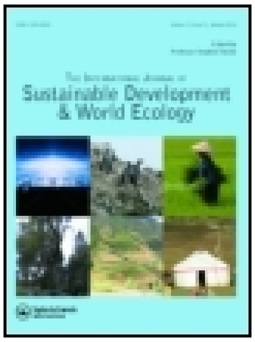

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Deciphering agricultural practices and environmental impacts in palm oil plantations in Riau and Jambi provinces, Indonesia

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ABSTRACT

Oil palm cultivation has drastically increased in the last decades and has become a key crop to meet the global vegetable oil demand, while raising environmental issues linked to deforestation, fertiliser or pesticide uses. Guidelines on best practices have been developed to limit these environmental impacts. However, there is little evidence on the field reality of concrete declination of these general guidelines and on the room for improvement of practices in light of the local diversity of oil palm systems. This study aimed to investigate in the field the actual practices in two contrasted areas in Indonesia, the first global palm oil producer. We carried out field surveys in Riau and Jambi provinces and collected data on annual applications of two synthetic mineral fertilisers, two herbicides and yields. We characterised the cropping systems of 88 smallholders' and 45 industrial plantation units including potential practice drivers. Both qualitative and quantitative analyses showed contrasted practices across growers. Fertiliser rates were variable across all grower types, while pesticide rates especially distinguished between industrial and smallholders' practices. Practices and performances were particularly variable amongst smallholders, and significantly different in Jambi compared to Riau. This study highlighted the great diversity of practices and potential environmental impacts. It stresses the need for a more systematic accounting of the local specificities of the cropping systems and their rationales in order to promote more adapted and efficient best practices recommendations.

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Oil palm; smallholders; industrial plantation; fertilisers; pesticides; environmental impact

1. Introduction

Reducing palm oil production environmental impacts is a main international issue (Tan et al. 2009). Recent expansion of palm oil production has been widely denounced for its impacts on deforestation resulting in soil degradation (Wösten et al. 1997; Wösten et al. 2008; Fitzherbert et al. 2008), biodiversity loss (Silalertruksa & Gheewala 2012), carbon release (Germer & Sauerborn 2008; Wicke et al. 2008; Harsono et al. 2012) and use of pesticides (Lord & Clay 2006; Sheil 2009). Such impacts can be limited by avoiding plantations in fragile areas (Mukherjee & Sovacool 2014), e.g. avoiding deforestation or plantation on area with high conservation values (RSPO Executive board 2013) or high carbon stocks such as peatlands. However, due to the large increasing demand for palm oil, which now accounts for 35% of the global vegetable oil production (FAO inRival & Levang 2013), reducing oil palm global environmental impact cannot only rely on restricting oil palm cultivation area. In 2012, the FAO recorded more than 17 million ha of oil palm plantations producing 50 million metric tons of palm oil. It is anticipated that production of palm oil will have to double before 2050 (Corley 2009), and the oil palm cultivation area largely increase (Tan et al. 2009). Expectations and concerns about palm oil are emblematic of the complex local/global nexus underpinning sustainable development, which may require optimisations at both local and global levels as well as compromises between both levels. Compromises between land sparing and land sharing in global strategies, for instance, need to rely on sound information on local practices and potential optimisation tracks. In this study, we focus on the local diversity of oil palm practices and their room for improvement, so as to feed the seek for sustainability with sound-based information to enhance environment-friendly agricultural practices in current and future plantations (Wicke et al. 2008; Wösten et al. 2008; Tan et al. 2009).

Indonesian oil palm area accounts 7.4 million ha and provides almost half of the global production (FAO 2016). It is managed through industrial state- or company-owned estates (58%) and smallholder-owned plantations (42%) (BPS 2013). Oil palm smallholders are defined as growers, who manage plantations smaller than 50 ha, sometimes along with subsistence production of other crops, where the family provides the majority of labour and the farm

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Supplemental data for this article can be accessed here.

provides the principle source of income (RSPO 2009). Two main kinds of smallholding systems can be distinguished: 'scheme smallholders' and 'independent smallholders'. According to the Roundtable on Sustainable Palm Oil (RSPO) Guidance on scheme smallholders: (i) independent smallholders are characterised as being free to choose how to manage their lands, self-organised, self-managed and self-financed, and as not being contractually bound to any particular mill or any particular association. They may, however, receive support or extension services from government agencies. On the contrary, (ii) scheme smallholders are characterised as being structurally bounded by contract, by a credit agreement or by planning to a particular mill or company. Depending on the scheme system, scheme smallholders can follow either their own field practices or be more or less directly managed by the large plantations or mills, to which they are bounded. Most of the scheme smallholders acquired their oil palm plantations through transmigration programme with a common allocation of a 2-ha palm plantation block per household. Transmigration refers to a programme of agricultural colonisation ended in the 2000s that aimed to enhance socio-economic development in remote islands and to balance demography between crowded Java island and remote outside islands such as Sumatra. Transmigrants were usually poor and beginners in oil palm cultivation as most of them used to be paddy rice farmers (Levang 1997). The level of involvement of the company in the oil palm plantation management may vary between companies, but the company usually manages the oil palms at least during the immature phase and sometimes during the whole crop cycle. Scheme smallholders have also a facilitated access to inputs, mill and agricultural extension services. On the other hand, independent smallholders are growers, who acquire agricultural lands and manage their oil palms plantations independently from oil palm companies or state incentive. These smallholders usually have poor access to agricultural inputs, extension services or mills (Feintrenie et al. 2010; Lee et al. 2014a).

The RSPO, created in 2004, provides a voluntary certification scheme for sustainable palm oil production. Other national regulations have also been developed more recently in Indonesia and Malaysia, aiming to provide similar schemes but compulsory. The way towards RSPO certification notably consists in complying with various principles and criteria that cover the three dimensions of sustainability. Despite this ambitious attempt to provide exhaustive guidelines, RSPO essentially provides a shared framework for committed stakeholders but not a detailed methodology to actually assess practices and ensure improvements in the palm oil production systems. It must hence be associated to complementary diagnosis steps in the light of the broad diversity of oil palm cropping systems and the local constraints faced by the producers including companies, scheme smallholders and independent smallholders.

Within oil palm plantations, main environmental impacts are related to fertilisers and pesticides management (Caliman et al. 2005; Fitzherbert et al. 2008). The high uptake by the plant and the poor quality of some tropical soils requires application of substantial amount of fertilisers in order to produce palm oil (Fairhurst & Härdter 2003). N and P nutrients are provided by mineral and organic fertilisers along the whole cycle, although rates commonly vary between immature and mature phases (Corley & Tinker 2008). Life cycle assessment (LCA) of the oil palm plantation system showed that N-fertiliser use and pesticide manufacturing are responsible for 48.7% and 32% of greenhouse gas emissions, respectively (Choo et al. 2011b). N and P nutrients from mineral fertilisers as well as herbicides are likely to leach and runoff into water streams (Comte et al. 2012), and N volatilisation may impact air quality (Corley & Tinker 2008). Finally, the use of herbicides can also increase erosion risk (Caliman et al. 2005) and biodiversity loss (Caliman et al., 2007) due to the decrease of soil cover.

Evaluations of the environmental impacts of oil palm agricultural practices are mostly LCA-based studies (Mukherjee & Sovacool 2014). Most of them do not account for the spatio-temporal variability of agricultural practices within the oil palm cycle (Bessou et al. 2013). A few discriminate agricultural practices between two oil palm stages: the immature phase practices (3-yr period) and the mature phase practices (around 22-yr period) (Schmidt 2010; Choo et al. 2011b; Silalertruksa & Gheewala 2012). However, the coarse texture of theses analyses (national averages, global regression models for field emissions etc.) does not allow for a proper assessment of the local drivers and levers to improve practices. In particular, there is a need to account better for soil variability as it plays a major role in fertilisation management (Fairhurst et al. 2005). Further assessments focusing on impacts on soil (Comte et al. 2013), water (Comte et al. 2012) or air (Hewitt et al. 2009) were carried out on industrial and experimental plots but not across the diversity range of existing systems. The description of the diversity of oil palm agricultural practices is still scarce (Lee et al. 2014b, 2014c), especially regarding smallholder production systems while Indonesian smallholders have the highest expansion rate of palm plantations (Lee et al. 2014a).

The objective of the study is to explore the diversity of oil palm agricultural practices and the potential drivers of this diversity in both smallholders' and industrial plantations in Indonesia. We focused on practices that potentially lead to most of the environmental impact and analysed their underpinning rationales in order to identify improvement levers. We proposed a multivariate analysis of oil palm agricultural practices and growers' types and crossed these results with potential drivers of agricultural practices.

2. Materials and methods

2.1. Study area and data collection

2.1.1. Study area

Our study was conducted in three different districts of Indonesia: Siak and Kampar districts (Riau province, 0.532898°N, 101.441962°E) and Bungo district (Jambi province, −1.590313°N, 103.609295°E) all located on Sumatra island, Indonesia. Rubber and oil palm are the two main cash crops cultivated in these districts. Siak and Kampar districts' area, respectively, account for about 28% and 32% of oil palm, and 2% and 9% of rubber; whereas Bungo district can be considered as dominated by rubber cultivation with 5.98% of its area planted with oil palm and 20.95% with rubber (BPS 2013). Oil palm cultivation in Riau has been developed for more than two decades through industrial plantations and scheme smallholders' plantations supported by the Indonesian state. Oil palm cultivation in Jambi has been developed through independent smallholders. The oil palm sector is hence much more developed in Riau than in Jambi. Riau is also characterised by a higher representation of scheme smallholders among smallholders compared to Jambi, where the industrial oil palm plantations are scarce. In this article, we further referred to 'Riau' and 'Jambi' in order to distinguish these two contrasted study sites in terms of palm oil history and infrastructure development.

2.1.2. Sampling of surveyed units

The reference unit of our analysis is the agricultural management unit: the complex (a hundred of hectares) in industrial plantations and the plot (between 1.5 and 10 ha) in smallholders' plantations. To clarify the terminology, we will refer to the management unit (e.g. complex and plot) as 'plantation' in the following parts of this article.

We assumed that agricultural practices would vary depending on the grower type and the study area. We first assumed a decreasing gradient in input access and management knowledge as following: industrial holders > scheme smallholders > independent smallholders. Industrial holders have access to a larger choice of techniques and materials for fertiliser management and weeding compared to smallholders, especially due to their easier access to mechanisation and various organic residues from their own mills. Moreover, industrial companies are generally better informed about the agronomic efficiency and impacts of their agricultural practices than scheme smallholders and even more than independent smallholders (Jacquemard 2013). Scheme smallholders acquire established plots that have benefited from the company management during the immature phase and they potentially get further technical support and access to inputs during the mature phase. On the contrary, independent smallholders manage their plots over the whole crop cycle by themselves and may have very heterogeneous background and access to inputs and technical support.

This heterogeneity may be exacerbated in regions where oil palm has not been much developed. A grower surrounded by industrial plantations already established for decades may access more easily knowledge even in an independent situation (Webb et al. 2011; Jacquemard 2013). The infrastructures in place should also improve the input supply compared to a location where oil palm is less developed. Riau is characterised by a high density of industrial oil palm plantations compared to Jambi. Therefore, we assumed that independent smallholders from Riau or Jambi should not have the same level of access to knowledge and inputs inducing variations in agricultural practices.

We surveyed 45 industrial oil palm plantation blocks in estates belonging to the same oil palm company in Riau, PT-SMART Tbk, and 88 smallholders' oil palm plantations (19 scheme, 69 independent). All the surveyed industrial plantations and the scheme smallholders, as well as 10 of the independent smallholders, were located in Riau (Siak and Kampar districts). To further explore the diversity of independent smallholders' practices, we surveyed 59 independent smallholder plantations (106 ha) in Jambi. The total area covered by the study was 16,000 ha of industrial plantations and 206 ha of smallholders' plantations.

2.1.3. Data collection on practices and their potential drivers

In this study, we focused on N and P supplies from synthetic mineral fertilisers, and on glyphosate and paraquat applications, which were the main practices shared by all types of growers (Molenaar et al. 2013). Paraquat and glyphosate are the most commonly used herbicides in Asian oil palm plantations, in particular glyphosate that can account for up to 88% of all applied active substances (Schmidt 2007). Regarding both agronomic performances and environmental risks, these field applications can be considered as key agricultural practices.

Industrial practices and fresh fruit bunch (FFB) yields were extracted from records of the 2012 inflows and outflows records of the company. All the industrial plantations surveyed were located in Riau study site. Biophysical and agronomical characteristics (stage of the plantation, topography and soil type) of the surveyed plantations were also collected from spatial databases of the company.

As no database was available on smallholders' oil palm practices, we interviewed directly 88 smallholders in both Riau and Jambi study sites in order to gather information on their oil palm plantation characteristics and practices. In 2013, we recorded smallholders' practices and FFB yields for the year 2012, as well as biophysical and agronomical characteristics of the plantations through semi-directive interviews (Table 1).

We identified potential drivers of the various key agricultural practices observed based on literature and local expertise. Besides the potential influence of the type of growers and the circumstantial location of the plantations, which were accounted for in the sampling selection (see section 2.1.2.), we also investigated key biophysical drivers.

The type of soil is a key physical driver in oil palm production suitability (Mutert 1999). Two main types of soil were found in the surveyed area, mineral and peat soils. As more detailed information on soil types (e.g. soil structure, detailed texture etc.) was not available for both industrial and smallholders plantations, we took into account the types of soil according to the two modalities mineral and peat. Peat soils represented 27% of the surveyed industrial plantation area and 16% of the surveyed smallholders' plantation area. We also took into account the topography of the plantation according to two modalities, i.e. flat or hilly plantations, which were consistently described for both smallholders and industrials' data sets. In industrial and smallholder plantations, 85% and 45% of the plantations were flat, respectively. The third potential driver linked to the biophysical context was assumed to be the stage of the oil palms (mature or immature phases) as fertiliser and herbicide levels usually vary between immature and mature phase (Schmidt 2007; Corley & Tinker 2008). The industrial data set only contained two immature plantations; therefore, this driver was actually only assessed across smallholders' plantations in this study.

2.2. Statistical analysis

To assess the diversity of oil palm agricultural practices, we performed statistical exploratory analyses that aimed to detect patterns in the data set structure and hence investigate links between patterns in the agricultural practices and their drivers. Patterns of agricultural practices where assessed with a Multiple Correspondence Analysis (MCA) were followed by Hierarchical Clustering Analysis (HCA) on the most informative axes. A graphical analysis based on cumulative bar charts was used to define the patterns more quantitatively. For MCA, the annual rates of applied mineral N (kg ha^{-1} yr^{-1}), mineral P_2O_5 (kg ha^{-1} yr^{-1}), glyphosate (g ai[1] ha^{-1} yr^{-1}) and paraquat (g ai ha^{-1} yr^{-1}) were split into five classes with equal number of plantations to avoid unwanted effects with Chi-square distance due to underrepresented classes. The two other practices concerning the application or not of organic fertilisers, i.e. EFB or POME, originally have binary responses: yes or no. The potential drivers (Section 2.2.3) were included in the MCA as supplementary variables, as well as the yields that were also converted into five classes with equal numbers, to identify which of these variables were linked to the patterns of practices. Patterns were identified by a Hierarchical Ascendant Clustering with Ward criterion based on the coordinates of the observations on the three first axes of the MCA (77.45% of cumulated inertia before a drop in the inertia gain with the fourth axis onwards).

The significance of the link between a potential driver and a pattern of practices was tested with a standard *z*-test between two proportions. Computations were carried out with XLStat 2016. For graphical quantitative analysis, continuous input variables were cut into five classes of equal range in order to compare between different categories the proportion of plantations applying known level of input.

2.3. Extrapolation to potential environmental impacts

Environmental impact assessments notably rely on the quantification of fluxes relating practices and emissions to the environment. These fluxes can be determined according to various principles and methods, which may vary depending on the studied substances. A mechanistic approach necessitates a complete understanding and modelling of substance cycling (Pardon et al. 2016a). However, knowledge is still lacking and most emission models used in environmental impact assessments consist of empirical

Table 1. Main characteristics of surveyed plantations.

	Number of plantations	Average yield (tFFB ha^{-1})	SD (%)	Average total N (kg ha^{-1} yr^{-1})	SD (%)	Average total P_2O_5 (kg ha^{-1} yr^{-1})	SD (%)	Average total Glyphosate (ai g ha^{-1} yr^{-1})	SD (%)	Average total Paraquat (ai g ha^{-1} yr^{-1})	SD (%)
Indep-Jambi	59	11.44	±51	30.31	±150	21.23	±154	537.28	±170	839.18	±137
Indep-Riau	10	24.92	±36	93.87	±84	92.70	±83	529.61	±192	1011.43	±94
Industrial-Riau	45	25.87	±13	112.87	±42	62.63	±44	221.56	±12	93.01	±20
Scheme-Riau	19	25.39	±16	106.34	±53	190.04	±40	521.05	±171	963.46	±90

operational models that allow for estimating potential rather than actual emissions and impacts.

Most published studies on the environmental impacts of palm oil and its derivatives are based on LCAs (Schmidt 2010; Choo et al. 2011; Milà I Canals et al. 2012; Guilbot et al. 2013). There exist a few emission models commonly used for the inventory phase within LCAs of agricultural products (Audsley et al. 1997; Brentrup et al. 2000; Nemecek et al. 2012). IPCC guidelines (2006) are the most widely applied for the estimation of nitrogen- and carbon-compound losses, as well as SALCA models for the estimation of both nitrogen- and phosphorus-compound losses and heavy metal emissions (Richner et al. 2006; Nemecek et al. 2012; Oberholzer et al. 2012). All these models calculate losses to the environment based on total inputs applied. In most cases, internal fluxes within the soil–plant system are not explicitly accounted for, neither is the plant uptake. Finally, pesticides are commonly assumed to be completed emitted to the soil given their long residence time in the medium (Nemecek & Kägi 2007). The calculation of environmental impacts, or impact characterisation in LCA methodology, then relied on linear models that relate fluxes towards various environmental compartments (i.e. N-compound emissions to the air) to various impact categories (i.e. climate change or acidification). We hence considered that a comparison of the practice patterns based on the total inputs was consistent with the existing environmental impact assessment within the LCA framework, and indicative in terms of potential environmental impact discrepancies. This extrapolation only allowed us for a relative assessment of risks. Actual impact calculation would require a more mechanistic approach that should be much more sensitive to local conditions and detailed practices but which is not yet available for palm oil.

3. Results

3.1. Agricultural practice patterns

The MCA confirmed contrasted practices between industrial plantations, scheme and independent smallholders' plantations (Figure 1, details on the variables and classes in Table S1). Three patterns of practices were delineated (HCA dendogram in Figure S1). The first pattern is specific to industrial plantations (cluster 1). The second pattern is specific to independent smallholders' plantations mostly in Jambi (cluster 2) and the third pattern encompasses independent smallholders' plantations from both Riau and Jambi, and all scheme smallholders' plantations except one (cluster 3). The proportion of smallholders from Riau was significantly higher in the cluster 3 compared to cluster 2 (p value < 0.0001).

Industrial plantations were characterised by moderate rates of input (classes 3–4) and application of organic fertilisers compared to the two other clusters. Smallholders from Jambi in cluster 2 tended to apply less fertilisers than all the other growers, whereas smallholders from cluster 3 were the one applying the higher rates of fertilisers, notably driven by scheme smallholders (along the second projection axis). The scheme smallholders within cluster 3 were those applying the higher doses of both fertilisers (classes 4–5). The only one scheme smallholder found in cluster 2 applied only low rates of all inputs (class 1). The relative intensity in pesticide usages was less discriminant across the clusters apart from the fact that the highest doses of both paraquat and glyphosate (class 5) were not found in industrial plantations.

There was an odd distribution of immature plantations within the sample and across the clusters, as immature plantations were only recorded in Jambi and represented there about half of the surveyed plantations. The lower input rates and yields (classes 1–2) associated with the cluster 2 may be partly explained by this driver. Indeed, fertiliser needs are slightly lower when palm trees are young (Corley & Tinker 2008), especially for phosphate and potassium, and smallholders may have limited resource to access to inputs during the first years as long as the production has not started yet. However, low nitrogen supply during the first years could be detrimental, especially in smallholders' plantations where the sowing of a legume cover is not as systematic as in industrial plantations. Low yields were particularly associated with Jambi-independent smallholders in cluster 2 by opposition to industrial plantations (first axis) and to the other smallholders' plantations (second axis). The three smallholders' plantations in Riau found in cluster 2 received either very low inputs or had low yields. Finally, the proportion of hilly plantations was higher in Jambi (19%) than in the rest of the sample (8%), which may be explained by the relief difference between the two surveyed zones. This driver, which was associated with cluster 2 (on axis 1), could also partly explain the variations in practices and performances due to potential higher erosion and run-off risks than in flat plantations.

Although not significant ($p = 0.051$), there was a much higher proportion of plantations on peat soil across scheme smallholders' plantations (32%) compared to the other plantations (10%). This driver notably discriminated those growers from the others on the third projection axis. The odd distribution of peat soils was likely an artefact from the sampling area. Palm plantations on peat soil are complex to manage; in particular, the physical anchorage and drainage as well as the nutrition may be difficult (Corley & Tinker 2008). The complex management

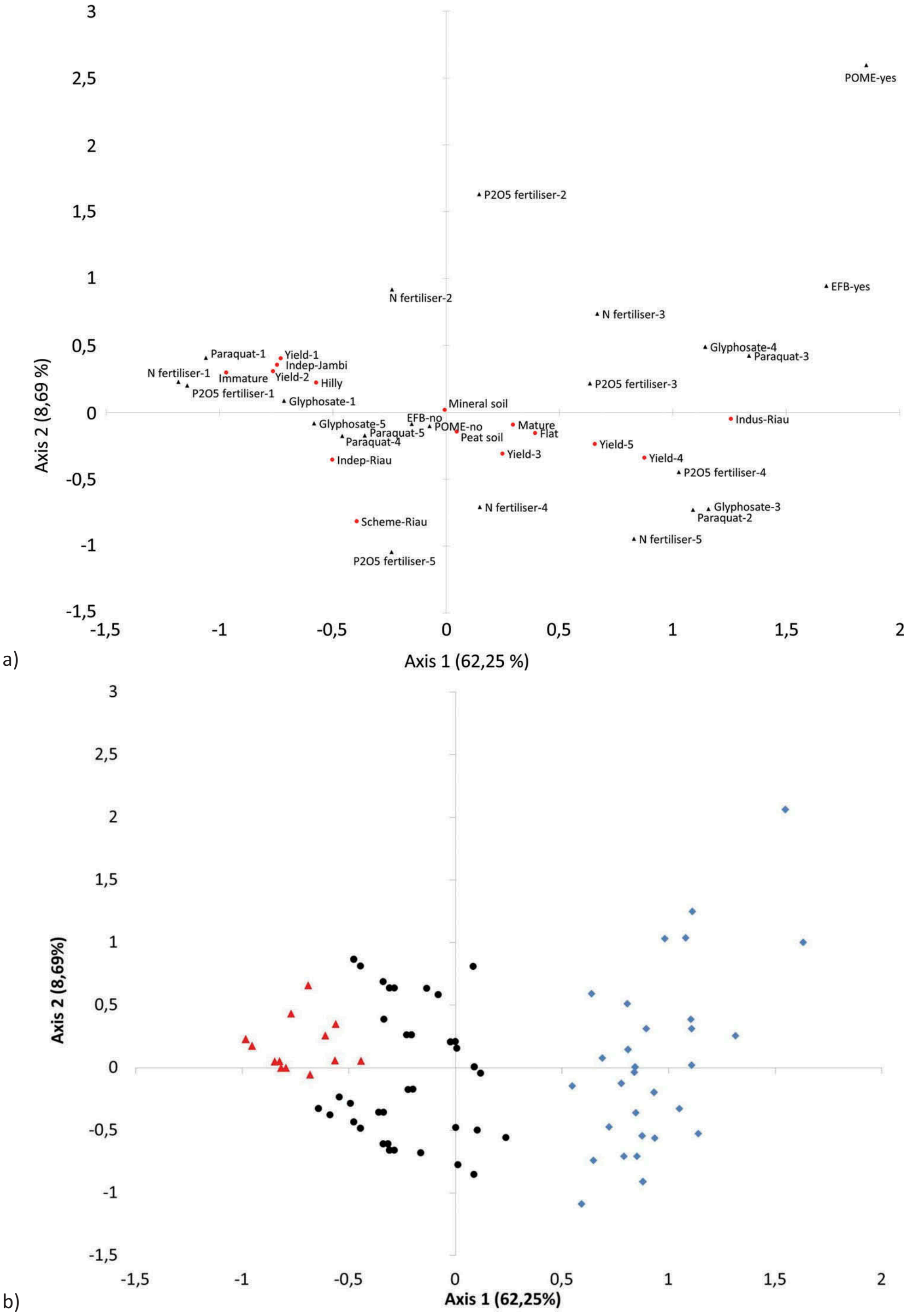

Figure 1. ACM projections of variables on the first two axes (Axis 1 + Axis 2 = 70.94%). Active variables are represented with black squares; inactive or supplementary variables are represented with red dots. b) Individuals projection on ACM axes according to ACH-defined clusters: diamonds = cluster 1; triangles = cluster 2; dots = cluster 3. Full colour available online.

of plantations on peat soil may have led to differentiated practices and performances compared to other plantations, although specific discrepancies could not be investigated within the surveyed parameters in this study (e.g. applied potassium rates).

3.2. Quantitative analyses of practices

We focused on the quantitative practices in order to further investigate discrepancies in practices across growers. Given the previous results that showed differences according to the grower type and location, we analysed the practices crossing these two parameters and hence kept four distinct groups, i.e. industrial plantations in Riau, independent smallholders' plantations in Riau, scheme smallholders' plantations in Riau and independent smallholders' plantations in Jambi (Table 1).

Differences in practices across all the groups were more contrasted concerning fertiliser than pesticide inputs. For both fertiliser inputs, cumulative bar charts

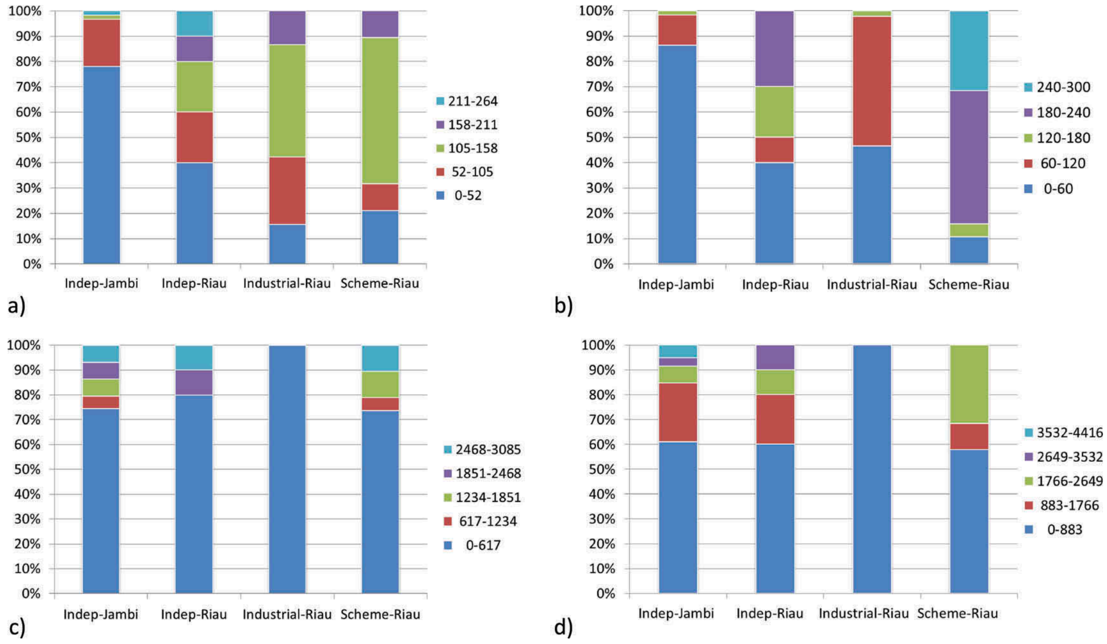

Figure 2. Distribution of applied doses across growers according to equal-sized dose classes; (a) nitrogen total (kg ha^{-1} yr $^{-1}$), (b) phosphate P_2O_5 total (kg ha^{-1} yr $^{-1}$), (c) glyphosate total (g ai ha^{-1} yr $^{-1}$), (d) paraquat total (g ai ha^{-1} yr $^{-1}$). 'ai' Stands for active ingredient.

(Figure 2) showed that the independent smallholders from Jambi had the outermost practices with a majority of them applying much lower nitrogen and phosphate inputs than the other growers. On average, the rates were 30 kg N ha^{-1} yr^{-1} and 21 kg P_2O_5 ha^{-1} yr^{-1} compared to 90–113 kg N ha^{-1} yr^{-1} and 63–190 kg P_2O_5 ha^{-1} yr^{-1} among the other growers. It confirmed the results from the qualitative analysis, highlighting further the differences between independent smallholders' from Jambi in clusters 2 and 3 from the other smallholders in those clusters.

In terms of nitrogen inputs, differences among the other growers were less pronounced in particular between industrial and scheme smallholders' plantations. Amounts applied by the independent smallholders' from Riau were distributed with frequencies close to those from the other growers from the same area. However, as for the independent smallholders' plantations from Jambi, the variation in the practices was quite high, i.e. coefficient of variation of ±84% (Riau) and ±150% (Jambi) compared to ±42% and ±53% for industrial and scheme smallholders' plantations, respectively. This high coefficient of variation was quite critical in the case of smallholders from Riau as there were only 10 growers interviewed. This also explained why they did not influence much the axis projection in the qualitative analysis. The high variability across independent smallholders' plantations may be related to more heterogeneous degrees in palm oil management knowledge than the other growers, whereby doses may be more fluctuant depending on more diverse drivers such as the available cash or the type of products.

From a greenhouse gas perspective, the variations in average annual nitrogen inputs among the growers represented a potential impact gradient from 188 up to 700 kg CO_2e ha^{-1} (IPCC 2006, Tier 1, 100 yr global warming potentials). Hence, the simple amount of nitrogen could generate a difference close to a four-fold factor among growers in terms of potential contribution to climate change. This indicator is based on a linear assumption and better site-specific modelling work would be needed to estimate with more accuracy potential impacts in individual plots, considering variation in soil holding water capacity, in fertiliser application methods etc. More modelling work would also be needed to assess potential environmental impacts related to further nitrogen, P_2O_5 and pesticides field emissions.

In terms of P_2O_5 inputs, practices were particularly variable across the growers. The outermost rates were the high applied by scheme smallholders, i.e. 190 kg P_2O_5 ha^{-1} yr^{-1} (±40%) on average. Applied rates in industrial and independent smallholders' plantations in Riau were quite lower, 63 kg P_2O_5 ha^{-1} yr^{-1} (±44%) and 93 kg P_2O_5 ha^{-1} yr^{-1} (±83%), respectively, with again a high variability in independent smallholders' plantations.

In terms of pesticide inputs, the most characteristic practices were found in industrial plantations, where rates were all similar and moderate. With average inputs of 93 g ai ha^{-1} yr^{-1} paraquat (±20%) and 222 g ai ha^{-1} yr^{-1} glyphosate (±12%), industrial paraquat rates were between 9 and 10-fold lower than those from the other growers and glyphosate rates half of those from the other growers. The coefficient of variation for pesticide rates varied between 90% and 190% across the other growers highlighting very variable practices compared to industrial plantations with some growers using no or few herbicide and other very high amounts of herbicide. This can be at least partly explained by the very selective application of herbicides in the surveyed industrial plantations. As paraquat is a prohibited molecule in many countries, and also targeted under 'RSPO Next', industrial plantation managers are potentially more concerned about reducing paraquat rates as much as possible. On the contrary, other growers may benefit from the unpopularity of this product leading to low prices. Paraquat is a cheap old herbicide especially popular and accessible to farmers in developing countries; and, because it is a contact herbicide, it may be applied with high frequency under humid climate conditions with rapid plant growth (Wesseling et al. 2001). During the interviews, smallholders explained their inclination for paraquat as they find it efficient and less risky for the palm trees compared to glyphosate.

Across practices, no noticeable similarities between scheme and industrial managements were observed despite potential closer technical relationships. Indeed, scheme smallholders can usually benefit from the supervision of the contracting industry that provides extension services and easier access to inputs. Nitrogen rates were close, albeit not significantly closer than those from independent smallholders in Riau.

3.3. Improving oil palm performances

Yields were very low in independent smallholders' plantations in Jambi compared to the other ones, i.e. 11 t FFBs ha^{-1} yr^{-1} (±51%) compared to averages of 25–26 t FFBs ha^{-1} yr^{-1} (±13–36%) from independent smallholders' plantations in Riau to industrial plantations. The closest yields were those from scheme smallholders' and industrial plantations in Riau with lower variability than those from independent smallholders' ones in the same area. The low input rates recorded in Jambi were likely to induce this yield difference between Jambi and Riau, at least partly. Marginal differences in climate and soil conditions could be observed between both sites but were not specifically recorded in the literature on oil palm. A deeper investigation would be needed to assess the potential influence of those factors on the yield performance in this area.

Another key parameter is the planting material, whose quality defines the optimum yield potential and whose price and availability vary with the location. The differences in the palm oil sector influence and related infrastructure development between Jambi and Riau may hence have led to the spreading of different quality of planting material between the two areas. Moreover, industrial plantations and associated scheme smallholders' plantations usually consist of selected high quality planting materials, which may also explained their closer yields.

Comparing total inputs across practice patterns and grower types, potential environmental impacts would be expected to vary among plantations. In particular, the great variations in pesticide application rates would very likely lead to contrasted potential impacts in terms of toxicity impacts. These impacts notably depend on the amounts of applied substances and their toxicities, their fate and exposure risks (Henderson et al. 2011; Rosenbaum et al. 2011). Paraquat represents high risks for both human health and the environment (Wesseling et al. 2001; Watts 2010). Likewise, risks associated to glyphosate have been much debated, with a recent focus on cancer risks (EFSA 2015; Fritschi et al., 2015). 'Generally speaking, low rates of application are desirable from an environmental point of view' (Van Der Werf & Zimmer 1998). Compared to other field inputs, the long residence time of pesticides in the medium may reinforce the dose effect. Nevertheless, impact assessment is not straightforward as average total herbicide amounts do not inform us on acute pollution events and as environmental sensitivity (e.g. soil leaching or adsorption potential, proximity of surface water) is not taken into account in this study. In the surveyed industrial plantations, the timing of fertilisers and pesticides applications is generally adapted to climate conditions (notably rainfalls) in order to reduce the risk of run-off or leaching. The environmental impact assessment should be based on the assessment of detailed agricultural practices and their locations at the landscape level.

At similar fertiliser input levels, despite the assumption of potential similar environmental impacts underpinned by the used models, difference in yields may imply higher uptake and efficiency and hence lower potential losses to the environment. This calls for adapting as much as possible inputs and practices to the realistic potential uptake by the plants and to the local conditions. Potential uptake will depend on the planting material and vary along the cycle. Soil and climate conditions will affect both production potential and environmental risks (Pardon et al. 2016b). Improving practices towards this optimum match involves good agronomic knowledge and experience, and monitoring tool such as soil and leaf analyses.

4. Discussion

Our study, albeit related to a restricted area and number of individuals, already showed differences in cropping systems beyond the sole distinction between industrial and smallholders' plantations. These agricultural practices notably differed in terms of amount of agricultural inputs (N, P_2O_5, glyphosate and paraquat annual rates), and hence potentially in terms of environmental impacts. Practices varied across grower types and within each type according to location and other drivers. Smallholders' practices were particularly variable. Practices applied in scheme smallholders' plantations were not significantly closer to those found in industrial plantations than to those in other smallholders' plantations. Similarly, Lee et al. (2014b) emphasised on the high variability in independent smallholders' practices and the relative higher N rates applied in scheme smallholders' plantations, 148 kg N ha^{-1} yr^{-1} ± 50% for supervised or scheme smallholders, and 111.5 kg N ha^{-1} yr^{-1} ± 94% for unsupervised or independent smallholders. Orders of magnitude and hierarchy in yields were also found similar to those in other previous studies (Lee et al. 2014a). The lowest yields were identified for the growers applying the lowestfertiliser rates and tend to increase with the mean N rates (Lee et al. 2014a).

The low inputs agricultural practices were associated with very low yields in smallholders' plantations in Jambi. As palm oil production is supposed to increase to meet Indonesian production targets, such low yields are not sustainable in terms of both economy and pressure on the land resource. In Jambi, an improved access to inputs for smallholders may be an important lever for improving oil palm performances. However, increasing this access should come along with an increase of extension services, i.e. capacity building, in order to limit the overuse of fertilisers and herbicides. Our results showed that higher input practices, such as high P_2O_5 or paraquat rates, were not systematically related to higher yields but could lead to potential high environmental impacts. The development of agronomic knowledge regarding oil palm cropping system for both independent and scheme smallholders seems then essential to improve oil palm cultivation sustainability. Beyond the short-term potential improvement regarding selective pesticide applications, long-term risk due to pesticide overuse should be anticipated as the number of weed species that have developed a resistance to paraquat and glyphosate is growing. By 2010, 22 weed species in 13 countries had developed resistance to paraquat, including 6 species in Malaysia (Watts 2010). The future inefficiency of the most used pesticides could further jeopardise smallholders'-plantation performances, if proper training and information are not provided in order to change practices.

As our study was focused on four agricultural practices (mineral N, mineral P_2O_5, paraquat and glyphosate herbicide applications), we can assume that there might be other practices that would also trigger the improvement of oil palm performances. Further investigations on the underlying parameters explaining yield differences across growers would also be needed. In particular, discrepancies in inputs and yields should be investigated over several years to check for delayed impacts, as well as potential discrepancies in soil quality or in the harvest logistics etc. A further detailed analysis on an extended set of practices could inform us further on the levers for palm oil sustainability improvement. Moreover, our study only encompassed one industrial palm oil holding. This holding is currently involved in environmental certification which indicates that this particular holding has an interest in palm oil sustainability. Further investigations in other industrial holdings seem then also necessary to broaden the exploration scope of practice discrepancies and improvement room. As our study aimed to identify links between the grower and plantation contexts and the practices in the field, we needed to pre-identify key factors to be investigated. These conditions did not make it possible to conduct field survey according to a simple random sampling design (Kish 1965) within the limited resources of the research project. Complementary field surveys are ongoing in order to wider the sample size and to further test the statistical robustness of our results in other contexts and on a more important number of holdings and plantations.

Our study showed a great diversity of practices across smallholders with a particularly high variability among independent smallholders. We focused on the environmental dimension of sustainability but highlighted the fundamental imbrication between environmental impacts and socio-economic contexts and potential impacts of the production systems. This calls for a deeper exploration of the practice drivers including the socio-economic conditions of smallholders and the trajectories of their holdings (Baudoin et al. 2015). Actions to enhance environmental performances of palm oil production imply to assess and understand both practices and underpinning rationales (Doré et al. 2008). Assessing the gap between actual practices and expected good practices in the light of both policy targets (Parris & Kates 2003) and growers' objectives (Doré & Meynard 2006) is crucial to target efficient actions and incentives towards sustainability (Veldkamp & Verburg 2004; Loyce & Wery 2006). In the context of RSPO, it implies that recommendations on best practices, in order to ensure differentiated impacts between certified and uncertified plantations, shall be defined in the light of the great diversity of both the systems and associated practices, and the growers' rationales and means.

5. Conclusion

Oil palm is cultivated by a wide range of growers. The diversity of these growers has still not been much investigated, especially regarding actual practices and their drivers. In our study, the diversity of agricultural practices and potential environmental impacts was very high even in neighbouring areas and across limited samples. First, we highlighted the fact that industrial and smallholder growers may have quite different practices in terms of input levels, inputs among independent smallholders' plantations being particularly variable. Second, we highlighted that the differences in input levels are contrasted across input types, including very critical differences regarding pesticide rates. High input rates may lead to high emissions to the environment and potential impacts. The conditions are particularly critical when the palm plantation is not very productive, whereby high inputs may not be used efficiently by the plants. The understanding of the underlying drivers is essential to lead towards to effective ways to improve practices.

Note

1. ai stands for active ingredient.

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