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1. Introduction

Vegetable oil consumption has continuously increased worldwide over the last decades (FAO, 2020). Because of its high oil-to-land ratio, oil palm is a promising crop to meet the fast growing demand in vegetable oil (Barthel et al., 2018). Palm oil and palm kernel oil account for more than one third of the global vegetable oil production (FAO, 2020). Yet, oil palm production in Indonesia faces deep environmental and social concerns due to conversion of tropical rainforest to oil palm monoculture and conflict between local and migrant communities (Cramb and McCarthy, 2016). Recently initiatives such as the RSPO (Roundtable on Sustainable Oil Palm) certification aim at promoting optimal practices for the development of oil palm cultivation limiting its negative impacts (Lee et al., 2020; Padfield et al., 2019). The largest producing country is Indonesia with 12 Mha planted, which account for 56% of the total planted area in 2019 (Oil World, 2019). In Indonesia, oil palm is produced by a large diversity of growers, namely: privately-owned, state-owned companies and smallholders (Cramb and McCarthy, 2016). Smallholders' establishment in Indonesia followed several pathways. Some smallholders settled on their own, and they are referred to as independent smallholders, while others followed governmental programs: these are scheme smallholders or plasma smallholders. Many smallholders also owned a combination of independent and plasma plots; therefore grower types are not exclusive.

Several governmental programs were put in place in order to promote an oil palm development that would include both industries and smallholders. Historically the oil palm sector in Indonesia was dominated by state owned companies after the Indonesian Independence (1960's and 1970's). In the late 1970s, the Indonesian Government notably initiated a specific type of farming contract named "Nucleus Estate and Smallholders" (NES) or "Perkebunan Inti Rakyat" (PIR) (Zen et al., 2016). NES schemes were sometimes adopted by the local population although they were initially linked to transmigration programs, which displaced people from overpopulated Java to the outer islands of Sumatra and Borneo (Fearnside, 1997). Plasma smallholders under NES program were organized around a nucleus estate managed by a state-owned company (Zen et al., 2016). Private companies as nucleus estates emerged quickly, and became the prominent model from the late 1980s to the 1990s. The nucleus estate supervised the land preparation and the planting of the 2 ha-plot per smallholder family, the plot management during immature stage and the supply of inputs. The estate was also in charge of coordinating harvesting rotation, road maintenance and providing technical assistance to the smallholders (Zen et al., 2016). Usually, plasma smallholders repaid the cost of plantation after 5 to 10 years, although they remained bound to the nucleus estate for plot management and for harvesting Fresh Fruit Bunches (FFBs) until the end of the oil palm cycle (Barlow et al., 2003). In the 1990s, a new version of the NES scheme emerged, called the KKPA (Kredit

Kooperasi Primer Anggota). In KKPA schemes, smallholders were organized in village cooperatives (KUD - Kooperasi Unit Desa) of around 500 farmers each, and each cooperative was divided into farmers' groups (Kelompok Tani) of about 20 members. By the end of the repayment period, smallholders under KKPA system managed their plots by themselves, sometimes with some assistance from the cooperatives services. Such farmers are referred to as "ex-plasma smallholders". Those schemes were abandoned in the early 2000's under the *reformasi* era but were instrumental in developing the smallholder sector with more than 900 000 ha planted under the NES scheme until 2003 (Zen et al., 2016). After this period, smallholders increasingly developed their own independent plantation outside of agroindustrial partnership, either with scheme smallholders looking to extend their area or with newcomer looking to join the growing oil palm sector (Feintrenie et al., 2010).

Both plasma and ex-plasma smallholders benefited from the planting standards adopted by the nucleus estate, using 100% selected high quality Tenera seedlings, as well as optimal planting density and maintenance during the immature stage. This initial good maintenance made it possible to fill part of the yield gap observed in smallholders' plantations (Rhebergen et al., 2020). Selected planting material indeed impacts both the yield and the extraction rate, leading to a potential increase of about +40% in oil production compared to non-selected material (Cochard et al., 2001; Tiemann et al., 2018). Management practices are also drivers of the performance of palms, especially fertilization and weeding practices (Darras et al., 2019; Rhebergen et al., 2020). Yields measured in plasma and ex-plasma smallholders' plots reach an average of 17-22 tFFB ha^{-1} yr^{-1} (Euler et al., 2016; Lifianthi and Husin, 2012). This is generally higher than for other independent smallholders established on their own (Baudoin et al., 2015), who attain yields of 10-15 tFFB ha^{-1} yr^{-1} (Jelsma et al., 2017).

Various development contexts have led to a great diversity of growers and production systems. Smallholders optimum management practices have usually been studied in broad groups that only allow for comparison between plasma and independent (Jelsma et al., 2019; Lee et al., 2020; Schoneveld et al., 2019; Woittiez et al., 2019). Thus, the linkages between the diversity of management practices in smallholders' plots and the oil palm performance at local scale remain poorly investigated, making it uneasy to propose adapted recommendations for both plantation management and replantation programs. Proposals at regional scales were recently made, exploring differences between various smallholder organization systems (Jelsma et al., 2019; Moulin et al., 2017; Woittiez et al., 2018). Such descriptive analysis performed at a large scale may not be locally explicit enough to feed local recommendations. In addition, it was found important to involve socio-economic aspects when analyzing the determinism of smallholders' plots performances. Economic constraints are indeed one of the main drivers of smallholders' choices in the management of systems based on perennial cash crops (Baudoin et al., 2015; Feintrenie et al., 2010).

In the present study, we explored the diversity of management practices implemented by ex-plasma oil palm smallholders in the Jambi province, Indonesia. We presented two typologies based on agricultural practices or economic variables, in order to decipher the local diversity at the plot level. Then, we explored the relationship between the two typologies, in order to understand better the agro-economic performances across ex-plasma smallholders' plantations. Our main hypothesis is that the diversity of practices in the study area would help to adjust a local agro-economical optimum that could further be a reference for management recommendations.

2. Material and Methods

2.1. Study area

The study was conducted in two neighboring villages located in the Petaling area (-1.73770°N, 103.83479°E), Sungai Gelam sub-district, Muaro Jambi regency, Jambi Province, in the Sumatra Island in Indonesia. Within Petaling, two oil palm cooperatives were studied, namely KUD Marga Jaya (in Petaling Jaya village) and KUD Makarti (in Sido Mukti village). The two cooperatives gather 461 ex-plasma smallholders owning 610 oil palm ex-plasma plots for a total planted area rounding 1,300 ha. KUD Marga Jaya was settled in 1984 and historically took responsibility for the development of the plasma plots in the area. Due to the increasing number of oil palm smallholders and the development of independent plots, KUD Makarti was then created in 2013 following a similar organization. The two cooperatives manage the harvesting of FFB every ten days for each plot and sell the fruits to the mill of the nucleus estate that is located at around 20 km from the study area. Besides, cooperatives retail subsidized fertilizers and pesticides to their members.

All studied ex-plasma plots are homogeneous in terms of pedo-climatic conditions and historical organization. First, the area is relatively small and plots are collated (25 km²), with flat to slightly hilly topography and Acrisols soils. Second, all the studied plots were established by a nucleus estate in 1995 and 1996 using Tenera seedlings planted according to a triangular pattern (9 m x 9 m x 9 m). The management (soil preparation, planting, management during immature phase) of plots was uniform as all plots were managed by the nucleus estate. This situation lasts until repayment of loans for plasma development. Since the beginning of the 2000s, smallholders have been managing their plots by themselves (fertilization, weeding and pruning).

2.2. Sampling method and data collection

As the historical and pedoclimatical context was rather homogeneous, we randomly selected 79 smallholders out of 461 (17%) from the cooperatives' database in September 2019. For smallholders owning several plots, only one plot was considered, in order to maximize the diversity of practices sampled. Directed interviews about management strategies and practices within each targeted plot were performed in November and December 2019 with an Indonesian expert on oil palm practices and staff members from the cooperatives. The help of local experts and some data triangulation based on cooperatives' records provided some safeguards regarding uncertainty embedded in farmers' interviews due to the lack of a systematic tracking of practices.

2.2.1. Smallholders' interviews and field visits

Interviews focused on agricultural practices implemented over the year preceding interviews. Through these interviews only, we collected quantitative information at the plot scale about the dose and application frequency for each type of fertilizer and herbicide. If any changes between year 2018 and year 2019 were recorded, we collected data for both years (see **Supplementary Material 1**) and worked on average practices for data analysis. We also collected information about the workforce involved in each activity. Field visits mainly consisted in assessing weed control practices. We defined four distinct zones in the central area of the plot, namely: the harvesting path, the weeded circle, the windrow and the remaining zone (called "Other" zone, see **Supplementary Material 2** (Carron et al., 2015)). We could not consider plot spatial heterogeneity for weed biomass measurements in the plot. We undertook all weed biomass observations in the "Other" zone that was considered as a proxy zone to describe the diversity of weed management between the plots. First, weeds height was scored into four classes (referred as "Height" indicator). Second, the biomass of understory vegetation was scored according to an adapted Braun-Blanquet scale (Wikum and Shanholtzer, 1978) at three locations in the plot, inside a 25 cm x 25 cm square (average score is referred as "Grass" indicator). Third, the number of woody weeds within each square was recorded (the average score is referred to as "Wood" indicator).

2.2.2. Complementary data

Palm tree density was checked based on satellite imagery from Bing aerial plugin on QGIS software (visited on March 10, 2020). No significant differences in tree mortality was recorded between plots. Average plot density was 130 tree ha^{-1}. We collected precise data on oil palm yields from KUD Marga Jaya and KUD Makarti cooperatives for each plot (t ha^{-1} yr^{-1}) over the January to December 2018 period.

The average selling price of FFB was estimated at 1,320 IDR kg^{-1} based on Governmental data communicated online (InfoSawit.com, retrieved 5 Feb. 2020) and values were crosschecked with information from experts. The cooperatives provided values for the cost of fertilizers and pesticides applied by the end of December 2019 and they provided data on irreducible costs (e.g. maintenance, loading,…). Costs and time for labor per activity were estimated with the help of the cooperatives, depending on the nature of provided services (**Supplementary Material 3**).

2.3. Description of input variables

2.3.1. Descriptors of agricultural practices

Descriptors of agricultural practices were divided into two categories: fertilization and weeding. Fertilization was characterized by inputs of key elements for oil palm nutrition, namely: N, P, K, Mg and Ca in kg ha^{-1} yr^{-1} (Dubos et al., 2018; Woittiez et al., 2017). The concentration in each element was recorded from fertilizer packaging. Measurements of leaf nutrient contents were performed in January and February 2021. Leaf K contents showed to be lower than results from Baron et al. (2019) obtained in the same pedoclimatic conditions in agroindustrial plantations. As we could not measure the K contents in EFB, we derived K EFB content for our data sample based on Baron et al. (2019) leaf contents results. This led to EFB content of 0.43% K in the dry matter on average.

Weeding practices were firstly characterized by the treatment frequency index (TFI). TFI estimates the number of registered doses of pesticide used per hectare and was calculated following **equation 1** (Gravesen, 2003; Lechenet et al., 2017).

$$TFI = \sum \frac{Wfq * Qa}{Md} \quad \textbf{(equation 1)}$$

Wfq is the frequency of chemical weeding done for a given commercial herbicide (yr^{-1}), Qa is the applied quantity of active product per application for the given commercial herbicide (mg ha^{-1} yr^{-1}), and Md stands for the minimal dose of active product ratified for the given herbicide for oil palm plantations (mg ha^{-1} yr^{-1}).

In addition to chemical weeding, we investigated the frequency of manual and mechanical weeding (NonChWeeding; times yr^{-1}).

Lastly, we generated an indicator of weed biomass observed in the plot. To do so, we performed a Principal Component Analysis (PCA) from the scorings of weed biomass observed in the field, referred as Height, Grass, Wood (see part 2.2.2; field visits), TFI and NonChWeeding (**Supplementary Material 4**). Height, Grass and Wood indicators were highly correlated on axis 1 and they were gathered into “Weed” indicator using individual contributions on axis 1. “Weed” score thus aggregated various components of the weed biomass observed in the field.

2.3.2. Indicators of economic performances

Economic performances was characterized with basic agro-economic indicators at the plot scale which included economic value of the production, gross margin and return to labor. The economic value of the production corresponds to FFB production per ha multiplied by the selling price at farm gate (Feintrenie et al., 2010). We calculated the indicator “Revenues” (IDR ha^{-1} yr^{-1}) following equation 2:

Revenues =[Yield]([FFB selling price] - [Compulsory cooperative’s costs]) (**equation 2**)*

Compulsory cooperatives costs were proportional to the production of FFB and corresponded to the costs for FFB harvest, weighing, loading, transportation, unloading, road maintenance and cooperative management.

The gross margin (GrossMargin; IDR ha^{-1} yr^{-1}) was calculated following **equation 3** :

GrossMargin=[Revenues]-[Variable Costs] (**equation 3**)

Variable costs were defined by the costs for fertilizers (CostFerti; IDR ha^{-1} yr^{-1}), herbicides (CostHerbi; IDR ha^{-1} yr^{-1}), labor for fertilization (LaborFerti; IDR ha^{-1} yr^{-1}) and weeding (LaborWeed; IDR ha^{-1} yr^{-1}). Costs for pruning were integrated in variable costs to calculate gross margin. However, it was not considered within economic indicator set because the service for pruning was a yearly flat fee, the same for all smallholders (500 000 IDR ha^{-1} yr^{-1}).

For labor, we considered both hired and family labor as costs, on the basis of a 7-hour- working day. Return to labor (ReturnToLabor, IDR day^{-1}) was the amount earned per day worked in the plot and it was obtained according to **equation 4** (Feintrenie et al., 2010):

ReturnToLabor=[Gross Margin]/[Number days of labor] (**equation 4**)

Number days of labor included time spent for harvest.

2.4. Data analysis

We performed two distinct clustering, on agricultural practices on the one hand, and on economic performances on the other hand, using R Software (R Development Core Team, 2008, R 3.6.1). Prior to clustering, we removed six individuals that had indicator values above three times the interquartile range. Those outliers were considered as performing extreme practices compared to representative practices in the area. The final dataset for both clusterings consisted of 73 smallholders. The PCA was computed (FactoMineR package; Husson et al. 2020) on components that cumulatively explained more than 60% of dataset variability. Individuals' coordinates were used to build Ascending Hierarchical Clustering (AHC) using K-means method (package FactoMineR, Husson et al. 2020). This enabled the generation of clusters of smallholders with homogenous practices or economic performances. Univariate analysis of indicators was then performed in order to understand differences between groups. ANOVA analyses were run after verifying residues normality through Shapiro-Wilk test and homoscedasticity through Levene's test (Car package; Fox and Weisberg 2019). If one of those conditions was not verified, we performed means comparison with Kruskal-Wallis statistical test. Pairwise comparisons were performed following Tukey's test after ANOVAs (Agricolae package, De Mendiburu, 2009) or Bonferroni method after Kruskal-Walllis tests (Stats package).

Lastly, we crossed both clustering in a contingency table. Relations between both clustering were analyzed through Correspondence Analysis using function CA() (FactoMineR Package, Husson et al. 2020). Chi-square value was used to explain dependency between agricultural practices and economic clusters (Bendixen, 2003). Relationships were then characterized while looking at the distance between practices and economic clusters on CA's asymmetric biplot (Greenacre, 2013).

3. Results

3.1. Analysis of agricultural practices

3.1.1. Fertilization and weeding performed by smallholders

The quantity and types of fertilizers applied by smallholders were variable, resulting in a high variability in nutrients inputs, as presented in **Table 1**. The most popular mineral fertilizers were NPK, KCl, Urea, and Dolomite. Only 15% of the smallholders did apply organic fertilizers, mainly using EFB around the weeded circle in order to benefit from its high K content. A mere 5% of the smallholders did not apply any fertilizer. Average N application rate was 84 kg ha^{-1} yr^{-1} with a coefficient of variation (CV) of 67%. Average K application rate was 117 kg ha^{-1} yr^{-1} with a CV of 67%. Applications of Mg, Ca and P were even more variable, with respective CV reaching up to 86%, 93% and 92% (resp. means: 35 kg Mg ha^{-1} yr^{-1}, 55 kg Ca ha^{-1} yr^{-1} and 21 kg P ha^{-1} yr^{-1}).

When weeding practices were considered, 28% of the interviewed smallholders used only chemical herbicides, and 15% of them cleared weeds only manually or mechanically. The 56% remaining used both chemical and mechanical weeding. Weeding practices are detailed in **Table 1**. The applied doses of herbicides varied from 0 to 5 times the minimal advised dose. TFI results showed that, on average, smallholders did not exceed 2 times the minimal advised dose. Manual or mechanical weeding was performed up to 2 times per year. Weed observation in the plots highlighted different strategies, ranging from blanket weeding to less managed vegetation (Grass, Wood and Height indicators, **Table 1**). Grass roughly covered 50% to 75% of the surface area in the studied zone (Score 3 for Grass indicator), while woody weeds were highly controlled (small average number for Wood indicator). The height of the understory vegetation was mainly contained under 50 cm.

3.1.2. Typology of agricultural practices

Figure 1 gathers the variables linked to agricultural practices. Dimensions 1, 2 and 3 were selected as they presented 63% of cumulative variance of the dataset. Fertilization practices varied towards two distinct directions. Indeed, Mg and Ca applications were highly correlated together on the first dimension and mostly contributed to this dimension (resp. 76.5% and 67.7%). Applications of N, K and P were highly correlated. They were represented on the first and third dimensions and mostly explained the construction of the third dimension. Weed and TFI indicators were negatively correlated on the second dimension, while the "NonChWeeding" indicator was not correlated to the other indicators on weeding practices and it only explained the variability within the dataset to a lesser extent.

The AHC highlighted four clusters of smallholders' practices (**Table 2**). The first cluster, called A1, consisted of 16 smallholders representing 22% of the total sample. This cluster was characterized by the lowest inputs in N and K fertilizers (resp. 55 kg N ha^{-1} yr^{-1} and 61 kg K ha^{-1} yr-[1]). Chemical weeding was also the lowest, with an average TFI of 0.6, indicating that A1 smallholders poorly managed weeds in their plot.

The second cluster, called A2, consisted of 18 smallholders representing 25% of the total sample. Fertilization practices of this cluster were similar to the ones found in cluster A1. The A2 cluster was mainly characterized by the use of chemical weeding with the highest average TFI (2.7). On the contrary, NonChWeeding and Weed indicators were found to be low, with average values of 0.3 times yr^{-1} and -1.0 times yr^{-1} respectively.

The third cluster, called A3, consisted of 24 smallholders representing 33% of the total sample. It differed from the other clusters by the high levels of Mg and Ca applied in the plots (resp. 66 kg Mg ha^{-1} yr^{-1} and 112 kg Ca ha^{-1} yr^{-1}). Inputs in N, P and K were statistically not different from the ones found in clusters A1 and A2. Smallholders from cluster A3 did highly control weeds through chemical and nonchemical weeding, resulting in low weed biomass in the plot.

The fourth and last cluster, called A4, consisted of 15 smallholders representing 20% of the total sample. This cluster differed from the others by the high levels of N and K applied in the plots (resp. 142 kg N ha^{-1} yr^{-1} and 211 kg K ha^{-1} yr^{-1}). Mg and Ca inputs were similar to the ones found in clusters A1 and A2. Weeding practices were similar to A3, mainly driven by nonchemical weeding (1.1 times yr^{-1}) and a rather low TFI (1.4).

Oil palm yields are presented in **Figure 2**. Overall average yield was of 18 $tFFB.ha^{-1}.yr^{-1}$. A significant difference was observed between clusters A1 (mean = 18 t ha^{-1} yr^{-1}, CV = 24%) and A4 (mean = 20 t ha^{-1} yr^{-1}, CV = 19%). Clusters A2 (mean = 19 t ha^{-1} yr^{-1}) and A3 (mean = 19 t ha^{-1} yr^{-1}) had quite variable responses to yields with respective CVs being equal to 32% and 27%.

3.2. Analysis of economic performances

3.2.1. The global economic performances

Results on economic indicators are presented in **Table 3.** On average, smallholders' revenues reached 20M IDR yr^{-1} ha^{-1} (eq. 1 209 € yr^{-1} ha^{-1} in 2020[1]). Fertilizers were the major source of expenses mobilizing around 15% of the revenues from FFB sales (**Table 3**). Wages both for weeding and fertilizer application represented the second main cost (3% of revenues). Expenditure in herbicides accounted only for 0.5% of revenues. Mean gross margin was 16 M IDR yr^{-1} (eq. 967 € yr^{-1} ha^{-1} in 2020), *i.e.* expenses for inputs and wages represented 20% of total revenues. Smallholders'

[1] Mean exchange rate for Indonesian rupiah (IDR) 2020 estimated at : 1 € = 16,549 IDR (after data from XE online, (2020))

family labor and hired workers together worked in total around 30 days.yr^{-1} for 1 hectare of oil palm. Thus, smallholders earned on average 564,000 IDR day^{-1} ha^{-1} (eq. 34 € day^{-1} ha^{-1} in 2020).

3.2.2. Typology on economic performances

Figure 3 gathers the indicators on economic performances. The first and second dimensions were used, as they represented 67% of cumulative variance of the dataset. First dimension was mainly explained by "Revenues", "GrossMargin" and "ReturnToLabor" indicators. The second dimension was mainly explained by the costs for fertilization (CostFerti and LaborFerti). Costs for weeding (CostHerbi and LaborWeeding) did not explain much the variability from the dataset.

Three clusters of smallholders with similar economic performances were built after AHC. (**Table 4**).

The first cluster, called E1, consisted of 33 smallholders representing 45% of the total sample. This cluster was characterized by the lowest revenues across of the studied population, which were mainly limited by low yields (15 t ha^{-1} yr^{-1} on average). Input and labor costs for fertilization and weeding were the lowest and they little impacted the gross margin and return to labor, which were also the lowest compared to other groups.

The second cluster, called E2, consisted of 22 smallholders representing 30% of the total sample. Revenue was the highest in this population, as reflected by high yields (23 t ha^{-1} yr^{-1} on average). Costs for fertilizer inputs and costs for labor for weeding were similar to E1 but costs for labor for fertilization were found to be 1.7 times higher. GrossMargin and ReturnToLabor were overall the highest and respectively averaged 20.7 M IDR yr^{-1} ha^{-1} (eq. 1,251 € yr^{-1} ha^{-1} in 2020) and 775,882 IDR day^{-1} ha^{-1} (eq. 47 € yr^{-1} ha^{-1} in 2020), indicating the group with highest profitability at plot level.

The third and last cluster, called E3, consisted of 18 smallholders representing 25% of the total sample. Revenues were similar to E2 with similar yields results (22 t ha^{-1} yr^{-1} on average). Costs for fertilization input were 1.8 times higher than E2 cluster. Costs for labor for fertilization and weeding were high. These costs had a high impact on gross margin and return to labor results: gross margin was 20% lower than for E2 smallholders and return to labor was similar to E1 smallholders (around 16.5 M IDR yr^{-1} ha^{-1} ; eq. 997 € yr^{-1} ha^{-1} in 2020).

3.3. Relations between agricultural practices and economic performances

The correspondence analysis between agricultural and economic clusters was significant (p-value < 0.01; chi-square = 21.2). This result indicated a strong link between the two clustering approaches as illustrated in **Figure 4**. The first dimension represented 86.6% of the global variance between the clusters. We mainly focused on the correlation found between A and E clusters on this dimension (**Figure 4**).

Cluster A1 was correlated with E1 cluster (distance=0.06). Low fertilization and low-intensity weeding practices (A1) were associated with economic performances that were limited by yields (E1).

A2 cluster was associated with E2 cluster (distance=0.43) and E1 cluster (distance=0.57). Indeed, 44% of the smallholders implementing chemical weed control but applying few nutrients (A2) were associated with the most profitable group (E2), 44% of them were associated with poor yield-limited economic performances (E1).

Cluster A3 was the cluster on agricultural practices that was the most correlated with E2 cluster (distance=0.04). The highest plot's profitability (E2) was related to medium use of chemical weeding and the application of Mg and Ca.

A4 cluster was associated with both clusters E2 (distance=0.55) and E3 (distance=0.75). 53% of A4 smallholders had economic performances that were limited by the costs for fertilization (E3). Then, 33% of smallholders had high profitability for the studied zone (E2).

4. Discussion

4.1. Oil palm ex-plasma plots are productive and profitable for smallholders

Our study focused on management practices implemented by smallholders in ex-plasma oil palm plantations. We observed relatively low "yield taking" gaps (Rhebergen et al., 2020) in the area. Indeed, all plots were established by the nucleus estate following similar practices for planting and immature stage. Planting design, plant material, field access and harvest frequency are known to be key factors explaining variability in oil palm production (Woittiez et al., 2017). The studied plots were around 25 years old and average production was 19 t ha^{-1} yr^{-1}. This result is far above the production recorded in areas cultivated by fully independent farmers (Euler et al., 2016; Jelsma et al., 2019; Lee et al., 2014; Lifianthi and Husin, 2012). Some plots even showed yields comparable with those from agroindustrial plantations producing around 26 t ha^{-1} yr^{-1} , a trend that was already highlighted in similar areas by Moulin et al. (2017).

Ex-plasma organization with cooperatives might have helped in limiting costs for inputs and intermediaries, and in pooling smallholders' economic efficiency. This led to high revenues, with an average gross margin of 16M IDR ha^{-1} yr^{-1} (eq. 967 € ha^{-1} yr^{-1} in 2020) for only 30 working days per year which is very low for labor needs. The return to labor of such systems is thus 3 times higher (average of 564 000 IDR day^{-1}; eq. 34 € ha^{-1} day^{-1} in 2020) compared to the one obtained in independent contexts (192 800 IDR day^{-1}; eq. 12 € ha^{-1} day^{-1} in 2020) (Euler et al., 2016). This revenue level makes oil palm productivity very competitive when compared to other agricultural commodities in Indonesia, like rubber monoculture or agroforests (Feintrenie et al., 2010).

Ex-plasma thus seemed to be an efficient system in terms of productivity and revenues for farmers (in terms of both margin and return to labor). However, trade-offs dealing with social and environmental aspects were not integrated in the present study. For example, smallholders are contractually bound to a specific mill to sell their production, and these bonds might increase vulnerability, such as price volatility (Cahyadi and Waibel, 2016; Gatto et al., 2017). Contracts also makes it impossible for smallholders to take benefit from market competition and to negotiate for advantages such as the access to organic matter from EFB to be used for fertilization.

4.2. From initial homogeneity to current diversity

Despite the homogeneity of the studied zone in terms of both pedoclimatic conditions and management of immature stage, our study highlighted a large diversity of agricultural practices implemented by smallholders. Based on fertilization and weeding practices, we were able to identify four groups of smallholders. A clear gradient in management intensity was observed. A1 smallholders were found to have lower management of their plots compared to other, especially concerning weeds management leading to a relatively high weed biomass in the plots. A2 and A3 were intermediary groups, with trends for an increase of fertilization and weed maintenance. On the opposite extreme of the gradient, the A4 smallholders were mostly different to other groups in terms of N and K fertilization. They represented around 20% of the smallholders of the area. Management practices in group A4 are the closest to conventional practices applied in agroindustry (Darras et al., 2019; Pardon et al., 2016) and recommended by best management practices (Rhebergen et al., 2020; Woittiez et al., 2017) to optimize oil palm yield.

After discussions with smallholders during interviews, it seems that A3 smallholders purchase fertilizers with high Mg and Ca contents for three main reasons: (i) Mg and Ca inputs are cheaper than NPK fertilizers; (ii) Mg and Ca inputs are more available at cooperatives' shops than other types of fertilizers; (iii) most smallholders believe they have acid soil and put Mg inputs to correct soil pH.

4.3. Linking practices to economic performances, where is the optimum?

We collected a large set of data on the economic performances at plot level, which were consistent with previously published studies (Euler et al., 2016; Feintrenie et al., 2010; Jelsma et al., 2017; Lifianthi and Husin, 2012). We identified three economic clusters covering three different strategies in terms of revenues *vs* expenses balance. E1 groups showed the lowest revenues in the ex-plasma area under study. Such results were still better than those observed for independent smallholders by Euler et al. 2016. Clusters E2 and E3 accounted for about 55% of the smallholders of the area, and got much higher revenues, due to high oil palm yields (+8M IDR ha^{-1} yr^{-1} compared to E1). In E2, the costs of fertilization and labor were similar to the ones incurred by E1 smallholders, whereas in E3 these costs are about two times higher (mainly because of fertilization costs, **Table 4**). The E2 group corresponds to the economic optimum found in the studied area.

It is worth to note that we could not cover practices and economic performances temporal dynamics and history. We based our analysis on actual plots performances. Crossing economic optimum with the analysis of the clusters on management practices stressed some optimal practices to meet economic efficiency at plot's level. On one side, A1 was close to E1 group due to poor yields that limit the gain-cost balance. Farmers from A1 group implemented a low plot maintenance (*e.g.* 31% of smallholders did not fertilize their plot). However, the study did not highlight any significant difference neither on N, P and K fertilization between A1, A2 and A3 groups nor on fertilization costs between E1 and E2 clusters. Fertilization may thus not be the only factor explaining the low production of A1 plots. For example, other possible co-factors such as plots management history could not be integrated in this study and may have interfered our causal link approach. Further experiments may be of interest if we want to better understand the production gap evidenced in A1 group. While not being at the very top, those farmers benefit from a sizeable gross margin from their oil palm plots reaching 12M IDR yr^{-1} ha^{-1} (±725 €).

On the other side, most of A4-type smallholders were close to those from the E3 group. The A4 smallholders tended to implement practices that were too costly when compared to benefits gained from harvesting. This can be linked to the large use of KCl fertilizer that are more costly than other. In this case, intensive management practices (A4) were costly for smallholders and less profitable.

Within the midrange, E2 group was at the economic optimum, with high revenues and relatively low costs for fertilization. A2 and A3 management practices were the closest to E2. In a context of relatively low palm oil prices, A2 and A3 farmers were at the same revenue range and the same main costs (N, P, K fertilization); these are optimal to provide a sufficient yield together with manageable costs. Practices of N, P and K fertilization for A2 and A3 corresponds to doses of fertilizer that were considered lower than best management practices (Jelsma et al., 2019; Woittiez et al., 2019). In best management practices guidelines, fertilizer recommendations are often derived from mineral balance models, in which the amount of nutrient to be supplied is theoretically estimated. However experimental optimisation of marginal economic gains through leaf sampling and yield analysis frequently leads to lower recommendations in terms of nutrient supply (Dubos et al., 2019). Based on our results, it is difficult to provide recommendation in terms of both weeding practices and Ca – Mg fertilisation. Indeed, their costs are relatively low compared to the other fertilization costs and no literature data could highlight any linkage between these practices with productivity in a similar soil context. However, indirect antagonisms between Ca-Mg fertilization and K nutrients have recently been observed, and excessive fertilization may limit K availability for oil palms (Dubos et al., 2017, 2011). Furthermore, we analysed the mineral content of the fertilizers used by farmers in October 2020. Result especially evidenced a lower content in Ca and Mg than indicated on packages for some fertilizers. This makes conclusions on the linkages between Ca - Mg applications and productivity even more hazardous. High chemical weeding in A2 group and high Ca-Mg fertilization in A3 group may also be detrimental to the environment.

Our results highlighted that technical studies aiming at filling yield gaps and spreading best management practices (Rhebergen et al., 2020; Woittiez et al., 2017) may not be sufficient. Indeed, the integration of economic parameters enabled us to show that smallholders might not have any economic interest in maximizing their production (reaching A4 group). In addition to technical evidence, we need to integrate socio-economic bottlenecks for a better understanding of farmers' performance, as shown by Woittiez et al. (2019).

4.4. Toward generic recommendations

Our study helped in providing recommendations to smallholders, aimed at optimising their management practices through the integration of economic aspects. We noticed that only 29% of the smallholders adopted the management practices we described as economically optimal (A3). A sizeable portion (50%) of the smallholders under study could reduce their herbicide use. The strong link between A4 and E3 smallholders stressed that reducing A4 farmers' inputs in fertilizers towards a more balanced fertilization might lead to reduced cost without affecting yields and then increase economic benefits. Moreover, results showed that an important proportion of smallholders is over fertilizing in Mg and under fertilizing in K. Thus, 30% of the interviewed smallholders could reduce or re-adapt their fertilization balance strategy towards more optimal outcomes. NES ex-plasma smallholders might benefit from the cooperatives' organizational capacity in improving their practices. There is thus a need for the dissemination of optimal practices at the cooperatives' level.

Our results can help in fine-tuning some of Principles and Criteria governing certification, especially within current RSPO (Roundtable on Sustainable Palm Oil) certification dynamics that aims at integrating more smallholders practices (Apriani et al., 2020). However, one must bear in mind that results from our study are site-specific and adapted to ex-plasma smallholders. It is rather risky to extrapolate our recommendations to other regions and other types of smallholders (e.g. independent smallholders). In addition, we need to understand local contexts and factors governing smallholders' organization at a larger scale before drawing up general outcomes from such a site-specific study. Our research focused on the plot level, but complementary plots and or activities will affect farm's performance.

To provide the full understanding of the agroecosystem performance that is needed to design recommendations, we need to complement this economic study with data measurements of the environmental component. For instance, nitrogen fertilization may rather be a driver of N loss than a driver of production. In addition, herbicide use and understory management are generally intensive, with no evidence of competition between weeds and oil palms. A full multicriteria study of various smallholders' management strategies, integrating environmental aspects would be of paramount interest (Darras et al., 2019).

4.5. Limitations of the study

Our study aimed at investigating the diversity of agricultural practices and related economic performances of ex-plasma smallholders settled in the same historical and pedoclimatic context and gathered into two neighboring cooperatives. Working with data collected during interviews from smallholders is known to be at the origin of uncertainties. Smallholders do not maintain proper records of inputs, applications rates or time needed to perform activities (for detailed labor costs calculation) in the plots, nor the exact person who performed each activity (Jelsma et al., 2019). In our context, the strict organization of the 2ha plots into farmers' group and cooperatives as well as crosschecks with Indonesian oil palm experts, staff members of the cooperatives and plots observation helped us to limit these uncertainties. Specific precautions were also taken with farmers owning several plots that mostly managed all their plots identically and thus avoid possible economy of scale.

Farmers may adapt supply in fertilizers and pesticides to prices and climate conditions like drought or outbreak of pests. The period considered did not include any extreme events or pest outbreak. Moreover, as we investigated practices in old plantations (end of first cycle), we could assume that plantations were in a rather stable state embodying long-term hysteresis effect. However, it is important to recall that as a perennial crop, oil palm performances may be affected by practices with some delay (Combres et al., 2013; Fairhurst and Härdter, 2003). A more complex panorama of practices all over the perennial cycle would be necessary to have a mechanistic assessment of all potential impacts of practices.

Finally, we did not investigate the reasons of divergence in practices nor the role of socio-economic context in the adoption of certain practices by the studied ex-plasma smallholders. That information would give some clue to better understand links between agricultural practices and economic performances.

5. Conclusion

The present study showed that ex-plasma smallholders implement a large range of agricultural practices within homogeneous contexts. The overall economic performances of oil palm plantations is globally very profitable. The gradient of management was not fully linked to economic performances. Integrating management costs proved that the practices linked to optimal management did not fit with optimal economic performance at the plot level. It was found more profitable for smallholders to reduce the level of inputs in order to increase plot profitability. This result opens up room to explore more in depth the present paradigm of yield optimisation for oil palm in the light of optimal ex-plasma smallholders' revenues. Further investigation is also needed to decipher the links between profitable practices and environmental impact, in order to fine tune recommendations to farmers.

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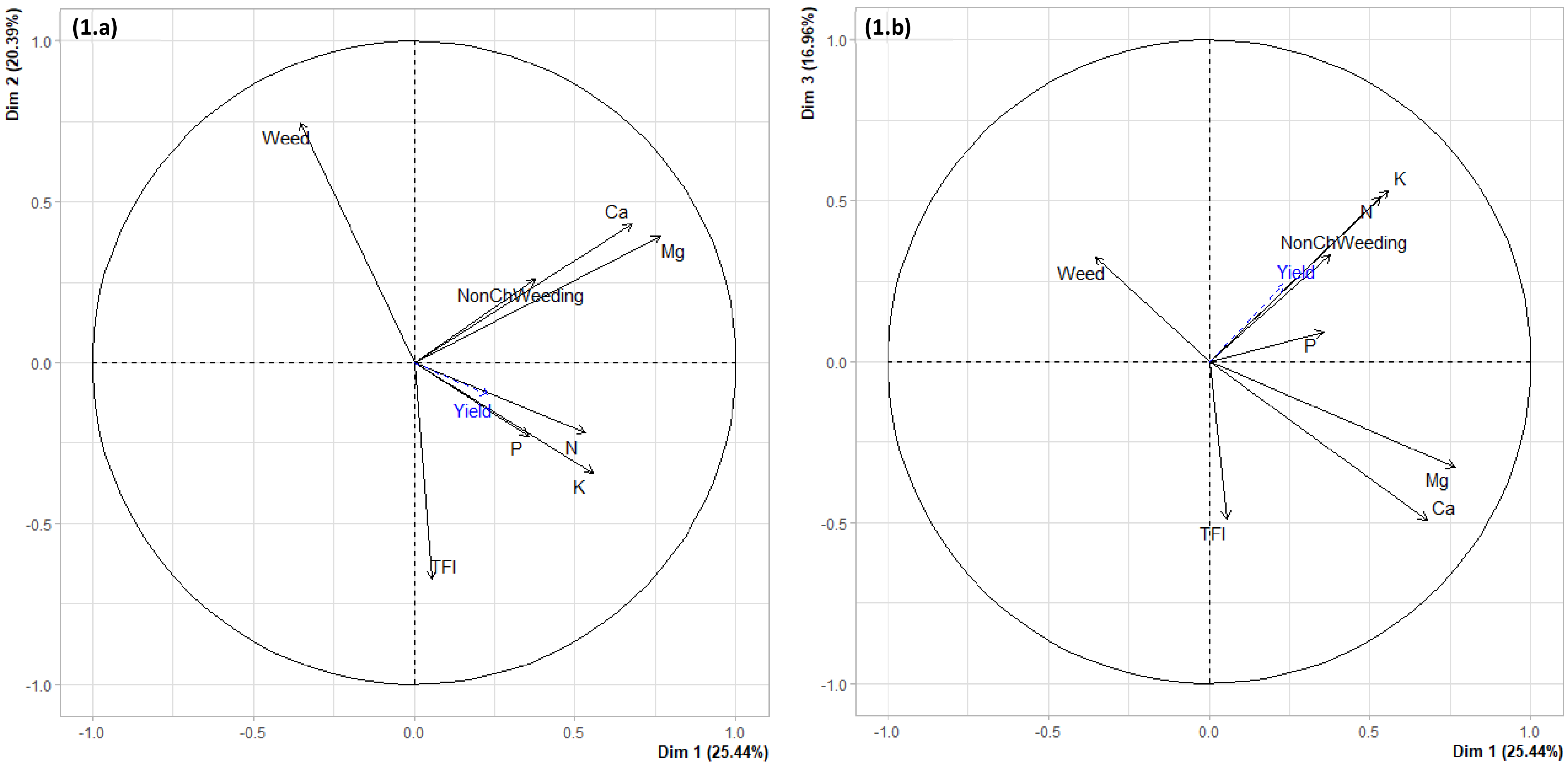

Figure 1: Principal Component Analysis performed on indicators relative to agricultural practices for the 73 studied plots. (1.a) is the graph of variables on dimensions 1 and 2. (1.b) is the graph of variables on dimensions 1 and 3. The variable Yield is not used for the construction of the PCA but is given as a supplementary variable.

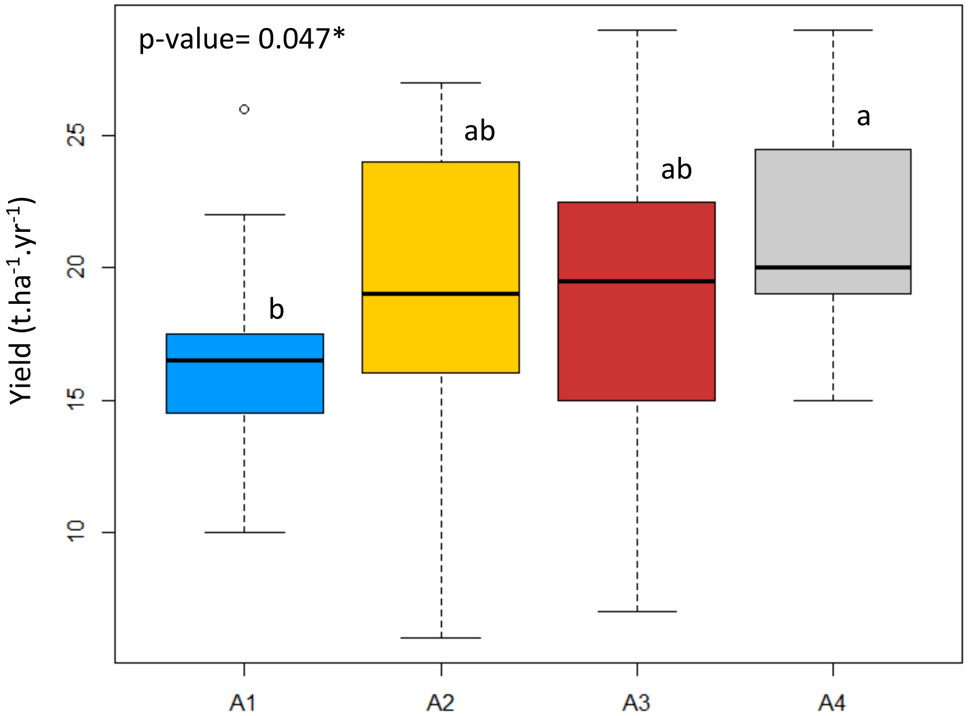

Figure 2: Yields per clusters of agricultural practices (A1; A2; A3; A4). The significance was obtained with Anova. Letters indicate significant differences between clusters based on a Tukey post-hoc test.

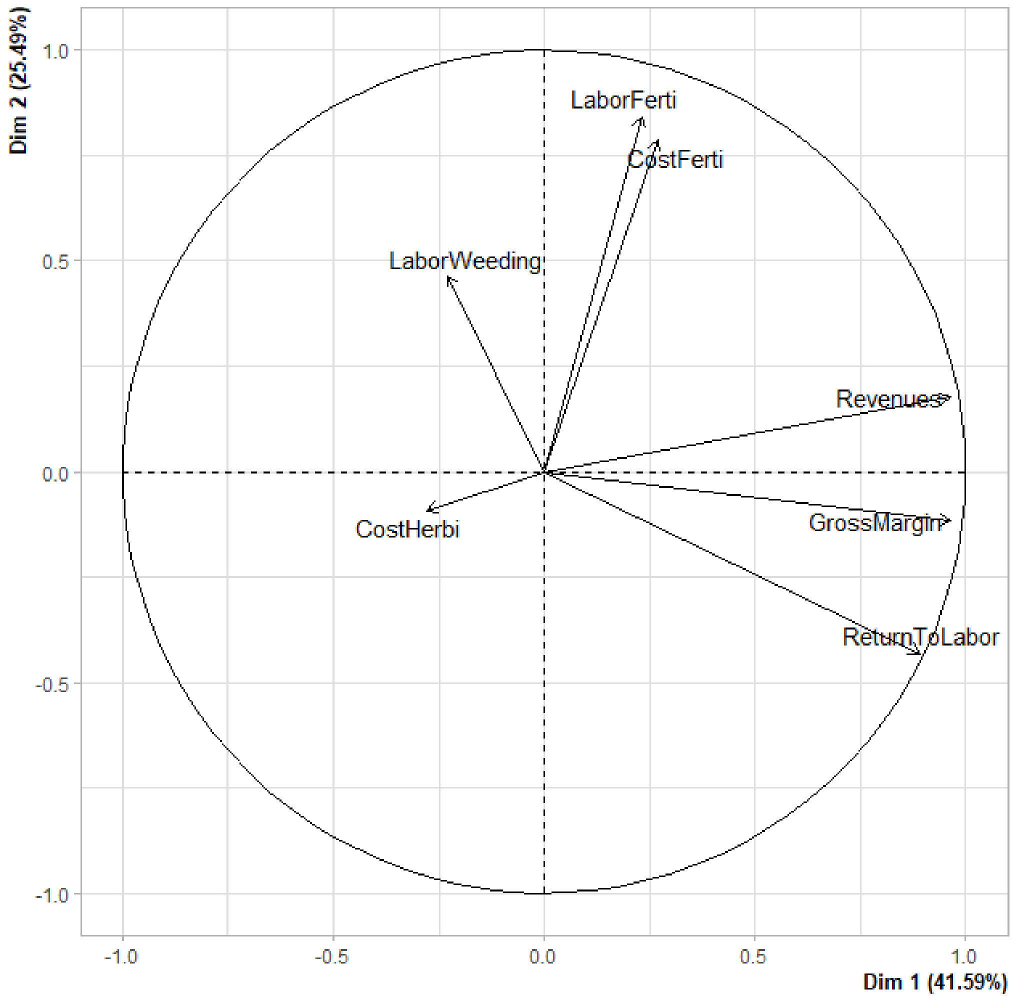

Figure 3: PCA performed for the 73 plots studied, on indicators relative to economic performances. The figure is for variables on dimensions 1 and 2.

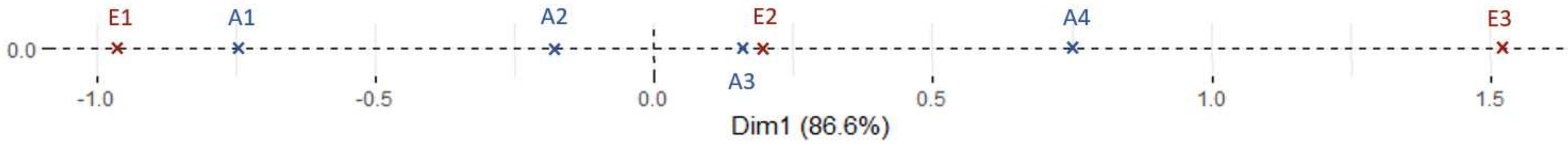

Figure 4: Results of the Correspondence Analysis between the clusters on agricultural practices and economic performances. Only projection on dimension 1 is presented for illustration as it explains a high percentage of inertia (86.6%). Biplot with dimensions 1 and 2 is available in **Supplementary Material 5**.

Table 1: Overview of the results obtained for agricultural practices for the 73 studied plots. The Weeds indicator combines Grass, Wood and Height indicators as presented in **Supplementary Material 4**.

Variable	N	P	K	Mg	Ca	TFI	NonChWeeding	Weed	Grass	Wood	Height
Unit	$kg\ ha^{-1}\ yr^{-1}$					score	Times yr^{-1}	score	score	individual	cm
Min	0	0	0	0	0	0.0	0.0	-2.1	1.0	0.0	0.0
Median	78	18	112	30	52	1.2	1.0	-0.3	3.3	2.3	30.0
Mean	84	21	117	35	55	1.6	0.8	0.0	3.2	4.1	45.2
Max	209	67	323	119	199	5.0	2.0	3.6	4.7	22.0	150.0
CV (%)	67%	92%	67%	86%	93%	87%	89%	-	29%	122%	96%

Table 2: Characterization of the clusters built for agricultural practices (A1; A2; A3; A4). The significances were obtained with Anova or Kruskal-Wallis([1]) tests and are indicated as following: *p-value<0.05 ; **p-value < 0.01 ; ***p-value < 0.001. Letters indicate significative differences between clusters based on post-hoc tests.

Variable	N	P[1]	K	Mg[1]	Ca[1]	TFI	NonChWeeding[1]	Weed[1]
Unit	kg ha^{-1} yr^{-1}					score	times yr^{-1}	score
A1 (n=16)	55**b** (±53)	16 (±18)	61**b** (±49)	16**bc** (±20)	27**b** (±28)	0.6**c** (±0.4)	0.8**a** (±0.7)	1.9**a** (±1.1)
A2 (n=18) mean	65**b** (±37)	15 (±11)	101**b** (±67)	14**c** (±14)	20**b** (±27)	2.7**a** (±1.5)	0.3**b** (±0.6)	-1.0**c** (±0.8)
A3 (n=24) mean	80**b** (±48)	26 (±23)	107**b** (±56)	66**a** (±25)	112**a** (±37)	1.6**ab** (±1.2)	0.9**a** (±0.6)	-0.3**b** (±0.8)
A4 (n=15) mean	142**a** (±48)	27 (±64)	211**a** (±64)	33**b** (±28)	34**b** (±31)	1.4**bc** (±1.3)	1.1**a** (±0.6)	-0.4**bc** (±0.7)
p-value	***	ns	***	***	***	***	**	***

Table 3: Overview of the results obtained on the indicators on economic performances for the 73 studied plots

Variable	Revenues	GrossMargin	ReturnToLabor	CostHerbi	CostFerti	LaborWeeding	LaborFerti
Unit	000 IDR yr^{-1} ha^{-1}	000 IDR yr^{-1} ha^{-1}	000 IDR day^{-1} ha^{-1}	000 IDR yr^{-1} ha^{-1}			
Min	6 305	1 094	34	0	0	0	0
Median	19 958	15 512	564	104	2 980	350	221
Mean	20 031	15 851	564	116	2 951	369	257
Max	30 890	26 914	1 096	370	6 987	1 025	1 202
CV (%)	27%	32%	35%	72%	55%	57%	79%

Table 4: Characterization of the clusters built on the indicators on economic performances (E1; E2; E3). The significances were obtained thanks to Anova or Kruskal-Wallis([1]) tests and are indicated as following: *p-value<0.05 ; **p-value < 0.01 ; ***p-value < 0.001. Letters indicate significative differences between clusters based on post-hoc tests.

Variable	**Revenues**	**GrossMargin**	**ReturnToLabor**	**CostHerbi[1]**	**CostFerti**	**LaborWeeding[1]**	**LaborFerti[1]**
Unit	000 IDR ha^{-1} yr^{-1}	000 IDR ha^{-1} yr^{-1}	000 IDR day^{-1}	000 IDR ha^{-1} yr^{-1}			
E1 (n=33) mean	15 463**b** (±3 596)	12 258**c** (±3 778)	459**b** (±155)	119 (±83)	2 087**b** (±1 319)	352**b** (±197)	148**c** (±197)
E2 (n=22) mean	24 530**a** (±3 195)	20 717**a** (±2 945)	776**a** (±128)	106 (±77)	2 728**b** (±1 331)	257**b** (±140)	245**b** (±140)
E3 (n=18) mean	22 906**a** (±3 544)	16 494**b** (±3 530)	496**b** (±111)	124 (±95)	4 806**a** (±822)	498**a** (±214)	389**a** (±214)
p-value	***	***	***	ns	***	***	***

Graphical abstract