness and abundance in Malaysia. It was found that smallholdings supported significantly more bird species and higher foraging guild diversity compared to large oil palm estates. It was also reported that the habitat heterogeneity of smallholdings at both local and landscape levels resulted in more carnivorous and herbivorous species than in plantation estates (Azhar et al., 2014). Although few studies suggest that smallholder plantations tend to have higher levels of ecological and species diversity than industrial plantations, it was noted that the conservation benefits associated with smallholder plantations may be limited by their low FFB yields. Improving yield is important as it not only enhances the income of smallholder households but also ensures the preservation of other land uses and valuable forest areas.

While oil palm plantations traditionally are monocultures, adopting approaches that may improve the ecological sustainability can enhance long-term resilience of the production system (Bessou et al., 2017)These approaches include reducing the need for herbicides and utilizing on-farm or locally available animal manure, which not only reduces input costs for farmers but also enhances soil quality and contributes to reducing the carbon footprint (Wezel, 2017). Additionally, to address the nutrient loss caused when removing the FFB from the production systems, farmers can compost oil palm side-products from the mills such as palm kernel cake and empty fruit bunches (EFB) for mulching. In terms of pest management, strategies such as installing pheromone traps for early signs of rhinoceros beetles and fostering natural predators such as barn owls can be practiced in the plantations (Bessou et al., 2017). This study focuses on farmers who have integrated practices to improve sustainability. Further, distinctive landscape elements were found in smallholder plantations that set them apart from larger estates. Gaining insight into these differences holds significant importance in advancing sustainable agricultural practices and promoting the transition toward an agroecological approach within the context of oil palm production systems.

With the adoption of diverse farming practices and transition to new land use, a multitude of challenges and trade-offs emerge. In this context, assessing the sustainability of agricultural systems at plot-level is necessary (Cicciù et al., 2022). Many authors have transformed the multi-dimensional perspective of sustainability in a farm system into results that are displayed in a visual and numerical form (Bockstaller et al., 2009). Deytieux et al. (2016) have studied various methodologies of multicriteria assessment (MCA) in crop systems; mainly statistics-based methods. MCA is advantageous for cropping systems which are complex and multifaceted and can capture the full range of impacts and trade-offs associated with different influencing factors, such as management practices. Principal Component Analysis (PCA) is an extensively used method in multivariate analysis for farm systems (Mądry et al., 2013), primarily known for its capacity to reduce the dimensionality of large datasets. This reduction allows for the transformation of extensive datasets into smaller ones while retaining most of the essential information present in the original dataset. In this study, I use an aggregate-based approach of PCA results to evaluate categorical performances. The sustainability framework, encompassing social, economic, and environmental dimensions, was evaluated through the criteria and indicators. In addition, the production performance of oil palms was integrated into this framework.

My research questions are:

1. To what extent do the previous land use and the current management practices affect smallholders' overall oil palm performance?
2. Which relevant criteria and indicators can be used to assess the sustainability of smallholder oil palm plantations?

In this scope, the literature on multicriteria analysis for farm systems was studied and a questionnaire for farmers was designed. Furthermore, characterization of palm vegetative parameters, tissue analysis, FFB analysis was performed along with investigation of soil properties such as physico-chemical and functional properties. Subsequently, data about farm characteristics, management practices, production performance and socio-economic aspects were collected from interviewing farmers. Finally, I decided to study three factors (management practices, previous land use, and age of plantation) that influence the four performances (economic, environmental, social and production performance) as shown in (Figure 2).

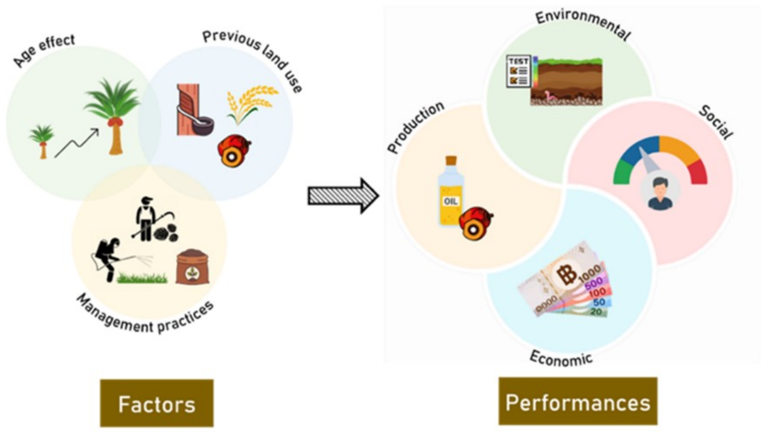


Figure 2: Illustration of three factors (management practices, age of plantation and previous land use) and their impact on performances (production, economic, social and environmental).

2. Materials and Method

2.1 Study site description

The study was implemented in Plai Phraya village, Krabi province (8.5073º N, 98.86732º E) (Figure 3) from May 2023 to July 2023. Krabi is one of the provinces in Thailand where 50% of the province's farmland is under oil palm cultivation (Bangkok Post, 2016). Krabi has seen a significant land use change from other crops such as rubber and paddy to oil palm, with over 30,000 hectares converted within an 8-year period from 2012 to 2020 (OAE, 2022). This transition makes Krabi a crucial area of interest for the present study. Plai Phraya village was especially relevant to select for our study because of diverse previous land use before cultivating oil palm plantations as illustrated in (Figure 3).

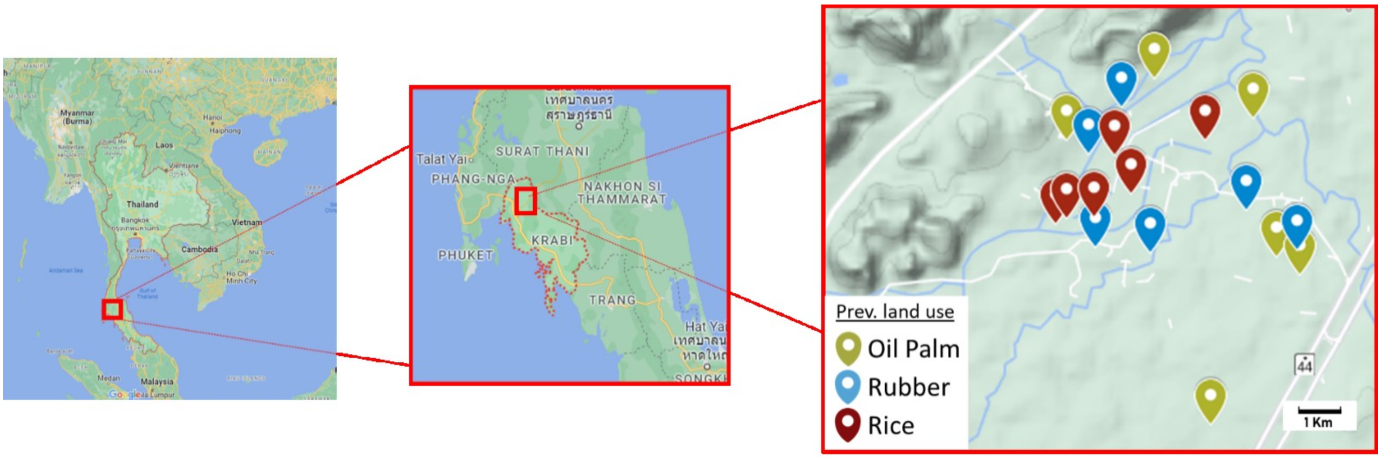


Figure 3: Geographical location of Plai Phraya study area. Land use transitions from rice, rubber and oil palm are show in different colors (Source: Google maps)

The historical monthly mean average temperature and precipitation data for Krabi from 1991 to 2020 is shown in (Figure 4). The region typically receives a substantial monthly average rainfall of more than 230 mm from May to November and, during this time, the mean temperature is reduced from 29 ºC to 27 ºC. On the other hand, during the dry season (December to April) the average rainfall was below 140 mm. The lowest rainfall can be expected during February and the average temperature from December to April increases by 2 ºC.

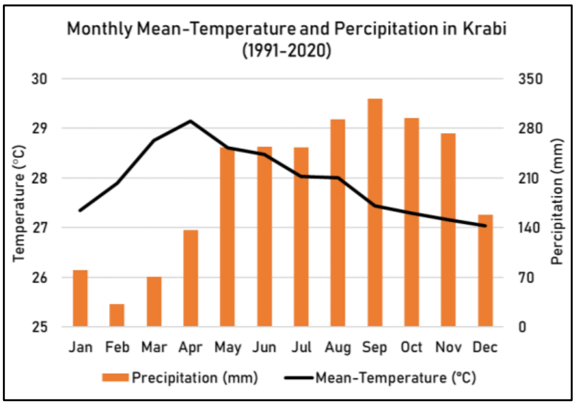
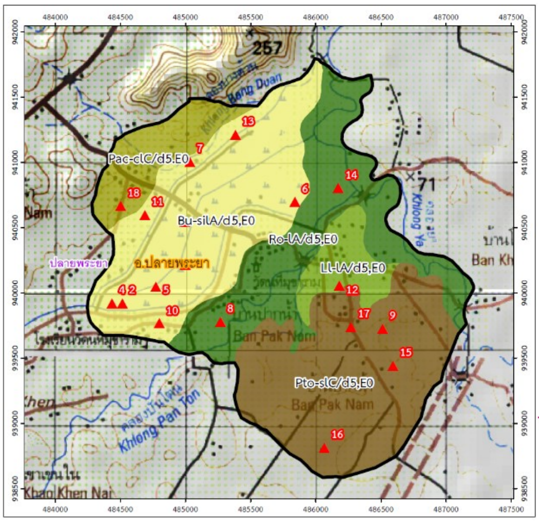


Figure 4: Monthly mean temperature and precipitation in Krabi, Thailand (World Bank, climate change portal)

The region experiences varying pedo-climatic conditions and to reduce the variability linked to pedo-climatic conditions we focused on a small study area of 9 km^2 in Plai Phraya district of Krabi province. In all the study areas, soils were Ultisols[2], however, they slightly differed in terms of soil series (Figure 5). The soil series that were observed are classified as Pac chan (Pac), Sai Buri (Bu), Rueso (Ro), Lamphu la (Ll), and Phato (Pto). The soil texture at 0-10 cm depth ranged from 4 to 47% clay, 23 to 66% silt, and 11 to 68% sand.

[2] One of the twelve soil orders in the United States Department of Agriculture soil taxonomy.



Soil series	Taxonomic classification
Pac chan (Pac)	Very-fine, Kaolinitic, isohyperthermic, Typic Palehumults
Sai Buri (Bu)	Fine-silty, Kaolinitic, isohyperthermic, Aquic Kandiudults
Rueso (Ro)	Fine-silty, mixed, semiactive, isohyperthermic, Typic Pulehumults
Lamphu la (Ll)	Fine, mixed, semiactive, isohyperthermic, Typic Palehumults.
Phato (Pto)	Loamy-skeletal, Mixed, semiactive, isohyperthermic, Typic Hapludults

Figure 5 : Soil series map compiled from soil surveys in the study region. Source: LDD, Bangkok.

2.2 Plot selection

The plots were selected in collaboration with the Land Development Department, which was managed under the Ministry of Agriculture and Cooperatives in Thailand. We selected 18 plots in the Plai Phraya district of Krabi provinces. Two criteria were considered for selection of smallholder plots: (i) Previous land use type (rubber, rice, or oil palm) and (ii) Age of existing oil palms. The idea was to have a well distributed number of plots for these two factors and be able to answer the research questions. Plots with previous land use types such as rice, rubber and oil palm will henceforth be referred to as RO, RBO and OO plots, respectively. We gathered 6 plots for each previous land use type and various age of plantations (Table 1). The area of the smallholders' plots ranges from 0.3 Ha to 3 Ha.

Table 1: Plot size and age of plantations in the study area.

Land use change	Plot code	Palm age (years)	Plot area (ha)
Oil palm to Oil palm (OO)	OOO1	13	1.64
	OOO2	15	3.08
	OOO3	18	1.67
	OOY1	7	1.44
	OOY2	6	2.25
	OOY3	6	1.74

Land use change	Plot code	Palm age (years)	Plot area (ha)
Rubber to oil palm (RBO)	RBOO1	20	0.78
	RBOO2	13	0.57
	RBOO3	25	0.91
	RBOY1	9	1.66
	RBOY2	6	2.63
	RBOY3	6	0.8

Land use change	Plot code	Palm age (years)	Plot area (ha)
Rice to Oil palm (RO)	ROO1	18	1.2
	ROO2	16	1.34
	ROO3	16	1.48
	ROY1	6	0.65
	ROY2	4	0.39
	ROY3	10	1.56

2.3 Biophysical measurements

2.3.1 Sampling strategy

In each plot, 3 oil palms (sub-replicates) were randomly selected for the study. These sub-replicates allowed us to consider the variations within a plot. At each sub-replicate, soil sampling was done at ring zone (circle around palm), 150 cm from the palm root plateau. To investigate soil properties, topsoil (0-10 cm) and subsoil

(10-30 cm) samples were taken from three specified zones (R, W and P) using auger soil sampling cylinder. Composite sampling of three sub-replicates was prepared for each depth and zone. Thus, a total of 36 soil samples were extracted (18 plots * 2 depths). In this study, I focused on the soil analysis for topsoil at ring zone only. Palm metrics were also measured at each sub-replicate.

2.3.2 Oil palm measurements

2.3.2.1 Vegetative characteristics

Vegetative parameters are valuable for assessing the health, growth, and productivity of oil palms (Corley et al., 1971). These measurements help to monitor the progress of individual palms and overall plantation development. By analyzing leaf nutrient content, it can be determined whether oil palms are receiving adequate nutrients (T. H. Fairhurst & Mutert, 1999). Palm height was measured by using a harvest knife as a reference. The number of fronds and the number of male and female flowers were observed and recorded.

For each palm (n=54), frond number 17 was sampled for various measurements, including the rachis length (from point C to A) and petiole cross-sectional area (at point C), as illustrated in Figure 6. Additionally, length and width of leaflets for every 10th leaflet (e.g., L10, L20, and so on) was measured. Leaflet length was determined from the rachis to the leaflet tip, while leaflet width was measured at the midpoint (where the leaflet folds). To calculate the total leaf area, a simplified method described by Tailliez & Ballo Koffi (1992) was employed. Initially, the product of leaf length and leaf width for every 10th leaflet was measured. Then, I interpolated values to encompass the entire range of leaf areas based on known leaflet areas. Given the symmetrical nature of oil palm leaves, only one side of the leaf was and then multiplied the result by 2. Furthermore, the overstory density was recorded using a densitometer at waist level, following the standard procedure outlined by Paletto & Tosi (2009). The investigation of nutrient uptake in oil palms involved analyzing the nutrient content in leaflet (N, P, K, Mg, Ca) and rachis (K). Nitrogen content was measured by the Kjeldahl method and Dumas combustion method. Phosphorus and Potassium content were measured by visible spectrophotometer and Flam photometer, respectively. Calcium and Magnesium were measured by atomic absorption spectrophotometer. To ensure leaf nutrients were not affected by fertilizer application, farmers were informed about the sampling process two months in advance so as not to apply fertilizers. After the leaf and rachis sampling were completed, the farmer applied fertilizers. Three recordings near the sub-replicate and 5 additional measurements were done randomly in the plot. The position for measurement in all the plot was at the windrow zone, usually at the center of the three palms. The list of vegetative variables used for evaluating production performance using PCA are shown in Table 2.

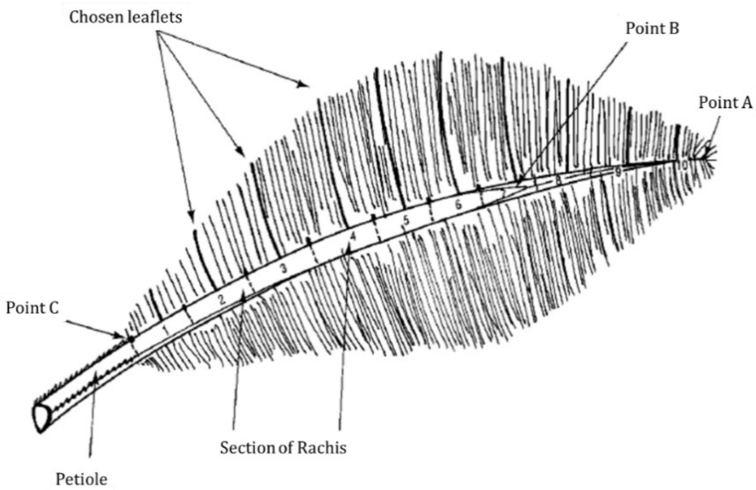


Figure 6: A schematic of oil palm frond. Image extracted from (Tailliez & Ballo Koffi, 1992)

Table 2: List of palm metrics used as indicators for assessing production performance.

Performance category	Criteria	Sub-criteria	Indicator	Unit
Production	Palm metrics	Growth characteristics	Palm height	m
			No of Fronds	
			Petiole area	m^2
			No of female inflorescence	
			No of male inflorescence	
			Total leaf area	m^2
			Overstory density	%
			Rachis length	m
		Leaf nutrients	Nitrogen	%
			Phosphorous	%
			Potassium	%
			Calcium	%
			Magnesium	%
		Rachis nutrients	Potassium	%

2.3.2.2 Fruitlet and fresh fruit bunch (FFB) analysis

Palm oil production metrics such as quantity of mesocarp and kernel in FFB, and fruit setting are crucial metrics in the palm oil industry. Another important metric was oil extraction rate (OER) which quantifies the amount of oil that can be extracted from a specific quantity of oil palm fruit bunches and typically expressed as a percentage. Three ripe FFBs were chosen at random from each plot. The selection of ripe FFBs was determined through visual inspection and the number of loose fruits around the oil palm. Oil from bunches were extracted in a laboratory setting, using the Soxtec™ 8000 extraction unit.

Parameters that were measured include kernel diameter, mesocarp thickness, shell thickness, fruit setting per FFB, total fruit weight per FFB, mesocarp weight per FFB, mesocarp weight per fruit, shell weight per fruit, kernel weight per fruit, and oil extracted ratio from FFB (Table 3). The standard method used to collect these parameters is described in Appendix 2.

Table 3: List of oil extraction metrics used as indicators for assessing production performance.

Performance category	Criteria	Sub-criteria	Indicator	Unit
Production	Oil extraction metrics	Kernel	Kernel diameter	mm
			Kernel weight per fruit	gms
		Mesocarp	Mesocarp thickness	mm
			Mesocarp weight per FFB	%
			Mesocarp weight per fruit	gms
		Shell	Shell weight per fruit	gms
			Shell thickness	mm
		Fruitlet	Fruit setting per FFB	%
			Total fruit weight	kgs
		Oil extraction ratio per FFB		%

2.4 Soil measurement and analysis

2.4.1 Soil quality

Soil holds immense importance as it plays a pivotal role in supporting ecosystems, regulating water quality, and influencing nutrient cycles. Understanding soil properties is crucial for sustainable land management and environmental preservation. The soil samples were analyzed by in-field and laboratory methods. For the in-field method, HORIBA pocket tester was used to measure Nitrate (NO3). A soil sample of 8.3 g was mixed with 30 ml of distilled water in a conical tube. After sealing the tube, it was manually shaken for 5 minutes with a consistent rhythm of one shake per second. Subsequently, the soil solution was applied to the sensor on HORIBA tester to measure the nitrate value. For physico- and chemical analysis, the soil samples were air-dried for 3-4 days and then sieved at 2-mm prior to sending them to the soil laboratory in the Land Development Department in Bangkok. Soil pH was determined in distilled water (1:1 soil-water ratio) with electrometric method, (Peech, 1965). Available phosphorus was measured using the Bray II method (Bray & Kurtz, 1945). Magnesium (Mg), Potassium (K), and Calcium (Ca) in the soil solution were extracted by neutral 1 N ammonium acetate (Chapman, 1965). Flame photometer (Sherwood model 420) was used to analyze K and Ca, while Mg was determined by Atomic Absorption spectrophotometer (Shimadzu AA 6200). The soil organic matter was analyzed by modified acid-digestion, $FeSO_4$ titration method (Nelson & Sommers, 1996). Cation exchange capacity was determined by Ammonium acetate method (Jackson, 2005).

To evaluate soil quality comprehensively, an integrative approach was adopted, taking into consideration the interrelationship between the physico-chemical properties and the biological activity of the soil. For this purpose, a few indicators were used from the Biofunctool® framework developed by Thoumazeau et al. (2019). The framework encompasses 9 indicators to assess three key soil functions: carbon transformation, nutrient cycling, and structure maintenance (Kibblewhite et al., 2007). Due to time and methodological constraints, the indicators related to soil function "Nutrient cycling" were not considered for this study. Structural maintenance indicators, such as soil aggregate stability, water infiltration potential, and Visual Evaluation of Soil Structure (VESS) were used. Soil faunal activity, compactness and structural porosity was evaluated by VESS (Franco et al., 2017). Aggregate stability score was linked to the capacity of the soil structure to withstand harsh rainfall events that may lead to soil erosion or surface crusting (Le Bissonnais, 1996). The Beerkan test was implemented for knowing the water infiltration rate thus providing information of soil run-off process (de Roo et al., 1992). In addition, I used Bait lamina, and basal soil respiration which indicates carbon transformation. The Bait lamina method assesses the soil fauna activity by observing the decomposition of an organic substrate (van Gestel et al., 2003). Soil respiration, measured through SituResp®, provides an on-site evaluation of carbon emissions resulting from soil microorganism activity (Thoumazeau et al., 2017). The soil physico-chemical variables that were included for analysis are listed in (Table 4).

Table 4: List of soil quality indicators used for assesing environmental performance.

Performance category	Criteria	Sub-criteria	Indicator	Unit
Environmental	Soil quality	Physico-chemical properties	Soil pH	
			Electrical conductivity (EC)	dS/m
			Soil organic matter (SOM)	%
			Phosphorous (P)	mg/kg
			Potassium (K)	mg/kg
			Nitrate (NO_3)	mg/kg
			Cation exchange capability (CEC)	cmol/kg
			Ex. Ca+	cmol/kg
			Ex. Mg+	cmol/kg
		Functions	SituResp	%
			Beerkan	score
			Aggregate stability (surface)	score
			Aggregate stability (sub-surface)	score
			Bait lamina (BL)	score
			VESS	score

2.4.2 Soil cover

Soil cover helps prevent erosion, maintains moisture, and supports biodiversity (Zuazo & Pleguezuelo, 2009). For evaluating soil cover, frond stacking width and weed density were considered (Table 5). Frond stacking width was measured at 5 locations randomly and mean values were calculated. For weed density score, a quadrat of 50 x 50 cm was placed in R zone, 1.5 m away from the oil palm and images of the weed were taken at 100 cm above ground. Finally, uniform weighting method was applied for these two variables to calculate an aggregated sum which defines soil cover index. To assess soil loss, erosion pins made from bamboo skewers were used. In each plot's sub-replicate area (1.5 m from palm), three of these pins were installed. After a period of 50 days, the pins were removed, and soil loss was measured.

Table 5: Soil cover indicators used for assessing environmental performance.

Performance category	Criteria	Indicator	Unit
Environmental	Soil cover	Frond width	cm
		Weed density	score

2.5 Plot visits

Plot visits were conducted in the June-July period to record single-harvest information, measure frond stacking width, and observe landscape elements. During harvesting, information gathered included the number of FFBs harvested per palm and weight of the individual FFB. In addition, the total number of FFBs harvested and the total weight of FFBs sold were recorded by visiting the collection center along with the farmer or transport team. Total production quantity per harvest was used as indicator to assess the production performance (Table 6)

Table 6: Single-harvest indicator used for assessing production performance.

Performance category	Criteria	Sub-criteria	Indicator	Unit
Production	Yield	Single--harvest yield		tons/ha/harvest

2.6 Interviews

To understand current farm management practices, as well as production-related and socio-economic performances, a structured interview format focused on plot scale was prepared. The interview consisted of five parts: Farm characteristics, previous crop management, current practices (irrigation, pest monitoring, weeding, fertilizing, pruning, harvesting, and transporting), plot economics, and social aspects. Farm characteristics include information about the farmers' age, education, workforce experience and training were also gathered. In addition, plot related data such as age of plantation, number of palms, plot size and previous land use management were collected (see Appendix 1). The interview was conducted with the individual responsible for overseeing most plantation activities in each place.

2.6.1 Management practices

Data on management practices were collected over three years (2020-21 to 2022-23) to assess potential variations over time. However, for data related to harvesting farmers were able to remember only for one year (June 2022- May 2023). I participated in the field for data collection from May 2023 to July 2023. Details related to planting material such as seed variety and location of purchase were gathered, and questions related to knowledge about planting material were also asked. If farmers irrigated their plots, data of irrigation frequency and area were collected. Additionally, to understand the drainage capability, farmers were asked if their plots were flooded during the past 3 years and information about the percentage of area flooded and number of days observed. Information about fertilizer applications such as fertilizer composition, period of application, quantity applied per palm, frequency per year, and location of application were collected. Similarly, data for organic amendments were recorded. For weeding activity, frequency, period of the year, and herbicide brand (chemical) and quantity of application were collected. In addition, information on weeding zones was also gathered during interviews. Disease and pest observations in the plantations and control measures for the same were also collected. The number of palms lost and palms that were replanted were asked. For pruning, we asked about the number of times pruning was performed per year, the pruning period, frond placement zones, knowledge of box-shape and number of fronds pruned per palm. Information related to harvest that was collected were harvesting interval, production quantity during peak and off-peak season, FFB ripeness check, unproductive palms, and challenges to harvest FFBs. Further, farmers were asked their choice of centers for selling FFBs. For chemical weeding and pest control, farmers were asked if they had experienced any health-related issues during or after applying herbicide/pesticide. Safety measures such as wearing boots, helmet, mask and full-body cover were also evaluated. The chemical treatment frequency index (TFI) was calculated based on an equation.

Eq. 1:

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

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 quantity of active product for the given commercial herbicide (mg ha^{-1}), and *Dr* is for the recommended dose of active product for the given herbicide for oil palm plantations (mg ha^{-1}).

2.6.2 Yield assessment

Initially, our intention was to collect accurate data from collecting centers to calculate yields per individual plot. However, this proved to be challenging because more than 80% of the farmers in the study area manage more than one plantation. At the time of harvest, the farmers mix FFB produce from different plots and sell them. The receipts collected by farmers did not serve the purpose of calculating yield per plot. Therefore, I relied on interview data. Farmers were asked about the months in which the production quantity of FFB was at its peak and when it was lower in their plots. They were also asked to provide the quantity of produce during these specific periods. Furthermore, farmers were requested to share the frequency of the highest and second highest quantities produced during peak season. The number of harvests that occurred during these periods was inquired about, and its correlation with the harvesting interval was explored. As most harvests were conducted by coordinating a schedule with the harvesting team, the number was calculated based on harvest interval. Finally, the equation below was used to calculate the annual yield for all the plots.

Eq. 2:

$$\mathrm{Yield} = \mathrm{Q_pM_p}\left(\frac{\mathrm{H}}{12}\right) + \mathrm{Q_lM_l}\left(\frac{\mathrm{H}}{12}\right) + 2 \times \mathrm{avg}(\mathrm{Q_p}, \mathrm{Q_l})\left(\frac{\mathrm{H}}{12}\right)$$

Where Q_p and Q_l are the mean quantity 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 harvesting interval. The calculated annual yield was then used as indicator for evaluating production performance (Table 7). I was able to collect actual yield data for 2022 from two farmers. This data was compared with the formula in Equation 2.

Table 7: Annual yield used as indicator for assessing production performance.

Performance category	Criteria	Sub-criteria	Indicator	Unit
Production	Yield	Annual yield		tons/ha/year

2.6.3 Economic indicators

For economic calculations, information was collected for one year (2022-23), as most of the farmers were able to recall only from the last one year. Labor related data such as wages paid for each activity and method of wage calculation were collected. Regarding the harvesting and transportation of the produce, I determined wages by calculating the cost per metric ton of FFB. For weeding, labor costs were calculated based on the plantation's total area. Typically, pruning expenses were paid per palm, considering the age of the plantation. In cases where labor was hired for fertilizer application, compensation was based on the number of fertilizer bags (each weighing 50 kgs) applied by the laborers. Farmers did not hire any paid labor for irrigation and pest monitoring.

Input costs such as fertilizers and herbicide were asked during the interview, and this information was later checked with corresponding fertilizer prices. Although farmers purchased fertilizers from 5 different sales outlets, price data for one year was available from only one cooperative. The price difference was not huge between the different sales outlets. Hence, this data was used for calculation of fertilizer costs for all the farmers. If herbicide was purchased and applied in the plot, information about brand (type of active ingredient) and quantity of purchase was collected. Monthly price data of FFB/kg was collected from two farmers who had receipts of their produce sold for 2022. This price did not vary much between different collecting centers and therefore was used for calculating gross product for all the farmers. Finally, the economic assessment was based on the cost benefit analysis described by Penot et al. (2021). The indicators include gross product (GP), which is the product of price and FFBs tons/hectare/year. Operational costs (OC) include all the expenses incurred for labor activities and inputs such as herbicide and fertilizers. Gross margin (GM) was calculated by GP-OC. Wage ratio was obtained by dividing labor costs by GP. Labor Valorization (LV) highlights GM/labor hours, while return to labor (RTL) assesses yield per labor hour invested. Here, both hired, and family labor hours were considered for calculation. Economic efficiency was calculated by 1-(OC/GP). The intensification ratio was calculated by OC divided by GM and return on investment (ROI) is the net margin divided by operational costs. These two indicators provide valuable insights into the intensification level of the production system and of the benefits and risks of maintaining and intensifying such a system (Penot et al., 2021). The indicators which were used for assessing economic performance are shown in Table 8.

Table 8: List of economic indicators for assessing production performance

Performance category	Criteria	Indicator	Unit
Economic	Profitability	Gross margin	thai baht
		Labor costs	thai baht
		Input costs	thai baht
		Operational costs	thai baht
	Labor	Wage ratio	%
		Family labor valorization	thai baht/hrs
		Return to labor	tons/ha/yr/hrs
	Efficiency	Economic efficiency	%
		Intensification ratio	%
		Return on investment	%

2.6.4 Social indicators

For each management practice, labor related data were collected. These include the number of family- and hired workers, and for each activity the total hours worked by family- and hired labor. Qualitative aspects related to management practices (skills, labor availability, drudgery, satisfaction, discomfort), access to socio-technical networks (training, policies, Thai Good Agricultural Practices, certification), and participation (gender roles, family-labor activities, multiple management, schedule conflicts) were also collected. For qualitative aspect, farmers were prompted to express their emotions using a smiley scale, where they selected a face corresponding to their responses. This scale comprises five faces, spanning from sad to happy, with each face's significance clarified to the farmers prior to every question (Appendix 1). All the questions were asked to individuals who manage the plot in general and may not be involved directly in plantation activities.

Finally, quantitative variables were derived to assess the social performance and are presented in (Table 9). Indicators that reflect farm characteristics such as farmer's age, family workforce and activities ratio were included for assessment. The family workforce represents the number of family members involved in performing activities on the plantation. It was observed that the intensity of family labor depends on the time available and the need for the activities. Additionally, plot managers hired labor for specific tasks only and in other tasks, family members worked along with hired labors. Therefore, the indicator family to hired ratio was used to estimate the percentage of activities that family members were involved in compared to hired labor. In addition, two key metrics were applied to assess social performance: workload and operational difficulty. Workload was assessed for all activities combined, while operational difficulty was assessed for each activity. Workload indicator is the labor hours performed in a plot over a course of one year (Deytieux et al., 2016). On the other hand, operational difficulty is the measure of total labor hours per activity divided by number people worked (Pelzer et al., 2012). Both indicators were evaluated for family- and hired laborers.

Table 9: List of social indicators for assessing production performance

Performance category	Criteria	Indicator	Unit
Social	Farm characteristics	Farmer age	years
		Family to hired ratio	%
		Family workforce	
	Total workload	Hired labor	hrs
		Family labor	hrs
	Operation difficulty (family labor)	Irrigation	hrs
		Fertilizing	hrs
		Weeding	hrs
		Pruning	hrs
		Harvesting	hrs
	Operational difficulty (Hired labor)	Fertilizing	hrs
		Weeding	hrs
		Pruning	hrs
		Harvesting	hrs

2.7 Statistical analysis

2.7.1 Typology of management practices

For building classes of management practices, I followed the first steps of the Typ-iti method (Akakpo et al., 2021; Renaud-Gentié et al., 2014). This method allowed to gather groups of farmers to implement similar practices and distinguish them from other groups. This approach recognizes that management practices should be comprehensively considered to gain a holistic understanding of technical management.

As a first step, interview responses for management practices were transformed into quantitative and qualitative variables and modalities. The continuous range of values were divided into quartiles and modalities for each variable were assigned (Appendix 4). Second, the data was categorized on a yearly basis from 2020-21 to 2022-23, resulting in 54 individuals (18 farmers * 3 years). Third, the 80/20 rule was applied to all the variables to minimize the variability, that is, if a value can be represented by more than 80%, then that variable was ignored for further analysis. Variables of water management activity such as irrigation frequency and irrigated hours were therefore not considered as 15 farmers (> 80%) do not irrigate their plot. Other variables such as planting material (seed source/name) were also discarded for analysis. Fourth, selection of variables for further analysis. Quantity of and application frequency of NPK fertilizers, chemical and mechanical weeding counts, pruning frequency and harvesting interval. Planting density of oil palms, which was the number of palms per hectare, has a significant effect on practices and economics (Latif et al., 2003) and hence it was also included for HCA.

Missing data values were imputed, and then multiple correspondence analysis was performed. Subsequently, the top 10 individuals contributing to the variation were plotted on first and second dimensions for visual interpretation. Ascending Hierarchical Correspondences was then followed to define the number of clusters. Variables and modalities significant for clustering, along with the most representative individuals, were identified.

2.7.2. Study of performance groups

A review by Mądry et al., (2013) on typology methodologies used for faming systems, among the various methods, multivariate analysis (principal component analysis) was the most preferred. The primary goal of the principal component analysis (PCA) was to condense an extensive set of diagnostic variables applied in an analysis into a significantly smaller set of formal variables known as principal components with less loss of information (Lesschen et al., 2005). Given the extensive array of quantitative variables associated with each categorical performance (social, economic, environmental, and production), PCA was used to aggregate data into indices.

First, as a data preprocessing step, the range of each variable was normalized to a value between 0 to 1, using feature scaling method (see Appendix 3 for list of variables). Second, PCA was computed using R software. The number of dimensions (PCs) were selected based on the contribution of variance, usually more than 75% of cumulative variance was considered. Third, variable contributions for each selected PC were used as relative weights (w). Then, for each dimension, a PC index I(PC) was calculated using the equation below.

Eq. 3:

$$\mathrm{I}(\mathrm{PC_x}) = \sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{w_i}\, \mathrm{S_i}$$

where, *x* is the selected dimension, m is the number of variables, w_i is the weight of variable *i* and *S* is individual score of variables.

Finally, the consolidated performance index (PI) for was constructed using the following equation.

Eq. 4:

$$\mathrm{PI} = \sum_{\mathrm{x}=1}^{\mathrm{n}} \mathrm{V_x} * \mathrm{I}(\mathrm{PC_x})$$

where *V* is the percentage of variance in *x* dimension, *n* is the number of dimensions.

Five consolidated performance indices were created. One PI for each economic and social performance, one for environment (soil quality) and two for production performance (palm metrics and oil extraction). Further statistical analysis was done for comparing indices within each factor, for this one-way analysis of variance (ANOVA) was used and P value below 0.05 was considered for identifying significant differences.

2.8 Sustainability framework

Limited literature exists regarding the sustainability assessment of oil palm plantations at plot-level (Deytieux et al., 2016). However, a substantial amount of research has been conducted at the farm level (Bockstaller et al., 2009; Deytieux et al., 2016). In this study, criteria and indicators have been selected from various literature sources that focus on the farm scale and have been adapted accordingly. The assessment of the sustainability of smallholder oil palm systems was based on four performance dimensions: social, economic, environmental, and production related (Figure 7). Two composite indicators were used to evaluate social and economic performances, respectively. Environmental performance was evaluated by two indicators: soil cover and soil quality. Four indicators were employed to assess production performance. They were single-harvest yield, annual yield, palm metrics and oil extraction metrics.

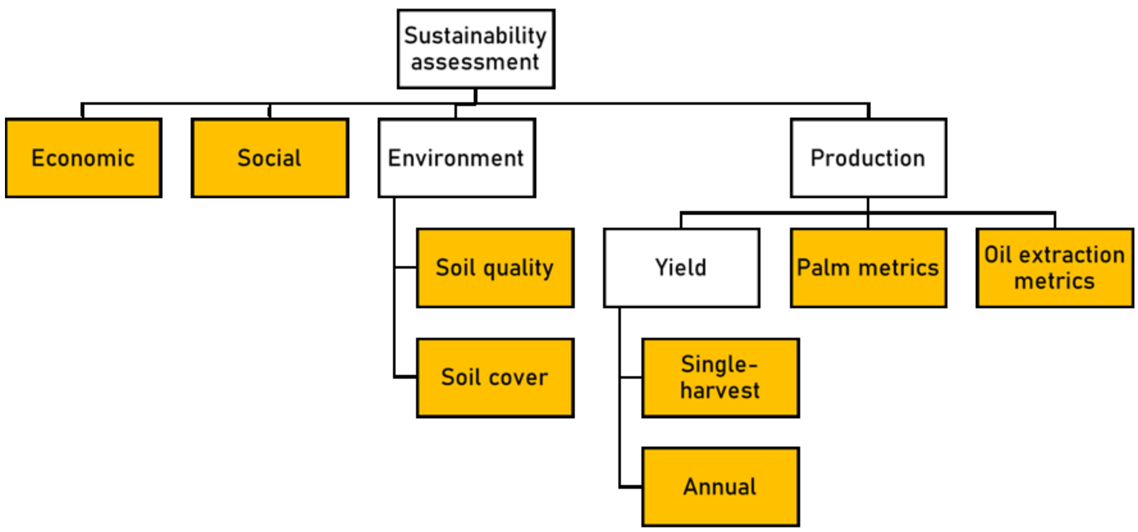


Figure 7: Overview of criteria and indicators used for sustainability assessment of smallholder oil palm production systems. Highlighted blocks represent the indices used for assessment.

3. Results and discussion

3.1 Heterogeneity of smallholder plantations

Field observations revealed interesting aspects of structural diversity within plantations and landscape heterogeneity. Rice fields are typically cultivated on flat lands with minimal slope, resulting in most of the RO plots falling into the low elevation class (slope <2%). In contrast, the OO plots were mostly located on steeper terrains (see Appendix 10). These areas were once forest lands or unused areas (more than 30 years ago). RBO plots do not show such strong distinction. High number of soil mounds (Figure 8) were observed for one plot in the study region. These are a result of bioturbation activities of ants/termites and can have effect on the nutrient accumulation and release into soil (Nkem et al., 2000).

Figure 8: One of the several mounds (encircled) present in a study plot.

Integration of water bodies were observed in 3 study plots (Figure 9). The area of these spans from 100 to 200 m^2 and was often surrounded by diverse weed plants. Such water bodies have potential to harvest rainwater and recharge ground water levels.

Figure 9: A water body integrated intoo an oil palm platation.

A diversity of non-oil palm trees such as coconut, areca nut, banana, and other fruit trees were observed in two plantations (Figure 10). These trees are randomly presented in the plot contributing to mosaic-like pattern of plant life. However, only in two smallholder plots more than 30 coconut palms were intentionally planted. In another plot, pineapple was intercropped randomly. Intercropping in oil palm plantations can enhance biodiversity, diversify income and benefits (Dissanayake & Palihakkara, 2019). However, designing intercrops in oil palm plantations is challenging as such practices may create constraints for harvesting and weeding activities and compete for nutrients. Yet, farmers find alternatives or maintain non-productive elements which may benefit plot biodiversity. These farm systems can be viewed as a step towards making an agroecological transition. More than 30% of the plots studied have neighboring plots with non-OP land use. A paddy field between two oil palm plantations can be seen in Figure 10. Such landscape heterogeneity is essential to improve biodiversity conservation in agricultural landscapes (Fahrig et al., 2011; Steckel et al., 2014).

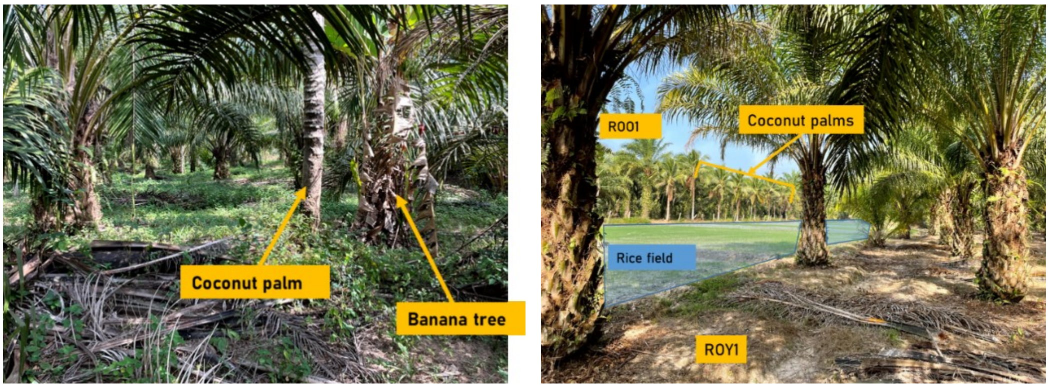


Figure 10: Images of non-OP trees (left) in a plot and paddy field (right) between two study plots.

The composition of different landscapes has encouraged species diversity and abundance particularly for birds (Azhar et al., 2015). Figure 11 shows a comparison of Plai Phraya (study area) with a nearby large estate plantation. To maximize production quantity, structural and landscape heterogeneity is usually reduced in large plantations. Teuscher et al. (2015) report that heterogeneity in a system has resulted in significant benefits in terms of biodiversity conservation; however, it has also led to a reduction in FFB yield, highlighting the trade-off between ecological and economic aspects. On contrary, Zemp et al. (2023) investigates increased vegetation structures in plantations and reports that oil palm yield did not decrease.

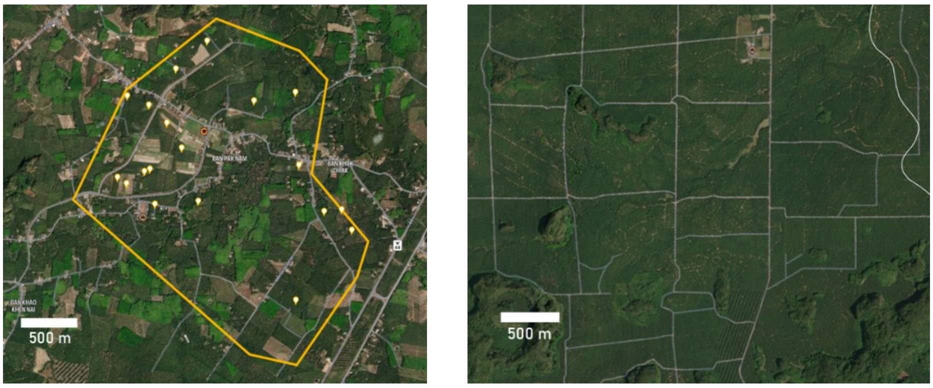


Figure 11: Landscape heterogeneity with different land uses in study area (left) compared to homogeneous large oil palm estate (right). Lighter shades of green in the image represent rubber plantations, while darker shades usually denote oil palm plantations. Source: Apple Maps

3.2 Factors

In this study, three factors were identified that may have influence on various performances of smallholder oil palm production systems. These factors are i. management practices, ii. plantation age and iii. influence of previous land use

3.2.1 Management practices

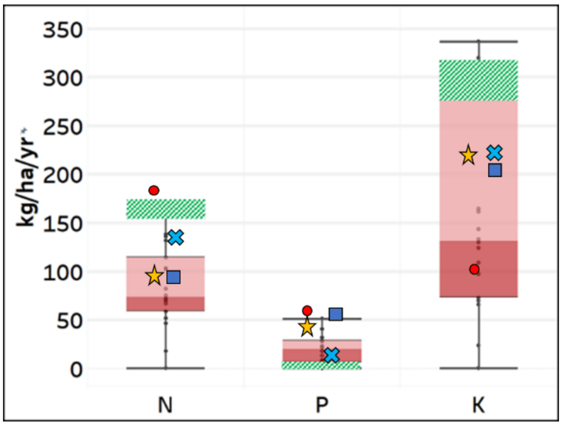
3.2.1.1 Description

Planting material. All the plots have tenera palms. In comparison to other study in Indonesia (Monzon et al., 2023), our farmers have zero dura palms (originally planted). However, in one plot, two palms were lost due to infestation of rhinoceros beetles and farmer decided to replant with his own seeds from the same plot. This has resulted in dura palms with thick shells, see (Figure 12). Although the farmer has acknowledged knowing this effect prior to replanting tenera seeds.

Figure 12: Cross-section of fruitlets illustrating tenera palm and replanted dura variety

Water management. Water canals and rivers run through the study area and have no sign of water scarcity. However, three farmers chose to irrigate in their plots, where it was performed only during the dry season (Dec-May), when rainfall was low (Figure 4). These farmers irrigate two times per season and irrigated hours per one time varies between 48 and 96 hours. All other plots were not irrigated. Three farmers have mentioned that more than 80% of their plot was submerged when there was heavy rain, which happens during July-November. Usually, the rainwater would stay from a few days to weeks in their plots, indicating poor drainage capability. Other 3 farmers shared similar experiences of having their plots flooded for 1-2 days after heavy rains. All these 6 plantations have “Bu” and “Ro” soil series, which are between upland terrain, see (Figure 5).

Fertilization. The average application rate of N, P and K per ha per year over three years varied between the study plots (Figure 13). Average N application rate was 82. 68 kg ha^{-1} yr^{-1} with a coefficient of variance (CV) of 50%. Average P application rate was 18.41 kg ha^{-1} yr^{-1} with a CV of 76%. Application rate of K was 150.6 with a CV of 69%. High variance was observed for K values and relatively higher than N and P. In Thailand, Department of Agriculture (DOA) has developed Good Agricultural practices (GAP) for oil palm plantations. For a study in north-eastern Thailand, plantation with Ultisols soil type, the recommended fertilization rates were 1.06, 0.04 and 1.99 kg $palm^{-1}$ yr^{-1} for N, P and K, respectively (Somnuek & Slingerland, 2018). Considering an optimal planting density of 143-160 palms ha^{-1}, the recommend application rates were 151-169, 5.7-6.4 and 284-318 kg ha^{-1} yr^{1}. On average, the farmers in the study region apply lower rates of N, P and K than these recommended rates. The average application rates by our farmers were still lower than other studies on smallholder plots with Ultisols (Figure 13). Signifying the need to close the gap in fertilizer demands by some farmers in study area. Nevertheless, it is essential to highlight that the N-P-K calculation in this research did not account for nutrient content derived from organic amendments.



N	P	K	References	Symbol in graph
70-115	30-49	178-260	(Rhebergen et al., 2014)	☆
90	52	205	(Goh et al., 2003)	■
178	55	102	(Woittiez et al., 2019)	●
112-145	14-19	202-247	(Ng et al., 1999)	✖

Figure 13: Box plot of mean N, P and K application rate over the last 3 years. The shaded area (green) in graph indicate the recommendation range of Thai GAP (Somnuek & Slingerland, 2018). N-P-K application rates (kg/ha/yr) from other studies with similar soil type are also shown.

Other necessary nutrients such as Boron were applied separately by 12 farmers and among these 8 of them regularly applied every year. The quantity applied was highly varied among farmers, and ranges from 1-2 tablespoons to 200 g. This is intriguing since the Boron requirement for palms decreases after 6 years of planting *(K. J. Goh et al., 2007)* and yet the majority of farmers have applied. Magnesium was applied only once in the last three years by 2 farmers, however the latter applied only for few palms that indicated deficiency in leaves. Regarding the fertilizer application zones, 10 farmers apply in R zone, and 4 farmers apply in R and W zones. Three farmers spread the area of fertilizer broadcast in R, P and W zones.

Most of the farmers purchased different compositions of fertilizer every year. Farmers purchased fertilizers from 5 different retail outlets. However, more than half the farmers purchase fertilizers from 2 co-operatives in the village. Three farmers travelled 20 kms to purchase the fertilizers, stating the reason for reduced price for bulk purchase. The list of fertilizers used by farmers is in Appendix 5. Although numerous fertilizers were used, these were indeed a composite of three commonly used fertilizers which were 21-0-0, 0-0-60 and 18-46-0.

A diverse range of organic amendments (OA) were used in the studied smallholder plots, from animal manure (chicken, goat, cow, and pigs) to recycled materials such as empty fruit bunches (EFB), palm kernel cake, and vegetable compost. One farmer also started to use nano bio-fertilizers (seaweed based). Around 50 % of the studied plots incorporate one or other mentioned organic amendments in their plots. Three out of the 18 plots applied at least one kind of OA in their plot every year. The application zone for OA is largely near W zone. The quantity, type, and frequency of using OA vary largely. This was due to availability in the case of animal manure and purchase price for palm kernel cake or EFB. The nutrient content (N, P and K) of these organic amendments used by farmers were not assessed in this study.

During field visits, I observed unique practices that differed from other farmers. For example, two farmers applied boron fertilizer in fallen petioles bases of the trunk (see Figure 14) rather than usual method of applying on soil. Another unusual practice was observed in one plot, where bags of animal manure were placed near or under the dry fallen fronds in the windrow area as seen in Figure 14. The reason explained by farmer was that manure can disintegrate slowly and helps palm roots to absorb nutrients with time. If applied directly, heavy rains would spread manure rapidly and perhaps be lost due to run-off. Nevertheless, these ideas emerged from smallholders are yet to be tested scientifically.

Figure 14: Boron applied (left) in the petiole bases and bags (right) of animal manure placed under/near windrows

Soil cover. More than 80% of the farmers, place dead fronds in windrows, among these 4 farmers stack fronds in alternating rows which makes harvesting easier. Three farmers spread fronds (Figure 15) in a U-shaped around the palms, usually causes difficulty in harvesting (Carron et al., 2015). Spreading fronds increases the soil cover area largely compared to typical method heap of fronds. It's worth noting that these farmers had received certification from RSPO trainers, which may explain their adoption of this practice. Nevertheless, an organized way of spreading leaves and frond butts in U-shape is highly recommended for distribution of nutrients and reduce soil erosion.

Figure 15: Comparison of fronds spread around palms (left) in a plot and fronds stacked (right) consistently in windrow in another plot.

Pruning. Frond pruning is important to maintain steady growth and efficient use of fertilizers. Thus, maintaining appropriate number of fronds can have significant effect on production in terms of number and weight of FFBs (Marcelino & Diaz, 2016). Pruning as a separate activity was done in fifteen plots once a year, and twice in two plots. For one plot, the owner asks the harvesting team to prune during harvesting activities rather than as a separate activity. In this case, the costs were paid at the end of every year. In the study area, the period of pruning activity for three years was consistent among all farmers. Famers perform pruning either in one of the four seasons Mar-May, Jun-Aug, Sept-Nov or Dec-Feb. Most preferred time of the year was between Jun-Aug and Mar-May, where palms were pruned by 8 and 7 farmers, respectively. Most of the farmers in the study area retained 24 fronds on palm after pruning activity. However higher yields area achieved for palms which have 32 - 40 fronds (Marcelino & Diaz, 2016).

Pest incidence and control. Most of the plantations have rat infestation and have damaged the FFBs. This was evident during harvest assessment, where many bunches had dried fruitlets (see Appendix 15). One plot had lost 75 out of 440 planted palms due to rats. Yet, the farmer took no measures to control or monitor. Such incident was unique among the study plots. Another pest infestation was rhinoceros beetle, where three plantations had lost (2-3) palms. None of the study participants have implemented any control measures to prevent pests. However, pest monitoring by visiting the plots was performed by five farmers and four among these are replanted palms.

Weed control. The weed control method done by farmers 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. The preferred period of year did not change significantly for the last 3 years, but the number of times this activity was performed varied. This is shown as mechanical weeding count in (Table 10). Mechanical weeding was done in either of the four seasons Mar-May, Jun-Aug, Sept-Nov or Dec-Feb. The number of farmers who performed per season is shown at the bottom of the table. More than half of the farmers perform mechanical weeding during the Jun-Aug period. As shown in (Table 10), the preferred period of application was Mar-May, Jul-Sept, or Dec-Jan. Half of farmers in the study applied during Mar-May period and rest of them chose Jul-Sept or Dec-Jan as preferred period of herbicide application. Herbicide treatment frequency index (TFI) was calculated based on Equation 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. These values are similar to TFI reported by Mettauer et al. (2021), however they report high variability (0 to 5) of TFI. Furthermore, on average our farmers applied 3.9 liters/ha of herbicide, which was lower than the amounts reported in another study on smallholders in Indonesia, where they applied 4.8 to 5.9 liters/ha (Euler et al., 2016).

Table 10: Mechanical weeding period (left) and number of times it was performed in last three years. Chemical weeding period (right) performed in last three years. Plots with previous land use such as oil palm, rubber and rice are shown as OO, RBO and RO, respectively.

Plot code	Mechanical weeding period												Mechnical weeding count (2023-20)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
OO01							X			X			6
OO02							X						3
OO03										X			3
OOY1									X			X	3
OOY2				X								X	6
OOY3					X						X		5
RBO01											X		3
RBO02					X							X	6
RBO03				X			X						2
RBOY1				X			X						6
RBOY2	X					X							6
RBOY3						X				X			3
RO01	X			X			X			X			7
RO02				X								X	5
RO03	X						X						6
ROY1				X									2
ROY2		X								X			3
ROY3				X				X				X	8
	7			8			10			8			

Plot code	Chemical weeding period		
	2023-22	2022-21	2021-20
OO01			
OO02			
OO03			
OOY1		Sept	Sept
OOY2	Jan	Jul	
OOY3			
RBO01			
RBO02			
RBO03	April	May+Sept	May
RBOY1			
RBOY2	Jan		
RBOY3		Jul	
RO01		Apr	Apr
RO02			
RO03	April		
ROY1		Mar	Mar
ROY2			Apr
ROY3			Dec

3.2.1.2 Typology

HCA results of four clusters for 54 individuals are shown in (Figure 16). Cluster 1 (C1) consists of 15 individuals, cluster 2 (C2) represents 11 individuals. Cluster 3 (C3) and cluster (C4) consists of 12 and 15 individuals, respectively. The merging points of clusters C1 and C2 in dendrogram (Figure 16) denote that they have moderate level of similarity. C1 overlaps with C2 and C3 indicating data points that share similarities between them or have data points with high variability.

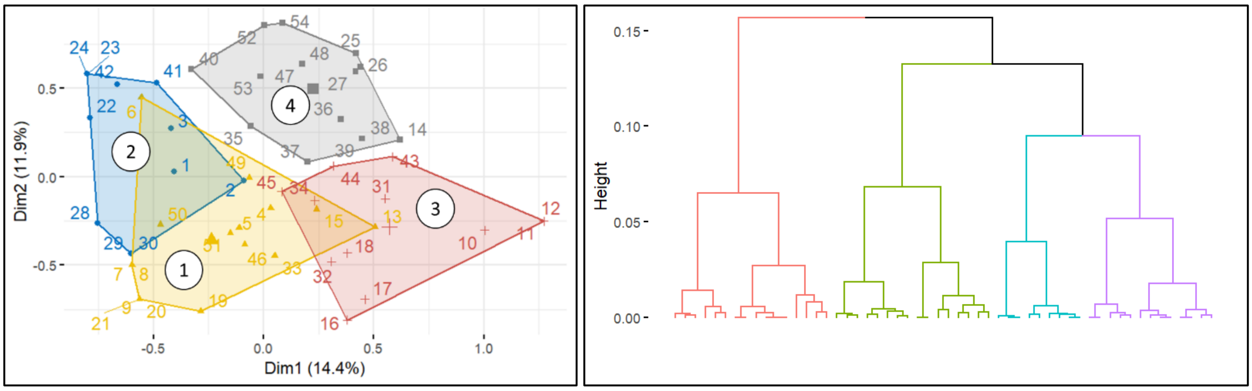


Figure 16: Factor map of individuals (left) and clusters plotted on dimensions 1 and 2. Cluster dendrogram of individuals (right).

Cluster assignment indicates that farmers did not change practices for the last three years. However, five farmers were assigned to two clusters, their modalities were checked, and no significant difference was seen in practices. Hence these farmers were reassigned to clusters which majorly represent them (Appendix 4). The significant variables that define clusters were oil palm planting density (OP density), frequency of chemical fertilizer application, quantity of chemical fertilizer (N, P and K) applied, frequency of chemical and mechanical weeding, and harvesting interval (Figure 17). Individuals in the C1 represent the farmers, who apply low quantity of fertilizer and perform mechanical weeding not more than once per year. These farmers also tend to have shorter harvesting intervals and thus more harvests per year. On other hand, C2 farmers' plots have medium spacing of palms, however these plots still have OP density below the recommended 143 palms/ha (Bonneau et al., 2018). C2 farmers also apply N in moderate quantity, close to average applicate rate (kg ha^{-1} year^{-1}) observed in Thailand (Heffer et al., 2013; Woittiez et al., 2017). However, they applied higher amounts of P and K than country's average application rates of 16 and 69 kg ha^{-1} yr^{-1}, respectively. On an average K/N ratio applied by C2 farmers (3.5) was twice that of other farmers (1.35 - 1.5). The recommended application K/N ratio was usually between 1.5 to 2.5 (K. Goh, 2004; Ng et al., 1999; Rhebergen et al., 2014; Somnuek & Slingerland, 2018). Another significant variable in this C2 cluster was the mechanical weeding intensity which was higher (>1) than C1 farmers. Optimal use of N and moderate application of K were observed for C3 farmers, however these farmers apply higher quantities of P than the recommended range for oil palm plantations in tropical soils (Ng et al., 1999). Application rate of K was in the range of 80 to 160 kg ha^{-1} yr^{-1} for C3 farmers which was less than C2 farmers. The variables that define C4 were fewer than other clusters. These farmers apply chemical fertilizers more frequently (3 to 4 times per year) and high amounts of N (>114 kg ha^{-1} year^{-1}). C4 farmers perform chemical weeding for their plots more often than other groups of farmers. It can be concluded that these clusters give a good indication of how intensely plantation was managed, particularly in terms of fertilizer use. C1 consists of low intensive farmers, C2 and C3 farmers were moderately intensive or optimal use of fertilizers and C3 were highly intensive farmers.

	Cluster 1 (5)	Cluster 2 (4)	Cluster 3 (4)	Cluster 4 (5)
OP density (Palms/ha)		Medium (126 to <140)	Very High (153 to <170)	
Ch. fertiliser count per year	Low (0 - 2)			High (3 - 4)
N (Kgs/ha/yr)	Low (0 to <65)	Moderate (65 to <72)	Optimal (72 to <115)	High (115 to <200)
P (Kgs/ha/yr)	Low (0 to <9)	Optimal (18 to <29)	High (29 to <65)	
K (Kgs/ha/yr)	Low (0 to <80)	Optimal to High (160 to <460)	Moderate (80 to <160)	
Mechanical weeding	Minimal (0 - 1)	Intensive (2 - 4)		
Chemical weeding	No	No		Yes (1 - 2)
Harvest interval (days)	Short (<18)	Moderate (18/19)	Extended (20/21)	

Figure 17: Variables and modalities of management practices grouped under different clusters. The number of farmers per cluster is shown in yellow sphere.

3.2.2 Age effect

To evaluate the impact of age on performance, I categorized plantations into three different age groups. Plantations with ages below 6 years were classified as "Young," while those aged 16 years and above were categorized as "Mature." The "Intermediate" group exhibited significant age variability, encompassing both young and mature palms with ages ranging from 7 to 15 years. Each of these groups comprised 6 plantations. Notably, the age distribution varied within the intermediate and mature groups (Figure 18). In contrast, the young group predominantly consisted of 6-year-old plantations, with 5 out of 6 falling into this category.

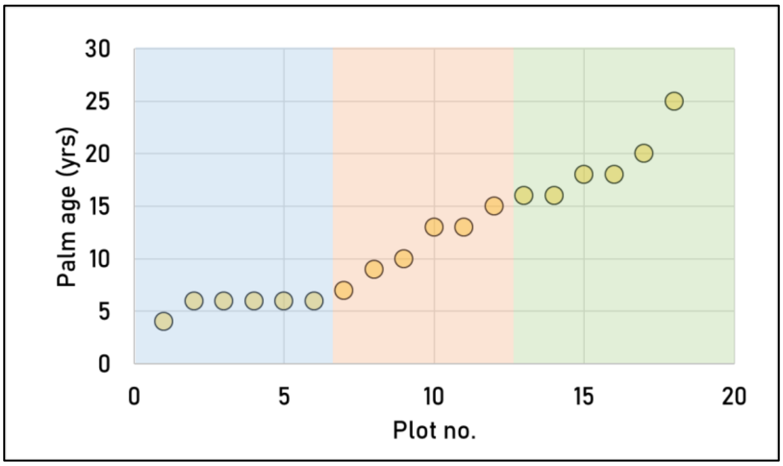


Figure 18: Distribution of plantation age among the study plots. Young: 0-6 years; intermediate: 7-15 years; mature: 16-25 years

3.2.3 Previous land use

The study region has a long history of diverse land uses such rice, coconut palms, rubber, forest and unused lands. For plots that had land use change from paddy to OP (RO plots), the former was cultivated for at least 30 years. Regarding land use change from rubber to OP (RBO plots), most rubber plantations were cultivated for 28-35 years. On the contrary, the average age of first-generation oil palm plantation (OO plots) was in the range 25-30 years. Four of six RO plots retained canals that were once used to irrigate paddy fields. On the other hand, plots with land use change from rubber to OP do not have such canals, as they are usually not present in rubber plantations.

It is important to highlight that the previous land use of the plots had a relatively strong dependence on soil inherent properties. All the plots with previous crops as rice, are in Sai Buri soil series. Also, soil texture analysis revealed a collective effect of previous land use and the soil texture (Figure 19). Soil samples collected from previous land use types of rubber and oil palm tend to have lower percentage of silt and clay content than to RO plots. High average values can be observed for clay % and silt % in RO plots irrespective of sampling zone. Most of the RO plots are in (Bu) soil series (see Figure 5). However, four plots with previous land use as rubber (3) and oil palm (1) located within the same soil series did not exhibit comparable soil texture composition.

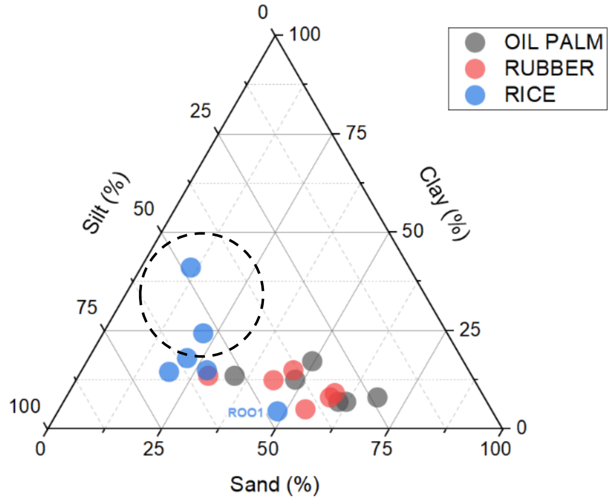


Figure 19: Soil texture triangle of topsoil samples collected near ring zone of palms from different plots.

3.2.4 Interaction between factors

Complex interplay of factors and their variables can be visualized from the (Figure 20). The width of the lines represents the number of plots connecting the factor variables. Young plantations were spread evenly among the previous land use variables than intermediate or mature plantations. Nevertheless, C2 group does not have any young plantation (< 7 years). Interestingly, C2 group consists majorly of oil palms as previous land use. Interestingly, C4 does not have any plots that had replanted oil palm.

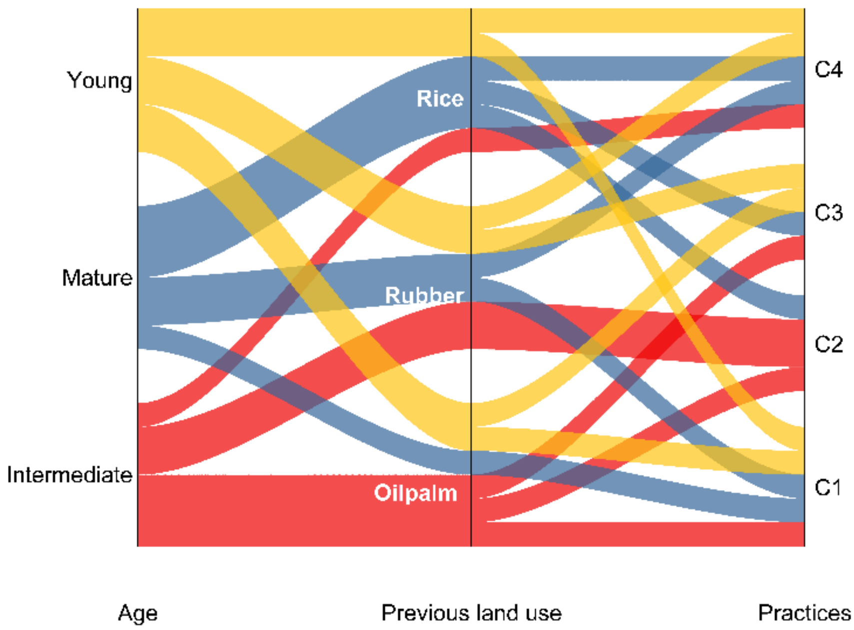


Figure 20: Parallel set graph illustrating interconnection of factor variables.

Age and management practices. It was observed that mature and tall palms were difficult to harvest as ripeness-check for FFBs become more challenging and results in damage to the fronds for visual inspection. As seen (Figure 21), the support of the frond was cut by harvester to check the ripeness, since FFB was still unripe, it was decided to skip harvest of this FFB. Absence of supporting frond may result in falling of FFB when it was completely ripe and probably losing the fruit content.

Figure 21: Supporting frond being cut for visual inspection of ripeness.

Previous land use and management practices. Planting material from plots with previous land use as rubber and rice were purchased either from Golden tenera or Univanich (Table 11). Seed varieties of these companies were easily available to farmers in the locality. Univanich is oldest and leading producer of crude palm oils and high-quality oil palm seeds in Thailand. On the other hand, more diversified seed variety was observed for plots with replanted oil palms. Seed varieties that were not available locally were still purchased by these farmers. Perhaps this could be linked to knowledge of already cultivating oil palms for a longer period of time than other farmers. Furthermore, in the case of replanted oil palms, the average amounts of N and K applied were 67.3 and 109.2 kgs/ha/yr, respectively. For plots with other land use transitions (rubber and rice), the application rates for N and K range from 87.9 to 93.4 kg/ha/year and 170 to 187 kg/ha/year, respectively. This demonstrates that on an average, farmers (replanted plots) applied relatively less N, and K quantitates in their plots compared to other farmers. It is possible that their prior knowledge and experience in growing palms in the plot influenced their ability to apply appropriate amounts of fertilizer.

Table 11: Seed names/sources of 18 study plots

Previous land use	Seed name/source
Oil palm	Taksin palm (Surathani)
Oil palm	Univanich
Oil palm	Univanich
Oil palm	Taksin palm (Surathani)
Oil palm	Nong ped tenera (Pao rong)
Oil palm	Surat thani 7 (DOA, Krabi)

Previous land use	Seed name/source
Rubber	NA
Rubber	Golden tenera
Rubber	Univanich
Rubber	Univanich or Golden tenera
Rubber	Univanich
Rubber	Univanich

Previous land use	Seed name/source
Rice	NA
Rice	NA
Rice	Univanich
Rice	Univanich
Rice	Golden tenera
Rice	Univanich

To summarize, farmers who change from rice or rubber to oil palms have less experience in terms of management practices (e.g., applying appropriate amount of fertilizer) compared to farmers who have cultivated oil palms for long time. However, as the plantations age increases, activities like pruning and harvesting would be challenging, and management quality reduces.

3.3 Performance evaluation

To evaluate sustainability of smallholder plantations, four performances were assessed through composite indices which were social, environmental, economic and production performances.

3.3.1 Social performance

3.3.1.1 Qualitative analysis

Trainings. The study on social aspects among the study participants reveals that 12 farmers (66%) have undergone training related to oil palm plantation management (Figure 22). Out of 12 farmers, 9 of them have received training primarily from co-operatives (oil palm and rubber) in the village. All these farmers mentioned that fertilizer application was the main theme of training. Training on other management practices such as weeding, or disease/pest control were received by 3 farmers. The farmers recalled that training included topics such as harvest and yield management (5), planting material (2), and oil extraction quality (1). Two farmers mentioned that they received Roundtable on Sustainable Palm Oil (RSPO) certification training from Krabi oil palm community co-operative in Ao-leuk, situated 40 kms away from the village.

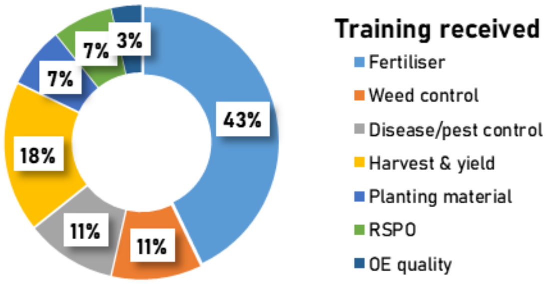


Figure 22: Donut chart representing the training themes that were received by smallhoders

Knowledge. Choice of planting material is of utmost importance considering plantations can produce FFBs for more than 2 decades and any wrong decision would result in substantial loss (Euler et al., 2017; Jelsma et al., 2017; Monzon et al., 2023). Therefore, during the interviews, pictures of tenera, dura and pisifera were laid out and asked to point out the planting material in their plot. In addition, if farmer was able to recall and point out correctly, then they were asked to explain more about the planting material. The responses were classified into four classes as shown in Figure 23). Individuals who were not aware of different seed varieties, such as dura, tenera, or pisifera and had no understanding of the distinctions between these seed sources or their characteristics were classified under “No knowledge”. Farmers who may know a few well-known seed sources but lack the ability to clearly specify differences between tenera and dura were grouped in “Poor”. Farmers with “sufficient” knowledge could differentiate between dura and tenera varieties and can accurately identify the various seed sources and understand the characteristics that set dura and tenera apart from each other. Farmers who possess a strong knowledge were those who have a thorough understanding of various seed sources, can accurately recall their planting material. These farmers take extra care in managing their plantations by visiting more often than other farmers in the study.

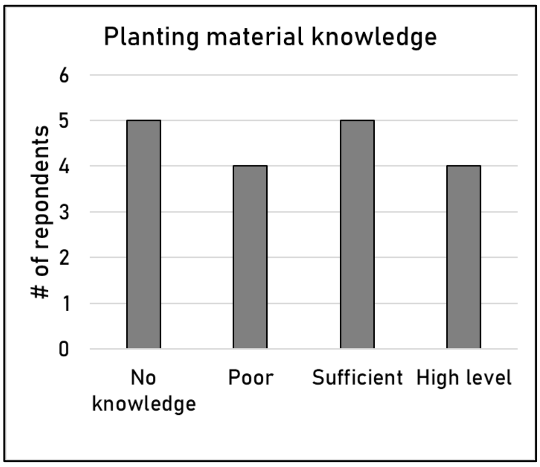


Figure 23: Graph depicting different levels of knowledge of individuals on planting material.

The plot owners were asked about the individuals influencing their choice of purchasing planting material from a specific seed source. Among them, four individuals stated that they personally visited a company or nursery, examined various seedlings, and made their purchases based on their own preferences. Half of the plot owners relied either on family (4) or non-family networks (5) for purchasing planting material. Family-network includes relatives such as uncle, aunt, and cousin, while non-family network includes neighbor, friend, or government official.

Certification & policies. According to the literature, RSPO certified smallholders have better management practices and can achieve high yields, which can lead to increased revenues (Vos et al., 2021). More than 80% of the farmers (15) in the study area have confirmed awareness of the RSPO certification, among these 6 of them were RSPO members before the program's dissolution in the village. Several farmers mentioned facing stringent regulations that restricted their eligibility to join the RSPO. Notably, those farmers who also sold their FFBs to other middlemen (Ramps) were excluded from participating in the RSPO program. A portion of the respondents conveyed their lack of belief in benefits from being RSPO members, attributing it to malpractices within the local organization. This sentiment was expressed by 25% of the study participants. Concerning policies, subsidies, and sustainable practices, ten farmers have responded that they follow updates on government policy particularly interested in the price guarantee, which was mentioned by half of these respondents. Thailand's standard of good agricultural practices (GAP) for oil palm production was known to less than half the study participants. Two farmers mentioned that they use herbicide/pesticide which was not within GAP guidelines.

Management decisions. Decisions for various plantation activities were taken by either one person or by a family-involved process. In the case of the family involved, the decisions were taken by two people. In most cases, it was husband and wife. Thus, if a plot was managed by two people, it was categorized as dual-manager plot (Figure 24). The decisions can vary from choice of fertilizer, weeding schedule to hiring labor for various activities. Over half of the plots studied have farmers who were under 52 years. All these farmers, except one, involve their family members in discussions before making management decisions. On the contrary, farmers who were above 52 years make their decisions independently. This suggests that farmer's age could play vital role in the decision-making dynamics in the plantation activities.

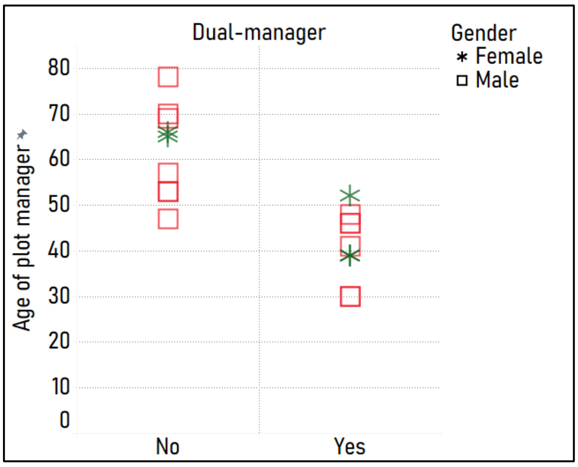


Figure 24: Interview respondent demographics and plot management status.

Gender balance. Women were engaged actively not only in plantation activities, but also take responsibility of managing the activities. Two out of 18 managers were women who decide alone the plantation activities, see Figure 24. Moreover, a significant majority of male individuals aged below 52, who manage the plot, actively seek input from their wives regarding plantation-related decisions. This displays that women were highly involved and have higher stake in decision-making power. This contrasted with the recent study by Mehraban et al., (2022) in Indonesia, where they report loss in female autonomy in terms of decision-making due to lower involvement in plantation. This can be associated with cultural differences which were stark between two countries (Akter et al., 2017). Women also play significant roles in plantation activities, such as applying fertilizers (16 plots), participating in harvesting (16), and assisting in pruning (14). During harvesting, usually a team of more than 3 members were present and among them were some women who help to collect the fallen loose fruits, and place fallen fronds in windrows. In some cases, less-weight FFBs were carried and loaded to pick-up van by women. For pruning activity, the fronds were cut by men alone, while women and other men assist in arranging the fronds. Weeding requires extensive effort holding the mechanical tool for a long period of time, where women usually do not participate (Mehraban et al., 2022). However, women assist in cutting the weed around the palms and on the bark.

Well-being & difficulty. Another aspect of evaluation comprised of individual's well-being and their experience with plantation activities. Most of the farmers have expressed that they were satisfied with the plantation

(Table 12). More than 80% of the respondents said they experience moderate to low levels of drudgery. Among those engaged in plantation activities, the respondents acknowledged some level of discomfort and expressed experiencing back pain due to tasks involving body bending, lifting, and carrying heavy objects. Many experienced moderate to severe pain after performing these tasks. However, they responded positively that by taking ample amount of rest, the pain was relieved, and they would be back to work very soon. This positive attitude was reflected when they were asked about the possibility of abandoning the oil palm plantation for more lucrative opportunities that relatively less stress. Among the 18 farmers, 12 expressed a strong likelihood of staying committed to plantation activities, emphasizing their contentment with the economic advantages in comparison to their previous crops such as rubber plantation. On the contrary, only 4 of them maintained a neutral stance in this regard.

Table 12: Well-being and difficulty level evaluation of farmers who have taken part in some or all plantation activites. *Farmers who do not participate in plantation activities have not responded to this.

						RATING SCALE
Satisfaction	1	-	5	4	8	Strong dissatisfied, dissatisfied, neutral, Satisfied, highly satisfied
Drudgery	-	-	3	7	8	Extreme, very heavy, heavy, moderate and low drudgery
Discomfort*	-	2	7	1	2	Mild, moderate, severe, very severe, extreme pain
Abandon	-	1	4	1	12	Very likely, likely, neutral, unlikely, very unlikely

3.3.1.2 Quantitative analysis

Univariate analysis. The results of quantitative variables used for social performance indicators are presented in the (Table 13). The average farmer's age in the study area was 51 years. All the farmers in the study area were involved in one or more activities in the plantation, except for two farmers who manage the plots entirely with hired labors. The mean value for family to hired activities ratio was 1.54. For workload, representing the total work hours, mean values stand at 65.26 and 265.98 hrs for family and hired labor, respectively. Regarding the labor hours spent for each operation, a family member on average spends most time in weeding (3.68 hrs/ha), whereas applying fertilizer or pruning, each member works around 2 hrs/ha. However, less than one hour was spent by a family member for irrigation or harvest activity. If harvesting activity were performed with a hired team, the role of farmer would mostly be helping to arrange fronds or with loose fruits. On the other hand, mean hours spent by a hired worker for weeding and pruning were 2.76 and 2.1 hrs/ha, respectively. A hired member spends less than an hour for fertilizing or harvesting in plantation. It appears from (Table 13) that the distribution of activity among the family or hired labor was high for harvesting and low for weeding and pruning. For fertilizer application, on average a family member spends more time in a plot than hired worker. Regarding the land use change, on average, rubber to oil transition plots had farmers relatively younger than other plots (see Appendix 6). For replanted plots, labor spent for fertilization was comparatively less.

However, the labor workload was high for major activities for plot with land use change from rice to oil palm. Concerning the practices, the mean age of farmers was highest in C3 group. C2 and C3 farmers spent more time in plantation activities than other farmers and hired activities was highest for C4 farmers. On other hand, C1 farmers are involved less in plantation activities. Furthermore, the age of plantation had a strong influence on workload, where family members spent less time in young plantations, particularly in applying fertilizers, while hours spent for pruning were high. This is due to the cost for fertilization is less compared to pruning and the latter activity is easier for short palms than taller palms. Finally, labor was hired for pruning and harvesting for mature palms, as it becomes challenging for tall palms.

Table 13: Descriptive analysis of social indicators for the 18 plots. Fam_WF= family workforce, Fam-Hired ratio= family-to-hired labor activities ratio, Fam_WL= family, Hire_WL= hired workload, Irri= irrigation, Fert= fertilization, Weed= weeding, Prune= pruning, Harv= harvesting

Vari-able (unit)	Farmer's age (yrs)	Fam_WF	Fam-hired ratio	Fam_WL (hrs/yr)	Hire_WL (hrs/yr)	Operation difficulty hrs/family labors/year					Operation difficulty hrs/hired labors/year			
						Irri	Fert	Weed	Prune	Harv	Fert	Weed	Prune	Harv
Min	30	0	0	0	19.5	0	0	0	0	0	0	0	0	0
Me-dian	50	1.5	1	28.8	248.8	0	1.4	3.8	0	0	0.4	0.9	0.9	0.4
Mean	51.6	1.4	1.5	65.3	266	0.2	2.2	3.7	2.1	0.4	0.9	2.8	2.1	0.6
Max	78	4	5.5	375.1	517.5	1.8	8.8	7.9	24.7	1.9	5.1	10.3	10.3	2.6
SD	13.8	1	1.6	91.3	123.2	0.5	2.4	3.1	5.9	0.7	1.4	3.7	3	0.6
CV	0.3	0.8	1	1.4	0.5	2.3	1.1	0.8	2.8	1.5	1.6	1.4	1.4	1.1

Multivariate analysis. Figure 25 illustrates the PCA graph of variables. Dimensions 1 and 2 represent 48.4% of the variation from the dataset. Family labor related variables such as family workforce, family to hired labor ratio and family workload significantly contribute to first dimension. Hired workload contributes moderately to the first dimension with negative correlation. Hired activities such as fertilizer, pruning and harvesting dominate PC2. The third dimension also has variables related to family labor such as irrigation, pruning and harvesting. Overall, family labor related variables in PC1 and PC3 contribute to 43% of data variation. Influence of farmer's age was moderate in second dimension and very low in PC1 and PC3. Thus, variability of the indicator was either due to family or hired labor activities. Confidence ellipses in each factor (Appendix 6) were overlapped, indicating that the data points from different groups were occupying similar regions in the reduced dimensions. Nevertheless, for management practices, C2 and C1 farmers can be distinguished by two separate ellipses, these two groups mainly differ in terms of family involvement in plantation activities.

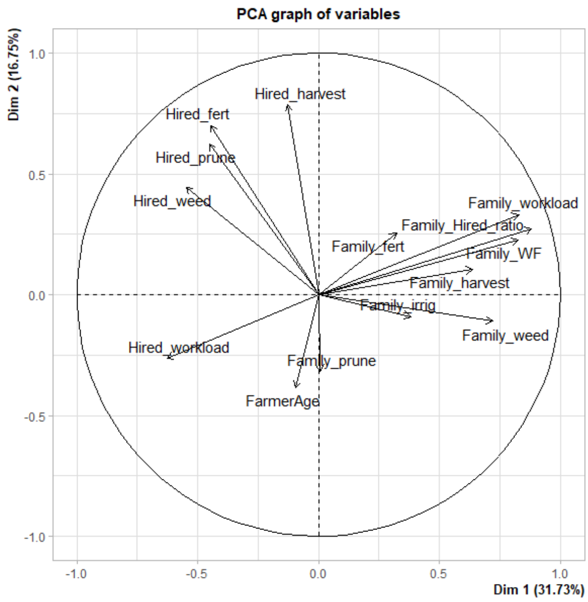


Figure 25: PCA graph for social indicators plotted on first and second dimensions.

Aggregation of indicators. Additionally, one-way ANOVA does not show statistically significant difference within each factor group. This was because of large variation within factor variable and small differences among factor variables as seen in (Figure 26). The highest social index value was typically achieved when family members actively participated in most of the plantation activities. Conversely, the lowest values indicate plots where the family members' involvement in activities was minimal. Consequently, this index serves as an indicator of how the plot was managed in terms of labor (family and hired). However, it's worth noting that, on average, C1 farmers tend to perform poorly compared to other farmers (Figure 26), particularly distinct from C2 farmers. Four out of five farmers in C1 group have social index ranging between 0.40 and 0.44, with SD ±0.09. In addition, from typology of practices discussed in section 3.2.1, these farmers apply very low quantities of N-P-K fertilizers. This suggests that, to some extent, management practices have an influence on social performance.

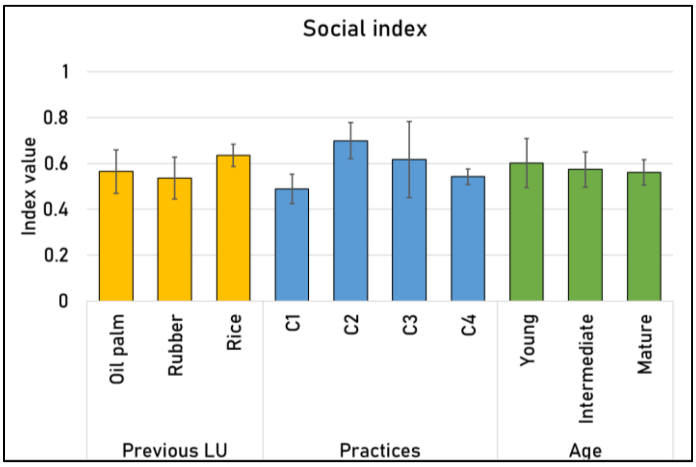


Figure 26: Bar graph of mean and SD values for oil extraction index for 3 factors (previous land use, management practices, and age of plantation)

3.3.2 Economic performance

Univariate analysis. Economic indicators used for analysis and their results are presented in the (Table 14). Typically, smallholders achieve an average gross product of approximately Thai Baht (THB) 101,830 yr^{-1}. ha^{-1} (USD 2850)[3]. On average, the operational costs, covering expenses like fertilizers and labor, account for about 30% of the sales from FFB. The labor costs are roughly 24% of the FFB sales. Mean gross margin comprised of ~70% of gross product which was THB 70,238 yr^{-1} ha^{-1} (USD 1966.6). The mean value for labor valorization, amount in THB for labor hours spent (family and hired), was 4198.7 THB per hour (USD 117.5). The average economic efficiency was observed to be 67%, this indicator signifies the degree of effectiveness with which resources like labor, capital, and land were engaged in producing FFBs. An intensification ratio exceeding 50% implies a heightened risk associated with maintaining the production system (Penot et al., 2021), and the mean value recorded for this in our study stands at 53%. The advantage of taking a risk of continuing with a production system was assessed by return on investment (ROI). A value greater than 200% indicates benefit in taking the risk of intensifying the crop (Penot et al., 2021). The average ROI for the 18 plots was 248%. The relation between ROI and intensification ratio can be best observed in the (Figure 27). The plot OOY3 has the highest ROI value with low intensification ratio. This was due to labor costs reduction by involving family members, including expensive labor like harvest. Hence a huge variation compared to other plots.

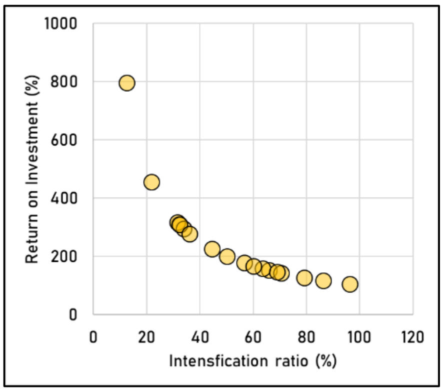


Figure 27: Graph depicting relation between return on investment and intensification ratio.

Table 14: Descriptive analysis of economic indicators for the 18 plots.

Variable (Unit)	Gross product (thb/yr/ha)	Gross margin (thb/yr/ha)	Operational costs (thb/yr/ha)	Wage ratio (%)	Labor valorization (thb/hrs)	Return to labor (yield per ha/hrs)	Economic efficiency (%)	Intensification ratio (%)	Return on investment (%)
Min	49278.15	27461.18	11048.71	2.35	234.19	0.04	50.9	12.58	103.65
Median	99532.35	63696.94	31435.72	17.96	1196.88	0.07	65.16	53.54	187.47
Mean	101830.71	70238.1	31592.61	16.97	4198.72	0.07	66.96	52.89	248.09
Max	170387.09	139661.2	44165.38	25.96	23841.6	0.1	88.83	96.48	795.11
SD	32247.35	30486.26	8780.52	5.4	7346.64	0.02	10.63	23.86	166.83
CV	0.32	0.43	0.28	0.32	1.75	0.3	0.16	0.45	0.67

[3] 1 THB = 0.028 USD (Average exchange rate for 2022-23)

A comprehensive summary of key factors and its economic variables across three categories: "Previous land use" (Oil Palm, Rubber, Rice), "Management practices" (C1, C2, C3, C4), and "Plantation age" (Young, Intermediate, Mature) is shown in (Appendix 7). Significant variability was evident across all the variables. Notably, when comparing previous land use, rubber (RBO) plots exhibit the highest mean gross margin, indicating the potential for greater profitability. Replanted plantations (OO plots) stand out with the highest mean economic efficiency and return on investment (ROI) while having the lowest labor and input costs. This suggests efficient labor resource utilization and better financial returns for OO plots. Among age groups, plantations with young palms have the lowest operational costs, along with relatively high economic efficiency and a favorable return on investment. On the other hand, the "Intermediate age group" strikes a balance between cost considerations and profitability, showing moderate values in metrics such as gross margin and ROI. Plantations with mature palms have the highest mean labor and input costs but also the highest gross margin, implying the potential for greater returns on investment. The C1 farmers group has relatively high mean labor costs but achieves the highest gross margin among the farmer groups, indicating the potential for good financial returns. Labor valorization and wage ratio were both high for this group. On average, C2 farmers have lower labor costs but higher input costs, resulting in a lower gross margin compared to C1. Their economic efficiency and return on investment were low. The C3 group exhibits the highest variability in labor costs but also has a high gross margin and a low wage ratio. It demonstrates efficient labor utilization and strong financial performance with high economic efficiency and ROI compared to other groups. C4 farmers have high labor and input costs, leading to a moderate gross margin. Their labor valorization was high compared to C2 and C3 farmers, indicating inefficiencies in labor utilization. Economic efficiency and return on investment were low for this group. In summary, C1 appears to prioritize maximizing profits with a significant investment in labor. C2 might need to optimize input utilization to enhance profitability. C3 demonstrates robust financial performance, while C4 needs operational optimization to improve profitability.

Multivariate analysis. Results of PCA on economic variables are shown in the (Figure 28). Principal components PC1 and PC2 together describe 78.2% of the variation in the dataset. Variables such as gross margin, economic efficiency and return on investment were contributing largely to dimension 1, while intensification ratio also does the same but correlate negatively. Gross margin, economic efficiency, and return on investment contribute to financial performance and hence positive correlation was expected since these metrics were typically used to evaluate the profitability and efficiency of an agricultural operation. However, a negative correlation with intensification ratio might indicate that higher resource utilization (intensification) results in reduced financial performance. Labor costs and operational costs contribute majorly to PC2. Strong correlation of labor costs in operational costs was expected as significant of operational costs was from labor, particularly for harvesting. The harvest rate ranges between 500 and 800 THB/FFB ton (14 – 22.4 USD). In 2022, the FFB price per kg was in the range of 5.13 to 10.87 THB (0.14 – 0.30 USD). Thus, the labor costs from harvesting alone may contribute to 4.6 to 15.6 % of FFB sales in 2022. While other labor related variables such as return to labor and wage ratio also influence moderately with positive correlation. Return on investment has slightly negative influence on PC2. This was expected as ROI (net margin/operational costs) was inversely proportional to operational costs. Thus, PC1 can be represented as profitability and efficiency, while PC2 variables mostly represent costs and resource utilization. Confidence ellipses plotted for each category group are shown in (Appendix 7). Large overlapping areas are observed for each category and no significant difference was observed. For management practices, ellipses for C1 do not overlap with C2 and C4, however the spread for individuals for C1 is wide and thus cannot be considered as distinct.

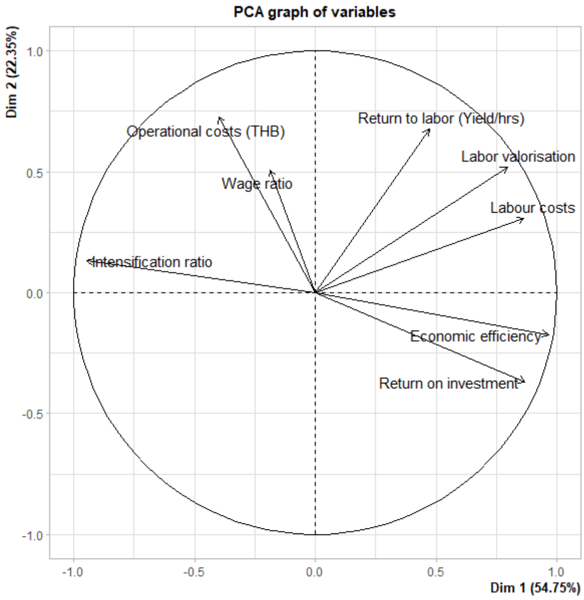


Figure 28: PCA graph for economic index plotted on first and second dimensions

Aggregation of indicators. A consolidated economic index was derived from incorporating weights of these indicators and scores in Equations 3 and 4. Mean and SD values for each factor are presented in the (Figure 29). One-way ANOVA indicate does not indicate significant difference for all the factors. Large variations within each variable and small differences among variables were observed for each factor.

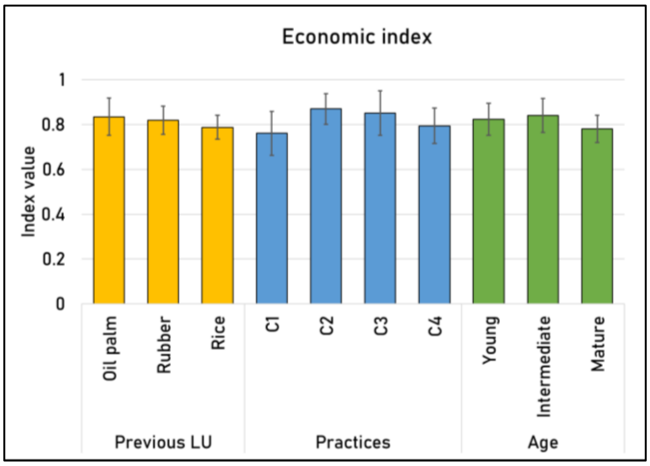


Figure 29: Bar graph of mean and SD values for economic index for 3 factors (previous land use, management practices, and age of plantation)

It appears that farmers' choice to increase profitability by reducing operational costs such labor and farm inputs do not have strong influence from the three factors (management practices, previous land use and plantation age). Although, to some extent practice (pruning activity) and age of the plantation have moderate influence on economic performance. In three out of six young plantations (<7 years old), fronds were pruned by the farmers without the need to hire labor. Shorter heights of these palms allow farmers to prune fronds easily than taller palms which need more effort to prune. Regarding its contribution to costs, pruning has a strong positive correlation with palm age, as observed in the (Figure 30). As palms grow taller, pruning becomes increasingly challenging for even experienced workers, resulting in higher costs. Nevertheless, on average pruning costs were not reflected strongly in total operation costs. This was due to harvesting and fertilizer expenses dominating the operating costs.

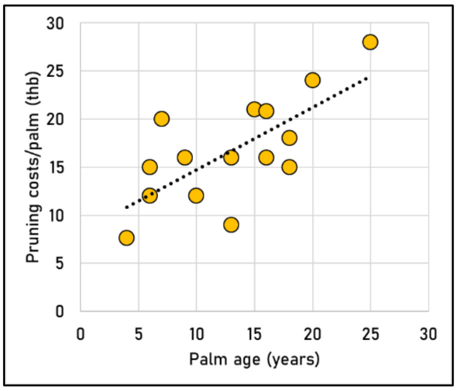


Figure 30: Pruning costs paid per palm over different age of plantations.

3.3.3 Environmental performance

3.3.3.1 Soil quality

Univariate analysis. Descriptive analysis of the soil physico-chemical and functional indicators is given in the (Table 15). The soil moisture content ranged from a minimum of 7.9% to a maximum of 48.5%, with a mean value of 23.53% with CV of 41%, indicating high variability. Soil pH values ranged from 4 to 6.8, with a median of 4.8, suggesting a slightly acidic to neutral pH range. The EC values were relatively low, ranging from 0.02 to 0.17 dS/m, with CV of 64%, indicating substantial variability. The SOM content varied from 0.79% to 4.34%, with a mean of 1.58% which was in moderate range (Goh, 2004). A positive correlation with the age of plantation was observed for SOM, similar to the trend reported by Brown et al. (2000). Nutrient concentrations exhibited large variability. For instance, P ranged from 1.3 to 683.4 mg/kg, with a remarkably high CV of 259%, while K concentrations ranged from 21.8 to 421.3 mg/kg. The cation exchange capacity (CEC) ranged from 5.79 to 22.67 cmol/kg, with a CV of 49%. Cations like K^{+}, Ca^{2+}, and Mg^{2+} exhibited high comparable variability with CVs of 90%, 107%, and 106%, respectively. Nitrate levels ranged from 13 to 51 mg/kg, with a relatively low CV of 35%, indicating relatively consistent nitrate concentrations. SituResp had a narrow range from 0.56 to 1.29, while scores such as Beerkan, bait lamina, and VESS scores showed moderate to low variability with CVs ranging from 0.09 to 0.76. Mean values for AggSurf and AggSoil were 5.32

(CV of 9%) and 4.99 (CV of 14%), indicating no significant difference. The results suggest that certain properties, like phosphorus concentrations and cation exchange capacity, exhibit greater variability compared to others.

Table 15: Descriptive analysis of soil quality indicators for the 18 plots

Variable (Unit)	Soil moisture (%)	Soil pH	EC (dS/m)	SOM (%)	P (mg/kg)	K (mg/kg)	CEC (cmol/kg)	K+ (cmol/kg)	Ca++ (cmol/kg)
Min	7.9	4	0.02	0.79	1.3	21.8	5.79	0.05	0.47
Median	21.67	4.8	0.06	1.39	10.6	72.05	8.43	0.2	2.31
Mean	23.53	4.95	0.08	1.58	61.41	103.03	9.94	0.28	2.97
Max	48.5	6.8	0.17	4.34	683.4	421.3	22.67	1.09	14.57
SD	9.7	0.73	0.05	0.84	158.93	94.32	4.91	0.25	3.17
CV	0.41	0.15	0.64	0.53	2.59	0.92	0.49	0.9	1.07

Variable (Unit)	Mg++ (cmol/kg)	NO_3 (mg/kg)	SituResp	Beerkan score	AggSurf score	AggSoil score	Bait lamina score	VESS score
Min	0.18	13	0.56	0	4.11	3.22	0.02	0.99
Median	0.84	29	1.1	2	5.36	5.14	0.17	1.92
Mean	1.14	28.65	1.07	2.72	5.32	4.99	0.19	2.16
Max	5.1	51	1.29	10	6	5.78	0.55	3.79
SD	1.2	10.02	0.18	2.99	0.5	0.68	0.14	0.79
CV	1.06	0.35	0.17	1.1	0.09	0.14	0.76	0.37

For rice to oil palm plots, the soil nutrient indicators CEC and Mg^{2+} were high and can be associated to high clay content observed in these plots (Figure 19). The mean CEC value of RO plots was 11.6 cmol/kg in RO soils, while the values for RBO and OO groups were 7.7 cmol/kg and 8 cmol/kg, respectively (Appendix 8). In, addition, soil moisture and water infiltration rates for RO plots were high compared to other plots. Other indicators such as P and K were less in rubber to oil palm plots.

Multivariate analysis. PCA results (Figure 31) show that first and second dimensions contribute to 40% of the total variance from the dataset. Variables such as soil pH, Ca^{2+}, and Mg^{2+} contribute strongly and have positive correlation, while CEC, surface soil aggregates and soil organic matter influence moderately in the first dimension. In the second dimension, the most influential variables were soil functional indicators such as bait lamina and SituResp (basal soil respiration).

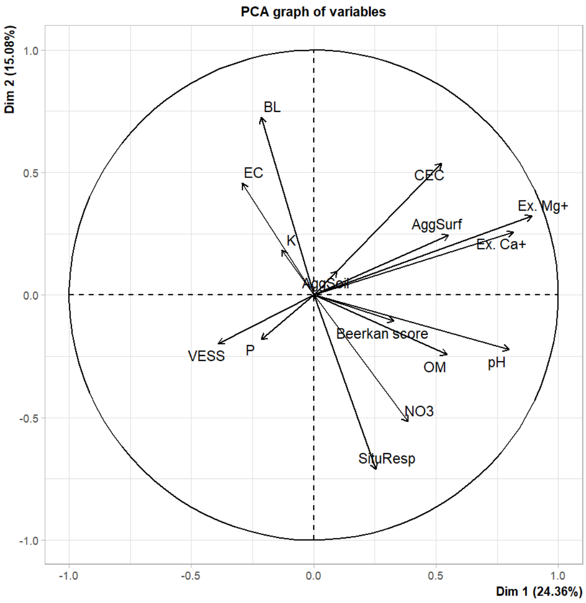


Figure 31: PCA graph for soil quality index plotted on first and second dimensions

These two indicators Bait Lamina and SituResp exhibit a negative correlation with each other, which can be attributed to the influence of distinct factors. The bait lamina score was significantly affected by the previous land use, whereas SituResp was influenced by age of plantation (Figure 32). Notably, the average bait lamina scores for OO plots were lower when compared to RBO and RO plots. This pattern was particularly pronounced in plots with young palms. Thus, exhibiting influence of previous land use and age factor.

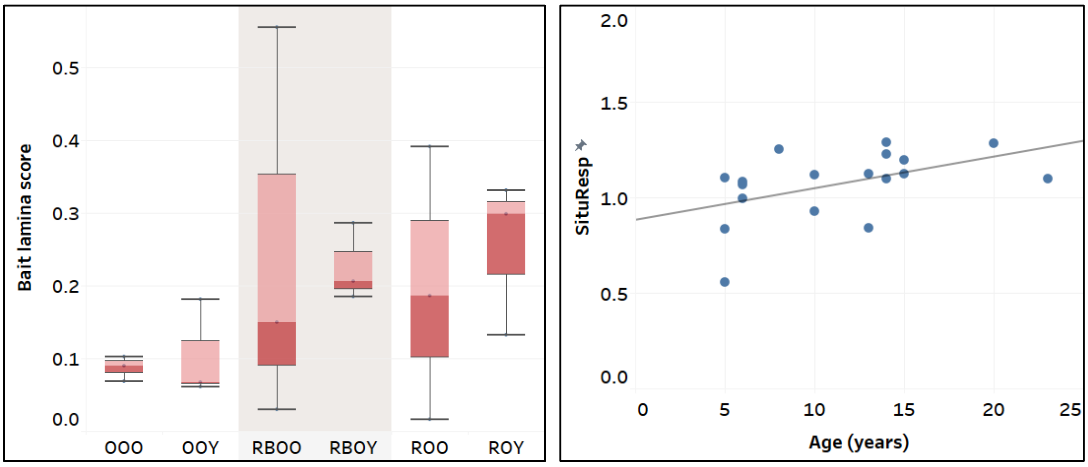


Figure 32: Box plot (left) of bait lamina score for plots grouped in previous land use type and age of plantations. OO: Oil palm to oil palm; RBO: Rubber to oil palm; RO: Rice to oil palm. Scatter plot (right) of Situresp values for age of plantation.

Nutrient availability indicators soil nitrate (NO_3) and CEC also show moderate influence on PC2. Soil moisture and sub-surface soil aggregates contribute to the third dimension that represent 11.35% of variance of dataset. However, these two variables correlate negatively. This effect was usually observed as soil moisture content increases, the cohesive strength of organic materials with mineral particles decreases and thus reducing the aggregate stability (Kay, 1997). Regarding previous land use, confidence ellipses for rice and rubber have distinct shapes and direction without overlay, while individuals for oil palm was spread and overlapping other two types (Appendix 8). For age and management practices, the confidence ellipses for variables overlap with each other, indicating uncertainty with the individuals. This suggests that among the factors studied, only previous land use may have significant difference on soil quality.

Aggregation of indicators. Mean and SD values of index for each factor group is shown Figure 33. High variation within factor variables and slight differences among the factor variables were observed. One-way ANOVA results do not reveal statistically significant difference for three factors. However, the p-value for the factor “previous land use” was 0.08, closer to the threshold value (0.05) compared to other two factors, indicating a moderate influence on performance.

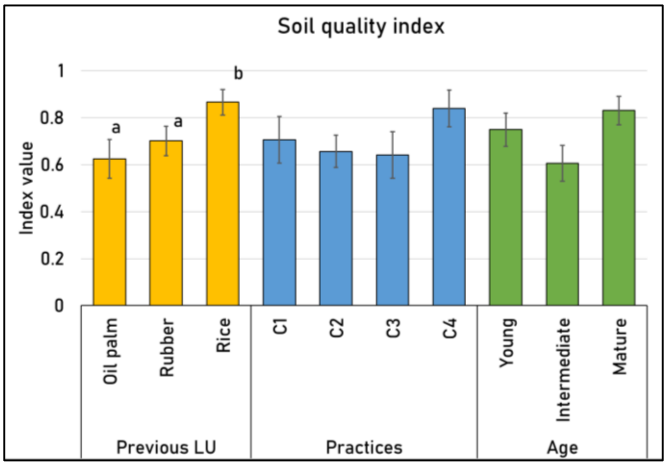


Figure 33: Bar graph of mean values for soil quality index for previous land use, management practices and age of plantation. Different letters represent significant differences (p-value < 0.05).

In Figure 33, RO-plots show a higher mean index value than OO- or RBO-plots. However, higher SQ values may not necessarily indicate balanced soil nutrients are available for uptake, as the index was composed of several soil physico-chemical and functional indicators. For instance, optimal plant growth nutrient ratios in soil such as Ca/Mg and K/Mg need to be well balanced (Fageria, 2001; Tiemann et al., 2018). In our study, for RO plots, the mean values of Mg concentration in soil were relatively higher than other plots. Our results are in good agreement with Kitprasong et al., (2021), who investigated the concentrations of Mg, and Ca/Mg, and K/Mg ratios in soil for various agricultural crops across southern Thailand. Their findings reveal that Mg concentrations were low in soils from oil palm and rubber plantations, but very high in paddy fields. In addition, they report Ca/Mg and K/Mg ratios in soil for paddy were very low compared to that of oil palm and rubber plantations, indicating land use effect on soil nutrient balance. Furthermore, the ratio of Ca/Mg in both soil and leaf samples were compared and results are presented in (Figure 34), categorized under two plantation age groups and previous land use type. To simplify interpretation, plantation age was grouped into two (<10 years and >10 years). For soil samples collected from plots in OOO group demonstrate low Ca/Mg values (<2), while the other groups exhibit higher values (>2). Despite having a higher Ca/Mg ratio in soil for RO plots, Ca/Mg ratios in leaf were lower than other plots. It is important to note that the Ca/Mg ratio in leaves should be within the 1.5–3.0 range, which indicates optimal oil palm growth (T. Fairhurst & Härdter, 2003). For both age groups of RO plots, this value was closer to the lower threshold. Also, the K/Mg ratio in soil collected from RO plots was lower than other plots, due to high values for exchangeable Mg (Appendix 8). A study by Goh (2004) suggests that for soils with high Mg^{2+} (>0.30 cmol/kg), nutrient correction is necessary. Regarding the interactions among ions like Ca, Mg, and K within the soil solution, a study conducted by Fageria (2001) found that ions which share similar chemical characteristics compete for functions (such as adsorption, absorption, and transportation) with each other for positions on plant root surfaces or within plant tissues. Hence, an imbalance in nutrient availability in soil for RO plots and complex cation (Ca-Mg-K) competition could have affected nutrient uptake (by roots) and subsequently accumulation in leaf (Tiemann et al., 2018).

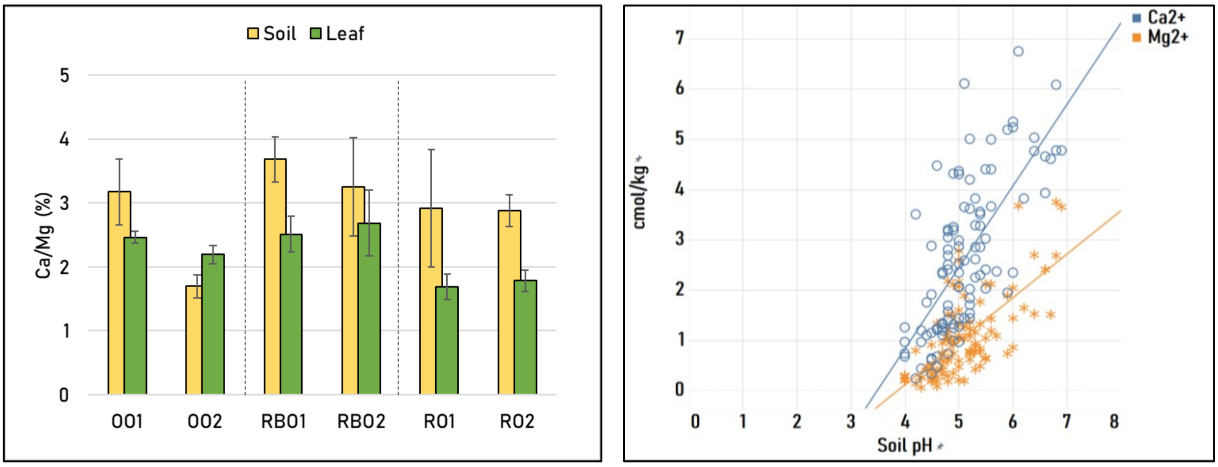


Figure 34: Bar graph (left) of mean and SD values of Ca/Mg in soil and leaf averaged over previous land use (OO, RBO and RO). Plantations age below 10 years are OO1, RBO1, and RO1 and above 10 years are OO2, RBO2, and RO2. Scatter plot (right) illustrating relationship between exchangeable basses (Ca^{2+} and Mg^{2+}) with soil pH.

Among the various variables considered for soil quality, exchangeable bases Ca and Mg have a strong relationship of soil pH (Figure 34). Higher values from these variables result in high soil quality index, but not balanced soil nutrient status for optimal plant growth. Thus, in our study the soil quality index with highest value corresponds to unbalanced soil nutrients and attention is needed for nutrient correction. On the other hand, the low index value ranging from 0.4 to 0.6 indicates soil condition with balanced nutrients. Thus, lower soil quality index values indicate the higher the performance (less is better).

3.3.3.2 Soil cover

Understory vegetation density. Soil cover has significant effect on soil erosion and run-off (Pardon et al., 2016). In plantations, diverse types of weed plants were grown in ring zone (1.5 m from palm) as shown in (Figure 35). Spatial coverage and density of weeds in the ring zone varied among the studied plots.

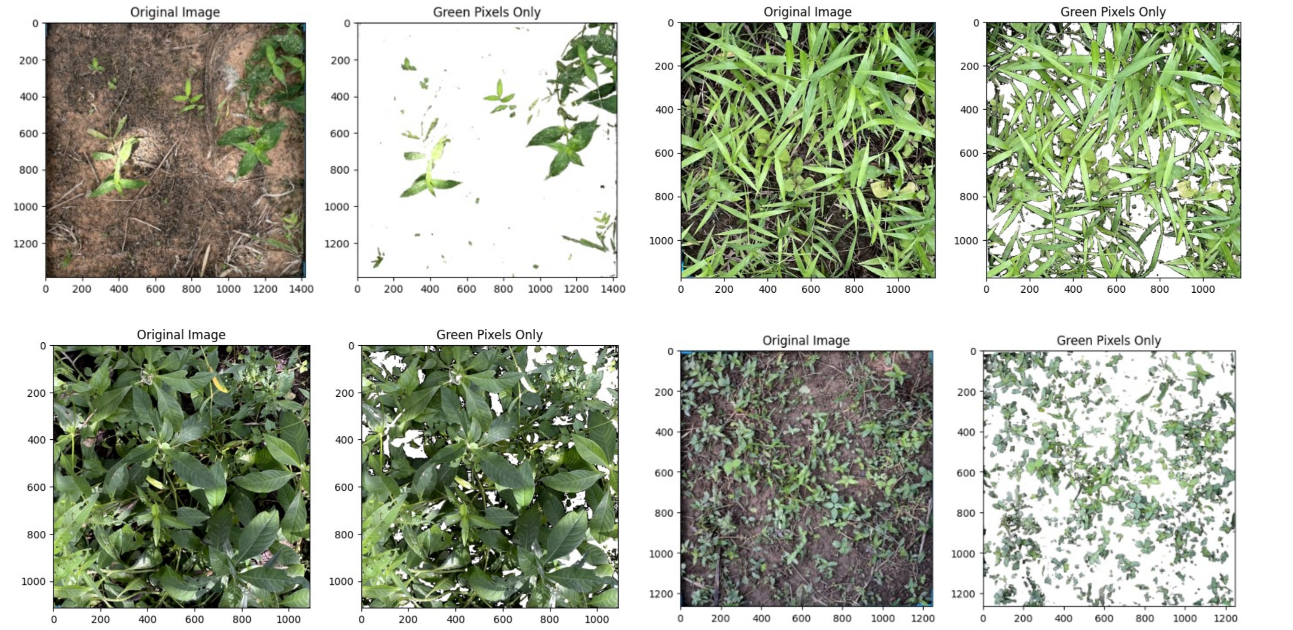


Figure 35: Pre- and post-image processed photographs of plant cover in frame of 50x50 cm taken in four plantations.

High weed density can significantly reduce soil loss in oil palm plantations (Hartemink, 2005), however there is nutrient competition from these plants. Although weed plants aid to prevent erosion, their growth dynamics and density change depending on the annual weeding frequency, microclimate, and other environmental conditions (Ali et al., 2021). In terms of the factors influencing our observations, I noticed significant variations within the variables (as detailed in Appendix 8). Both previous land use and management practices had a low level of influence. However, when considering the age of the plantations, there were noticeable distinctions. The mean and standard deviation (SD) values for mature, intermediate, and young plantations were as follows: 6.17 ± 2.23, 3.83 ± 2.14, and 3.67 ± 2.73, respectively. Tall palms contribute to higher weed density.

Frond stack. Contrary to understory density, the dead fronds placed in inter-rows are permanent. If these fronds are piled consistently, with the age of plantation the heap of dead fronds increase. These frond stacks not only recycle nutrients, but also reduce soil erosion (Formaglio et al., 2021). In an ideal planting scenario with palms placed at 8 m apart and fronds stacked with a width of 100 cm within a 7*8 cm elementary block, as depicted in the (Figure 36), the fronds would cover approximately 14.2% of the soil surface. Thus, frond stacking area play a key role in prevention of soil erosion. Height and width of stacks is shown in a box plot in (Figure 36). The mean values for stack width and height were 200 and 50 cm, respectively. The values for stack width range from 90 to 320 cm, while stack height was in range of 20-90 cm. The height of stack has positive correlation with the plantation age. A summary of mean values for variables across each factor group is shown in (Appendix 8). High mean values of weed density score and frond stacking area were observed for mature plantations, while young and intermediate exhibit low values. In terms of "management practices," C1 demonstrates the lowest values for both indicators, whereas C4 exhibits the highest mean values. Regarding previous land use, there was notable variability, with mean values ranking as rice > rubber > oil palm.

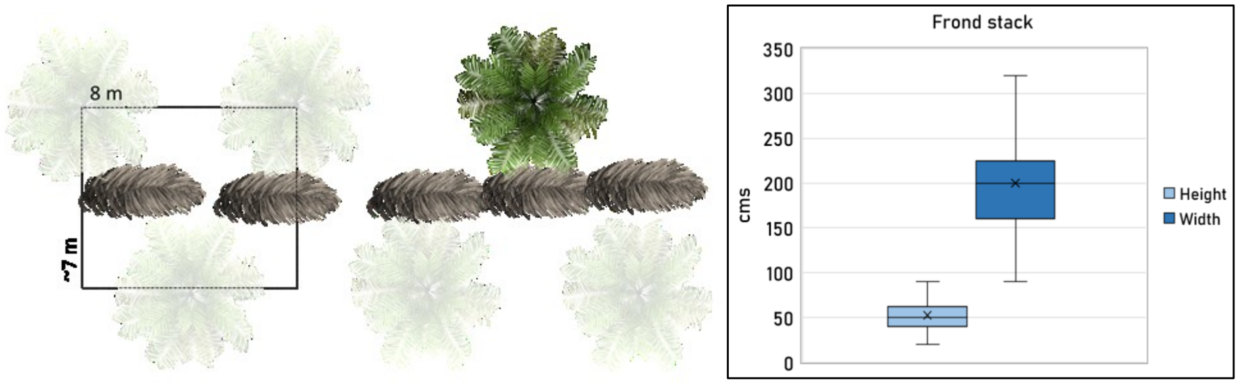


Figure 36: Aerial schematic view of plantation with 8 m spaced palms and highlighted is elementary block with stacked fronds. Box plot of frond height and width measured in the study plots.

Aggregation of indicators. A uniform weighting method was applied to combine frond width and the weed density score, resulting in an aggregated sum that defines the soil cover index. The mean and SD values for soil cover index is depicted in Figure 37. One-way ANOVA analysis reveals the age of plantation shows statistically significant (p-value=0.03). High soil cover index was observed for mature plantations. This was expected as plantations age, contributing to many fronds over time, reducing the soil exposure area. On the other hand, for weed growth conditions there are numerous dependent parameters such as light intensity, soil moisture and soil temperature (Satriawan & Fuady, 2019). However, tree physiognomy particularly tree height and crown length have strong positive correlation with soil temperature and soil moisture (Müller et al., 2016). Thus, mature palms could have accommodated favorable conditions for dense understory vegetation growth. In addition, poor correlation between canopy area and weed density was observed. This could be due to the different pruning period chosen by farmers resulting in a high variation in the number of fronds contributing to canopy area. For management practices, the mean value was lowest for C1 group, who represent less-intensive farmers. C2 and C3 have similar mean value, but high variance. On the other hand, the average index value for C4 was highest. Regarding previous land use, rubber and rice have higher value compared to oil palm. Nevertheless, one-way ANOVA analysis did not reveal statistically significant differences (Figure 37). This was due to large variation within a variable and small difference among variables.

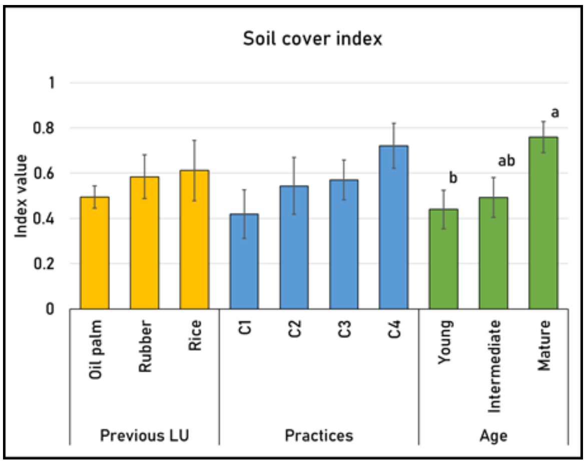


Figure 37: Bar graph of mean and SD values for soil cover index for previous land use, management practices and age of plantation. Different letters represent significant differences (p-value < 0.05)

3.3.4. Production performance

3.3.4.1 Palm metrics

Univariate analysis. The descriptive analysis of various botanical and physiological characteristics of palm trees is shown in (Table 16). In terms of palm height, the data ranges from a 0.49 to 11.06 m, with an average of 5.06 meters with CV of 63%. The number of fronds ranges from 27 to 51, with an average of 36.65, and a CV of 16%. The mean petiole area was 22.95 m^2 with a CV of 35%, showing moderate variability. On an average relatively high number of female flowers was noted compared to male flowers. Leaf area ranges from 3.72 to 12.52 m^2, with a CV of 28%. Canopy coverage was relatively high, with a mean of 95.71% and low variability (CV of 3%). Finally, rachis length ranges from 3.56 to 6.96 m, with a mean of 5.25 m and a CV of 15%. Nitrogen (N_leaf) content in the leaves has a narrow range (1.53% to 2.06%) with a CV of 8%, indicating minimal variability. The mean values for phosphorus (P_leaf) and potassium (K_leaf) in the leaves were 0.12 (with CV of 11 %) and 0.74 (with CV of 24%), respectively. Calcium (Ca_leaf) content in leaf varies between 0.55 to 0.92 with CV of 14%. The mean value for magnesium (Mg_leaf) content in leaves was 0.33 with CV of 19%. Potassium content in the rachis (K_rachis) range between 1.24% and 2.6%, with a CV of 21%. We compared the nutrient levels from our data with the established optimal ranges provided by Fairhurst & Mutert (1999) and the Krabi Oil Palm Research Center (as detailed in Appendix 9). Our data fell below the optimal range for N, P, and K, indicating a deficiency in these nutrients. Interestingly, N and K values were relatively high for two plots[4] due to different genetic material which has caused comparatively different values of leaf nutrients (Tan & Rajaratnam, 1978).

On the other hand, for Ca and Mg, we observed nutrient levels within the optimal range, with the latter slightly exceeding the upper limit of the optimal range. A comprehensive summary of palm metric variables across three categories: "Previous land use" (Oil Palm, Rubber, Rice), "Management practices" (C1, C2, C3, C4), and "Plantation age" (Young, Intermediate, Mature) is shown in (Appendix 9). When considering the previous land use type, the land's history significantly influences the variables in the study. Oil palm (OO plots), as the previous land use type, consistently exhibits higher values for variables such as number of fronds, petiole area, rachis length, total leaf area, and the number of male and female flowers, and overstory density. This suggests that land previously used for oil palm tends to have better growth characteristics with higher reproductive activity compared to land previously used for rice or rubber cultivation. Mature palms showed the highest mean value for palm height and total leaf area among the age categories, indicating that older palms tend to be larger and have more extensive leaf cover. Young palms had a higher number of female flowers, suggesting early reproductive activity. Regarding the management practices, on average C3 farmers maintain a high number of fronds on palm. These palms produce higher number of female flowers compared to other palms in other groups. This was reflected in higher nutrient content in leaf (Ca, K) and rachis (K).

[4] Planting material were Nong-ped tenera and Surath thani 7

Table 16: Descriptive analysis of palm metric indicators for the 18 plots

Variable (unit)	Palm height (m)	No of Fronds	Petiole area (m^2)	Female inflorescen ces	Male inflorescen ces	Leaf area (m^2)	Canopy (%)	Rachis length (m)
Min	0.49	26.67	9.37	0	0	37247.53	91.03	3.56
Median	5.54	35.83	20.83	3	0.67	86922.78	96.3	5.31
Mean	5.06	36.65	22.95	4.44	0.72	83492.81	95.71	5.25
Max	11.06	50.67	46.22	12	1.67	125235.09	99.61	6.96
SD	3.18	5.97	8.1	4.08	0.61	23257.99	2.86	0.78
CV	0.63	0.16	0.35	0.92	0.84	0.28	0.03	0.15

Variable (unit)	N_leaf (%)	P_leaf (%)	K_leaf (%)	Ca_leaf (%)	Mg_leaf (%)	K_rachis (%)
Min	1.53	0.1	0.5	0.55	0.2	1.24
Median	1.71	0.12	0.77	0.68	0.33	1.89
Mean	1.72	0.12	0.74	0.69	0.33	1.9
Max	2.06	0.16	1.25	0.92	0.46	2.6
SD	0.13	0.01	0.18	0.09	0.06	0.41
CV	0.08	0.11	0.25	0.14	0.19	0.21

Multivariate analysis. Principal Component Analysis (PCA) reveals interesting relationships among various variables (Figure 38). PC1 and PC2 contribute to 60% of the dataset variation. Notably, growth-related parameters such as rachis length, leaf area, and petiole area were strongly positively correlated with palm height. In addition, attributes like the number of fronds per palm, female inflorescence, and N (leaf) also contribute to PC1. In the second principal component (PC2), factors like canopy cover, nutrient indicators such as P (leaf), and K (leaf) play a substantial role in driving the variation. However, Mg (leaf) introduces a negative correlation within PC2. Interestingly, petiole area displays a moderate influence across both the primary and secondary dimensions, suggesting its significance in the overall dataset structure. In the context of PC3, which accounts for 10% of the dataset's variability, K (rachis) and male inflorescence have strong influence. Thus, PC1 predominantly captures palm structural variables, while PC2 primarily represents tissue nutrient characteristics. PCA graph of individuals with confidence ellipses for each factor is presented in (Appendix 9). For management practices, the variables overlapped with no distinction. On the other hand, for previous land use category, the ellipses for rice and oil palm have different direction and do not overlap. Individuals for rubber were spread across overlapping oil palm and rice. The spread of individuals was narrow for rice compared to the other two variables. Finally, the age of plantations has strong distinction, with narrow and elongated spread of individuals for mature group and widespread for young plantations group.

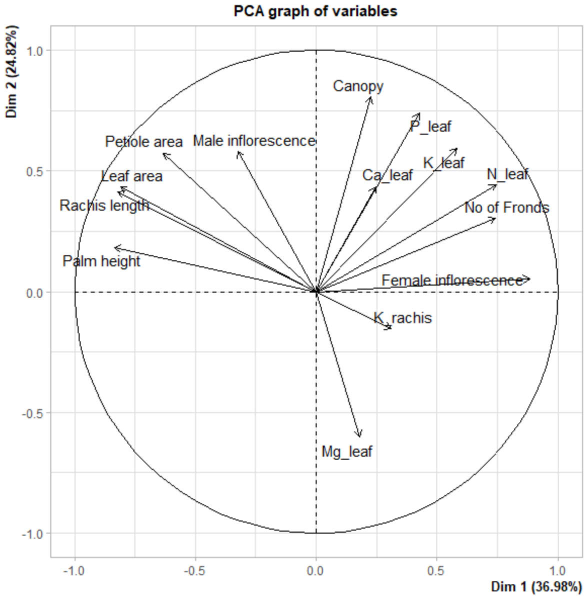


Figure 38: PCA graph for economic index plotted on first and second dimensions

Aggregation of index.

Mean and SD values of index for each factor group is presented in (Figure 39). The higher the index value the better is the performance. For practices, no significant difference observed, however, it is noteworthy that C4 exhibits the lowest mean value and minimal variation among the variables, indicating comparatively poorer performance. C4 farmers are high-intensive farmers but may not be implementing optimal practices. Previous land use type demonstrates strong influence on palm vegetative parameters. One-way ANOVA reveals statistically significant difference (p-value=0.016). Plots with replanted oil palms perform better than RBO or RO plots. This is due to better soil properties compared to other plots (see Figure 37).

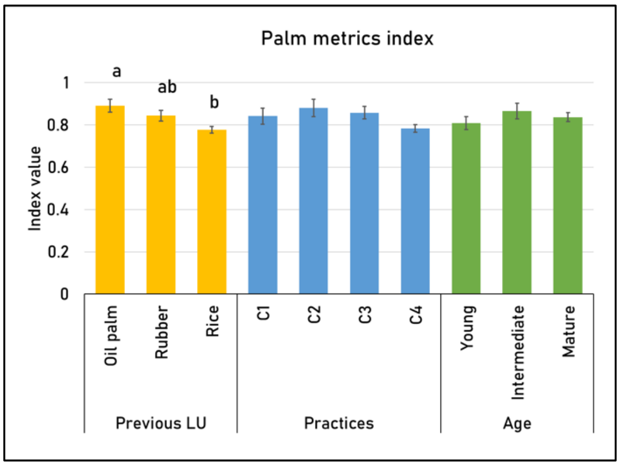


Figure 39: Bar graph (right) of mean and SD values for palm metrics index for 3 factors (previous land use, management practices, and age of plantation). Different letters represent significant differences (p-value < 0.05).

Univariate and multivariate analysis illustrate some influence of plantation age; however one-way ANOVA reveal no statistically significant difference due to minor differences among variables. Additionally, palm vegetative parameters related to growth such as height, number of leaflets per frond, petiole area, length of rachis and petiole and others have positive correlation with palm age. The number of fronds maintained and female flowers on palm have slightly negative trend with palm age, as see in the (Figure 40). Huge variation within each group was large and thus shadowing the influence from age (see Appendix 9). It is also possible that the vegetative metrics may respond more strongly to other factors such as climate or soil conditions, making age-related differences less pronounced.

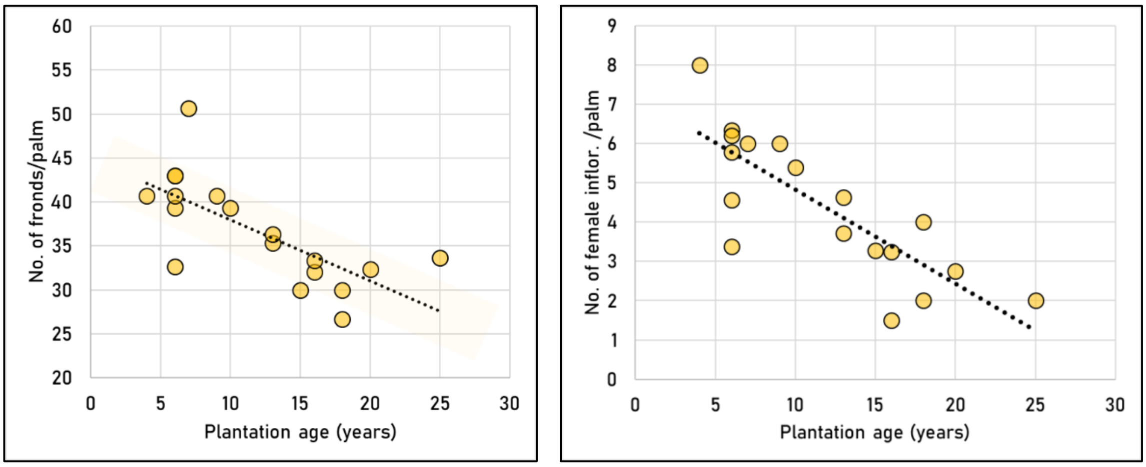


Figure 40: Graph (left) illustrating relationship between age of palm trees and the number of green fronds. Graph (right) illustrating distribution of female inflorescences among palms of varying age.

3.3.4.2 Oil extraction metrics

Univariate analysis. The descriptive analysis for various variables related to fruit and FFB characteristics are presented in (Table 17). These variables include kernel diameter (mm), mesocarp thickness (mm), shell thickness (mm), FFB weight (kgs), fruit setting per FFB (%), shell weight per fruit (%), kernel weight per fruit (%), total fruit weight per FFB (kg), dry weight of mesocarp per fruit (g), dry mesocarp weight per FFB weight (kg), and oil extraction ratio (%). The mean values for kernel, mesocarp and shell thickness were 10.45, 6.46, and 1.55 mm with CV 10, 21 and 22% respectively. FFB weight varies from 8.33 kgs to 27.67 kgs, with a mean of 17.44 kgs. The mean value for fruit setting per FFB was 73.67%, with a low CV of 6%. The dry weight of mesocarp per fruit and per FBB range between 45.49 – 60 g and 2.9 – 11.4 kgs, respectively. An analysis of several factors and their corresponding variables was conducted (see Appendix 9). It becomes evident that the type of land used prior to oil palm cultivation can influence certain fruit characteristics. FFBs from RBO plots showed similar bunch weights to those from OO plots, but slightly smaller kernel diameters and mesocarp thicknesses. On the other hand, FFBs from RO plots displayed a low value for bunch weight, mesocarp thickness, fruit setting, dry mesocarp weight. More importantly, oil extracted per bunch is relatively high in OO plots than other plots. This suggests that previous land use may have had some impact on FFB attributes. Additionally, diverse planting material was observed from OO group (Table 11) and two varieties in RBO and RO group. Among the practices (C1, C2, C3, C4), C2 showed the highest bunch weight and high fruit setting per bunch. On contrary, C1 had a low bunch weight and lowest oil extracted per bunch, although the bunch weight did not correlate to oil extracted ratio for other groups. C4 had the low values for bunch weight, kernel and mesocarp thickness, and fruit setting. This can be related to poor performances in vegetative characteristics as observed in (Figure 39). Young oil palms displayed the highest bunch weight and mesocarp thickness, suggesting potential benefits in terms of quantity and mesocarp quality. Kernel/fruit and shell/fruit percentage was low in intermediate group compared to other two groups. Intermediate palms had a notably high oil/bunch percentage, while mature palms had the lowest percentage. This was expected as the intermediate group consists of palms in prime period (producing high yield), see Figure 1.

Table 17: Descriptive analysis of oil extraction metric indicators for the 18 plots.

Variable (Unit)	Kern. diameter (mm)	Meso. thick (mm)	Shell thick (mm)	Bunch wt. (kgs)	Fruit set (%)	Shell/Fruit (%)	Kern/Fruit (%)	Fruit wt. (kg)	DM/F (g)	DM/B (kg)	OER (%)
Min	8.12	4.41	1.06	8.33	62.73	3.87	6.01	6.5	45.49	2.97	23.07
Median	10.2	6.16	1.54	17.34	73.98	6.74	8.2	12.46	53.19	6.55	28.77
Mean	10.45	6.46	1.55	17.44	73.67	6.92	8.31	12.74	53	6.71	28.2
Max	12.87	9.08	2.59	27.67	80.85	10.02	10.51	20.75	60	11.44	34.91
SD	1.09	1.38	0.35	5.7	4.25	1.51	1.3	4.07	4.48	2.2	3.2
CV	0.1	0.21	0.22	0.33	0.06	0.22	0.16	0.32	0.08	0.33	0.11

Multivariate analysis. PCA results are shown in the (Figure 41) reveal that mesocarp weight per fruit and FFB and oil extracted ratio dominate their influence on PC1, while kernel and shell weight per fruit correlate negatively with moderate influence. For PC2, kernel diameter, mesocarp thickness and fruit setting majorly contribute, while other variables have very low dominance. Around 12.5% of the dataset variation was represented by PC3, where the variable “total fruitlet weight per FFB” contributed to 50%. In summary, PC1 represents oil extraction efficiency and PC2 illustrates fruit dimensions and setting. Confidence ellipses for each factor are shown in (Appendix 9). For age category, confidence ellipses for young and mature do not overlap and demonstrate distinct direction, but the individuals were widespread within each ellipse (see Appendix 9). For management practices, the variables have overlapping ellipses and show less distinction. However, ellipses for C3 and C4 have distinct shape and directions with minimum overlap, indicating some significant difference. In terms of previous land use, confidence ellipses do not reveal significant difference for previous land use category variables.

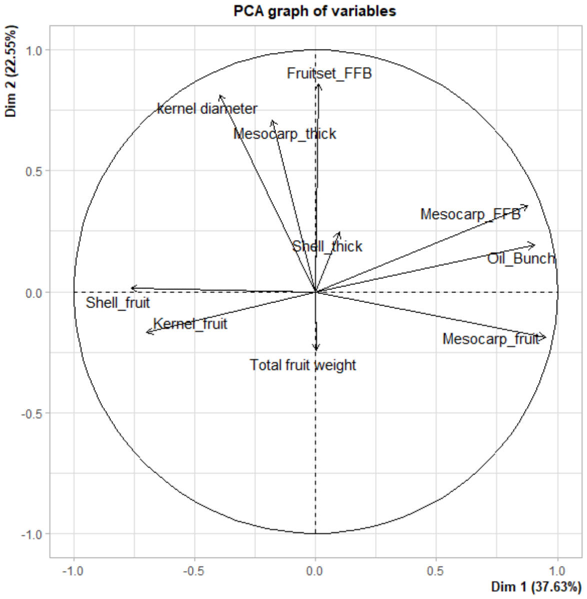


Figure 41: PCA graph for oil extraction indicators plotted on first and second dimensions

Aggregation of indicators. The mean and SD values for oil extraction index are presented in Figure 42. The higher the index value the better is the performance. One-way ANOVA analysis confirms statistically significant difference for age and previous land use groups. On the contrary, for management practices, no significant difference was observed with one-way ANOVA. C4 has the lowest mean among the variables in the group. One-way ANOVA analysis for factor "previous land use" does reveal statistically significant difference, however the p-value observed was 0.0664, which was slightly above the threshold to distinguish among the variables. A glance at bar graph for oil extraction index in (Figure 42), show the mean value for plots with replanted oil palms was higher than other two groups, indicating influence of the factor. This is expected as the vegetation performance of OO plots was relatively high (Figure 39). For plantation age, a strong difference (p-value=0.006) was observed, where mature plantation has lowest mean value. This is expected as older palms have reduced OER (Taniputra, 1977), due to large bunches (Corley & Law, 2001). Furthermore, a study by Sing (2020) high values of OER was observed for palms with age between 6 to 15 years. The OER further reduced for mature palms (above 15 years).

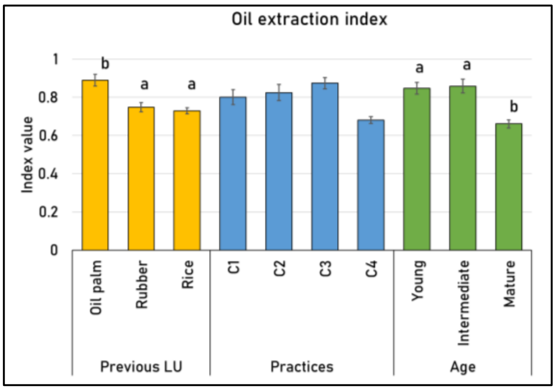


Figure 42: Bar graph of mean and SD values for oil extraction index for 3 factors (previous land use, management practices, and age of plantation. Different letters represent significant differences (p-value < 0.05).

3.3.4.3 Single-harvest yield

Figure 43 depicts the weight distribution of individual FFB for all the plots. Small lines below the distribution denote the density. The range of distribution curve varied from narrow to widespread. Plantations with young palms (< 10 years) produced FFB with relatively less weight and less dispersive (dense rug lines), while the weight distribution is very dispersive for palms aged above 10 years. This is due to the number of FFBs (see Appendix 11) is more for young palms. The previous land use type has affected current palm productivity, particularly in terms of FFB weight. Four OO plots and four RBO plots had FFBs that weighed more than 30 kgs, in contrast none of the RO plots had a FFB with 30 kgs and above. This signals poor performance of plots with transition from rice to oil palms.

Age effect. We observed that average FFB weight rises with increase in age of the palms, this is in good agreement with Segara & Santoso (2019). In our study, plantations with younger palms (< 10 years) have produced more FFBs than mature plantations (see Figure 44). This was confirmed with the high number of bunches harvested per hectare which has strong correlation with palm height as seen in Figure 44. Palm height and palm age have positive correlation, however the trend for palm height was clearer for interpretation and hence used for comparison. Two young plantations (ROY1 and RBOY3) fall out of this trend as they produced less quantity compared to their counterparts, this was due to seasonal variation. These two plantations were transiting from off-peak to peak season which was confirmed by interview data (Figure 45) and presence of high number of female inflorescences during our field observations. The mature plantations on other hand, go through transition period (peak to off-peak season) during May-June, and hence fit in the lower part of the curve. In the mature plantations group, the FFB yield observed was very low for OOO3, and ROO2 compared with their counterparts (Figure 44).

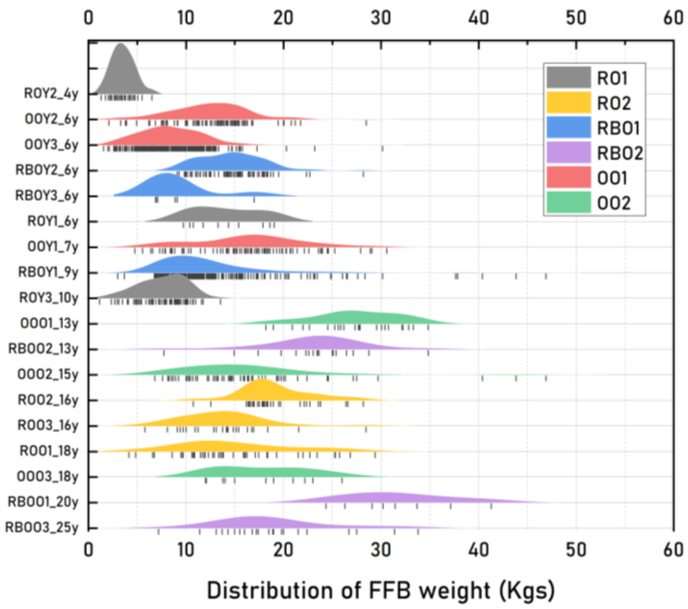


Figure 43: FFB weight distribution across the studied plots. Kernel smoothing was used, and rug lines were added to the curve. Plots with previous land use as rice, rubber and oil palm were named as RO, RBO, and OO, respectively. Plantations aged below 10 years are: OO1, RBO1, and RO1 and above 10 years are: OO2, RBO2, andRO2. The age of the plantation is affixed to the plot code.

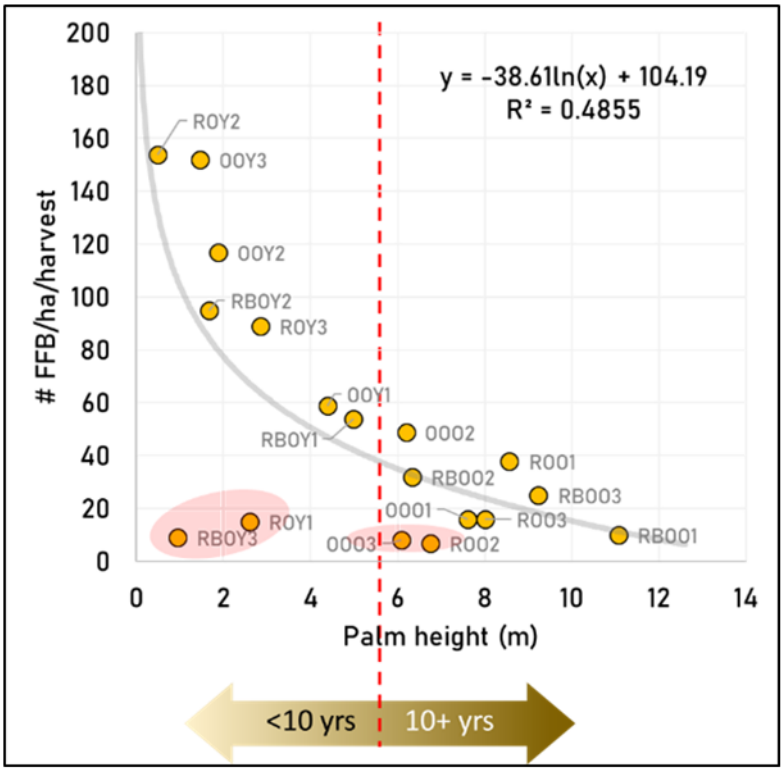
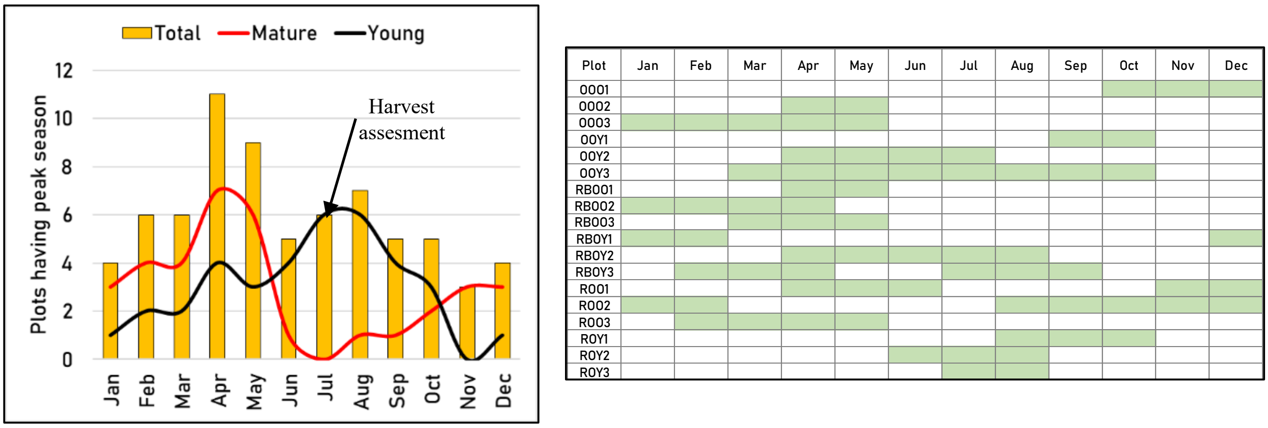


Figure 44: Scatter plot of number of harvested FFBs plotted against palm height. The data points were fitted with logarithmic curve and the dotted line shows the difference in age.

Peak and off-peak season data collected during the interview is shown in Figure 45. More than half of the plantations achieve maximum yield during the April-May period, both young and mature plantations contribute during this period. However, during the July-August period, young plantations dominate the yield in the study region. Thus, some young plantations (palms < 10 years) may have double peak season in a year with gentle rise and fall curve. On the contrary, most of the mature plantations have a gentle rise towards peak, then steep decline thereafter. As seen from the (Figure 45), the number of months and occurrence of peak season varied hugely across all the plots. The lack of reliable data on planting material added more complexity of explaining this variability. Furthermore, results from one-way ANOVA confirm significant difference (p-value=0.049) with lowest mean value for group of mature palms and high for young and intermediate plantations, see (Figure 46).



Plot	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
OOO1												
OOO2												
OOO3												
OOY1												
OOY2												
OOY3												
RBOO1												
RBOO2												
RBOO3												
RBOY1												
RBOY2												
RBOY3												
ROO1												
ROO2												
ROO3												
ROY1												
ROY2												
ROY3												

Figure 45: Bar graph (left) representing total number of plots with peak season. Line graphs indicate the number of mature and young plantations with peak season. Table with highlighted in green(right) indicate months with peak production for each plot based on interview data (right).

Previous land use. Mean and SD values for variables within factor "previous land use" is shown in Figure 46. The production quantity has huge variation within each factor variable (see Appendix 9) and therefore no significant difference was observed. Nevertheless, on an average, the FFB produced from plots with rice as previous land use was lowest, while plots with replanted oil palms had the highest mean value. This observation implies that the choice of previous land use significantly influences oil palm production performance, with the order being oil palm > rubber > rice.

Practices. Regarding the practices, C3 farmers stand out with the highest mean value, as seen from the (Figure 46). However, C4 farmers performed poorly, due to the group having 3 RO plots. Overall, a high degree of variability was observed within each variable.

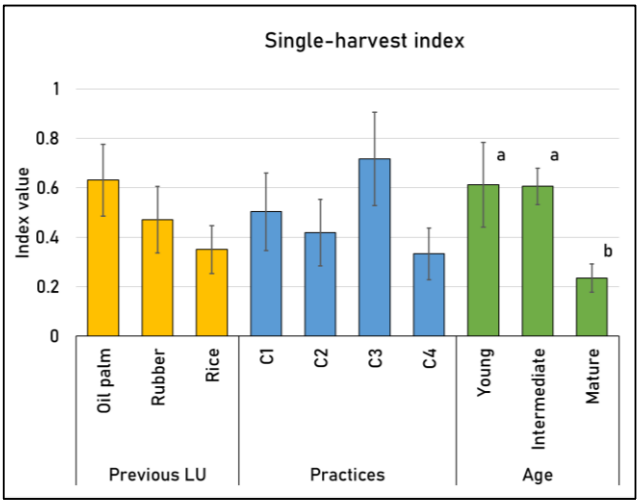


Figure 46: Bar graph of mean and SD values for single harvest index for 3 factors (previous land use, management practices, and age of plantation. Different letters represent significant differences ($p < 0.05$).

3.3.4.4 Annual yield

Only two farmers (OOO1 and RBOY2) in the study area have documented their production quantity for every harvest in 2022. Therefore, annual yield for all plots were calculated using a formula derived from equation 2.

The calculated annual yield (model) was compared with real data of two plots. From the bar graphs in Figure 47, there is no strong difference between actual and calculated data for two plots. In addition, from the line graph (Figure 47), monthly real data of OOO1 plot has good fit with the calculated values, demonstrating the strong reliability of the calculation method.

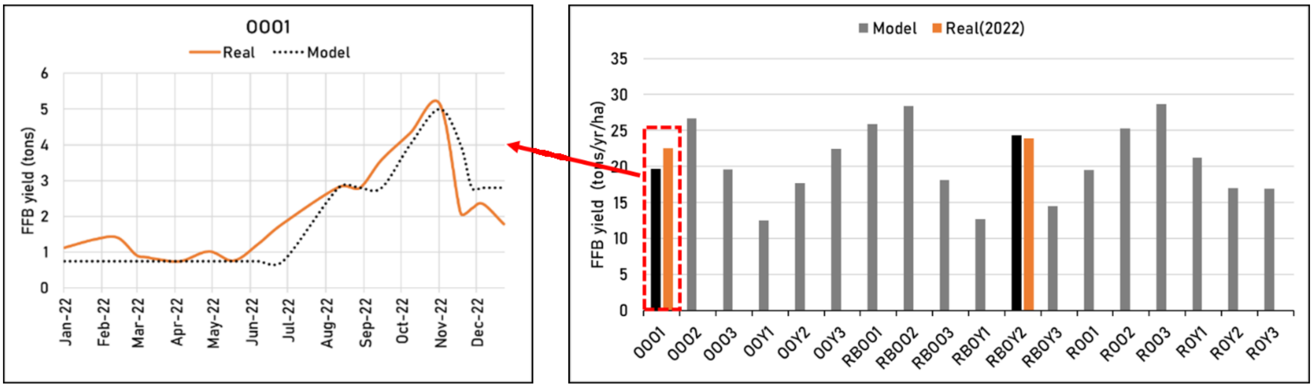


Figure 47: Line graph (left) of monthly model data of production quantity compared with real data for OOO1 plot. Bar graph (right) illustrating model annual yield for all the study plots and compared with two real data from OOO1 and RBOY2.

The annual yield of smallholder plots is shown in Figure 48 along with attainable yield (Yatt) and yield data from large plantations in Thailand and Indonesia. Khaokhen estate was located closer (~ 20 kms) to the study area Plai Phraya and hence used for comparision. Three clusters (S1, S2, S3) were identified from the smallholders' yield graph.

Age effect. The S1 cluster contain young plantations with five of them aged 6 years and one plantation with 4 years. The cluster demonstrates FFB yield with high variability (15 -25 FFB tons/ha/yr). This behavior is expected since Yatt ranges between 18.6 and 30 tons/ha/yr for plantation age with 5 -6 years. Thus indicating that the majority of smallhoders in this cluster might be achieving yield closer to Yatt. Comparing with the large estate data in Indonesia, two data points in this group fall behind suggesting relatively poor performance. Cluster S3 contain 5 plots with three mature plantations and two intermediate plantations. The FFB yield of smallholders ranges betweem 25.3 and 28.6 FFB tons/ha/yr, with very low variability within the cluster. This group achieve yield closer to Yatt and large estate (Yind) in Indonesia (Figure 48). Additionally, trend of this cluster appears to be declining with age of plantation, similar to that of Yatt curve. On the other hand, S2 consists around 40% of the plots in this study area, which consists of three mature and four intermediate plantations. The smallholders in this cluster achieve yield between 12.5 and 19.6 tons/ha/yr. The range was far below the Yatt cuve, particularly for intermediate age group. The data from large estate Khaokhen, Thailand (Ykk) have plantations with similar age group as S2, palms aged from 8 to 13 years. They produce FFBs varying from 16.2 to 23 tons/ha/yr, also falling behind Yatt. On the the other hand, Yind achieve yield closer to attainable yield. To summarize, age of plantation show large varitation, however no statistically significant difference was not observed. This could be due to other factors such as planting material (genetic variability) or soil conditions.

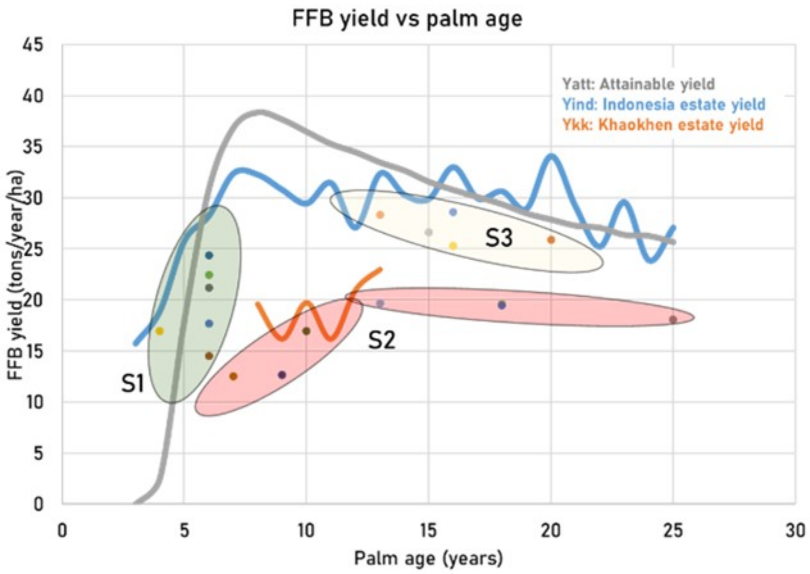


Figure 48: Annual yield of smallholders (scatter points) compared with attainable yield (grey line) and large estate in Khaoken, Thailand, (orange line) and estate in Indonesia (blue line). Source for Yatt: www.yieldgap.org; Ykk and Yind: Ollivier (2018) and personal communicaton.

Previous land use. The mean and SD values of annual yield in terms of index for different types of land use transition is shown in Figure 49. The data reveals high variations within each variable, and average annual yield being 19.6, 20.6, and 21.4 FFB tons/ha/year for the previous land use categories of oil palm, rubber, and rice, respectively. Low variation among the factor variables and a smaller number of sample size were constraints to observe the influence of land use transition. Furthermore, cluster group S1, S2 and S3 consists of all three land use change variables.

Practices. From the Figure 49 C4 falls out behind other group of farmers. The average yield produced by these farmers was 18 tons/ha/yr, while the lowest among the other three grousp was 21.36 tons/ha/yr. Although high variations within each group was observed, the trend for C4 groups was relatiely low who were high-intesive farmers. Comapring with the cluster groups (S1,S2 and S3), relatively more C4 farmers are present in S2 cluser, (see Appendix 12). Thus explaining the practices influence on annual yield. Another aspect that shows relationship of annual production performance is knowledge of planting material. Among the farmers in the S2 group, five out of seven were evaluated as having inadequate or minimal knowledge[5] concerning planting material.On contrary, S3 group, 4 out of 5 farmers had suffient or strong knowledge on planting material, while for S1 group a strong distinction was not observed.

[5] See section 3.3.1 qualitative analysis for details of assessment of knowledge on planting material

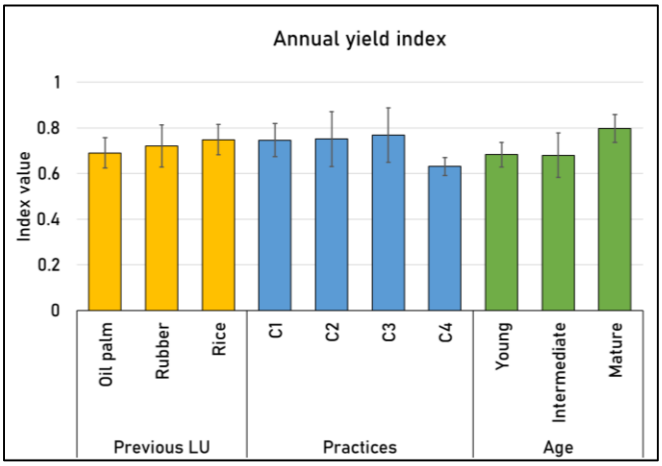


Figure 49: Bar graph of mean and SD values for single harvest index for 3 factors (previous land use, management practices, and age of plantation.

3.4 Sustainability assessment

A radar plot was utilized to assess the sustainability performance of three different land use types: oil palm, rubber, and rice. The assessment considered multiple indices, each represented along its respective axis on the radar plot. Environmental performance was represented by soil quality (SQ) and soil cover (SC) indices. Social (SOCI) and economic (ECON) performances are indicated by one axis each. Oil palm performance assessed by four indices: palm vegetative metrics (PALM), oil extraction metrics (OER), single-harvest yield (YELD_1) and annual yield (YIELD_YR).

Previous land use. Replanted oil palm plots exhibit a substantial influence on palm growth and production parameters as discussed earlier and evident by higher index values for YIELD_1, PALM, and OER (Figure 50). In contrast, land previously used for rice cultivation demonstrates notably lower values for these indices. Other indices related to economic and social performances do not show significant differences. Regarding soil quality, plots from rice to oil palm transition show higher index value for SQ than other plots. As discussed, highest SQ values indicate unbalanced soil nutrients are available for uptake and lower SQ values mean more balanced nutrients. Hence rubber-to-oil palm plots and replanted oil palm plots perform better than rice to oil palm plots.

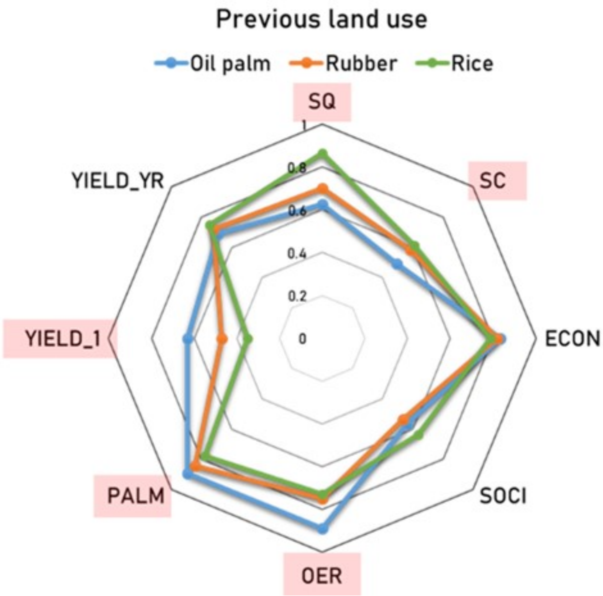


Figure 50: Radar plot illustrating performances of smallholder oil palm production systems for different types of previous land use (rice, rubber, and oil palm). Indices for which notable difference observed are highlighted in red.

Age effect. The performance of age factor assessed using a radar plot is shown in (Figure 51) with each index represented along its axis. Young and intermediate plantations have higher value for production indicator OER. This group also produced more FFBs than mature plantations during month of June (YIELD_1) and on other hand, extremely poor performance was observed for mature palms. This was due to seasonal variation as explained before, but when annual yield (YIELD_YR) was considered the difference between young and mature plantation was reduced and the latter has slightly higher index value. Vegetative characteristics (PALM) index for three groups were similar. Social and economic indices were not significant when the age of plantations was compared. In terms the soil cover, young plantations have low values for SC, and high for mature plantations. The difference in soil quality index (SQ) is less for young and mature plantation. On the contrary, intermediate group has relatively low value, as the group consists of only one RO plot. Overall, the connecting lines of young and intermediate groups sort of overlap with each other and this trend is quite distinct from mature plantations. This could mean that the intermediate age group, though having a wide range of age distribution, performs like young plantations. Additionally, Ling (2012) explains the ageing effect and categorizes the plantation age between 8 and 18 years as prime period, where the yield curve is stable than steep increase or decrease.

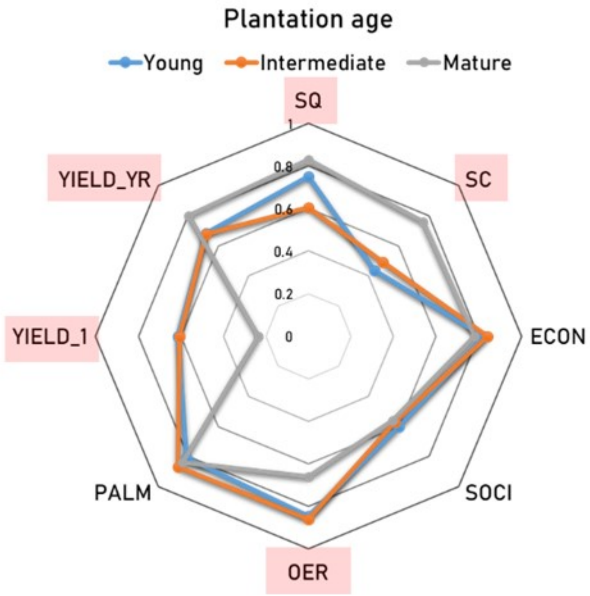


Figure 51: Radar plot illustrating performances of smallholder oil palm production systems for different plantation age groups (young, intermediate, and mature). Indices for which notable difference observed are highlighted in red.

Management practices. Radar plot for management practices (C1, C2, C3 and C4) is shown in Figure 52. In the context of environmental performance, C4 displayed the highest index values for soil quality (0.8), followed by C1 farmers. However, C2 and C3 farmers had values closer to optimum, performing better than the other two groups. Regarding SC index, C4 farmers performed relatively better than rest of the farmers, while C1 farmers had very low soil coverage. In terms of economic and social performance, C2 stood out with the highest economic performance index (0.87) and social performance index (0.7), indicating its significant positive impact in these domains. C3 performed better in terms of economics but lagged slightly behind C2 for social aspects. On the contrary, C1 and C4 displayed poor social and economic performances. Concerning the collective production performance, stark contrast between C3 and other farmers can be seen in Figure 52, especially for YIELD_1. Overall C3 farmers have outperformed others, while C4 farmers exhibit the very poorest performance. No strong distinction in terms of performance between C1 and C2 farmers was observed. To summarize, C2 and C3 farmers perform better than C1 and C4 farmers, however the season yield YIELD_1 distinguishes the former two groups. It could be attributed to high K/N ratio of fertilization by C2 farmers (see section 3.2.1).

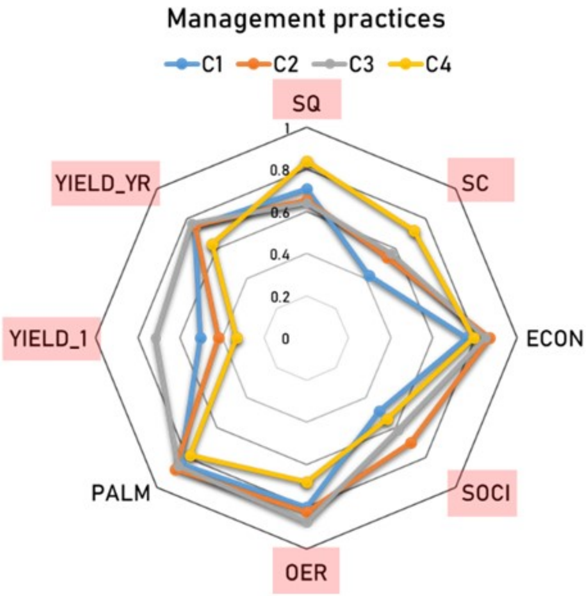


Figure 52: Radar plot illustrating performances of smallholder oil palm production systems for different management practices (C1, C2, C3 and C4).

Linkages between the performances

The sustainability assessment did not reveal a strong distinction for socio-economic performance for age and previous land use, but moderate influence from management practices. However, comparing these two performances reveals a strong positive correlation. The Pearson correlation between these two indices is also confirmed with a p-value less than 0.05. In Figure 53, the data points were fitted within 95% confidence ellipse. The two data points at the highest and lowest extremes represented high involvement and no involvement in plantation activities, respectively. In our study, economic performance was strongly influenced by involvement of family members in plantation activities.

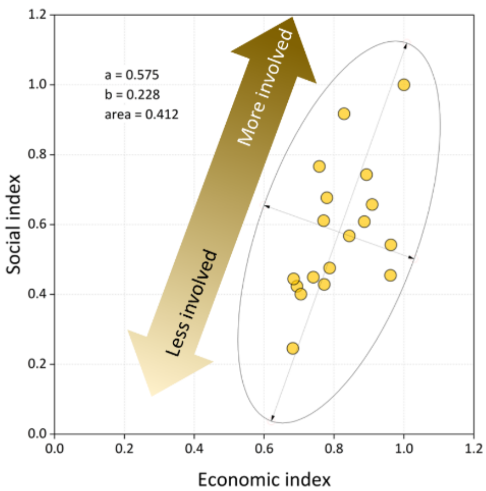


Figure 53: 2D scatter plot for social and economic index with 95% confidence ellipse.

Higher involvement resulted in high profitability. From Figure 53, management of plantation can be defined whether it is manager-based (less involved) or farmer-based (more involved). However, balancing hired and family labor for plantation activities could result in the best financial performance. A study by Skevas et al.,

(2021) indicates that efficiency of social indicators was found to be positively related to profitability in a dairy farm system. Another study on tribal agriculture reveals that social relations and cultural norms have positive influence on production performance such as yield (Zugravu-Soilita et al., 2021).

Fertilizer costs are a significant part of the total expenses for plantation operations, and the amount of fertilizer used can greatly influence production performance. As discussed in 3.3.4.1, the leaf nutrients N, P and K are lower than the minimum values, indicating nutrient deficiency. This is due to the high variability of fertilizer application quantity. Around 30 % of the farmers have significantly reduced quantity of fertilizer (N and K) application during last year (2022-2023). The reason was fertilizer prices were high. This was not unique to our study region, as the global price index saw a huge increase Q3 2021 until Q4 2023 (Global X. ETFs, 2022; IMF, 2022). Thus, such high prices have affected farmers' decisions on purchasing fertilizers.

Among the relationship between other performances, soil quality index (SQ) and production performance indices OER, PALM and YIELD_1 show strong correlation (see Figure 54). Among the three indices, palm vegetative metrics (PALM) are sensitive to soil quality. From the earlier discussion in 3.3.2, lower the SQ values, better the performance of index (less is better, see Appendix 3), on contrary rest of the indices have "more is better" response. In Figure 54, the plots with transition from rice to oil palm (ellipses in the graphs) lag behind other plots in terms of overall production performance. Also, most indicators in soil quality show low values for plots with rice to oil palm transition (see Appendix 13). Thus, suggesting these plots need corrective measures to balance nutrients in soil for better oil palm performance.

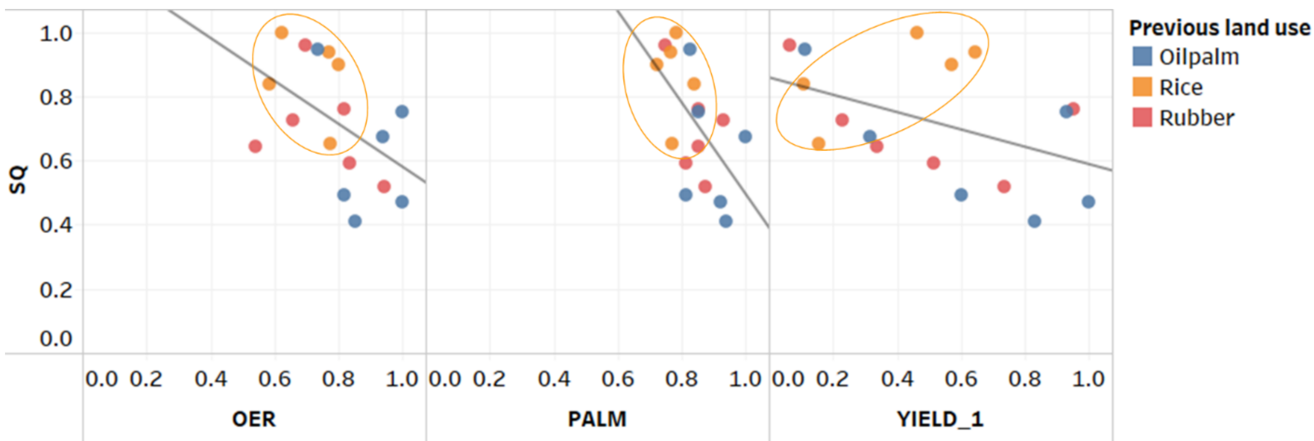


Figure 54: Scatter plot illustrating relationship between soil quality index and production performances.

4. Limitations

The research on smallholder oil palm plantations was a valuable endeavor; however, it is essential to acknowledge several limitations that influence the scope and applicability of our findings. Firstly, there was huge variability in our results which is due to the study sample size (n=18) which was a constraint. This limited our ability to comprehensively investigate the intricate interactions between the factors within smallholder oil palm plantations. A larger sample size would have allowed for a more robust analysis of these relationships, particularly to assess the influence of management practices. However, reduced number of parameters for study can be considered. Second, the age of the oil palm plantations under study exhibited significant variability. Young palms were of similar age (6 years), while it was not the case for intermediate and mature plantations. Unfortunately, it was not feasible to access plantations with identical age groups, which was a critical factor in understanding various performances, including yield. Third, the uncertainty of planting material quality and source made it more challenging to evaluate the production performance of plantations and reduce the variability. Additionally, during this research we observed there was lack of consistent recording of practices and FFB sales data among smallholder farmers. This hindered our ability to access accurate and comprehensive data on practices (yield and fertilizer) and expenses, which affected the precision of our analysis. Furthermore, the dynamics of plantation activities was combination of hired labor and family labor. Therefore, interviews with hired labors would have provided us an opportunity to delve into the social aspects of these workers and management practices. Lastly, the scarcity of relevant literature related to land use transition and oil palm performance have constrained our ability to build upon existing knowledge and frame our research within a broader context.

5. Conclusion

In this research we have provided insights into the multifaceted factors that influence smallholder oil palm performance, with a particular focus on the effects of previous land use, management practices, and the age of plantations. Through rigorous research and a comprehensive analysis of data, several key findings have emerged.

The typology of management practices unveiled the varying degrees of intensity in activities carried out by farmers. On average, farmers applied less than half of the quantities of nutrients (N and K) recommended by the Thai GAP standards. High-quality of planting material (non-presence of dura plantations) were adopted by all farmers. Sustainable practices such as reduced herbicide application and increasing soil cover area were observed, which reflects the impact of RSPO training, despite its dissolution. Additionally, a unique set of practices and diverse organic amendments were applied by smallholders in the region, emphasizing the experimental mindset of these farmers. The majority of the farmers did not monitor pest, although adopting some monitoring methods and an agroecological approach of having biological predators (such as barn owls) could perhaps reduce damages of FFBs from rats.

This study has highlighted the significance of understanding the history of land use in oil palm cultivation. Land use transition from rice to oil palm performed poorly compared to a land use transition from rubber or replanting of oil palm. This is mainly due to an imbalance in soil nutrients and a high clay content that have strongly affected the palm's vegetative growth and consequently resulted in poor production performance. Farmers who have replanted oil palms have more diverse planting material than farmers with other land use transitions. Furthermore, plots with replanted oil palms collectively produced more FFBs (during June), in terms of number and quantity, than other plots.

The age of oil palm plantations has a strong influence on the productivity, which also changes during the year. Specifically, during our visit in June, we noticed that young plantations excelled in terms of production, whereas mature plantations exhibited notably poorer performance. More importantly, the productivity transition from peak to off-peak season was sharp for mature palms and gradual for a plantation less than 10 years old. Due to such variations, temporal financial disparities affected farmers with older plantations. Furthermore, economic costs for practices such as pruning become expensive for tall, matured palms. Conversely, mature plantations contribute to a larger soil cover area than young or intermediate plantations, reducing overall soil loss from plantations.

The sustainability assessment revealed that economic performance strongly correlated with the involvement of family members in plantation activities, indicating that higher involvement leads to increased profitability. Additionally, the balance between hired and family labor was identified as a crucial factor for optimal financial performance. Moreover, a strong correlation between soil quality and production performance indicates the need for corrective measures of soil nutrients for plots transitioning from rice to oil palms. Lastly, many smallholders achieve substantial yield, some also close to attainable yield, nevertheless, 40 % of them produced a low quantity annually. The lower annual yield is mostly attributed to practices such as fertilizer application rates and additionally not having sufficient knowledge about the planting material. Additionally, farmers must maintain more than 32 fronds to enhance yield.

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Appendix list

Appendix 1: Interview questionnaire

GENERAL INFORMATION

1. Information of the respondent (major activities carried out on this plot):
   - □ Contractor/manager
   - □ Farmer

Name:	
Age:	
Gender:	
Plot code:	

2. Family information of the respondent:
   - i. Family size (people financially dependent on farmer, includes also who are not living together with farmer): ____________
   - ii. What is the highest level of education attained by you and head of the family?
     1. No formal education
     2. Primary education
     3. Secondary education
     4. Others: _____________________
3. Are there more than 1 person deciding activities of this plot? Yes □ No □
   - a. If yes, please elaborate how it is managed: ___________________________
4. OP Plantation's main information
   - a. Area of this plot: ____________ Rai
   - b. Age of the palms: __________
5. Do you have other OP plots owned/managed? Yes □ No □
   - a. If yes, Number of oil palm plots you own/manage: ________________________
   - b. Total OP area (excluding this plot): _____________________________ Rai
6. Indicate who does the following activities in most cases in this plot.

	Water management	Pruning	Fertilization	Weeding	Disease and pest control	Harvesting	Transport to ramp/mill	Other activity
Manager/Contractor								
Farmer								
Family members								
Hired labors								
Others								

7. Distance between your house and plot: ___________________________ kms
   - a. Which mode of transportation do you often use? _____________________.
   - b. Mileage of the vehicle_________________________
8. How often do you visit the plot? ____
9. Have you received any training or support for oil palm?
   □ Yes □ No
   - a. If yes, which institution/organization provided ______________________________
   - b. Select all the training received,
     - i. Water management
     - ii. Pruning
     - iii. Fertilization
     - iv. Weeding
     - v. Disease and pest control
     - vi. Harvesting
     - vii. Others: ___________________________________

PREVIOUS CROP PRACTICES

1. What was the previously cultivated crop in this plot?

□ Rubber/Oil palm:
   - o At which age were the trees/palms logged? _________________________________
   - o Did you make specific land preparations after logging?
     - ▪ If yes, comment ____.
   - o What was the land use before that?_____________________________________
   - o Were young palms planted before cutting old palms?

□ Rice:

- How long have you cultivated rice here before oil palm? ____
- Did you make specific land preparations after shifting from rice?
    - If yes, comment ____.
- What was the land use before that?____

2. Did you receive any training specially for shifting from rubber/rice to oil palm (which was not mentioned before)?
    a. If yes, comment what kind of training ____

CURRENT PRACTICES

A. Planting material (OP seedling information)

1. Number of palms in the plot ____________
2. Were all seedlings planted at once? Yes □ No □
    a. If not, why? ____.
3. Where (name and location) did you get the seedlings? ____________________________
4. Do you remember the seedling name (Surathani from DoA, Cirad or Univanish)?
    Yes □ No □
    a. what is the name: ___________________________________
5. Who recommended to buy there? ____________________________
6. How much did you pay for the seedlings? ____________________________
7. Do you know the palm breed? Yes □ No □
    a. If yes,

No. of pisifera palms	No. of tenera palms	No. of dura palms

B. Water management

1. Do you have canals? Yes □ No □
2. Do you irrigate the plot? Yes □ No □
    a. If yes,
        i. Mention the months when plot was irrigated.
        ii. How do you irrigate the plot? _______________________________
        iii. Where do you irrigate? (show schematic) ___________________
        iv. How many hours you irrigate per one time? ______________________
3. Did you observe flooding in the past three (2020-2022) years? Yes □ No □
    a. If yes, which years? 2020 □ 2021 □ 2022 □
    b. Approximate number of days if observed? ____________. Days/year
    c. % of flooded area in the plot: _____________________
4. Is there drainage (for excess rain water) infrastructure in the plot? Yes □ No □
    a. If yes, please mention ____
5. Mention the costs for each water management activity or maintenance of canals?

Type of labor (Paid, unpaid)	**Input costs** (optional)	**No. Of people needed**	**Labor hours**	**Labor days**	**Labor Costs**

6. Provide information about other costs related to energy usage for oil palm activities

Fuel charges	**Electricity charges**	**Other charges**

C. Fertilization

1. Where do you buy fertilizers and how far is it from your house? _____________________
2. Where do you put the **fertilizers**? How much **quantity** of fertilizer do you put per palm? (show the schematic)

	Organic (manure, EFB)	Chemical
Ring area		
Harvesting path		
Between palms		
Between rows		
Other areas		

3. Change of fertilizer costs (reduced by half, same, doubled, tripled)

Name of fertilizer (M/O)	**Price (2023)**	**Price (2022)**

4. Can you mention the months which fertilizer application (O, M, B) and when was it done?
5. Indicate the following information per fertilizer product.

Type of labor (paid/unpaid)	**Input type** (organic or mineral)	**Input amount (kgs)**	**Input costs (Baht)**	**No. Of people needed**	**Labor hours/day**	**Labor days**	**Labor Costs (Baht)**

6. Did you ever change fertilizer application from one method to another in last 3 years (e.g. Organic to Mineral)? Yes □ No □
   a. If yes, explain when and why? ____
7. Are there other charges during fertilizers? Yes □ No □

D. Weeding

1. Select all the weeding methods done in this plot
   □ Herbicide (H) □ Mechanical (M) □ Manual (A)
   a. If mechanical (M), what kind of machine was used? □ Electric □ Mechanical
      i. If gasoline-based was mentioned, how much gasoline is needed for weeding entire OP plot____________
      ii. If electric, name of machine________________________.
2. Where did you perform weeding (H, M, A) in the last 3 years? (ask farmer to write, if not possible then show schematic)
   □ Ring area □ Harvesting path □ Between palms □ Between rows
   □ other areas_____________________
3. Do you weed all above areas at once? Yes □ No □
   a. If not, please explain_______________________________
4. Can you mention the months where weeding was done and type of weeding (H, M, A)?
5. Did you buy herbicide for weeding? Yes □ No □
   a. If yes, indicate the following information.

Herbicide name	**Purpose of use**	**Dilution**	**Quantity per application**	**No. of applications/year**	**Comments**

6. Safety measure while preparing and applying herbicides! Select all the those are used:
   □ Gloves □ Glasses□ Mask □ Boots □ full body cover (sleeve shirt and pants) □ __________
7. What kind of machine is used for spraying? ____
8. Have you ever experienced any health problems as a result of herbicide exposure in your oil palm plantation?
   □Yes □No
   a. If yes, what kind of health problems have you experienced?
      □ Skin irritation or rashes
      □ Respiratory problems
      □ Headaches or dizziness
      □ Other (please specify)
9. Change of Herbicide costs (reduced by half, same, doubled, tripled)

Name of herbicide	**Price (2023)**	**Price (2022)**

10. Mention the input and labor costs.

Type of labor	**Input type**	**Input amount**	**Input costs**	**No. Of people needed**	**Labor hours**	**Labor days**	**Labor Costs**

11. Did you ever change weeding practice from one method to another in the last 3 years (e.g. Mechanical to Chemical)? Yes □ No □
    a. If yes, explain when and why?
    ____
12. Are there any other charges? □Yes □No

E. Disease and pest control

1. Do you monitor pests and diseases in your oil palm plantation? □Yes □No
   a. If yes,
      i. how often do you do? Every ______________________________ Days/months
      ii. Type for inspection/monitoring?
         1. Regularly inspect the palms for signs of damage or infestation
         2. Use monitoring tools such as pheromone traps and sticky traps
         3. Other (please specify) ___________________________________
      iii. Explain the procedure of monitoring. Select the options provided by respondent.
         □ **Rats**: Damage to <u>bunches</u> in mature palms and young shoots in immature palms.
         □ **Rhinoceros beetle**: Round <u>holes in leaf bases</u>, deformed leaves with some leaflet tips missing.
         □ **Leaf-eating caterpillars**: <u>Irregular holes in the leaflets</u> and/or larvae on the lower fronds or the fresh fronds on the stack.
         □ **Ganoderma**.
         □ Spear rot, crown disease, bud rot
         □ Others: ____
2. Did you ever had issues with pest or disease (ex: mushrooms, rhinoceros beetles, defoliating caterpillars)? □ Yes □ No □ Do not know

If yes, please mention the control measures,

Type of control	Against which pest/ disease	Location of application	Dosage per application	Frequency per year	application date

3. Do you regularly apply pesticides? □Yes □No
   a. If yes, can you mention the months where pesticide application was done?
4. Have you lost/cut down palms due to,
   a. disease (ex: Ganoderma) ___________________________
   b. other reasons (ex: lightening) ____________________
5. If you have answered yes to previous, how many have you replanted? _______________________
6. Labor costs

Type of labor	No. Of people needed	Labor hours	Labor days	Labor Costs

7. Have you experienced any changes in pest and disease incidence or severity in your oil palm plantation over the past five years? □Yes □No
   a. If yes, what changes have you observed?
      - □ Increase in the incidence or severity
      - □ Decrease in the incidence or severity
      - □ Shift in the types of pests and diseases affecting
      - □ Other ____________________________________
8. Have you ever experienced any health problems as a result of pesticide exposure in your oil palm plantation?
   □Yes □No
   a. If yes, what kind of health problems have you experienced?
      - □ Skin irritation or rashes
      - □ Respiratory problems
      - □ Headaches or dizziness
9. Other (please specify)
   Change of pesticide costs (reduced by half, same, doubled, tripled)

Name of pesticide	Price (2023)	Price (2022)

10. Are there any other charges? □Yes □No

F. Pruning

1. How often do you prune leaves per year? □ Once □ Twice □ _________
2. Can you mention the months where pruning was done?
3. If the pruning is not done regularly or periodically, describe the process __________________________
4. During pruning activity, how many leaves do you prune per time per palm?
   □ 0 □ 1 □ 2 □ 3 □ >3 (____) □ Do not know
5. During harvesting, how many leaves do you prune per time per palm?
   □ 0 □ 1 □ 2 □ 3 □ >3 (____) □ Do not know
   Comment_________________
6. How many numbers of cycles of fronds do you maintain per palm? _____________
7. Do you use all the pruned fronds in this OP plot? □ Yes □ No
   a. If no, mention the reason _________________________.
8. Where do you put the fronds? (ask farmer to draw, if not possible then show schematic)
   □ Ring area □ Harvesting path □ Between palms □ Between rows
   □ other areas_________________
9. Do you know about U-shaped method of placing fronds? □ Yes □ No
   a. If yes and not practicing, comment the reason, ____________________
10. Mention the pruning costs per pruning activity

Type of labor (Paid, unpaid)	Input costs (optional)	No. Of people needed	Labor hours	Labor days	Labor Costs

11. Are there any other charges? □Yes □No

G. Harvesting

1. If harvesting is done by a team, please select the activities done
   - □ Pruning
   - □ Harvesting
   - □ Transporting to collection center/mill/________
   - □ Selling to collection center/mill/___________

- Others________________________________
2. How frequent do you harvest?
   a. During peak season (from _________. to_________): Every ______ days
   b. Other seasons: Every ______ days
3. Indicate the **yield** during peak and other season.
   a. 2022:
      i. During peak season_______________
      ii. Other seasons_______________
   b. Last 5 yield per harvest
4. Who decide the harvest? ____________________
5. When to harvest? (many answers possible)
   □ Color: the FFB are yellow/orange/red
   □ Loose fruits: on ground or at frond butts
   □ Shake: FFB shaking with harvesting pole to check if any loose fruits fall out.
   □ Labor: When the labor is available
   □ Scheduled: Fixed time, for example every 2 weeks.
   □ When I need money
   □ When the cooperative/farmer group organize it
   □ Other reasons___________________________.
6. Are loose fruits collected during harvesting?
   □ some □ most of them □ none □ don't know
7. How many palms are unproductive in this plot?
   □ 0 □ 1-5 □ 5-10 □ 10-20 □>20
8. What is the biggest challenge you face with regards to harvesting your oil palm fruit bunches?
   □ Labor shortage
   □ Inadequate harvesting tools
   □ Difficulty in accessing the fruit bunches
   □ Other ____________________________________.
9. How do you sell your harvested oil palm fruit bunches?
   - Directly to mill/cooperative/ramps
   - Middleman or trader
   - Local market or to local businesses
   - Cooperatives
   - Other _______________.
10. Select the payment to the harvester.
    - Paid per kg harvest
    - Paid per day
    - Share of harvest
    - Other payment method: ___________________________.
11. Labor costs per harvest.

Type of labor (paid/unpaid)	**Input type** (optional)	**Input amount** (optional)	**Input costs** (optional)	**No. Of people needed**	**Labor hours**	**Labor days**	**Labor Costs**

12. Are there any other charges?

H. Transportation

1. Do you transport the harvest by yourself? □ Yes □ sometimes □ No
   a. If no, who transports to mill/collection center? __________________
   b. Do you always transport the FFB to one specific mill/collection center?
      □ Yes □ No
      1. if yes, how far is the mill/collection center from plot? __________kms
      2. Name of the mill/collection center? _____________________________________
      ii. If no, Comments: _________
2. Is transportation of harvest paid by you? □ Yes □ No
   a. If yes, how is it paid? ______________________________
3. Are there any other charges?

PLOT-LEVEL ECONOMICS

A. General

1. Can you indicate how much of oil palm income from this plot is your total income?
   □ 0-25% □25-50% □50-75% □75-100%
2. Is there any income from this plot apart from oil palm production? □ Yes □No
   a. If yes, please mention (what & how much) ____.
3. How much do you earn per harvest on monthly basis from OP (excluding expenses and costs)?_____________
4. Do you have other non-oil palm activities?

a. Because of this, are you not able to able to take up OP activities?

5. Do you receive subsidies for oil palm (this plot only)? Yes No
   a. If yes, Mention type of subsidy
   b. How much do you receive ______ per (month/year)
      i. Comments ___________________________.

B. Loans

1. Do you have debts or loans for this oil palm farming activities? Yes No
   a. If yes, what type of debts/loans? ___________________________.
2. Periodic payment of loan (capital + interest): _________ per month or per year

C. Miscellaneous

1. Do you have any other expenses(taxes) related to this OP plot that was not mentioned before?
2. In your opinion, do you have any production risk from this plot?
    Weather
    Pests and diseases
    Market conditions
    Labor availability
    Management practices and decisions
    ____

SOCIAL ASPECTS

1. Are there any activities done by women on this plot? Yes No
   1. If yes, which are they?
       Water management
       Pruning
       Fertilization
       Weeding
       Disease and pest control
       Harvesting
       Others ________________________
2. Do other people (mill, harvester, training center etc.) ask information about this oil palm plot (to share your experience and practices)? Yes No
   1. If yes, who are they? _______________
   2. How often do they visit?___________________________
   3. What information are interested in? ______________________
3. How satisfied are you with your current oil palm plantation farming occupation from this plot? Please rate on a scale of 0-10, with 0 being very unsatisfied and 10 being very highly satisfied.
   Overall satisfaction: market access, economic gains and implement/manage activities
4. Drudgery_______________________
5. On a scale of 0 to 10, rate availability of workers when you need them for each activity, with 0 no worker available, and 10 available all times.
   i. Water management: _______
   ii. Pruning: _______
   iii. Fertilizing: _______
   iv. Weeding: _______
   v. Pest management: _______
   vi. Harvesting: _______
   vii. Transportation
6. On a scale of 0 to 10, rate the physical demands for each activity, with 0 being not physically demanding and 10 being very physically demanding,
   i. Water management: _______
   ii. Pruning: _______
   iii. Fertilizing: _______
   iv. Weeding: _______
   v. Pest management: _______
   vi. Harvesting: _______
   vii. Transportation
7. Have you experienced any physical pain or discomfort related to your work on oil palm plantation in this plot?
   i. If yes, can you rate your physical pain or discomfort?
   Can you describe the nature of your pain/discomfort? __________________
   ii. How has this affected your ability to perform your work?
   Comments: ____.
8. If given a better opportunity, how likely are you to abandon oil palm activities in the next few years? Please rate your likelihood on a scale of 0-10, with 0 being very unlikely and 10 being very likely.
   Access to knowledge regarding oil palm
   1. Are you aware of the following?

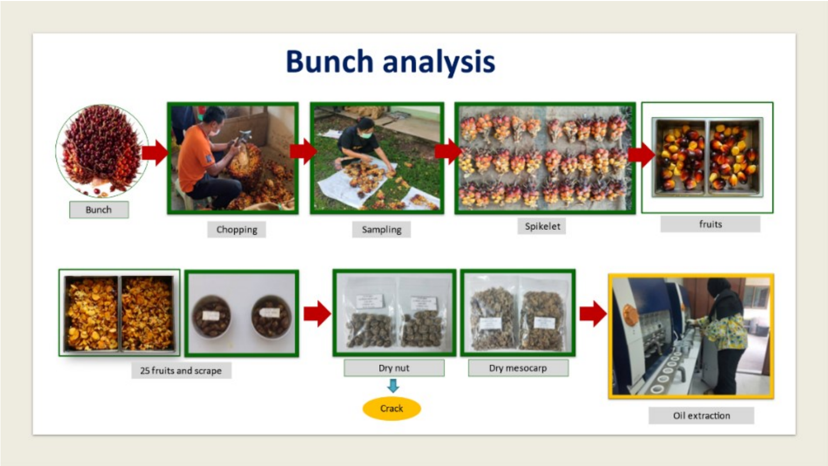
 Government policies Schemes or subsidies RSPO certifications Thai Good Agricultural Practices (GAP)

If one of the option selected, then Please comment: ____

2. In your opinion do workers have sufficient skills and experience about what they do? On a scale of 0 to 10, rate the worker skills and knowledge, with 0 being poor and 10 being expert level
    i. Harvesting: ___
    ii. Pruning: ___
    iii. Fertilizing: ___
    iv. Weeding: ___
    v. Pest management: ___

9. Do you think buyers prefer to buy from your plot than others? Explain ____

Appendix 2: Standard protocol for oil extraction measurement implemented by Krabi oil palm research center.



Standard method for sampling palm fruit from bunches must be established, referring to the bunch composition analysis method of the Department of Agriculture. Take the oil palm bunch samples, weigh the whole bunch, and record the results. Then chop the stalk of bunch and spikelet. Separate the spikelet into 3 parts from the end of the bunch, the middle bunch, and the base bunch. Then randomly selected from all three parts to get15 spikelets as one duplicate If the palm bunch size is 3-5 kg will be randomized only once, but for larger palm bunches, randomized 2 duplicates. Then weigh 15 spikelets and record the results. Remove the fruit from the spikelet and remove the sepals as well. The empty spikelet and sepals were weighed and the results were recorded. Palm fruits were separated into two groups, large and small. Weigh each group and record the results. Then calculate the number of fruits that will be randomly from each fruit group from formula 1-2 and then select 25 palm fruits from the large and small fruit groups for each duplicate.

Formula 1:

Number of fruits randomly from a large fruit group = $\frac{(25 \times \text{Weight of the large fruit group})}{(\text{Weight of the large fruit group} + \text{Weight of the small fruit group})}$

Formula 2:

The number of fruits randomly from a small fruits group= 25- The number of fruits randomly from a large fruits group

Bring the palm fruit to cut the skin It is a thin sheet, about -1millimeter-thick, scrape to leave only the kernels Weigh each part, record the results and then dried a 70°C for 72 hrs after that put in desiccator. Wait for the sample to cool down then weigh and record the results and then blended to make a finely dried sample Packed in a plastic envelope. To send the sample to measure oil percentage by solvent extraction method Soxtec system. The results obtained from the experiment were used for primary analysis of bunch composition. With the analyzed variables Including moisture percentage, fruit percentage per bunch, average fruit weight, fresh skin percentage per fruit, Percentage of dry skin per fruit according to formula 11-3

Formula 3

Peel moisture percentage= $\frac{(\text{fresh peel weight} - \text{dry peel weight}) \times 100}{\text{fresh peel weight}}$

Formula 4

Spikelet weight= bunch weight- stalk of bunch weight

Formula 5

Total fruit weight= $\frac{\text{Spikelet weight} \times \text{Fruit weight of 15 spikelet}}{\text{weight 15 spikelet}}$

Formula 6

Fruit percentage per bunch= $\frac{\text{Total fruit weight} \times 100}{\text{Total fruit weight}}$

Formula 7

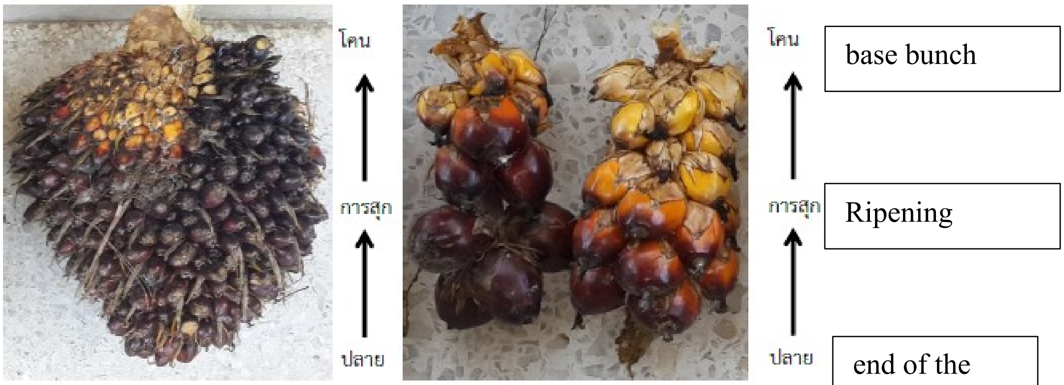
Average fruit weight= $\frac{\text{Weight 25 fruits}}{25}$

Formula 8
Fresh skin weight= weight 25fruits - seed weight of 25fruits

Formula 9
Percentage of fresh skin per fruit= $\frac{\text{Fresh skin weight} \times 100}{\text{Weight 25 fruits}}$

Formula 10
Dry skin weight = fresh skin weight – {(skin moisture x fresh skin weight100/(}

Formula 11
Percentage of dry skin per fruit $= \frac{\text{Dry skin weight}}{\text{Weight 25 fruits}}$

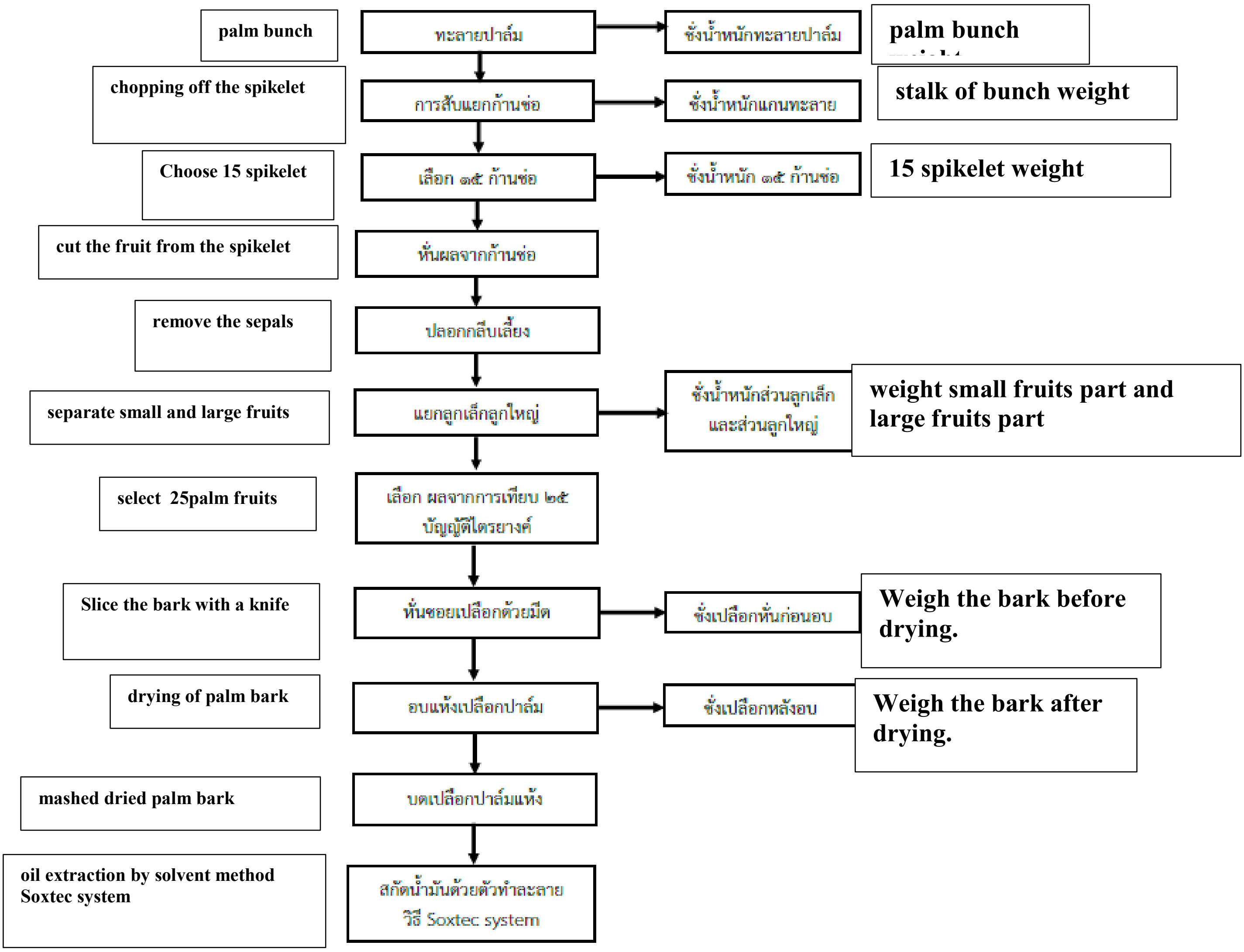


Picture 1 Ripening characteristics of palm bunches

1. Percentage analysis of oil from finely dried palm bark standard reference American Oil Chemists Society (AOCS) official method AC- 44-3หลักการ principle Solvent Extraction (Soxtec System) There is a way to operate as follows.
   1.1 Weigh samples of finely dried palm bark. Wrapped in filter paper, put into Cellulose thimble
   1.2 Weigh the fat support cup.) W(2
   1.3 Set the temperature of the extractor and heat dispenser to 130°C and set the temperature of the water cooler at 15°C.
   1.4 Bring the Cellulose thimble from 4.1 to the Thimble adapter and put it in the Thimble support, then import the fat extraction machine.
   1.5 Add 80ml of Hexane, put into a cup of fat of known weight, then put in cap holders, enter the fat extraction machine.
   1.6 The sample was distilled by boiling (boiling) the sample with Hexane for 2hours at a temperature of 100 °C, then rinsing the sample for 53minutes and evaporating the Hexane for 15minutes.
   1.7 After the hexane has evaporated from the cup, dry the fat cups in an oven at 90°C for 30minutes, then put them in desiccator to cool down. Then taken out to weigh and record the weight (W .(3The percentage of oil is calculated from formula .12

Formula 12
oil percentage $= \frac{(W2-W1)\times 100}{W3}$

By W1 = Sample weight about 3.0000g
W2 = cup weight
W3 = cup weight + fat weight



Picture 2 Analysis method of bunch composition

Appendix 3: Indicators included in each index and responses curves. With Vmax=maximum value observed of indicator, Vmin=minimum value observed of indicator.

Performance category		**Criteria**	**Indicator**	**Unit**	**Linear response trend**	**Vmin**	**Vmax**
Economic		Profitability	Gross margin	thai baht	More is better	27461.18	139661.2
			Labor costs	thai baht	Less is better	2326.52	26365.76
			Input costs	thai baht	Less is better	3174.9	26829.8
			Operational costs	thai baht	Less is better	11048.71	44165.38
		Labor	Wage ratio	%	Less is better	2.35	25.96
			Family labor valorization	thai baht/hrs	Less is better	0	48765.55
			Return to labor	tons/ha/yr/hrs	Less is better	0.03	0.24
		Efficiency	Economic efficiency	%	More is better	0.51	0.89
			Intensification ratio	%	Less is better	0.13	0.96
			Return on investment	%	More is better	1.04	7.95
Social		Farm characteristics	Farmer age	years		30	78
			Family to hired ratio	%	More is better	0	5.5
			Family workforce		More is better	0	4
		Total workload	Hired labor	hrs	Less is better	19.53	517.5
			Family labor	hrs	More is better	0	375.11
		Operation difficulty (family labor)	Irrigation	hrs		0	1.77
			Fertilizing	hrs	More is better	0	8.83
			Weeding	hrs	More is better	0	7.94
			Pruning	hrs		0	24.69
			Harvesting	hrs	More is better	0	1.86
		Operational difficulty (Hired labor)	Fertilizing	hrs		0	5.14
			Weeding	hrs		0	10.29
			Pruning	hrs		0	10.29
			Harvesting	hrs	More is better	0	2.57
Environment	Soil quality	Physico-chemical properties	Moisture	%		7.9	48.5
			Soil pH			4	6.8
			Electrical conductivity	dS/m		0.02	0.17
			Soil organic matter	%	More is better	0.79	4.34
			Phosphorous (P)	mg/kg		1.3	683.4
			Potassium (K)	mg/kg	More is better	21.8	421.3
			Nitrate (NO_3)	mg/kg	More is better	0	51
			Cation exchange capability	cmol/kg	More is better	5.79	22.67
			Ex. Ca+	cmol/kg	More is better	0.47	14.57
			Ex. Mg+	cmol/kg	More is better	0.18	5.1
		Functions	SituResp	%	More is better	0.56	1.29
			Beerkan	score	More is better	0	10
			Aggregate stability (surface)	score	More is better	4.11	6
			Aggregate stability (sub-surface)	score	More is better	3.22	5.78
			Bait lamina	score	More is better	0.02	0.55

			VESS	score	More is better	0.99	3.79
	Soil cover	Frond width		cm	More is better	90	320
		Weed density		score	More is better	1	9
Production	Palm metrics	Growth characteristics	Palm height	m	More is better	0.49	11.06
			No of Fronds		More is better	26.67	50.67
			Petiole area	sq.m	More is better	9.37	46.22
			No of female inflorescence		More is better	0	12
			No of male inflorescence		More is better	0	1.67
			Leaf area	sq.m	More is better	37247.53	125235.1
			Canopy coverage area	%	More is better	91.03	99.61
			Rachis length	m	More is better	3.56	6.96
		Leaf nutrients	Nitrogen	%	More is better	1.53	2.06
			Phosphorous	%	More is better	0.1	0.16
			Potassium	%	More is better	0.5	1.25
			Calcium	%	More is better	0.55	0.92
			Magnesium	%	More is better	0.2	0.46
		Rachis nutrients	Potassium	%		1.24	2.6
	Oil extraction metrics	Kernel	Kernel diameter	mm	Less is better	8.12	12.87
			Kernel weight per fruit	gms	Less is better	6.01	10.51
		Mesocarp	Mesocarp thickness	mm	More is better	4.41	9.08
			Mesocarp weight per FFB	%	More is better	32.48	46.84
			Mesocarp weight per fruit	gms	More is better	45.49	60
		Shell	Shell weight per fruit	gms	Less is better	3.87	10.02
			Shell thickness	mm	Less is better	1.06	2.59
		Fruitlets	Fruit setting per FFB	%	More is better	62.73	80.85
			Total fruit weight	kgs	More is better	6.5	20.75
		Oil extracted per FFB		%	More is better	23.07	34.91
	Yield	Single harvest		tons/ha	More is better	0.09	1.4
		Annual		tons/ha/yr	More is better	12.54	28.63

Appendix 4 : Hierarchial cluster analysis

1. List of variables and modailities before MCA computation

Variable	Type	Value 1	Value 2	Value 3	Value 4
Palm age (Years)[6]	Text	Young (0 to 10 years)	Mature (11 -25 years)		
Year[6]	Text	Year 1	Year 2	Year 3	
OP density (trees/Ha)	Range	118 to <145	145 to <180	180 to 205	
Organic fertilizer application count	Binary	0	1 to 3		
Chemical fertilizer application count	Range	0 to 2	3 to 4		
N per Ha (Kgs)	Range	Less than 24	24 to <45	45 to <68	68 to 260
P per Ha (Kgs)	Range	Less than 3	3 to <10	10 to <15	15 to 50
K per Ha (Kgs)	Range	Less than 35	35 to <65	65 to <125	125 to 530
Boron application count	Binary	0	1 to 2		
Weeding count	Range	0 to 1	2 to 4		
Herbicide count	Binary	0	1 to 2		
Treatment frequency index	Range	0	>0 and <2	2 to 5	
Number of harvests	Range	Less than 18	18 to 19	More than 19	

2. Variables and modalities after MCA computation

Variable	Modalities			
Palm age group	Young (0 to 10 years)	Mature (11 -25 years)		
Year	2020-21	2021-22	2022-23	
OP density (trees/Ha)	Low (109 to <126)	Medium (126 to <140)	High (140 to <153)	Very high (153 to <170)
Organic fertilizer application count	0	1 to 3		
Chemical fertilizer application count	0 to 2	3 to 4		
N per Ha (Kgs)	Less than 65	65 to <72	72 to <115	115 to <200
P per Ha (Kgs)	Less than 9	9 to <18	18 to <29	29 to <65
K per Ha (Kgs)	Less than 80	80 to <160	160 to <250	250 to <455
Boron application count	0	1 to 2		
Mechanical weeding count	0 to 1	2 to 4		
Herbicide application count	0	1 to 2		
Number of harvests	<18	18 to 19	20 to 21	

[6] Supplementary variable

3. Cluster assignment after hierarchal cluster analysis

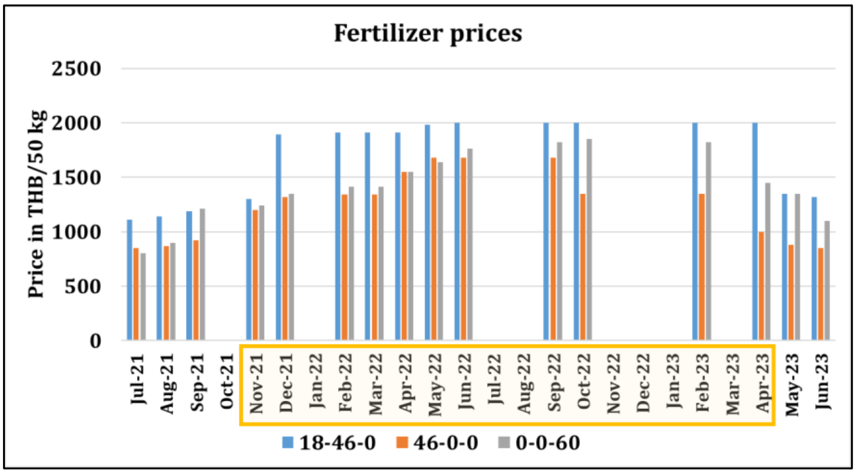
	Cluster assignment by HCA method				Cluster re-assigned
Plot code	2020-21	2021-22	2022-23		
OOO1	C2	C2	C2		C2
OOO2	C1	C1	C1		C1
OOO3	C1	C1	C1		C1
OOY1	C3	C3	C3		C3
OOY2	C1	C4	C1		C1
OOY3	C3	C3	C3		C3
RBOO1	C1	C1	C1		C1
RBOO2	C2	C2	C2		C2
RBOO3	C4	C4	C4	=>	C4
RBOY1	C2	C2	C2		C2
RBOY2	C1	C3	C3		C1
RBOY3	C4	C4	C3		C4
ROO1	C4	C4	C4		C4
ROO2	C2	C2	C4		C2
ROO3	C3	C3	C3		C3
ROY1	C4	C4	C1		C4
ROY2	C1	C1	C1		C1
ROY3	C4	C4	C4		C4

Appendix 5:

1. List of fertilizers farmers used in their plots over the past 3 years.

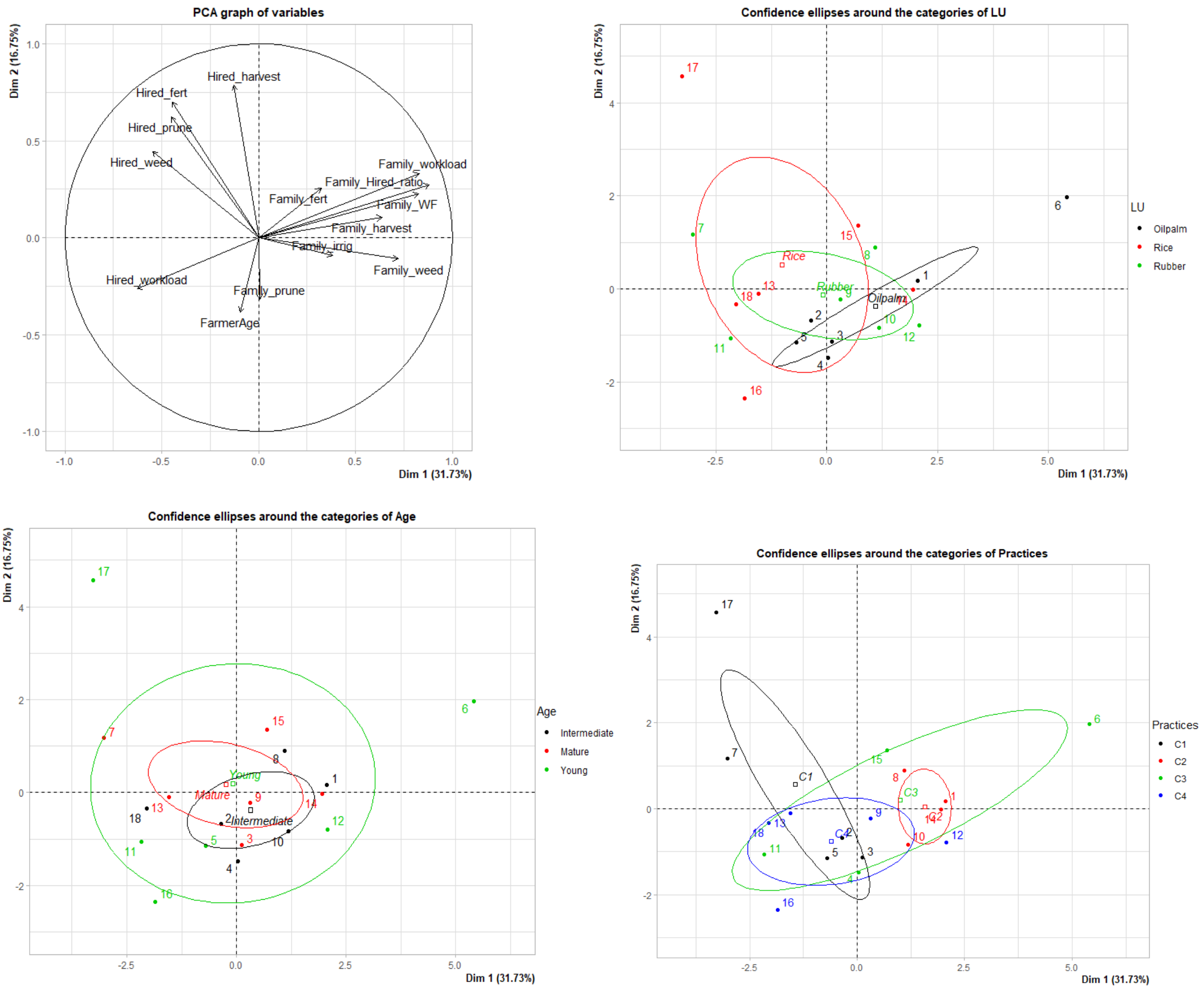
Fertilizers	
12-9-24	22-7-18
12-9-34	23-23-12
13-13-21	25-5-15
13-9-36	30-5-18
14-8-30	5-5-30
14-9-35	14-10-30
15-15-15	13-9-34
15-5-36	46-0-0
15-7-18	10-10-30
16-12-30	14-14-21
18-8-30	18-46-0
20-8-20	0-0-60
21-15-26	21-0-0

2. Fertilizer prices from 2021 to 2023 in a co-operative in Plai Phraya.



Appendix 6: Social performance

1. PCA graph for social indicators and confidence ellipses around category of each factor: Management practices, age effect and previous land use.



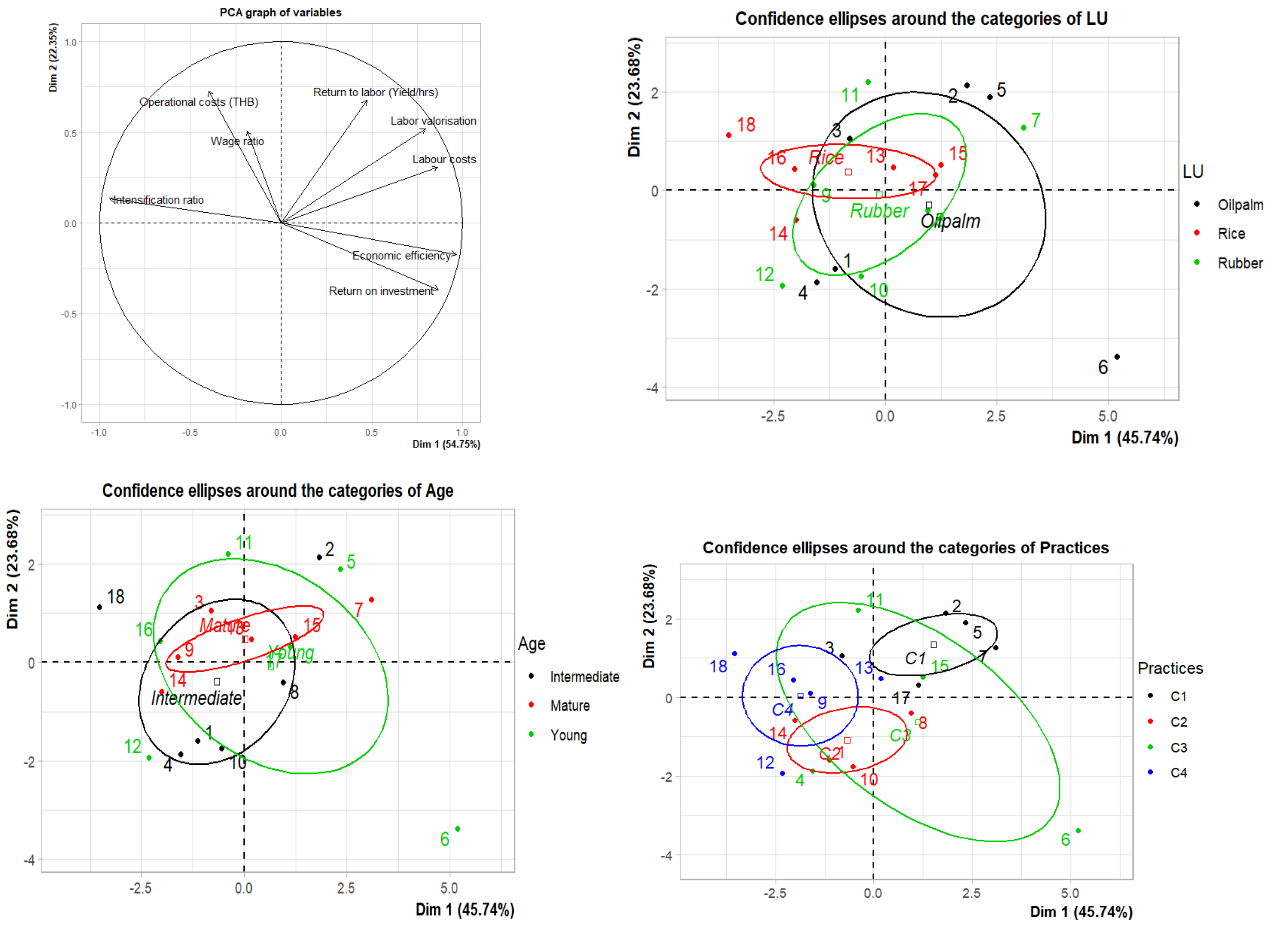
2. Mean and SD values of social indicators calculated for variables under each factor. Oil palm, rubber and rice are the variables for factor “previous land use”. C1, C2, C3 and C4 are variable for factor "management practices". Young, intermediate and mature are variables for factor “age of plantation”.

	Factor	Variable	Farmer’s age	Family_WF	Family_Hired_ratio	Family_workload	Hired_workload	Family_irrig	Family_fert
Mean±SD	Previous LU	Oil palm	57.33±12.63	1.83±1.17	1.8±1.98	102.15±144.12	190.39±117.86	0.1±0.24	1.56±1.05
		Rubber	41.83±9.43	1.17±0.98	1.5±1.38	39.07±34.05	271.92±99.69	0.41±0.72	2.42±3.4
		Rice	55.67±14.88	1.5±0.55	1.35±1.57	54.55±61.54	335.63±122.8	0.11±0.26	2.48±2.48
	Practices	C1	51.8±14.72	0.8±0.45	0.3±0.2	12.39±14.59	244.94±42.69	0±0	1.74±1.4
		C2	50±2.94	1.75±0.5	2.46±0.42	101.49±40.03	240.31±142.33	0.17±0.34	4.92±3.47
		C3	56.25±9.64	2±1.63	2.79±2.44	138.56±171.53	218.17±138.68	0.15±0.3	1.59±1.74
		C4	49±21.89	1.6±0.55	1.08±1.14	30.5±14.74	345.81±147.08	0.48±0.77	0.79±0.66
	Age	Young	52.67±18.37	1.5±1.38	1.56±2.23	73.88±148.31	232.04±144.53	0.5±0.69	0.92±0.98
		Intermediate	53.5±11.67	1.5±0.55	1.6±1.11	63.04±50.35	283.64±119.95	0.11±0.28	2.83±3.09
		Mature	48.67±12.4	1.5±0.84	1.5±1.48	58.85±60.3	282.26±119.5	0±0	2.71±2.49

	Factor	Variable	Hired_fert	Family_weed	Hired_weed	Family_prune	Hired_prune	Family_harvest	Hired_harvest
Mean±SD	Previous LU	Oil palm	0.21±0.24	5.43±1.63	0.12±0.29	1.41±2.39	1.27±2.11	0.6±0.68	0.59±0.63
		Rubber	1.13±1.37	4.67±3.68	1.43±1.49	0.83±2.03	2.17±4	0.2±0.49	0.36±0.21
		Rice	1.21±1.96	0.93±1.48	6.73±3.98	4.12±10.08	2.86±2.98	0.48±0.79	0.77±0.89
	Practices	C1	1.58±2.13	2.91±2.88	2.83±4.49	0±0	3.98±4.69	0.18±0.4	0.98±0.91
		C2	0.88±1.77	5.58±2.39	0±0	0.69±1.37	1.69±2.53	1.15±0.81	0.25±0.26
		C3	0.3±0.33	2.99±3.74	3.31±4.66	1.44±2.87	1.45±2.22	0.54±0.63	0.61±0.75
		C4	0.53±0.31	3.48±3.53	4.46±3.38	5.93±10.7	1.06±1.32	0±0	0.41±0.15
	Age	Young	1.16±1.97	3.32±3.79	3.26±4.03	5.9±9.57	1.61±3.03	0.19±0.47	0.99±0.96
		Intermediate	0.83±1.36	5.12±2.78	0.97±2.06	0.46±1.12	1.61±2.25	0.46±0.71	0.35±0.3
		Mature	0.55±0.76	2.59±2.48	4.05±4.58	0±0	3.08±3.86	0.63±0.76	0.38±0.14

Appendix 7: Economic performance

1. PCA graph for economic indicators and confidence ellipses around category of each factor: Management practices, age effect and previous land use.



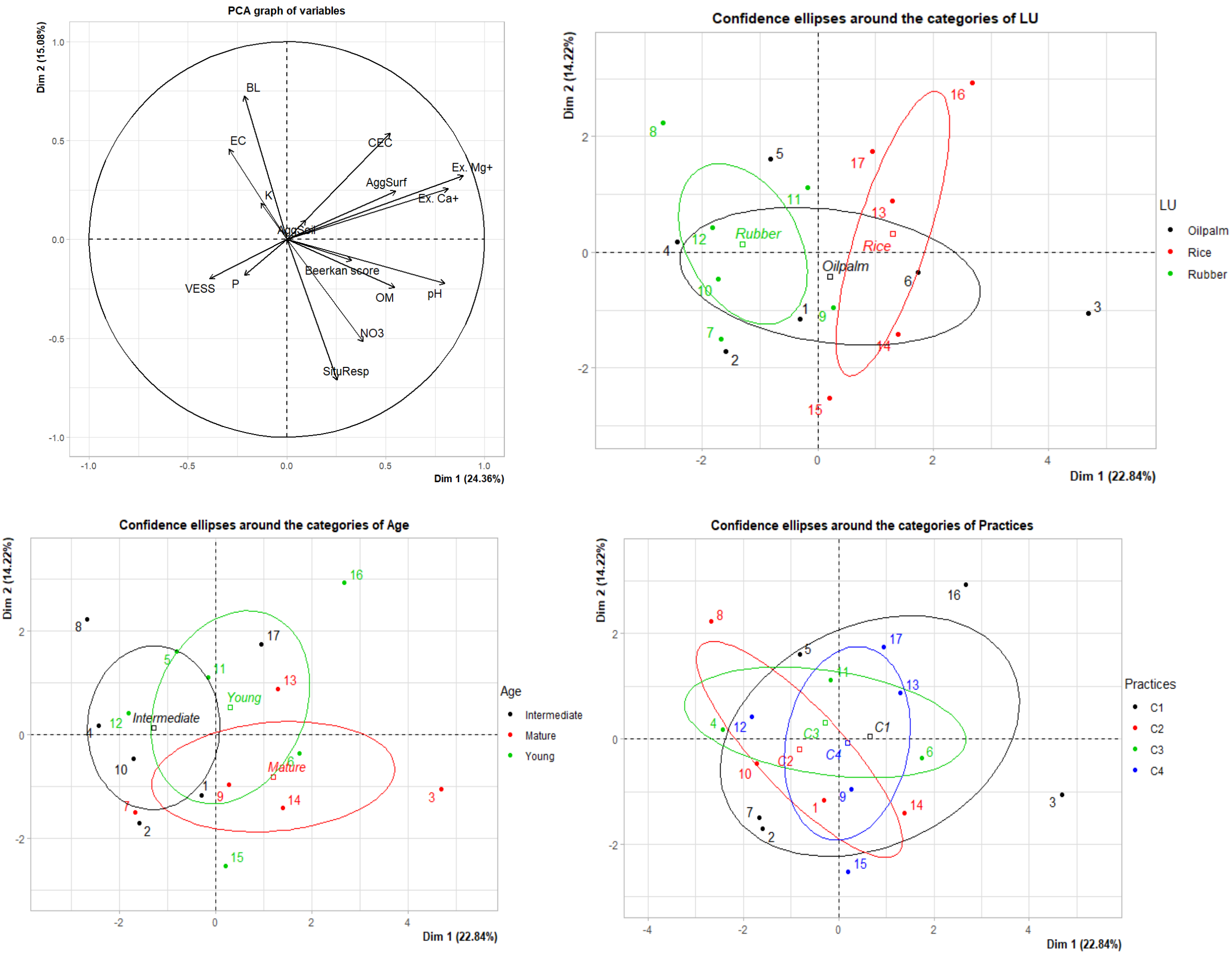
2. Mean and SD values of economic indicators calculated for variables under each factor. Oil palm, rubber and rice are the variables for factor "previous land use". C1, C2, C3 and C4 are variable for factor "management practices". Young, intermediate and mature are variables for factor "age of plantation".

	Factor	Variable	Labor costs	Input costs	Gross margin	Operational costs (THB)	Wage ratio
Mean±SD	Previous LU	Oil palm	14075.46±8539.57	11747.53±5159.91	66894.45±28278.06	25823±9145.96	15.32±6.74
		Rubber	17510.3±7388.61	15975.48±6169.56	76802.75±40050.78	33485.78±6522.12	15.91±3.71
		Rice	19546.82±2975.69	16366.42±8572.22	67606.61±24284.95	35913.23±8335.49	19.68±5.15
	Practices	C1	21652.12±2603.25	7877.31±5221.65	89123.39±32444.94	29529.43±6112.4	18.99±3.07
		C2	12221.65±3787	19465.65±5500.51	60363.83±30435.84	31687.3±8222.25	13.83±1.48
		C3	14198.12±10654.52	13492.59±3977.03	77700.48±36704.8	27690.71±13772.35	13.73±8.5
		C4	18571.16±5469.83	18663.41±5346.38	53989.72±12114.49	37234.57±6101.31	20.05±4.61
	Age	Young	16280.65±8813.18	12220.29±8019.89	67077.07±18453.54	28500.94±11511.16	16.85±7.87
		Intermediate	15132.39±7209.63	15636.54±4498.97	59756.45±34121.4	30768.94±8509.86	17.13±4.95
		Mature	19719.54±3376.04	16232.6±7622.78	84470.28±34281.41	35952.14±4722.29	16.93±3.55

	Factor	Variable	Labor valorization	Return to labor (Yield/hrs)	Economic efficiency	Intensification ratio	Return on investment
Mean±SD	Previous LU	Oil palm	4870.79±8326.34	0.07±0.02	0.7±0.13	0.47±0.25	3.12±2.5
		Rubber	1007.31±262.77	0.07±0.02	0.67±0.1	0.53±0.23	2.31±1.25
		Rice	5654.26±9017.62	0.06±0.02	0.64±0.09	0.58±0.25	1.99±0.82
	Practices	C1	12866.82±11458.07	0.08±0.01	0.74±0.07	0.36±0.13	3.06±1
		C2	666.18±397.42	0.06±0.02	0.63±0.08	0.58±0.16	1.88±0.71
		C3	692.31±432.99	0.06±0.02	0.72±0.14	0.44±0.28	3.57±3.01
		C4	2194.11±1364.66	0.05±0.02	0.59±0.07	0.72±0.2	1.49±0.47
	Age	Young	9825.72±11856.65	0.07±0.01	0.7±0.13	0.48±0.27	3.07±2.51
		Intermediate	1395.08±1038.68	0.06±0.02	0.63±0.1	0.61±0.25	1.92±0.88
		Mature	1936.08±1643.63	0.07±0.02	0.68±0.09	0.49±0.19	2.43±1.2

Appendix 8: Environmental performance

1. PCA graph for soil quality indicators and confidence ellipses around category of each factor: Management practices, age effect and previous land use.



2. Mean and SD values of soil cover and soil quality indicators calculated for variables under each factor. Oil palm, rubber and rice are the variables for factor “previous land use”. C1, C2, C3 and C4 are variable for factor "management practices". Young, intermediate and mature are variables for factor “age of plantation”.

Soil quality indicators

	Factor	Variable	SituResp	Beerkan score	AggSurf	AggSoil	BL	VESS
Mean±SD	Previous LU	Oil palm	1.05±0.26	2±0.63	5.17±0.5	4.91±0.75	0.1±0.04	1.83±0.43
		Rubber	1.06±0.11	1±1.26	5.18±0.56	5.2±0.29	0.24±0.18	2.46±1.16
		Rice	1.1±0.18	5.17±4.12	5.62±0.38	4.87±0.92	0.23±0.14	2.2±0.61
	Practices	C1	1±0.3	1.6±1.14	5.13±0.83	5.04±0.73	0.16±0.09	2.13±1.04
		C2	1.07±0.16	3±4.76	5.51±0.4	5.28±0.44	0.24±0.24	2.24±0.67
		C3	1.06±0.04	1.75±1.71	5.38±0.39	4.92±0.65	0.13±0.07	1.59±0.46
		C4	1.14±0.14	4.4±3.36	5.32±0.29	4.78±0.91	0.22±0.15	2.6±0.73
	Age	Young	0.98±0.25	1.5±1.22	5.45±0.38	4.68±0.98	0.18±0.08	2.08±0.96
		Intermediate	1.04±0.14	1.67±1.86	5.2±0.43	5.12±0.57	0.24±0.19	2.22±0.57
		Mature	1.18±0.09	5±4	5.31±0.7	5.19±0.33	0.14±0.14	2.2±0.94

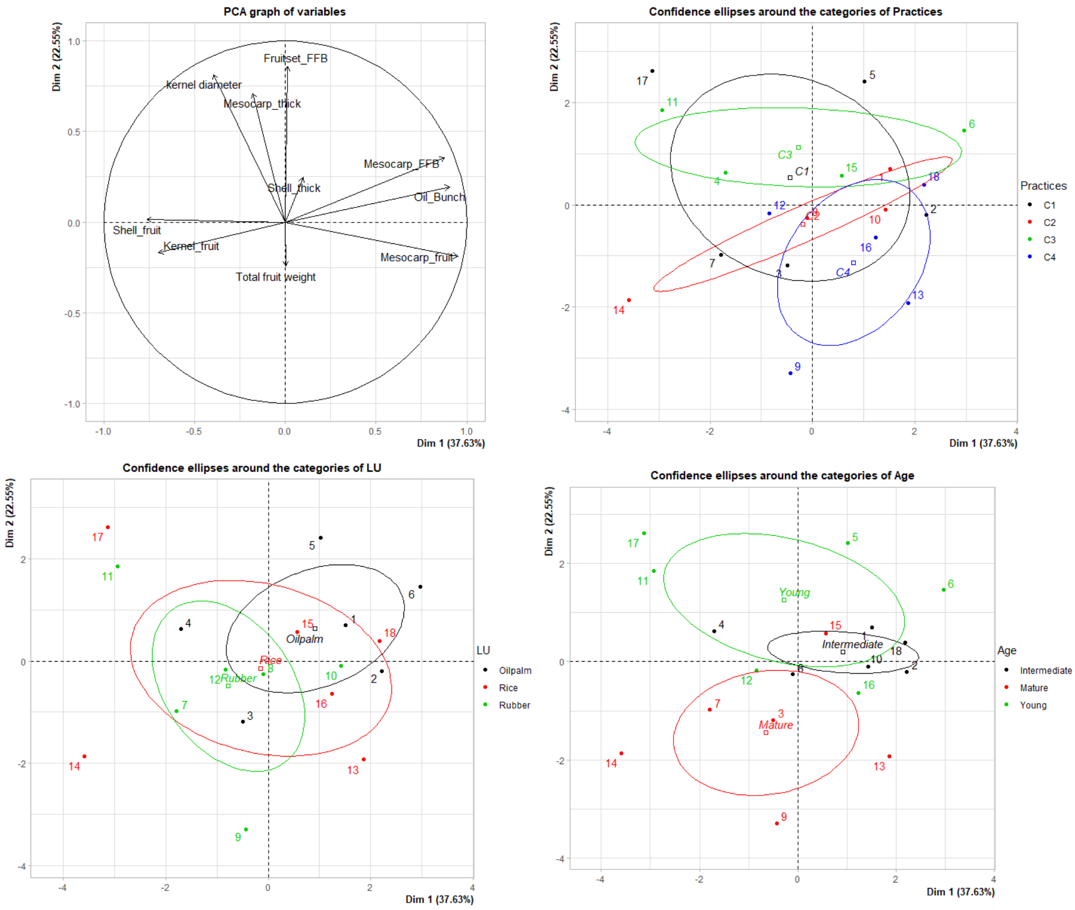
	Factor	Variable	Moisture	pH	EC	OM	P	K	NO3	CEC	Ex. Ca+	Ex. Mg+
Mean±SD	Previous LU	Oil palm	22.02±5.02	5.05±0.87	0.05±0.03	1.55±0.65	12.17±15.66	72.87±39.78	24.83±7.36	8.02±2.84	2.09±1.5	0.96±0.79
		Rubber	19.34±4.65	4.65±0.46	0.09±0.06	1.26±0.31	45.63±51.65	100.5±74.9	22.17±13.61	7.78±1.18	1.63±1	0.48±0.3
		Rice	29.21±14.52	5.15±0.82	0.08±0.05	1.93±1.26	126.43±273.29	135.73±143.79	34.17±11.89	14.02±6.51	5.2±4.68	1.98±1.67
	Practices	C1	20.65±3.61	5.22±0.81	0.04±0.02	1.53±0.65	13.54±17.69	67.72±31.4	26.2±6.3	10.27±6.1	2.26±1.63	1.3±1.11
		C2	18±7.22	4.55±0.39	0.06±0.04	1.53±0.3	57.55±56.51	70.23±49.33	26±10.1	7.24±2.1	1.23±0.78	0.58±0.41
		C3	27.16±10.13	5.15±1.18	0.11±0.06	2.13±1.56	188.55±331.05	186.38±168.72	24±21.56	13.01±6.97	5.48±6.12	1.88±2.18
		C4	27.91±13.9	4.84±0.38	0.09±0.05	1.24±0.45	10.66±13.65	97.92±63.55	31.2±9.88	9.33±2.82	3.08±1.26	0.83±0.46
	Age	Young	23.15±12.97	4.87±0.27	0.08±0.06	1.24±0.42	13.6±24.04	108.78±68.21	26.67±15.86	10.91±5.53	2.55±0.57	1.08±0.78
		Intermediate	23.13±4.29	4.45±0.37	0.07±0.04	1.4±0.39	34.55±54.07	66.07±39.94	21.5±7.29	7.19±2.16	1.46±1.51	0.54±0.47
		Mature	24.3±11.52	5.53±0.94	0.07±0.05	2.11±1.24	136.08±268.48	134.25±145.44	33±9.59	11.72±5.71	4.9±4.92	1.79±1.77

Soil cover indicators

Mean±SD	Factor	Variable	Weed Score	Frond mulching width
	Previous LU	Oil palm	4.17±2.48	185.83±30.4
		Rubber	4.67±2.42	198.33±20.41
		Rice	4.83±3.06	216.67±85.24
	Practices	C1	4.2±2.17	169±49.8
		C2	4.5±3.51	202.5±33.04
		C3	3.75±1.71	215±71.88
		C4	5.6±2.97	218±49.7
	Age	Young	3.83±2.14	183.33±63.46
		Intermediate	3.67±2.73	184.17±32.31
		Mature	*6.17±2.23*	*233.33±46.33*

Appendix 9: Production performance

1. PCA graph for oil extraction indicators and confidence ellipses around category of each factor: Management practices, age effect and previous land use.

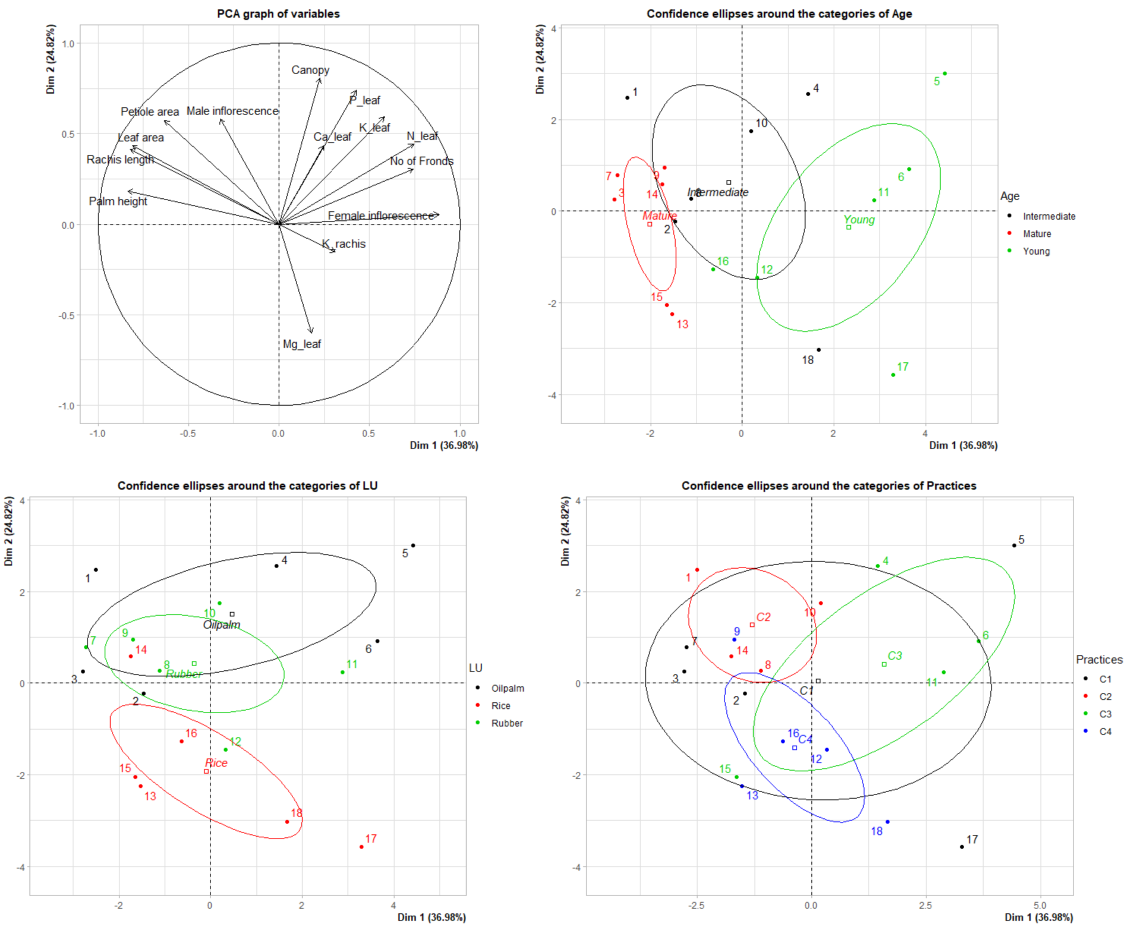


2. Mean and SD values of oil extraction indicators calculated for variables under each factor. Oil palm, rubber and rice are the variables for factor "previous land use". C1, C2, C3 and C4 are variable for factor "management practices". Young, intermediate and mature are variables for factor "age of plantation".

	Factor	Variable	kern_dia (mm)	Mesocarp_thick (mm)	Shell_thick (mm)	Bunch weight (kg)
Mean±SD	Previous LU	Oil palm	10.54±0.58	7.01±1.45	1.54±0.2	18.25±6.59
		Rubber	10.31±1.09	6.48±1.48	1.37±0.3	18.87±6.4
		Rice	10.52±1.59	5.91±1.19	1.74±0.44	15.18±4.09
	Practices	C1	10.91±1.18	6.57±1.04	1.44±0.3	15.63±4.87
		C2	10.02±0.07	6.6±1.79	1.45±0.21	23.39±4.3
		C3	11.23±0.84	7.26±1.58	1.69±0.13	16.52±6.54
		C4	9.73±1.22	5.61±1.05	1.64±0.57	15.22±4.68
	Age	Young	11.15±1.21	6.84±1.67	1.77±0.49	12.23±4.03
		Intermediate	10.53±0.67	6.99±1.32	1.43±0.18	21.45±5.97
		Mature	9.69±0.93	5.56±0.64	1.45±0.22	18.63±2.25

	Factor	Variable	Fruit set/bunch (%)	DM/F (g)	Fruit weight (kg)	%DM/B	Shell/fruit	kernel/fruit	Oil/bunch (%)
Mean±SD	Previous LU	Oil palm	75.52±3.92	54.83±4.36	13.59±4.6	41.43±4.05	6.23±0.52	8.1±1.49	29.61±3.37
		Rubber	72.61±4.91	51.68±3.36	13.63±4.73	37.42±2.98	7.43±0.97	8.9±0.79	27.35±2.95
		Rice	72.88±3.95	52.5±5.63	11.02±2.75	38.11±3.2	7.12±2.36	7.94±1.51	27.64±3.34
	Practices	C1	75.7±4.35	52.48±5.13	11.68±3.22	39.61±3.76	7.31±1.67	8.51±1	26.97±3.3
		C2	73.86±1.95	52.13±4.67	17.2±3.35	38.6±4.16	7.29±1.59	8.43±1.92	28.41±3.73
		C3	75.97±2.45	51.56±5.59	12.44±4.67	39.2±5.56	6.8±1.62	8.52±0.92	28.64±4.76
		C4	69.65±4.44	55.38±3.02	10.49±2.77	38.5±2.64	6.34±1.5	7.85±1.55	28.91±1.57
	Age	Young	76.65±3.82	51.66±4.96	9.34±2.79	39.59±4.53	7.56±1.64	8.26±1	28.7±4.18
		Intermediate	73.93±1.92	55.01±4.34	15.81±4.58	40.66±2.79	5.78±1.09	7.95±1.41	29.14±2.19
		Mature	70.42±4.44	52.33±4.17	13.09±1.56	36.71±2.87	7.43±1.21	8.73±1.55	26.75±2.96

3. PCA graph for palm metric indicators and confidence ellipses around category of each factor: Management practices, age effect and previous land use.



4. Mean and SD values of palm metric indicators calculated for variables under each factor. Oil palm, rubber and rice are the variables for factor "previous land use". C1, C2, C3 and C4 are variable for factor "management practices". Young, intermediate and mature are variables for factor "age of plantation".

	Factor	Variable	Palm height	No of Fronds	Petiole area	Female flowers	Male flowers	Total_leaf_area	OS_density	Rachis_length
Mean±SD	Previous LU	Oil palm	4.6±2.5	38.06±8.03	25.36±11.16	5.83±4.17	1.17±0.59	84359.55±23889.52	97.83±1.6	5.44±1
		Rubber	5.71±4.02	37.78±4.3	25.25±5.8	3.67±4.27	0.56±0.35	91939.06±22518.14	96.1±2.7	5.34±0.51
		Rice	4.88±3.33	34.11±5.15	18.22±4.95	3.83±4.17	0.45±0.66	74179.81±23891.69	93.2±2.19	4.95±0.8
	Practices	C1	5.14±4.16	35.2±6.19	21.34±9.57	4.4±4.83	0.93±0.59	79559.89±34864.51	96.75±2.66	5.08±1.13
		C2	6.42±1.09	36.08±3.57	29.82±11.18	2.5±1.73	1±0.61	98273.16±15467.72	97.27±1.33	5.96±0.67
		C3	3.89±3.06	41.58±7.25	20.43±3.37	8±4.97	0.42±0.84	81663.23±17578.25	97.08±2.77	4.92±0.4
		C4	4.84±3.79	34.6±5.63	21.06±4.84	3.2±2.86	0.53±0.38	77065.1±19479.9	92.33±0.84	5.1±0.39
	Age	Young	1.51±0.74	39.89±3.82	16.97±3.83	7.33±5.01	0.5±0.59	61994.71±15945.76	95.82±3.35	4.63±0.7
		Intermediate	5.4±1.67	38.72±6.93	26.08±10.82	4.83±2.48	0.89±0.66	89442.25±21345.73	96.51±2.47	5.54±0.79
		Mature	8.29±1.78	31.33±2.62	25.78±5.18	1.17±1.47	0.78±0.62	99041.46±15558.9	94.8±2.96	5.57±0.49

	Factor	Variable	N_leaf	P_leaf	K_leaf	Ca_leaf	Mg_leaf	K_rachis
Mean±SD	Previous LU	Oil palm	1.79±0.2	0.13±0.02	0.88±0.22	0.71±0.06	0.31±0.04	1.73±0.49
		Rubber	1.67±0.06	0.12±0.01	0.77±0.07	0.75±0.11	0.3±0.07	1.9±0.34
		Rice	1.69±0.09	0.12±0.01	0.58±0.09	0.62±0.05	0.37±0.06	2.07±0.37
	Practices	C1	1.72±0.2	0.12±0.02	0.8±0.26	0.67±0.06	0.33±0.07	1.92±0.57
		C2	1.69±0.08	0.13±0.01	0.72±0.13	0.71±0.1	0.3±0.05	1.8±0.29
		C3	1.76±0.17	0.13±0.01	0.84±0.11	0.75±0.16	0.33±0.04	2.01±0.51
		C4	1.7±0.06	0.12±0.01	0.64±0.16	0.66±0.06	0.33±0.09	1.87±0.3
	Age	Young	1.81±0.15	0.13±0.02	0.84±0.26	0.71±0.13	0.34±0.06	2.12±0.27
		Intermediate	1.71±0.12	0.12±0.01	0.76±0.11	0.71±0.08	0.33±0.08	1.69±0.36
		Mature	1.63±0.06	0.12±0.01	0.63±0.09	0.66±0.08	0.32±0.06	1.88±0.5

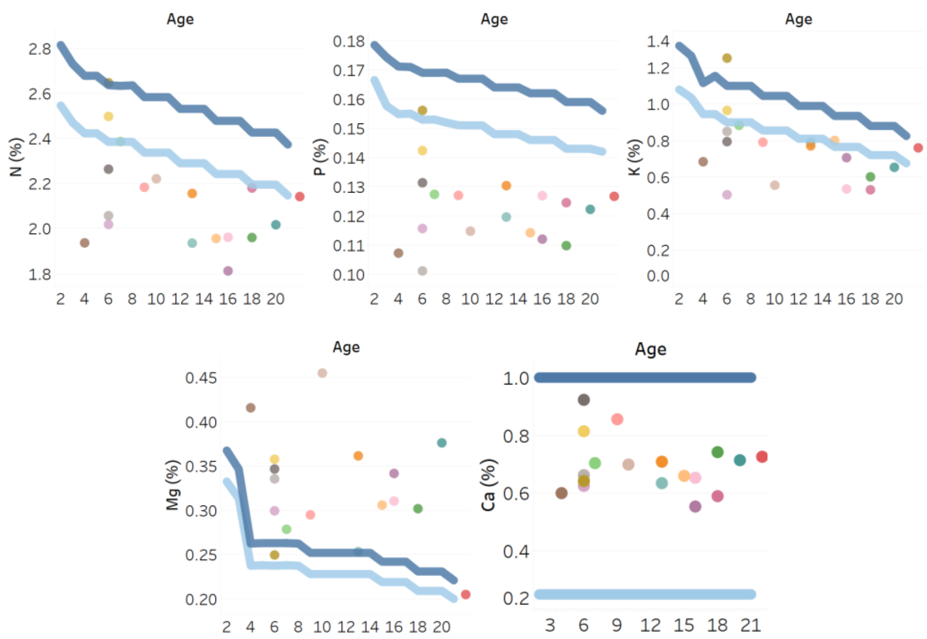
5. Mean and SD values of single harvest, annual yield and palm metric indicators calculated for variables under each factor. Oil palm, rubber and rice are the variables for factor “previous land use”. C1, C2, C3 and C4 are variable for factor "management practices". Young, intermediate and mature are variables for factor “age of plantation”.

	Factor	Variable	Annual yield	Single-harvest
Mean±SD	Previous LU	Oil palm	19.77±4.72	0.88±0.5
		Rubber	20.66±6.46	0.66±0.46
		Rice	21.42±4.7	0.49±0.33
	Practices	C1	21.36±4.6	0.7±0.49
		C2	21.49±6.9	0.59±0.38
		C3	22.01±6.82	1±0.53
		C4	18.05±2.54	0.47±0.33
	Age	Young	19.54±3.74	0.86±0.59
		Interme-diate	19.47±6.8	0.85±0.25
		Mature	22.84±4.31	0.33±0.2

6. Comparison of nutrient levels in leaves

Nutri-ent	Krabi oil palm research center				(T. H. Fairhurst & Mutert, 1999)				Our study		Leaf nutrient status
	Optimum (< 6 years)		Optimum (6+ years)		Optimum (< 6 years)		Optimum (6+ years)		Mean (<6 years)	Mean (6+ years)	
N	2.45	2.71	2.32	2.57	2.6	2.9	2.4	2.8	1.81	1.71	Deficiency
P	0.16	0.17	0.15	0.17	0.16	0.19	0.15	0.18	0.13	0.12	Deficiency
K	0.98	1.19	0.84	1.03	1.1	1.3	0.9	1.2	0.84	0.76	Deficiency
Mg	0.27	0.3	0.23	0.25	0.3	0.45	0.25	0.4	0.34	0.33	Optimum
Ca	0.25	1	0.25	1	0.5	0.7	0.5	0.75	0.71	0.71	Optimum - Ex-cess

7. Leaf nutrient concentrations in our study samples compared to critical levels as per krabi oil palm research centre.

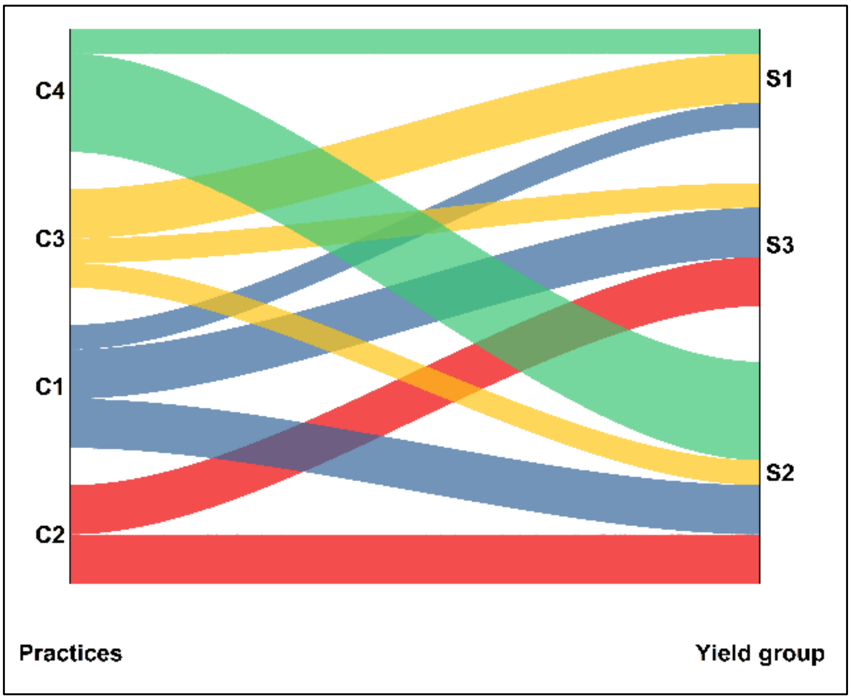


Appendix 10: Soil loss measured and categorized in different elevation class

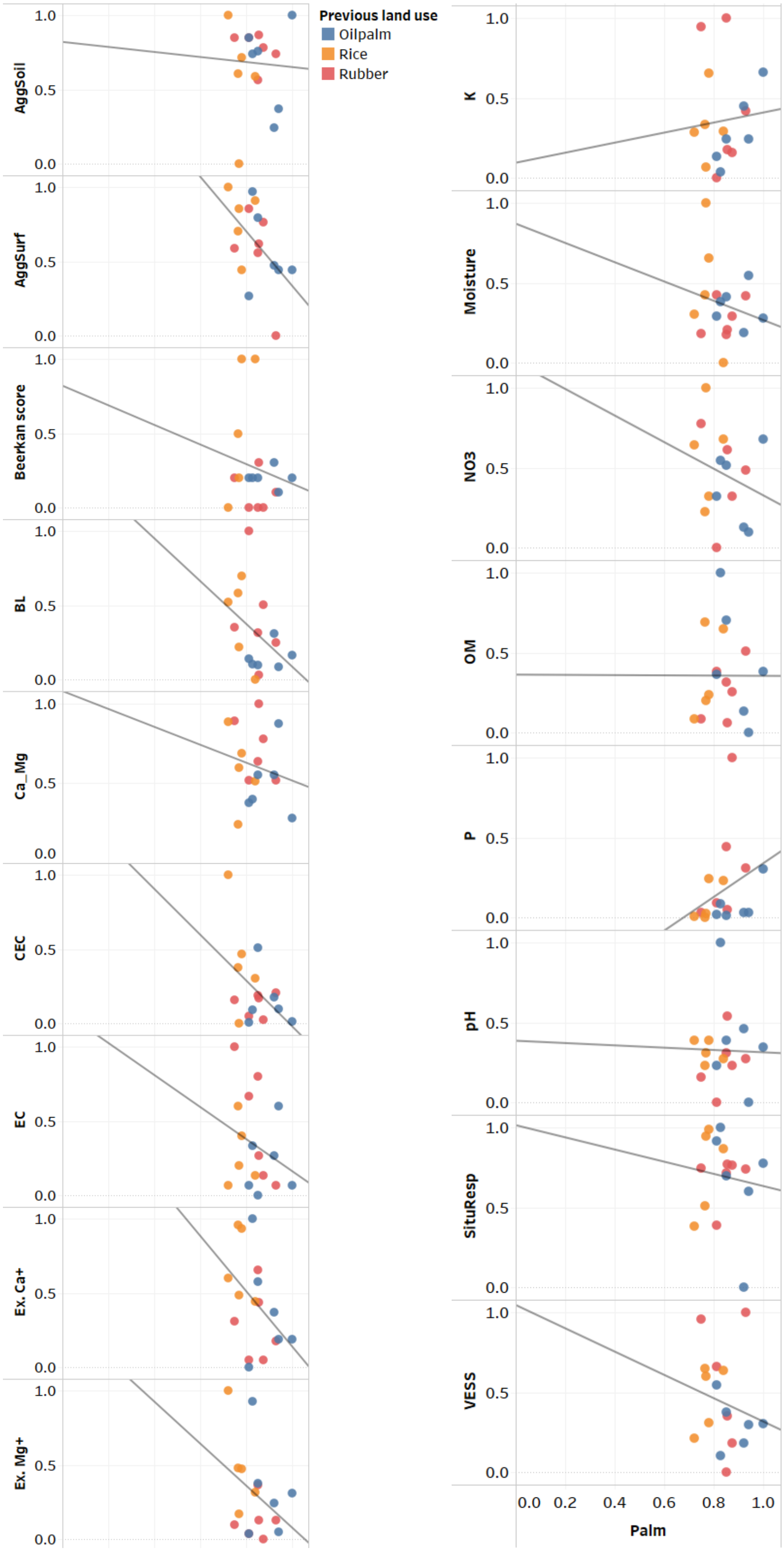
Appendix 11: Total FFB weight in tons and tons/ha, number of harvested FFB and percentage of FFB for which weight is measured.

Plot code	Harvested FFB weight		No. of harvested FFBs		% of FFB weight measured
	(tons)	(tons/ha)	Total	per hectare	
OOO1	0.72	0.44	26	16	100
OOO2	2.58	0.84	151	49	39.7
OOO3	0.26	0.16	13	8	84.6
OOY1	1.67	1.16	84	59	100
OOY2	3.16	1.4	263	117	36.1
OOY3	2.26	1.3	265	152	100
RBOO1	0.25	0.32	8	10	100
RBOO2	0.41	0.72	18	32	100
RBOO3	0.43	0.47	23	25	100
RBOY1	1.71	1.03	90	54	74.4
RBOY2	3.5	1.33	250	95	30
RBOY3	0.07	0.09	7	9	100
ROO1	0.78	0.65	46	38	95.7
ROO2	0.2	0.15	10	7	100
ROO3	0.33	0.22	24	16	100
ROY1	0.21	0.22	10	15	100
ROY2	0.31	0.8	60	154	50
ROY3	1.4	0.9	138	89	52.2

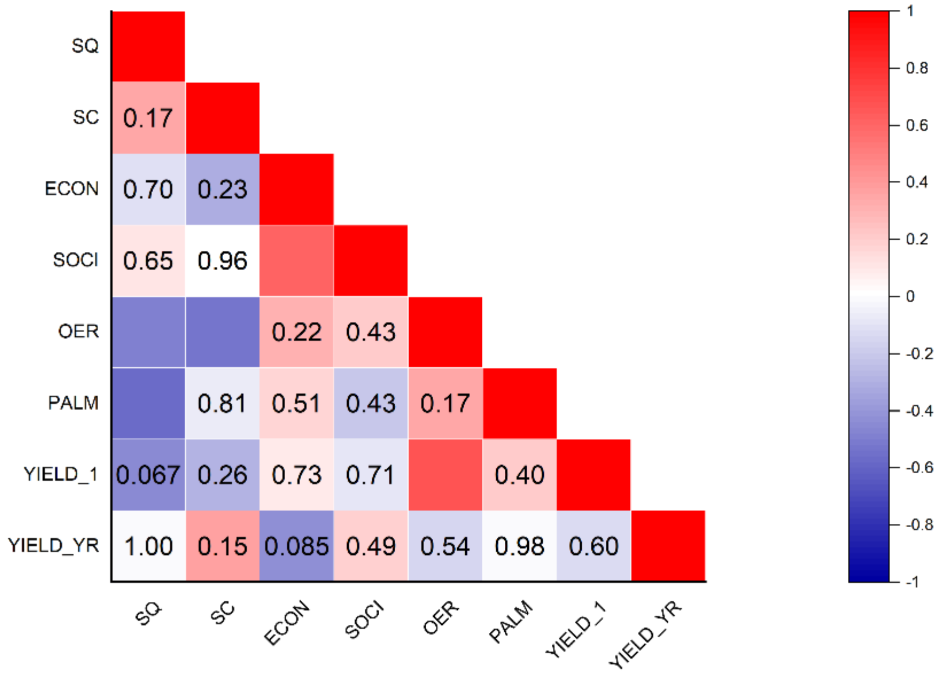
Appendix 12: Parallel set graph showing relationship between management practices and yield groups



Appendix 13: Correlation of palm metric index with soil quality indicators



Appendix 14: Correlation matrix for performance indices. Only p-values > 0.05 are shown.



Appendix 15: Images of fresh fruit bunches with damaged portions.