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1 Investigating the links between management practices and economic
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3 province, Indonesia.

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15 1. Introduction

16 Vegetable oil consumption has continuously increased worldwide over the last decades (FAO, 2020).
17 Because of its high oil-to-land ratio, oil palm is a promising crop to meet the fast growing demand in
18 vegetable oil (Barthel et al., 2018). Palm oil and palm kernel oil account for more than one third of
19 the global vegetable oil production (FAO, 2020). Yet, oil palm production in Indonesia faces deep
20 environmental and social concerns due to conversion of tropical rainforest to oil palm monoculture
21 and conflict between local and migrant communities (Cramb and McCarthy, 2016). Recently
22 initiatives such as the RSPO (Roundtable on Sustainable Oil Palm) certification aim at promoting
23 optimal practices for the development of oil palm cultivation limiting its negative impacts (Lee et al.,
24 2020; Padfield et al., 2019). The largest producing country is Indonesia with 12 Mha planted, which
25 account for 56% of the total planted area in 2019 (Oil World, 2019). In Indonesia, oil palm is
26 produced by a large diversity of growers, namely: privately-owned, state-owned companies and
27 smallholders (Cramb and McCarthy, 2016). Smallholders' establishment in Indonesia followed several
28 pathways. Some smallholders settled on their own, and they are referred to as independent
29 smallholders, while others followed governmental programs: these are scheme smallholders or
30 plasma smallholders. Many smallholders also owned a combination of independent and plasma
31 plots; therefore grower types are not exclusive.

32 Several governmental programs were put in place in order to promote an oil palm development that
33 would include both industries and smallholders. Historically the oil palm sector in Indonesia was
34 dominated by state owned companies after the Indonesian Independence (1960's and 1970's). In the
35 late 1970s, the Indonesian Government notably initiated a specific type of farming contract named
36 "Nucleus Estate and Smallholders" (NES) or "Perkebunan Inti Rakyat" (PIR) (Zen et al., 2016). NES
37 schemes were sometimes adopted by the local population although they were initially linked to
38 transmigration programs, which displaced people from overpopulated Java to the outer islands of
39 Sumatra and Borneo (Fearnside, 1997). Plasma smallholders under NES program were organized
40 around a nucleus estate managed by a state-owned company (Zen et al., 2016). Private companies as
41 nucleus estates emerged quickly, and became the prominent model from the late 1980s to the
42 1990s. The nucleus estate supervised the land preparation and the planting of the 2 ha-plot per
43 smallholder family, the plot management during immature stage and the supply of inputs. The estate
44 was also in charge of coordinating harvesting rotation, road maintenance and providing technical
45 assistance to the smallholders (Zen et al., 2016). Usually, plasma smallholders repaid the cost of
46 plantation after 5 to 10 years, although they remained bound to the nucleus estate for plot
47 management and for harvesting Fresh Fruit Bunches (FFBs) until the end of the oil palm cycle (Barlow
48 et al., 2003). In the 1990s, a new version of the NES scheme emerged, called the KKPA (Kredit

49 Kooperasi Primer Anggota). In KKPA schemes, smallholders were organized in village cooperatives
50 (KUD - Kooperasi Unit Desa) of around 500 farmers each, and each cooperative was divided into
51 farmers' groups (Kelompok Tani) of about 20 members. By the end of the repayment period,
52 smallholders under KKPA system managed their plots by themselves, sometimes with some
53 assistance from the cooperatives services. Such farmers are referred to as "ex-plasma smallholders".
54 Those schemes were abandoned in the early 2000's under the *reformasi* era but were instrumental in
55 developing the smallholder sector with more than 900 000 ha planted under the NES scheme until
56 2003 (Zen et al., 2016). After this period, smallholders increasingly developed their own independent
57 plantation outside of agroindustrial partnership, either with scheme smallholders looking to extend
58 their area or with newcomer looking to join the growing oil palm sector (Feintrenie et al., 2010).

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

71 Various development contexts have led to a great diversity of growers and production systems.
72 Smallholders optimum management practices have usually been studied in broad groups that only
73 allow for comparison between plasma and independent (Jelsma et al., 2019; Lee et al., 2020;
74 Schoneveld et al., 2019; Woittiez et al., 2019). Thus, the linkages between the diversity of
75 management practices in smallholders' plots and the oil palm performance at local scale remain
76 poorly investigated, making it uneasy to propose adapted recommendations for both plantation
77 management and replantation programs. Proposals at regional scales were recently made, exploring
78 differences between various smallholder organization systems (Jelsma et al., 2019; Moulin et al.,
79 2017; Woittiez et al., 2018). Such descriptive analysis performed at a large scale may not be locally
80 explicit enough to feed local recommendations. In addition, it was found important to involve socio-
81 economic aspects when analyzing the determinism of smallholders' plots performances. Economic

82 constraints are indeed one of the main drivers of smallholders' choices in the management of
83 systems based on perennial cash crops (Baudoin et al., 2015; Feintrenie et al., 2010).

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

91 2. Material and Methods

92 2.1. Study area

93 The study was conducted in two neighboring villages located in the Petaling area (-1.73770°N,
94 103.83479°E), Sungai Gelam sub-district, Muaro Jambi regency, Jambi Province, in the Sumatra Island
95 in Indonesia. Within Petaling, two oil palm cooperatives were studied, namely KUD Marga Jaya (in
96 Petaling Jaya village) and KUD Makarti (in Sido Mukti village). The two cooperatives gather 461 ex-
97 plasma smallholders owning 610 oil palm ex-plasma plots for a total planted area rounding 1,300 ha.
98 KUD Marga Jaya was settled in 1984 and historically took responsibility for the development of the
99 plasma plots in the area. Due to the increasing number of oil palm smallholders and the development
100 of independent plots, KUD Makarti was then created in 2013 following a similar organization. The
101 two cooperatives manage the harvesting of FFB every ten days for each plot and sell the fruits to the
102 mill of the nucleus estate that is located at around 20 km from the study area. Besides, cooperatives
103 retail subsidized fertilizers and pesticides to their members.

104 All studied ex-plasma plots are homogeneous in terms of pedo-climatic conditions and historical
105 organization. First, the area is relatively small and plots are collated (25 km²), with flat to slightly hilly
106 topography and Acrisols soils. Second, all the studied plots were established by a nucleus estate in
107 1995 and 1996 using Tenera seedlings planted according to a triangular pattern (9 m x 9 m x 9 m).
108 The management (soil preparation, planting, management during immature phase) of plots was
109 uniform as all plots were managed by the nucleus estate. This situation lasts until repayment of loans
110 for plasma development. Since the beginning of the 2000s, smallholders have been managing their
111 plots by themselves (fertilization, weeding and pruning).

112 2.2. Sampling method and data collection

113 As the historical and pedoclimatical context was rather homogeneous, we randomly selected 79
114 smallholders out of 461 (17%) from the cooperatives' database in September 2019. For smallholders

115 owning several plots, only one plot was considered, in order to maximize the diversity of practices
116 sampled. Directed interviews about management strategies and practices within each targeted plot
117 were performed in November and December 2019 with an Indonesian expert on oil palm practices
118 and staff members from the cooperatives. The help of local experts and some data triangulation
119 based on cooperatives' records provided some safeguards regarding uncertainty embedded in
120 farmers' interviews due to the lack of a systematic tracking of practices.

121 2.2.1. Smallholders' interviews and field visits

122 Interviews focused on agricultural practices implemented over the year preceding interviews.
123 Through these interviews only, we collected quantitative information at the plot scale about the dose
124 and application frequency for each type of fertilizer and herbicide. If any changes between year 2018
125 and year 2019 were recorded, we collected data for both years (see **Supplementary Material 1**) and
126 worked on average practices for data analysis. We also collected information about the workforce
127 involved in each activity. Field visits mainly consisted in assessing weed control practices. We defined
128 four distinct zones in the central area of the plot, namely: the harvesting path, the weeded circle, the
129 windrow and the remaining zone (called "Other" zone, see **Supplementary Material 2** (Carron et al.,
130 2015)). We could not consider plot spatial heterogeneity for weed biomass measurements in the
131 plot. We undertook all weed biomass observations in the "Other" zone that was considered as a
132 proxy zone to describe the diversity of weed management between the plots. First, weeds height
133 was scored into four classes (referred as "Height" indicator). Second, the biomass of understory
134 vegetation was scored according to an adapted Braun-Blanquet scale (Wikum and Shanholtzer, 1978)
135 at three locations in the plot, inside a 25 cm x 25 cm square (average score is referred as "Grass"
136 indicator). Third, the number of woody weeds within each square was recorded (the average score is
137 referred to as "Wood" indicator).

138 2.2.2. Complementary data

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

144 The average selling price of FFB was estimated at 1,320 IDR kg⁻¹ based on Governmental data
145 communicated online (InfoSawit.com, retrieved 5 Feb. 2020) and values were crosschecked with
146 information from experts. The cooperatives provided values for the cost of fertilizers and pesticides
147 applied by the end of December 2019 and they provided data on irreducible costs (e.g. maintenance,
148 loading,...). Costs and time for labor per activity were estimated with the help of the cooperatives,
149 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).

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

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:

$$Revenues = [Yield] * ([FFB \text{ selling price}] - [Compulsory cooperative's costs]) \quad (\text{equation 2})$$

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

187 The gross margin (GrossMargin; IDR ha⁻¹ yr⁻¹) was calculated following **equation 3** :

188
$$\text{GrossMargin} = [\text{Revenues}] - [\text{Variable Costs}] \text{ (equation 3)}$$

189 Variable costs were defined by the costs for fertilizers (CostFerti; IDR ha⁻¹ yr⁻¹), herbicides (CostHerbi;
190 IDR ha⁻¹ yr⁻¹), labor for fertilization (LaborFerti; IDR ha⁻¹ yr⁻¹) and weeding (LaborWeed; IDR ha⁻¹ yr⁻¹).

191 Costs for pruning were integrated in variable costs to calculate gross margin. However, it was not
192 considered within economic indicator set because the service for pruning was a yearly flat fee, the
193 same for all smallholders (500 000 IDR ha⁻¹ yr⁻¹).

194 For labor, we considered both hired and family labor as costs, on the basis of a 7-hour- working day.

195 Return to labor (ReturnToLabor, IDR day⁻¹) was the amount earned per day worked in the plot and it
196 was obtained according to **equation 4** (Feintrenie et al., 2010):

197
$$\text{ReturnToLabor} = [\text{Gross Margin}] / [\text{Number days of labor}] \text{ (equation 4)}$$

198 Number days of labor included time spent for harvest.

199 2.4. Data analysis

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

215 Lastly, we crossed both clustering in a contingency table. Relations between both clustering were
216 analyzed through Correspondence Analysis using function CA() (FactoMineR Package, Husson et al.
217 2020). Chi-square value was used to explain dependency between agricultural practices and

218 economic clusters (Bendixen, 2003). Relationships were then characterized while looking at the
219 distance between practices and economic clusters on CA's asymmetric biplot (Greenacre, 2013).

220 3. Results

221 3.1. Analysis of agricultural practices

222 3.1.1. Fertilization and weeding performed by smallholders

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

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

241 3.1.2. Typology of agricultural practices

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

251 The AHC highlighted four clusters of smallholders' practices (**Table 2**). The first cluster, called A1,
252 consisted of 16 smallholders representing 22% of the total sample. This cluster was characterized by
253 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
254 was also the lowest, with an average TFI of 0.6, indicating that A1 smallholders poorly managed
255 weeds in their plot.

256 The second cluster, called A2, consisted of 18 smallholders representing 25% of the total sample.
257 Fertilization practices of this cluster were similar to the ones found in cluster A1. The A2 cluster was
258 mainly characterized by the use of chemical weeding with the highest average TFI (2.7). On the
259 contrary, NonChWeeding and Weed indicators were found to be low, with average values of
260 0.3 times yr⁻¹ and -1.0 times yr⁻¹ respectively.

261 The third cluster, called A3, consisted of 24 smallholders representing 33% of the total sample. It
262 differed from the other clusters by the high levels of Mg and Ca applied in the plots (resp. 66 kg Mg
263 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
264 found in clusters A1 and A2. Smallholders from cluster A3 did highly control weeds through chemical
265 and nonchemical weeding, resulting in low weed biomass in the plot.

266 The fourth and last cluster, called A4, consisted of 15 smallholders representing 20% of the total
267 sample. This cluster differed from the others by the high levels of N and K applied in the plots (resp.
268 142 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
269 A1 and A2. Weeding practices were similar to A3, mainly driven by nonchemical weeding (1.1 times
270 yr⁻¹) and a rather low TFI (1.4).

271 Oil palm yields are presented in **Figure 2**. Overall average yield was of 18 tFFB.ha⁻¹.yr⁻¹. A significant
272 difference was observed between clusters A1 (mean = 18 t ha⁻¹ yr⁻¹, CV = 24%) and A4 (mean = 20 t
273 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
274 responses to yields with respective CVs being equal to 32% and 27%.

275 3.2. Analysis of economic performances

276 3.2.1. The global economic performances

277 Results on economic indicators are presented in **Table 3**. On average, smallholders' revenues
278 reached 20M IDR yr⁻¹ ha⁻¹ (eq. 1 209 € yr⁻¹ ha⁻¹ in 2020¹). Fertilizers were the major source of
279 expenses mobilizing around 15% of the revenues from FFB sales (**Table 3**). Wages both for weeding
280 and fertilizer application represented the second main cost (3% of revenues). Expenditure in
281 herbicides accounted only for 0.5% of revenues. Mean gross margin was 16 M IDR yr⁻¹ (eq. 967 € yr⁻¹
282 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))

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

285 3.2.2. Typology on economic performances

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

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

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

297 The second cluster, called E2, consisted of 22 smallholders representing 30% of the total sample.
298 Revenue was the highest in this population, as reflected by high yields (23 t ha⁻¹ yr⁻¹ on average).
299 Costs for fertilizer inputs and costs for labor for weeding were similar to E1 but costs for labor for
300 fertilization were found to be 1.7 times higher. GrossMargin and ReturnToLabor were overall the
301 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
302 day⁻¹ ha⁻¹ (eq. 47 € yr⁻¹ ha⁻¹ in 2020), indicating the group with highest profitability at plot level.

303 The third and last cluster, called E3, consisted of 18 smallholders representing 25% of the total
304 sample. Revenues were similar to E2 with similar yields results (22 t ha⁻¹ yr⁻¹ on average). Costs for
305 fertilization input were 1.8 times higher than E2 cluster. Costs for labor for fertilization and weeding
306 were high. These costs had a high impact on gross margin and return to labor results: gross margin
307 was 20% lower than for E2 smallholders and return to labor was similar to E1 smallholders (around
308 16.5 M IDR yr⁻¹ ha⁻¹ ; eq. 997 € yr⁻¹ ha⁻¹ in 2020).

309 3.3. Relations between agricultural practices and economic performances

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

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

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

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

324 A4 cluster was associated with both clusters E2 (distance=0.55) and E3 (distance=0.75). 53% of A4
325 smallholders had economic performances that were limited by the costs for fertilization (E3). Then,
326 33% of smallholders had high profitability for the studied zone (E2).

327 4. Discussion

328 4.1. Oil palm ex-plasma plots are productive and profitable for smallholders

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

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

347 Ex-plasma thus seemed to be an efficient system in terms of productivity and revenues for farmers
348 (in terms of both margin and return to labor). However, trade-offs dealing with social and
349 environmental aspects were not integrated in the present study. For example, smallholders are

350 contractually bound to a specific mill to sell their production, and these bonds might increase
351 vulnerability, such as price volatility (Cahyadi and Waibel, 2016; Gatto et al., 2017). Contracts also
352 makes it impossible for smallholders to take benefit from market competition and to negotiate for
353 advantages such as the access to organic matter from EFB to be used for fertilization.

354 4.2. From initial homogeneity to current diversity

355 Despite the homogeneity of the studied zone in terms of both pedoclimatic conditions and
356 management of immature stage, our study highlighted a large diversity of agricultural practices
357 implemented by smallholders. Based on fertilization and weeding practices, we were able to identify
358 four groups of smallholders. A clear gradient in management intensity was observed. A1 smallholders
359 were found to have lower management of their plots compared to other, especially concerning
360 weeds management leading to a relatively high weed biomass in the plots. A2 and A3 were
361 intermediary groups, with trends for an increase of fertilization and weed maintenance. On the
362 opposite extreme of the gradient, the A4 smallholders were mostly different to other groups in terms
363 of N and K fertilization. They represented around 20% of the smallholders of the area. Management
364 practices in group A4 are the closest to conventional practices applied in agroindustry (Darras et al.,
365 2019; Pardon et al., 2016) and recommended by best management practices (Rhebergen et al., 2020;
366 Woittiez et al., 2017) to optimize oil palm yield.

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

371 4.3. Linking practices to economic performances, where is the optimum?

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

382 It is worth to note that we could not cover practices and economic performances temporal dynamics
383 and history. We based our analysis on actual plots performances. Crossing economic optimum with

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

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

399 Within the midrange, E2 group was at the economic optimum, with high revenues and relatively low
400 costs for fertilization. A2 and A3 management practices were the closest to E2. In a context of
401 relatively low palm oil prices, A2 and A3 farmers were at the same revenue range and the same main
402 costs (N, P, K fertilization); these are optimal to provide a sufficient yield together with manageable
403 costs. Practices of N, P and K fertilization for A2 and A3 corresponds to doses of fertilizer that were
404 considered lower than best management practices (Jelsma et al., 2019; Woittiez et al., 2019). In best
405 management practices guidelines, fertilizer recommendations are often derived from mineral
406 balance models, in which the amount of nutrient to be supplied is theoretically estimated. However
407 experimental optimisation of marginal economic gains through leaf sampling and yield analysis
408 frequently leads to lower recommendations in terms of nutrient supply (Dubos et al., 2019). Based
409 on our results, it is difficult to provide recommendation in terms of both weeding practices and Ca –
410 Mg fertilisation. Indeed, their costs are relatively low compared to the other fertilization costs and no
411 literature data could highlight any linkage between these practices with productivity in a similar soil
412 context. However, indirect antagonisms between Ca-Mg fertilization and K nutrients have recently
413 been observed, and excessive fertilization may limit K availability for oil palms (Dubos et al., 2017,
414 2011). Furthermore, we analysed the mineral content of the fertilizers used by farmers in October
415 2020. Result especially evidenced a lower content in Ca and Mg than indicated on packages for some
416 fertilizers. This makes conclusions on the linkages between Ca - Mg applications and productivity
417 even more hazardous. High chemical weeding in A2 group and high Ca-Mg fertilization in A3 group
418 may also be detrimental to the environment.

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

425 4.4. Toward generic recommendations

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

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

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

453 4.5. Limitations of the study

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

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

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

477 5. Conclusion

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

486 decipher the links between profitable practices and environmental impact, in order to fine tune
487 recommendations to farmers.

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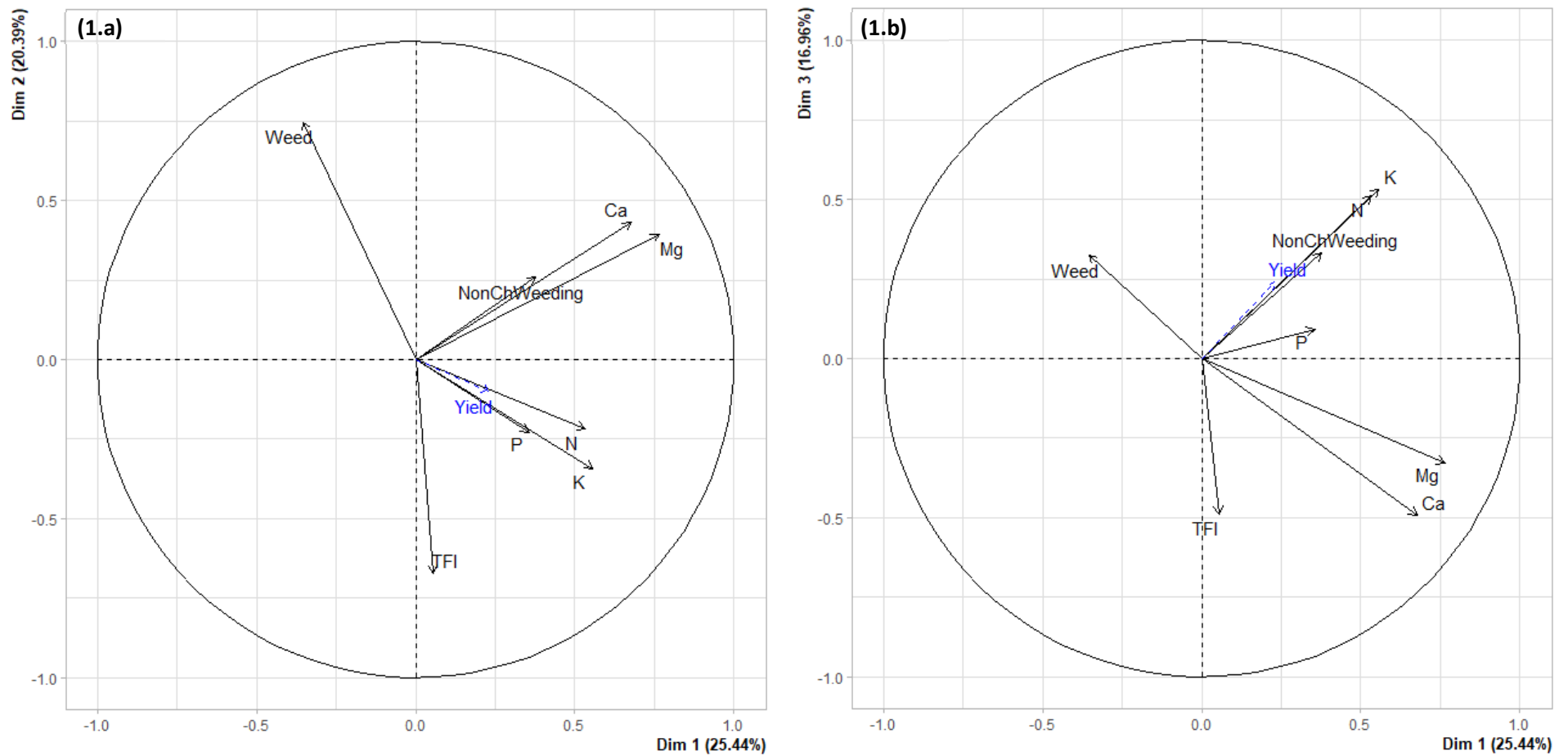


Figure 1: Principal Component Analysis performed on indicators relative to agricultural practices for the 73 studied plots. (1.a) is the graph of variables on dimensions 1 and 2. (1.b) is the graph of variables on dimensions 1 and 3. The variable Yield is not used for the construction of the PCA but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

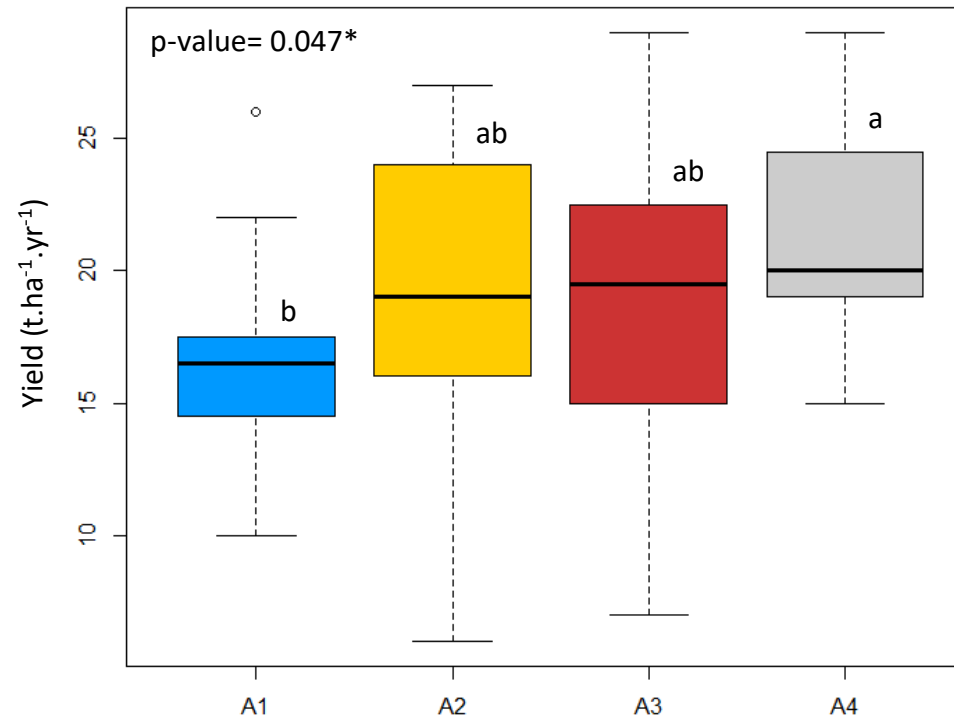


Figure 2: Yields per clusters of agricultural practices (A1; A2; A3; A4). The significance was obtained with Anova. Letters indicate significant differences between clusters based on a Tukey post-hoc test.

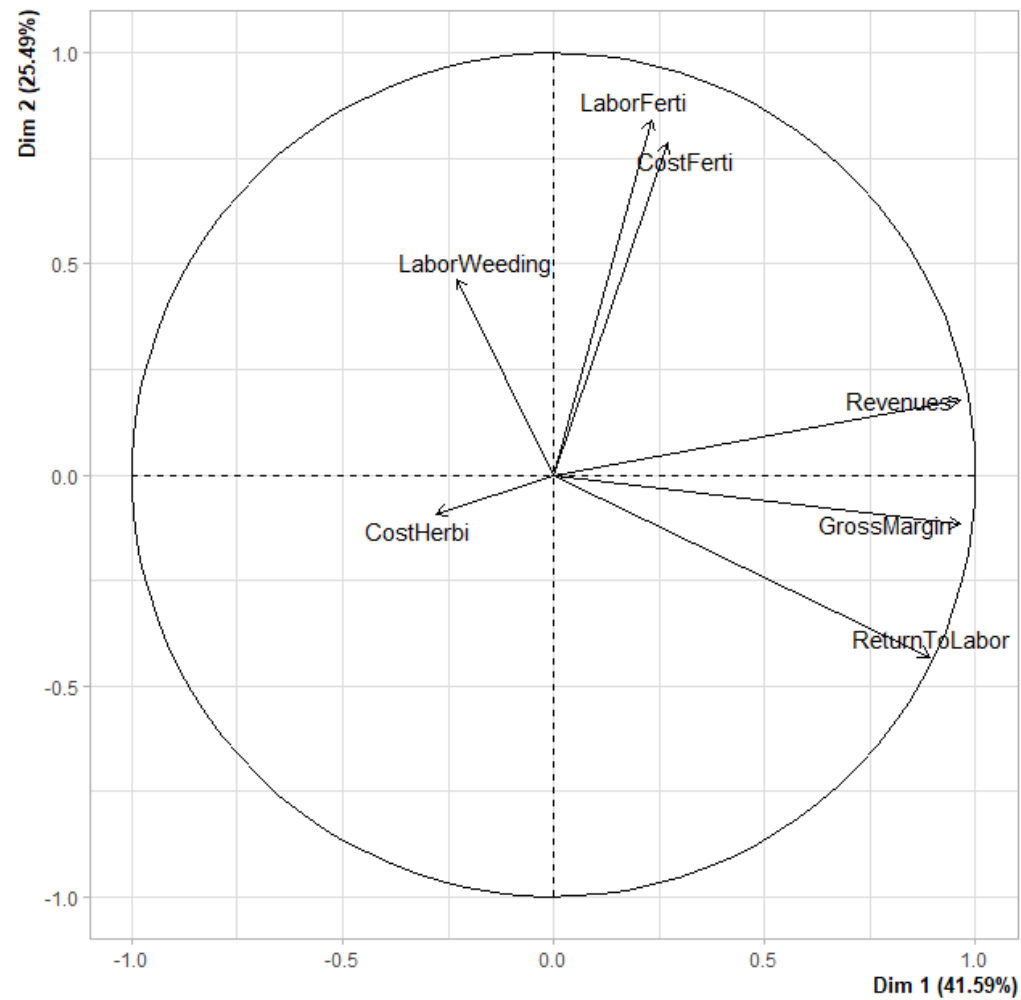


Figure 3: PCA performed for the 73 plots studied, on indicators relative to economic performances. The figure is for variables on dimensions 1 and 2.

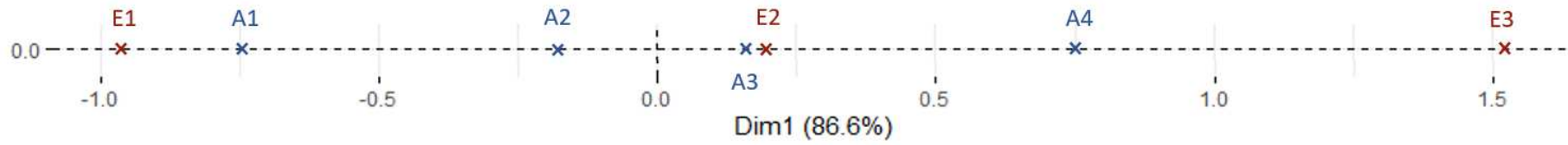


Figure 4: Results of the Correspondence Analysis between the clusters on agricultural practices and economic performances. Only projection on dimension 1 is presented for illustration as it explains a high percentage of inertia (86.6%). Biplot with dimensions 1 and 2 is available in **Supplementary Material 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	CostHerbi¹	CostFerti	LaborWeeding¹	LaborFerti¹
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

