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# Exploring yield gaps in smallholder oil palm production systems in eastern Sumatra, Indonesia

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ABSTRACT

Oil palm (*Elaeis guineensis*) has become the most important oil crop throughout the world. The growing palm oil production was mainly based on the expansion of cultivated area into forest areas, causing serious environmental and social concerns. Increasing yields on existing plantations is a potential pathway to reduce the undesired ecological impacts of oil palm agriculture while enhancing its social benefits. Although oil palm production is still dominated by large private estates, smallholder farmers are increasingly engaging in its cultivation. While there is some evidence that smallholders' palm oil yields show large variations and are often far below plantation standards, empirical studies on their agronomic performance are scarce. Based on crop modeling analysis and farm household survey data from Sumatra, Indonesia, this paper quantifies smallholder yield gaps relative to exploitable yield levels and analyses smallholders' production constraints. Results show that oil palm smallholdings offer a tremendous potential for future yield increases, because they obtain, on average, only around 50% of the cumulative exploitable yield over a 20 year plantation life cycle. In particular, we find yield gaps to be largest during the most productive phase of oil palm. Our results indicate that farmers do not adapt their labor and fertilizer inputs to the higher resource demand of the palm. In general, significant determinants of yield gaps are management practices such as fertilizer dosage, length of harvesting intervals and plant mortality. Supported smallholders perform relatively better compared to independent farmers. In summary, our study shows that there is large potential to increase productivity of smallholder oil palm systems in Sumatra. In order to exploit this opportunity, farmers' awareness about the changing management requirements of oil palm over the plantation life cycle needs to be enhanced.

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## 1. Introduction

Over the last two decades, the total production of crude palm oil (CPO) has increased more than four-fold, making palm oil the most produced and traded vegetable oil in the world (FAO, 2015). One reason for this rapid expansion is oil palm's superior yield potential compared to alternative oil crops (Sayer et al., 2012). However, in the major producer country Indonesia, average national yields per hectare have stagnated at around 17 tons fresh fruit bunches (FFB). Past production increases have mainly resulted from the expansion of oil palm plantations into forest areas, causing massive forest clearance and raising serious environmental and social concerns. The global demand for vegetable oils is expected to double by 2050 (Sayer et al., 2012; Corley, 2009). Strategies to increase palm oil production that are based on the expansion of cropping area are likely to contribute to additional deforestation and environmental degradation (Margono et al., 2014; Lee et al., 2013; Wilcove and Koh, 2010; Buttler and Laurence, 2009).

Although, in Indonesia palm oil production is still dominated by private sector companies, smallholder farmers are gaining in importance in oil palm production (Rival and Levang, 2014; Feintrenie and Levang, 2009; Vermeulen and Goad, 2006) and are expected to outnumber the private sector in both production and area under cultivation in the future (Feintrenie and Levang, 2009). Existing studies suggest that smallholder yields show large variations and are often far below plantation standards (World Bank, 2011; Vermeulen and Goad, 2006; Hartemik, 2005; Corley and Tinker, 2003). While average yields of Indonesian smallholders are reported to be around 11 tons FFB/ha (BPS, 2014), private sector plantations in favorable sites often reach yields of more than 30 tons FFB/ha (Hoffmann et al., 2015). Single blocks, the smallest management unit (<25 ha) frequently report yield levels of over 40 tons FFB/ha, which are confirmed by field trials under optimum management conditions (Hoffmann et al., 2014; Donough et al., 2009).

Given the growing importance of smallholder farmers at the national scale, increasing smallholder yields in existing oil palm sites appears as an important instrument to enhance local incomes and livelihoods.

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In order to do so, a detailed understanding of why higher yields are not achieved is necessary. Existing literature suggests that smallholders face a set of agronomic and institutional constraints including the use of poor planting material, inadequate dosage and application of fertilizers, as well as overlong harvesting cycles, which hinder the achievement of the crop's full production potential (Cramb, 2013; Corley and Tinker, 2003). Nonetheless, there is little empirical evidence on smallholder oil palm agriculture. A few recent studies looked at the profitability of smallholder oil palm production in Malaysia and Indonesia using gross margin analysis (Rahmat, 2013; Feintrenie et al., 2010; Rist et al., 2010). Another study has analyzed the determinants of smallholder yields and income variations (Lee et al., 2014). However, due to lack of data, the authors of the latter study were not able to quantify the effect of fertilizer application rates, which may be an important constraint for smallholder production (Corley and Tinker, 2003). Earlier studies have performed a financial cost–benefit analysis based on primary data from 3 villages in Kalimantan (Belcher et al., 2004) and have analyzed the level of technical efficiency of smallholder oil palm farmers in a supported production scheme in West Sumatra (Hasnah and Coelli, 2004). To the best of our knowledge, no study has quantified smallholder yield gaps and identified their underlying determinants. Based on crop modeling and household survey data from Jambi Province, Indonesia, the present study contributes to the existing literature by: (i) quantifying smallholder yield gaps relative to simulated potential and exploitable yields; and (ii) identifying the major agronomic and institutional constraints in smallholder oil palm production.

## 2. Material and methods

### 2.1. Study area

The study was carried out in Jambi province, Sumatra. For the years 2010–12, the mean annual temperature was recorded at 27.0 °C with mean annual precipitation of 2403 mm (BMKG, 2014). Jambi is inhabited by around 3.26 million people with agriculture employing the main share of the working population. After rubber, oil palm is the second most important crop in the province, being cultivated on approximately 532 thousand hectares (Dinas Perkebunan, 2011). While around 154 thousand hectares are managed by private and 19 thousand hectares by government estates, 359 thousand hectares are operated by smallholder farmers (Dinas Perkebunan, 2011).

The group of small scale farmers can be classified into supported and independent smallholders, depending on the mode of engagement into the oil palm sector (Rival and Levang, 2014; Vermeulen and Goad, 2006; Zen et al., 2006). While supported smallholders typically engage in a contract with a private sector or government led company, independent smallholders operate without any form of support. In Indonesia, the first oil palm smallholders were linked to estates in the framework of so called nucleus estate and smallholder schemes (NES). In such schemes a large scale plantation ('nucleus') is surrounded by oil palm smallholdings ('plasma'). Typically smallholders receive – on a loan basis – technical and financial assistance with the establishment and management of their parcels, including agronomic extension services, input provision and subsidies, as well as marketing support (Rival and Levang, 2014; Rist et al., 2010; McCarthy and Cramb, 2009; Vermeulen and Goad, 2006; Zen et al., 2006). The loan is repaid through subtracting a certain amount from the smallholders' factory processing returns. Once the debt is cleared smallholders obtain land titles for their oil palm parcels (Zen et al., 2006). With a decrease of political support after the end of the New Order regime, independent smallholders gained in importance (Rival and Levang, 2014; Zen et al., 2006). In 2011, around 98 thousand supported (or formerly supported) smallholders managed around 196 thousand hectares of oil palm plantations, while 83 thousand independent farmers cultivated 163 thousand hectares (Dinas Perkebunan, 2011).

### 2.2. Farm household survey

Within Jambi province, data was collected in five regencies (Sarolangun, Batanghari, Muaro Jambi, Bungo, and Tebo), which were selected purposely. According to secondary data sources, these regencies represent the major share of smallholder oil palm producers and smallholder oil palm plantations in Jambi province (BPS, 2011). Smallholder oil palm cultivation is also widespread in the regencies of Tanjung Jabung Barat and Tanjung Jabung Timur. However, in both regencies oil palm plantations are often established on peatland areas and thus have different management requirements and life cycle characteristics that cannot directly be compared to plantations that are established on mineral tropical lowland soils (Lee et al., 2013; Budidarsono et al., 2012). In order to capture geographical disparity and regional diversity of selected regencies, we randomly selected 4 districts per regency and 2 villages per district (for more details see Faust et al., 2013). The study further includes 5 purposively selected villages, which are located near the protected areas 'Bukit Duabelas' national park and 'Harapan' rain forest. Within these villages and under the roof of a 'Collaborative Research Centre' additional research activities are carried out by a range of scientific projects (Faust et al., 2013). The location of the 45 sample villages was geo-referenced and is shown in Fig. 1.

As villages were found to differ significantly with respect to population size, randomly selected villages were divided into 4 quarters. Accordingly, 6 households were selected randomly from each of the 10 villages in the lowest population quartile (villages consisting of 90–249 households), 12 household per village from the second quartile (296–437 households), 18 household per village from the third (460–648 households) and 24 per village from the largest quartile (718–2000 households). Additionally, about 20 households were selected from each of the 5 purposively selected villages, including a number of purposively selected households which manage oil palm and rubber plantations where supporting research activities are carried out.

Thus, our survey includes 701 farm households, out of which 248 cultivate oil palm. As we are interested in quantifying smallholder yield gaps and determining their underlying causes, 12 farmers that are not managing their oil palm parcels and thus could not give detailed input–output information were excluded from the analysis. Our final analysis is based on farm level data of 236 oil palm farmers, as well as production data from 363 oil palm plots. More precisely, our sample contains 170 independent smallholder households cultivating 241 oil palm plots and 66 supported smallholder households with 122 plots. While the main share of supported farmers was associated with the government led trans-migration program, a minority consists of farmers of local origin who have engaged in contract farming with the private sector through farmer groups.

A structured questionnaire was developed and pre-tested during August and September 2012, in order to ensure consistency and accuracy of the data. The final questionnaire was introduced to a team of field assistants, which were carefully trained at the University of Jambi. The questionnaire included (1) detailed input–output data from all oil palm parcels cultivated by a given household; (2) institutional framework of farm activities; and (3) socio-economic household characteristics. Input–output details were collected for the 12 month period preceding the date of interview. Data collection took place between October and December 2012.

### 2.3. Potential and exploitable yield

Key information for yield gap analysis is the determination of potential yields for a given region. For annual crops this is widely done by detailed mechanistic crop models (van Ittersum et al., 2013). However, available soil and climate data are often not sufficient to run such models for tropical perennial crops. While a few detailed oil palm models exist, these are hardly tested outside of their region of

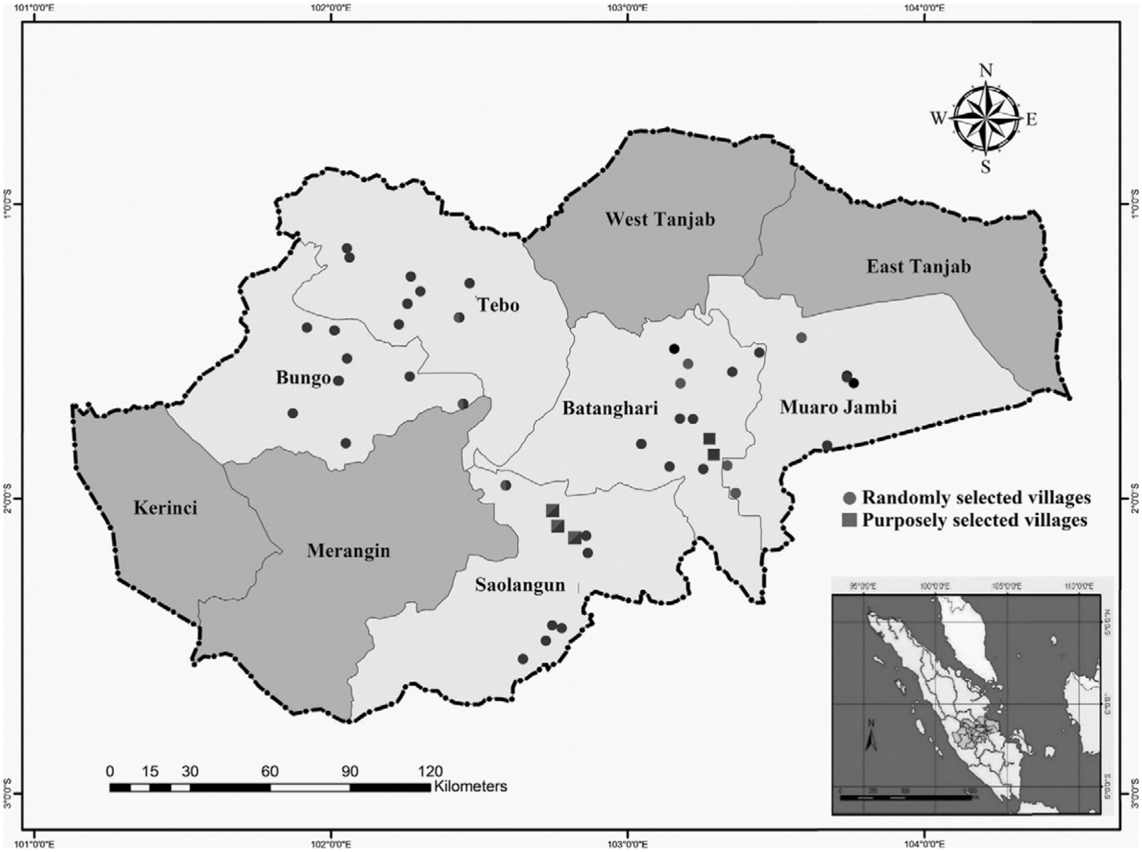

**Fig. 1.** Map of selected regencies and villages in Jambi province.

development (Huth et al., 2014; Combres et al., 2013; Henson, 2009). We therefore use a recently published simple physiological oil palm model called PALMSIM (Hoffmann et al., 2014). PALMSIM simulates potential oil palm growth and yield on a monthly time step for the typical commercial life time of 25–30 years. In PALMSIM yield levels are only limited by incoming solar radiation, assuming optimal nutrient and water supply. It is further assumed that yields are sink limited in the first 48 months after planting. Thereafter, they are assumed to be source limited (for a more detailed discussion also see Hoffmann et al., 2014). Management practices are assumed to be optimal (planting density 143 plants/ha; pruning). The model was evaluated against a range of sites across Southeast Asia. Model yield levels matched yields from fertilizer trials suggesting that the model is capable to estimate average annual potential yield levels (Hoffmann et al., 2014). A limitation of the model is that it cannot capture seasonal yield variations, which is, however, not needed for the purpose of this study. Necessary input data, i.e. monthly solar radiation, was derived using the MarkSim weather generator, which was also used for Southeast Asia in a previous study (Pasuquin et al., 2014). Based on observed data from the WORLDCLIM data base, MarkSim stochastically generates a range of possible annual weather scenarios for a given region (Jones and Thornton, 2013). In order to derive the potential yield ($Y_p$) for Jambi province, we generated weather scenarios for 99 years and ran PALMSIM with each of it.

In general, the exploitable yield is considered to be around 75–80% of the yield potential, which can be attributed to limitations in resource use efficiency and cost effectiveness (van Ittersum et al., 2013). In fact, yields that were recorded in a field trial in east Sumatra (Riau province) in which palms received high levels of fertilization (planting density of 143 plants/ha on a flat terrain with palms receiving 1.75 kg N/palm, 0.8 kg P/palm, 2.2 kg K/palm, 1.5 kg Mg/palm and 0.05 kg B/palm), reach around 85% of the yield potential as modeled by PALMSIM (Hoffmann et al., 2014). Agro-ecological conditions of Riau and Jambi province are very similar (solar radiation around 5800–6300 MJ/m$^2$/year, high rainfall >2000 mm/year). Thus, under similar management practices, observed yields in Riau Province are likely to also be attainable in the area of research. We therefore assess smallholder performance against the exploitable yield, which is set as 85% of the yield potential obtained from PALMSIM.

### 2.4. Determinants of yield gaps

Each farmer faces a particular yield gap, which is defined as the difference between the exploitable yield (as introduced in the previous section) and the realized yield (as recorded in the household survey). Based on a literature review, we hypothesize that yield gaps are a function of plantation attributes (i.e. plantation age), the type and intensity of agricultural management practices (i.e. the level of input and labor use), as well as farmer and household characteristics (i.e. age and education of the farmer). When appropriate, we allow for non-linear relationships by including squared terms.

We estimate this relationship by ordinary least squares (OLS), because OLS is computationally straightforward and it produces under certain assumptions unbiased and efficient estimates (Greene, 2008). The two assumptions, which most often cause issues in applied work, are the assumption of homogeneous variance in the residuals and normally distributed residuals. The Shapiro–Wilk test for normality, however, reveals that the residuals are normally distributed and the Breusch–Pagan test shows, that the variance of the residuals is homogenous.

**Table 1**
Definitions and descriptive statistics for variables used in the yield gap model.

| Variable | Definition (unit of measurement) | Mean (std. dev.) |
|---|---|---|
| Yield gap | Difference between the exploitable yield and the attained yield (kg FFB/ha). | 12,546.0 (9350.9) |
| Oil palm area | Farm level area under oil palm (ha). | 6.4 (9.9) |
| Plantation age | Age of the oil palm plantation (years after planting). | 10.6 (6.1) |
| No. of productive palms | Number of productive oil palms (no./ha) | 100.9 (48.0) |
| N application | Quantity of applied N per plot (kg/ha). | 88.4 (96.5) |
| P application | Quantity of applied P per plot (kg/ha). | 14.5(22.8) |
| K application | Quantity of applied K per plot (kg/ha). | 69.7(131.9) |
| Herbicide use | Quantity of herbicides applied per plot (liter/ha). | 5.6 (5.4) |
| 30 day harvesting cycle | Dummy variable indicating a 30 day cycle between FFB harvests. Reference in the model. | 0.1 |
| 15 day harvesting cycle | Dummy variable indicating a 15 day cycle between FFB harvests. | 0.7 |
| 10 day harvesting cycle | Dummy variable indicating a 10 day cycle between FFB harvests. | 0.1 |
| Plantation age ∗ fertilizer use | Interaction term between plantation age and fertilizer use. | 5195.2 (6738.6) |
| Age | Age of the household head (years). | 46.9 (11.8) |
| Education | Education level of the household head (years of schooling). | 8.1 (0.8) |
| Supported smallholder | Dummy variable indicating whether the farmer participated in oil palm scheme. | 0.4 |
| Muaro Jambi | Dummy variable indicating whether the household lives in Muaro Jambi regency. Reference in the model. | 0.2 |
| Sarolangun | Dummy variable indicating whether the household lives in Sarolangun regency. | 0.3 |
| Batanghari | Dummy variable indicating whether the household lives in Batanghari regency. | 0.4 |
| Tebo | Dummy variable indicating whether the household lives in Tebo regency. | 0.1 |
| Bungo | Dummy variable indicating whether the household lives in Bungo regency. | 0.1 |
| Random household | Dummy variable indicating whether a household was selected randomly. | 0.9 |
| Random village | Dummy variable indicating whether a village was selected randomly. | 0.8 |
| Unproductive plot | Dummy variable indicating whether a plot is in the physiological stage of production (≥3 years), but still unproductive. | 0.15 |

Notes: N = 317. Mean values for dummy variables indicate the mean share of observations for which the respective dummy takes on the value 1. Regency dummies do not sum due to rounding. Harvesting cycle dummies do not sum to 1 due to a share of farmers that do not harvest their plots, although these are in the physiological stage of production.

Formally, we estimate the following model:

$$Y_i = \alpha + \beta P_i + \gamma M_i + \delta H_i + \rho C_i + \varepsilon_i \qquad (1)$$

where $Y_i$ is our dependent variable, the exploitable yield gap on plot *i*. We include all plots that are in the physiological stage of production (i.e. all plots that are 3 years and older).

Vector $P_i$ contains plot and plantation attributes including the age of the plantation and the number of productive oil palms. In order to account for possible scale of operation effects we further include the total oil palm area on the farm level.

Vector $M_i$ entails information about agricultural management practices including the use of external inputs and labor. In terms of input use, we include the quantity of applied fertilizers and herbicides. As applied fertilizers differ with respect to their mineral composition, we calculate the total rate of Nitrogen (N), Phosphor (P), and Potassium (K) for each plot. For herbicide applications, we use the total quantity. Details on applied fertilizer types and quantities are provided in Table A1.

In oil palm agriculture, most labor is used for harvesting. In order to capture labor input, we use the monthly frequency of FFB harvests, reflecting the length of harvesting intervals. In perennial crops, yield levels (and yield gaps) are partly determined by an age specific, plant physiological pattern. We need to account for possible structural changes of a given explanatory variable over time. In the context of our model, we introduce an interaction term between plantation age and use of N, P, and K quantities. We also interacted plantation age with applied herbicide quantities, and harvesting frequencies. Both interaction terms were, however, not significant and we removed them from the final model to increase the stability of the estimates.

Vector $H_i$ contains a set of household and farmer characteristics including the age and level of education of the household head, and a dummy variable capturing whether a farmer has participated in a supported smallholder scheme. As previously indicated supported smallholders receive technical assistance during plantation establishment and management and often have access to extension services, which might improve their agronomic performance.

The vector $C_i$ contains a set of control variables. In order to account for regional differences, a set of regency dummies is included in the model. We also control for the mode the household was selected into the sample. As previously indicated, some villages and households are purposively selected into the sample. Introducing control variables allows checking whether non-random selection significantly influences the estimation results. Vector $C_i$ also includes an unproductive plot dummy that takes on the value 1 for all plots that do not yield FFB, but which are in the physiological stage of production (3 years or older). For these plots, a low number of productive palms/ha (0) is correlated with a relative small yield gap (due to the low simulated yield potential in early years).

$\varepsilon_i$ is the error term which is assumed to be normally distributed with mean zero and variance $\sigma^2$. $\alpha$, $\beta$, $\gamma$, $\delta$ and $\rho$ are the parameters to be estimated by the model. A detailed description and summary statistics of all variables included in the model is given in Table 1.

Although we captured the type of planting material in our survey, we could not use this information in the model because we lack information on cultivars' names and quality. In particular, around one quarter of farmers does not have information on the name of the planted cultivar. Further, although among the farmers who have information on the planting material, the large majority (~78%) use the same planting material (Marihat), we do not have information on the seedlings quality. Seedlings may be purchased from certified dealers (high quality) or from input traders, which often sell lower price (and lower quality) seedlings. Further details on planting material are provided in Table A2.

## 3. Results and discussion

### 3.1. Quantifying yield gaps

In order to be able to quantify smallholder yield gaps, precise production information over the whole oil palm life cycle is needed. Fig. 2 shows FFB yields as realized by smallholders over different plantation ages. Attained yields are plotted against potential and exploitable yields.

Potential yields average at 33.2 tons FFB/ha (average annual production between years 3–25 after plantation establishment), and peak at 40.4 tons FFB/ha in year 10 after plantation establishment. Likewise, exploitable yields average at 27.9 tons FFB/ha and peak at 34.3 tons FFB/ha. Smallholder yields are well below both potential and exploitable yields. Smallholder farmers realize yield levels that average at 15.1 ± 9.0 tons FFB/ha (average annual production between years 3–25 after

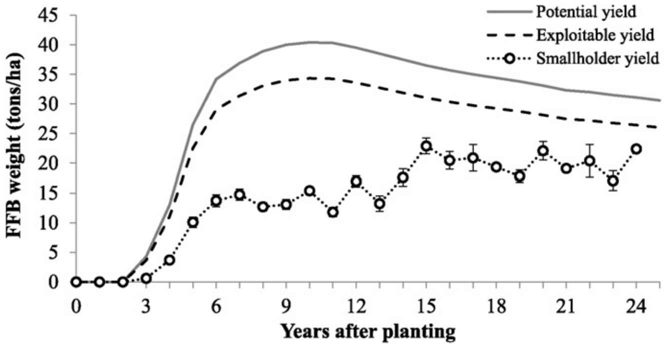

**Fig. 2.** Potential, exploitable and smallholder fresh fruit bunch (FFB) yields over a 25 year plantation life cycle. Potential and exploitable yields are derived by PALMSIM. Smallholder yields include 363 oil palm plots cultivated by 236 farmers. Error bars indicate mean standard errors.

plantation establishment) and peak at 22.9 ± 2.7 tons FFB/ha in year 15 after plantation establishment. Yield gaps are especially large during the period of peak oil production (years 8–16 after plantation establishment), in which smallholders only manage to obtain around 50% of the exploitable yield.

In general, the observed smallholder yields are in the range of yields as reported by other studies. Average smallholder yields are reported to be 15.4 ± 7.5 tons FFB/ha in Sumatra (Lee et al., 2014); 15.9 tons FFB/ha in Malaysia (Ismail et al., 2003); and 15 tons FFB/ha in managed smallholder schemes in Malaysia (Cramb and Ferrano, 2010). As agro-ecological conditions and hence potential and exploitable yields are comparable across all studies, it is not unlikely that smallholder yield gaps have a similar magnitude in other oil palm growing regions in Indonesia and Malaysia.

In a next step, we quantify the yield gaps of smallholder oil palm plantations over a 20 year plantation life cycle by deducting their cumulative yields from the exploitable yield (Fig. 3). As it has been shown that the status of smallholder support is an important factor in explaining smallholder yield variations (World Bank, 2011; Vermeulen and Goad, 2006; Hartemik, 2005; Corley and Tinker, 2003), we further show yield gaps for independent and supported farmers. Over a 20 year plantation life cycle, the potential yield for Jambi province cumulates to 600 tons FFB/ha and the exploitable yield to 508 tons FFB/ha. Smallholders are able to attain cumulative yields that are around 240 tons FFB/ha below the exploitable yield corresponding to 53% of the exploitable yield. The exploitable yield gap for supported smallholders cumulates to 183 tons FFB/ha, which corresponds to around 64% of the exploitable yield. Independent smallholders achieve yields that are on average 260 tons FFB/ha below the exploitable yield, thereby obtaining only 49% of the exploitable yield.

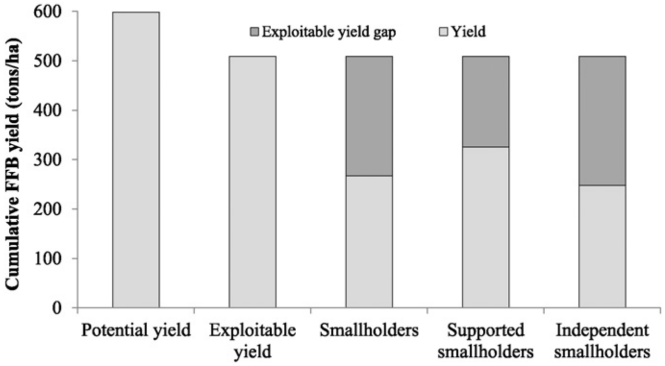

**Fig. 3.** Cumulative potential, exploitable and smallholder yields along with exploitable yield gaps of smallholder farmers over a 20 year plantation life cycle. The cumulative potential yield is the sum of annual potential yields as derived by PALMSIM. The cumulative exploitable yield is set as 85% of the cumulative potential yield. The cumulative smallholder yield is the sum of average annual smallholder yields for different plantation ages (1–20 years after planting).

Combining the average annual yield gap (cumulative exploitable yield gap / 20 year plantation life cycle) for independent (13.0 tons FFB/ha) and supported (9.2 tons FFB/ha) farmers with the area under smallholder oil palm plantations (Dinas Perkebunan, 2011) we quantified annual yield losses for Jambi province. Assuming an oil extraction rate of 20% (Corley and Tinker, 2003), around 784 thousand tons of CPO were lost in 2011 due to production constraints. This is equivalent to 55% of the total CPO production of Jambi province in 2011, which reached 1.4 million tons CPO (BPS, 2011). Such figures are only a rough estimation, as they assume normally distributed yield gaps and plantation ages in the population of oil palm smallholders. However, they underline the magnitude and economic implications of smallholder yield gaps.

### 3.2. Determinants of smallholder yield gaps

To identify the factors determining the observed yield gaps, we estimate a yield gap model, as described in Eq. (1), using ordinary least squares. Table 2 gives the estimated coefficients along with standard errors. As the dependent variable is the exploitable yield gap, a negative coefficient indicates that an increase in the respective independent variable will lead to a reduction in the yield gap. A positive coefficient, in turn, amplifies the observed yield gap.

Our results indicate that plantation age is highly significant in determining smallholder yield gaps. As the relationship between plantation age and yield gaps is not linear, we introduce a squared term (plantation

**Table 2**
Determinants of yield gaps.

| | Coefficient (std. err.) |
|---|---|
| Plantation characteristics | |
| Plantation age (years) | 2793.6$^{***}$ (347.2) |
| Plantation age squared | −102.6$^{***}$ (13.0) |
| Number of productive palms | −47.3$^{**}$ (20.5) |
| Oil palm area (ha) | −505.4$^{***}$ (160.5) |
| Oil palm area squared | 12.2$^{***}$ (3.3) |
| Management characteristics | |
| N application (kg/ha) | −23.9$^{*}$ (10.7) |
| N application ∗ plantation age | −1.2$^{*}$ (0.7) |
| P application (kg/ha) | 69.4$^{***}$ (46.2) |
| P application ∗ plantation age | −9.1$^{***}$ (3.4) |
| K application (kg/ha) | −14.7$^{***}$ (12.0) |
| K application ∗ plantation age | 0.1$^{***}$ (0.7) |
| Herbicide use (liter/ha) | 341.4$^{*}$ (239.2) |
| Herbicide use squared | −24.7$^{*}$ (12.8) |
| 15 day harvest cycle (dummy) | −1288.5 (1791.0) |
| 10 day harvest cycle (dummy) | −5434.4$^{***}$ (2136.1) |
| Household characteristics | |
| Age (years) | 25.8 (42.1) |
| Education (years of schooling) | 131.7 (129.2) |
| Supported smallholder (dummy) | −2089.3$^{*}$ (1244.8) |
| Sarolangun (dummy) | 3412.1$^{**}$ (1455.8) |
| Batanghari (dummy) | 658.1 (1313.5) |
| Tebo (dummy) | −1927.6(2340.3) |
| Bungo (dummy) | 967.0 (2212.8) |
| Random village (dummy) | 2541.0 (1664.6) |
| Random household (dummy) | −3691.4$^{*}$ (1935.4) |
| Unproductive plot (dummy) | −8475.7$^{***}$ (2897.3) |
| Constant | 8049.1 (4695.8) |
| Adj. $R^2$ | 0.38 |
| F | 8.72 |

Notes: N = 317. $^{***}$, $^{**}$, $^{*}$ indicates independent samples t-test significant at 1%, 5% and 10% level, respectively. The dependent variable is the yield gap between the exploitable and observed yield (kg FFB/ha). Coefficient estimates are shown with standard errors in parentheses. The reference harvesting cycle is 30 days between harvests. The reference regency is Muaro Jambi.

age squared) into the model. The interpretation of the coefficients concerning plantation age (main and interaction terms) indicates that smallholder yield gaps grow continuously up to year 14, where the maximum gap is reached (to obtain these findings, the first derivative of the equation is solved for plantation age). Thus, yield gaps are largest during the phase of initial yield increase (years 3–7) and peak oil production (years 8–16). During the most productive phase the palm has the largest demand for resources (especially nutrients). Our results indicate that smallholders do not adapt their management practices to the changing plant requirements, i.e. increase the supply of nutrients and shorten the harvesting interval.

Thus, it is not surprising that we find management practices to have a strong effect on yield performance: Fertilization and harvesting frequencies significantly affect yield gaps. The application of N and K reduces the yield gap. The interaction term between these nutrients and plantation age suggests that the negative fertilization effect on yield gaps becomes slightly weaker, as plantations mature. In contrast, P applications are found to have a negative effect on yield gaps only for plantations that are around 8 years and older (interpreting the main and interaction term for P applications). Overall, these results suggest that fertilizers are underused, especially during the productive phase, which could be due to limited access to input markets. A case study from Bungo also finds that the dosage and application of fertilizers are crucial in determining FFB yields (Feintrenie et al., 2010).

With respect to the use of herbicides, we find yield gaps to increase up to application quantities of around 7 l per ha and to decrease thereafter (solving the first derivative for herbicide applications).

Concerning harvesting frequencies, we find a shortening of the harvesting cycle to 10 days between FFB harvests to significantly reduce yield gaps when compared to a harvesting cycle of 30 days. Other studies also find smallholders harvesting once a month to have the lowest yield levels when compared to smallholders with shorter harvesting intervals (Lee et al., 2014; Feintrenie et al., 2010), and find a positive effect of shorter harvesting intervals on yields on commercial estates (Donough et al., 2009). Harvesting frequencies are in fact a measure of minimizing FFB loss, rather than increasing FFB yields. A low number of harvests, and thus long harvesting cycles, potentially reflect a growing amount of overripe FFB which decay on the ground, as they are not harvested on time (Corley and Tinker, 2003).

We further find a significant influence of the number of productive palms per ha on the observed yield gap. According to our estimates, each additional productive palm above the mean (119 palms/ha) reduces the yield gap (in OLS regressions estimated coefficient for continuous variables are interpreted as the effect of an increase in the respective continuous variable by one unit above its arithmetic mean). Commonly, an optimal planting density of about 140 palms/ha for oil palm in Indonesia is used (Hoffmann et al., 2014). This finding might seem trivial, yet it points to a potential shortcoming in smallholder oil palm agriculture. Considering the significantly larger planting density at plantation establishment (128 palms/ha for included plots), some farmers seem to face significant losses due to plant mortality. The underlying reasons are not entirely clear. Potentially, inadequate treatment during the nursery stage or during the immature plantation phase cause palm losses.

In addition, there is a significant effect of the total oil palm area of a given farm on plot level yield gaps. Solving the first derivative of Eq. (1) for oil palm area, we find the yield gap to decrease with each additional hectare under oil palm up to around 21 ha. Thereafter, the yield gap is observed to grow with a further increase in oil palm plantation size. This result suggests that medium sized farms have a comparative advantage over small and large farms.

With respect to household characteristics, age and education levels of the household head have no significant effect on yield gaps. Interestingly, yield gaps of supported oil palm producers are significantly lower compared to those of independent farmers. This result suggests that technical support (fertilizers, herbicides and planting material) and agricultural extension services offered to supported smallholders by their contract partner have increased their agronomic management skills allowing the achievement of higher yields compared to independent farmers.

With respect to included regency dummies we find significantly larger yield gaps for households residing in Sarolangun compared to households residing in Muaro Jambi. Sampled villages in Sarolangun are among the most distant from Jambi city, the province capital and gateway to international in-and output markets. Potentially, oil palm farmers in Sarolangun face infrastructural and information flow constraints. Other regency dummies do not significantly influence yield gaps. The dummies controlling for the mode of household and village selection into the sample suggest that randomly selected households have lower yield gaps compared to purposively selected households.

The coefficient for the unproductive plot dummy is negative and significant. As indicated the dummy merely serves to exclude the effect of unproductive plantations from the coefficient estimate for the number of productive palms/ha.

### 3.3. Characteristics of supported and independent oil palm farmers

Apparently, management practices and yield levels between independent and supported smallholders differ considerably. In this section we explore such differences in greater detail. Table 3 shows farm attributes, and plot and agronomic management characteristics for independent and supported smallholders. We start by comparing yield levels. We find a yield difference of 6.8 tons FFB/ha between independent and supported famers. Yield differences of around 3.6 tons/ha, with independent smallholders achieving 14.2 tons FFB/ha and supported farmers achieving 17.8 tons FFB/ha have been reported previously for Riau, West and South Sumatra (Lee et al., 2014). Our data also confirms the presence of a large variation of yields across smallholder farms. Such variation has also been observed by previous studies (Lee et al., 2014; Vermeulen and Goad, 2006). However, only Lee et al. (2014) quantify yield variations and find similar results, indicating that oil palm production is relatively heterogeneous within the smallholder sector.

With respect to agricultural activities, we find supported smallholders to have significantly smaller oil palm and rubber plantations and to specialize in oil palm agriculture. Looking at plot level and management characteristics, we find that supported smallholders have started oil palm cultivation earlier than independent farmers, as their plots are on average more mature. This can be attributed to the fact that oil palm agriculture was introduced to Jambi province via supported smallholder schemes. With respect to agronomic management practices, supported farmers apply significantly more fertilizer, invest more labor, use less herbicides and have significantly shorter harvesting intervals (although the difference is quite small in absolute terms). Supported smallholders also have a significantly larger number of productive palms compared to independent farmers. Potentially, palms that are planted and grown under the supervision of a contract partner receive a more careful treatment during the nursery stage and early plantation development which may translate into lower mortality rates during the productive stage of the plantation.

Observed differences in yields and management practices are also mirrored in smallholders' economic performance. Table 4 compares mean values of revenues, input costs and gross margins between independent and supported smallholders for oil palm plantations. Revenues refer to the output multiplied by output price; input costs include all external inputs purchased by the farmer (excluding labor costs); labor costs include costs for all hired labor; sharecropping costs include all costs that arise from share-cropping arrangements between the farmer and a share-cropper (typically the share-cropper receives a certain yield share); gross margins are defined as revenues less input, labor, and sharecropping costs.

We find supported smallholders to achieve significantly higher revenues due to higher yields but also higher output prices. They receive on

**Table 3**
Farm, plot, and management characteristics of independent and supported smallholders.

| | Independent smallholders | | | Supported smallholders | | |
|---|---|---|---|---|---|---|
| | Mean (std. dev.) | Range | | Mean (std. dev.) | Range | |
| | | Min. | Max. | | Min. | Max. |
| Farm characteristics[a] | | | | | | |
| Farm size (ha) | 7.5 (12.3) | 0.25 | 86 | 4.3 (2.9) | 1 | 19 |
| Oil palm area (ha) | 3.8 (6.9) | 0.12 | 51 | 3.3*** (2.6) | 0.75 | 19 |
| Rubber area (ha) | 3.7 (7.1) | 0 | 60 | 1.0*** (1.6) | 0 | 7.5 |
| Plot and management characteristics[b] | | | | | | |
| Plantation age (years) | 6.9 (4.8) | 0 | 20 | 14.5*** (6.6) | 0 | 31 |
| No. of productive palms (no./ha)[c] | 113.4 (25.6) | 28.5 | 188.7 | 126.6*** (18.8) | 55 | 186 |
| No. of fertilizer types (no./ha) | 1.3 (1.1) | 0 | 3 | 1.8*** (1.2) | 0 | 5 |
| Fertilizer use (kg/ha) | 306.5(334.8) | 0 | 1500 | 527.3***(404.3) | 0 | 1800 |
| Herbicide use (liter/ha) | 5.9 (5.6) | 0 | 30 | 4.8*** (5.2) | 0 | 22.5 |
| Labor use (days/ha) | 21.6 (20.3) | 0 | 162.8 | 30.4*** (19.0) | 0 | 116.5 |
| No. of harvests (no./month) | 2.1 (0.3) | 1 | 3 | 2.2*** (0.4) | 1 | 3 |
| Yield (tons FFB/ha)[c] | 12.7 (8.4) | 0.1 | 39.2 | 19.5*** (7.3) | 1.2 | 37.0 |

Notes: Mean values are shown with standard deviation in parenthesis.
*** Independent samples t-test significant at 1% level.
[a] n = 170/66.
[b] n = 241 independent and 122 supported farmers.
[c] Productive plots only.

average almost 21% higher prices than independent smallholders. We also find gross margins to be significantly larger for supported farmers, although they have considerably higher expenses for external inputs and hired labor. Previous gross margin comparisons between independent and supported smallholders confirm these findings (Lee et al., 2014).

The difference in gross margins between independent and supported smallholders is particularly large during the phase of initial yield increases in the years 4–7 (Fig. 4). The difference gets smaller with increasing age of oil palms, which might indicate on the one hand a learning effect among the independent producers, on the other in the later phase of the palm the yield potential is decreasing the demand for harvest and fertilizer input decreases well. We do not find a significant difference during the early phase of the plantation life cycle, including plantation establishment and management of the immature stand.

In order to better understand the reasons for observed price differences, Table 5 gives further insights on output marketing channels for independent and supported smallholders. In general, processing mills play a crucial role in the oil palm sector, as fatty acids start to decay 48 h after harvesting of FFB, leading to a decline in oil quality (Corley and Tinker, 2003). As the production quantity of independent smallholders is limited, they are typically not able to sell directly to the processors and hence sell their produce primarily to traders. Private sector companies and farmer groups only play a minor role. Moreover, processing mills are often located relatively far away from the oil palm plots and most smallholders do not have the means to transport their produce to the mill. Traders often pick up the FFB directly from the plot and deliver it to the processing mill. Independent smallholders hence often depend on middlemen to secure their access to the mills (Feintrenie et al., 2010).

Supported farmers in contrast, either operate in village level famer groups, or -by contract design- are able to deliver their output to the mill of their contract partner. As a result, supported farmers are mainly selling to farmer groups and private sector companies. Apparently, supported smallholders are able to avoid middlemen (traders) and hence receive significantly higher prices as compared to independent farmers.

## 4. Concluding remarks

Driven by the increasing demand for vegetable oils and biofuels, the area under oil palm has more than doubled during the last two decades. In Indonesia, the major producing country, the recent expansion in palm oil production has mainly relied on an expansion of cultivated area. Like few other crops, oil palm production has been associated with deforestation and environmental degradation. Closing the yield gap in existing smallholder oil palm systems is an important tool to

**Table 4**
Revenues, costs and gross margins of oil palm production for independent and supported smallholders.

| | Independent smallholders (n = 241) | Supported smallholders (n = 122) |
|---|---|---|
| Revenues (000 IDR/ha) | 6986.4*** (8764.5) | 17,903.3 (10,040.5) |
| Input costs (000 IDR/ha) | 1826.8*** (1802.3) | 2731.9 (2055.8) |
| Labor costs (000 IDR/ha) | 806.1*** (1226.7) | 1832.3 (2153.4) |
| Sharecropping costs (000 IDR/ha) | 188.0 (1325.8) | 90.8 (689.9) |
| Gross margin (000 IDR/ha) | 4165.5*** (7433.5) | 13,248.4 (9053.4) |
| Average price received (000 IDR/kg FFB) | 0.796*** (0.252) | 0.963 (0.224) |

Notes: Mean values are shown with standard deviation in parenthesis.
*** Independent samples t-test significant at 1% level.

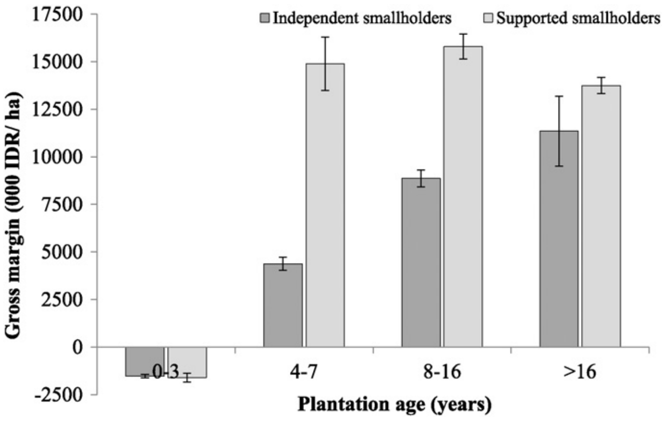

**Fig. 4.** Gross margins of supported and independent smallholders over different plantation ages. Gross margins are calculated as annual revenues (output multiplied by output price) less input, labor and sharecropping costs. Error bars indicate mean standard errors.

**Table 5**
Output marketing details for independent and supported smallholders.

| Share of farmers selling to… | Independent smallholders (n = 113) | Supported smallholders (n = 63) |
|---|---|---|
| Traders | 81% | 17%[***] |
| Farmer groups | 8% | 50%[***] |
| Processing mills | 14% | 41%[***] |

[***] Independent samples t-test significant at 1% level.

enhance the social benefits of oil palm agriculture and may help to reduce its undesired ecological impacts. Despite smallholders´ growing importance in the oil palm sector, they have received relatively little attention in recent research. Based on crop modeling analysis and household survey data, this paper has quantified smallholder yield gaps and identified major production constraints.

We find that oil palm smallholdings offer a tremendous potential for future yield increases, since they obtain only around 50% of cumulative exploitable yields over a 20 year plantation life cycle. This gap is largest during the peak production phase of oil palm. Thus, the most important determinants of smallholder yield gaps, namely low fertilizer use, plant mortality and overlong harvesting cycles, might become even more limiting. Therefore, adapting management practices to the production cycle of oil palm could be a viable strategy to increase yields. Our analysis suggests that supported smallholders stand superior with respect to relevant agronomic practices and hence are able to achieve higher yields. Apparently, technical assistance and extension services offered by their contract partner have helped to increase agronomic productivity in supported smallholder oil palm sites. Results suggest that especially independent smallholders are constrained by limited knowledge about best management practices and by imperfect access to input markets. Policy makers should focus on improving the public agricultural extension service and the availability of fertilizers through, for example, reducing transaction costs. Such measures should primarily focus on independent farmers as they show larger deficits in plantation management and offer a greater potential for yield increases.

However, changes in management practices in existing oil palm sites only tackle one part of the total exploitable yield gap. Potential yield levels are also determined by the planting material. Thus, any short term measures need to be supplemented by initiatives that aim at improving the quality and availability of planting material. Unfortunately, our data did not allow us to disentangle yield effects of the planting material, something that should be addressed by future studies.

Beyond agronomic limitations, we find evidence that especially independent smallholders do not have direct access to the processing industry, but are dependent on middlemen and thus receive lower FFB prices. Investments in infrastructure and the promotion of smallholder marketing cooperatives are potential policy measures to improve smallholders' access to the processing industry.

The net ecological outcomes of yield increases are hard to predict. In principle, higher yields imply that the same amount of palm oil could be produced on less land, reducing the pressure on forest resources. Higher returns, however, also improve the profitability of oil palm cultivation against other land uses including forests and may generate incentives for further plantation expansion. For example, Villoria et al. (2013) show that higher palm oil yields in Indonesia and Malaysia lead to a relocation of vegetable oil production from temperate to tropical regions, causing a net expansion of oil palm acreage and a slight decrease in forest area in both countries. Thus, it is essential that policy measures addressing yield intensifications at the farm level also entail environmental safeguards on the regional and national level. The potential economic gains of yield increases are, however, substantial. Increasing smallholder yields has the potential to improve the livelihoods of smallholders and foster the economic development of rural communities, thereby strengthening the oil palm sector as a whole.

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## Appendix A

**Table A1**
Type, frequency and amount of applied fertilizers among sample farmers.

| Type of fertilizer | Contained nutrients (share of total) | No. of plots applied in | Mean annual application (kg/ha)[a] |
|---|---|---|---|
| Urea | N (46%) | 165 (34%) | 653.4 (1034.6) |
| KCl | $K_2O$ (61%) | 74 (15%) | 479.1 (549.8) |
| NPK Mutiara | N (16%), $P_2O_5$ (16%), $K_2O$ (16%), MgO (2%), CaO (5%) | 63 (13%) | 927.6 (1779.7) |
| Phoska | N (15%), $P_2O_5$ (15%), $K_2O$ (15%), S (10%) | 44 (9%) | 434.8 (414.8) |
| TSP | $P_2O_5$ (47%), $H_3PO_4$ (5%) | 35 (7%) | 306.6 (258.4) |
| MOP | $K_2O$ (16%) | 32 (7%) | 530.0 (575.0) |
| Za | N (21%), S (24%) | 26 (5%) | 486.3 (290.0) |
| Borat | $B_2O_3$ (47%), $Na_2O$ (22%) | 16 (3%) | 360.7 (391.0) |
| Super phosphate 36 | $P_2O_5$ (36%) | 16 (3%) | 671.9 (996.5) |
| Rock phosphate | $P_2O_5$ (30%) | 14 (3%) | 337.8 (166.3) |
| KBM Kiesrite | MgO (27%), S (21%) | 1 (<1%) | 800 |
| Suburin tablet | N (16%), $P_2O_5$ (10%), $K_2O$ (17%), MgO (2%) | 1 (<1%) | 50 |

Notes: N = nitrogen, $K_2O$ = potassium oxide, $P_2O_5$ = phosphorus pentoxide, MgO = magnesium oxide, CaO = calcium oxide, S = sulfur, $H_3PO_4$ = phosphoric acid, $B_2O_3$ = boron trioxide, $Na_2O$ = sodium oxide.

[a] Mean values are shown with standard deviations in parenthesis.

**Table A2**
Type of planting material, frequency and share of its use among sample farmers included in yield gap model.

| Type of planting material | Frequency of planting | Percentage share (%) of… | |
|---|---|---|---|
| | | All observations | Observations with known planting material |
| Marihat | 187 | 59 | 78.2 |
| Sofindo | 18 | 5.7 | 7.5 |
| Costa Rica | 14 | 4.4 | 5.9 |
| Tenera | 8 | 2.5 | 3.3 |
| Local variety | 5 | 1.5 | 2.1 |
| Tropar | 2 | 0.6 | 0.8 |
| Dura | 2 | 0.6 | 0.8 |
| Pisifera | 2 | 0.6 | 0.8 |
| Serika | 1 | 0.3 | 0.4 |
| No information | 78 | 24.6 | |
| Total | 317 | 100 | 100 |

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