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RESEARCH ARTICLE

Oil palm smallholder yields and incomes constrained by harvesting practices and type of smallholder management in Indonesia

Janice Ser Huay Lee · Jaboury Ghazoul · Krystof Obidzinski · Lian Pin Koh

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Abstract The oil palm industry in Indonesia faces several challenges in its bid to adopt more sustainable practices. These challenges include finding ways to increase smallholder palm oil production and to promote benefit sharing with local communities. However, factors that influence oil palm yield and income among oil palm smallholdings are poorly known. We surveyed 379 households in 15 villages in Sumatra, Indonesia, to identify factors controlling smallholder yield and income. We found that decreasing monthly harvesting rotation of oil palm smallholdings decreases oil palm yield, whereby once-a-month harvesting resulted in the lowest annual fresh fruit bunch yields (14.82 t/ha). We also found that independent smallholder households receive lower gross monthly incomes compared to scheme and managed smallholder households, whereby independent smallholders received the lowest gross monthly income from oil palm cultivation (2.17 million Indonesian rupiah). Our results provide quantitative evidence that harvesting rotation and type of smallholder management are important constraints on oil palm yields and incomes of smallholders.

Keywords *Elaeis guineensis* · Smallholders · Livelihoods · Productivity · Agribusiness

J. S. H. Lee (✉) · J. Ghazoul · L. P. Koh
Department of Environmental Systems Science (D-USYS), ETH Zurich, CHN G 73.1, Universitätstrasse 16, 8092 Zurich, Switzerland
e-mail: janice.lee@env.ethz.ch

K. Obidzinski
Center for International Forestry Research, Jalan CIFOR, Situ Gede, Bogor Barat 16115, Indonesia

1 Introduction

Global demand for palm oil has led to a rapid increase in oil palm acreage and production over the last three decades (World Bank 2011). Today palm oil contributes to 36 % of the world's total vegetable oil due to its high productivity and low costs compared to other vegetable oils such as rapeseed and soya (USDA-FAS 2010). However, the sustainability of palm oil is debated widely, especially within the region of Southeast Asia, due to negative impacts on the environment and social relations with local communities (Casson 2000; Colchester et al. 2006; Fitzherbert et al. 2008; Koh and Wilcove 2008; Miettinen et al. 2011). Indonesia, in particular, is the largest producer of palm oil in the world, supplying approximately 45 % of global crude palm oil (World Bank 2011), and has been at the receiving end of various social and environmental concerns over its rapid expansion of oil palm plantations (Colchester et al. 2006; Koh and Ghazoul 2010; Obidzinski et al. 2012).

Between 2000 and 2009, the most rapid oil palm expansion in Indonesia was among smallholders, with annual growth rates of 11.12 %, far higher than government estates (0.37 %) and private companies (5.45 %) (Indonesian Palm Oil Council 2010). Increasing attention is being paid to the Indonesian smallholder oil palm sector, partly due to its rapid expansion of planted area, but also to address various sustainability issues facing the Indonesian oil palm industry, namely increasing existing palm oil production and promoting benefit sharing with local communities (World Bank 2010; Widjaja 2012). At present, Indonesia's 6.7 million ha of mature oil palm plantations produce 23.6 million t of crude palm oil, approximately 50 % below its maximum production capacity (considering a yield potential of 7 t of crude palm oil per hectare) (Ministry for Economic Affairs 2011). Part of this underperformance in production is due to low yields from the smallholder sector. On average, the Indonesian smallholder produces 3 t of crude palm oil per hectare a year, which is approximately 35–40 % lower than yields from private and government sectors (Molenaar et al. 2010). Intensifying smallholder yields has direct benefits to smallholder household incomes and has been touted as a "land sparing" approach to increase crude palm oil production without expanding over forested land (Widjaja 2012). However, the latter concept should be approached with caution since higher yields may also increase land rents and result in more deforestation (Angelsen 1999). When managed properly, oil palm has also been shown in several case studies to raise total income and assets for rural smallholders by at least 60 % on average (Susila 2004). Based on a preliminary study on district-level assessment of poverty reductions from oil palm activity in Indonesia, a 1 % increase in oil palm area of cultivation contributes to a reduction of 0.15–0.25 percentage points of people in poverty (World Bank 2011). Smallholder activity also makes a larger contribution to poverty reduction as compared to private or government oil palm development. Promoting smallholder development has therefore been cited by government agencies as well as international organizations as an important avenue for the Indonesian oil palm industry to increase benefit sharing with local communities (Bahroeny 2009; World Bank 2011).

In order to improve yields and increase benefit sharing with local communities in the smallholder oil palm sector, it is therefore important to understand what contributes to variations in yields and income among smallholder plantations and households, respectively. Factors which determine successful smallholder oil palm development have been classified under (1) the agronomy of the oil palm production system, (2) the supply chain for the production and sale of the oil palm fruit, and (3) an enabling environment which sets the context for smallholder development (World Bank 2010). Factors associated with agronomy of oil palm production fall under various subcategories such as knowledge, input quality and quantity, and land use, all of which require extensive interactions with smallholders and technology transfer from agricultural extension institutions or private companies. Factors associated with the supply chain for the production and sale of oil palm fruit involve smallholder access to credit, infrastructure, and access to mills to ensure good investment in the beginning of oil palm production and ease of transportation of the oil palm fruit or fresh fruit bunch to processing mills. These factors require the support of credit institutions such as banks, international donor organizations, and governmental assistance in improving public infrastructure. Factors related to the enabling environment of smallholder development include organizing structures (i.e., farmer cooperatives), legal structures, market dynamics, and social development, all of which lie outside the direct influence of smallholders and, to a large extent, rely on government policies to shape how smallholders organize themselves, improve land tenure security, ensure fair prices for smallholder produce, and increase access to health and education services among others. As the Indonesian oil palm industry looks towards improving its smallholder oil palm sector, identifying the most important groups of factors for yields and income derived from oil palm agriculture for smallholders can help prioritize the approaches and target relevant stakeholders and institutions.

Based on an empirical dataset collected from 379 smallholders in three separate districts in Sumatra, we test competing hypotheses of which groups of factors under the agronomy of oil palm production, supply chain for the production and sale of oil palm fruit, and enabling environment for smallholder development are most important in explaining variations in smallholder oil palm yields and income. Our main objectives are to (1) test alternative hypotheses regarding the most important factors that predict annual yield per hectare in smallholder oil palm plantations and (2) test alternative hypotheses regarding the most important factors that predict gross monthly income from oil palm cultivation for oil palm smallholders.

2 Materials and methods

2.1 Study site

Sumatra (00°N, 102°E) covers 25.2 % of Indonesia's land area at 480,793 km^2 and has a population of close to 50 million inhabitants (Badan Pusat Statistik 2009). At present, Sumatra accounts for ~67 % (6.2 million ha) of total oil palm area in Indonesia and 81 % (2.9 million ha) of Indonesia's smallholder oil palm acreage (Indonesian Ministry of Agriculture 2011) (Fig. 1). We focused our study on three districts where oil palm plantations were established ~30 years ago—Pelalawan from the province of Riau, Pasaman Barat from West Sumatra, and Musi Banyu Asin from South Sumatra. Based on reports provided by the Department of Plantation (*Dinas Perkebunan*) at the district level, smallholder oil palm plantations made up 34 % (~64,000 ha), 39 % (87,000 ha), and 64 % (96,000 ha) of total planted oil palm area in Pelalawan, Musi Banyu Asin, and Pasaman Barat, respectively. All three districts receive high annual rainfalls (2,000–5,000 mm) and high annual temperatures (22–32 °C). Dry seasons are experienced annually from August to October (Indonesian Agency for Meteorology Climatology and Geophysics 2013), during which oil palm yields have been reported to be lower (Corley and Tinker 2003). Due to a fairly long presence of oil palm in these districts, there exists a range of differently managed smallholder oil palm plantations, hereafter also addressed as "smallholdings." Scheme smallholdings are comanaged by smallholders and a parent oil palm company, and the fresh fruit bunches produced are sold directly to the parent company's oil palm mill. The role of the parent oil palm company is to provide technical assistance during the establishment of these scheme smallholdings and provide agronomic inputs

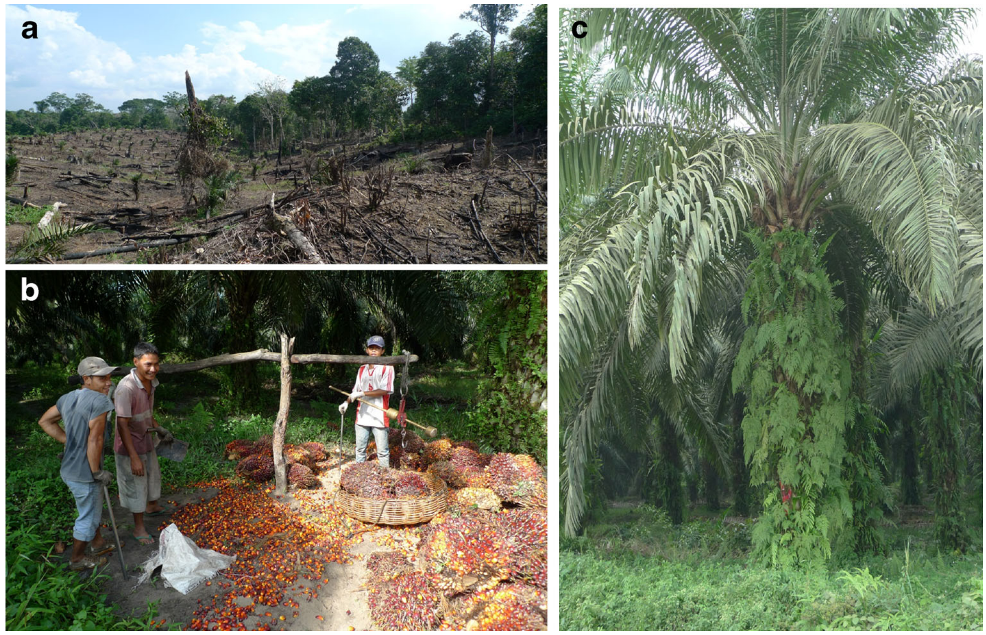

Fig. 1 Oil palm development in Sumatra: **a** Conversion of rubber agroforests in South Sumatra for oil palm smallholdings, **b** laborers weighing fresh fruit bunch collected from an oil palm smallholding, **c** mature oil palm tree from an oil palm industrial estate

and services at a cost to smallholders. Managed smallholdings are similar to scheme smallholdings except that smallholders hand over the entire management of their smallholdings to the oil palm company and receive a monthly share of the profits derived from oil palm production. Independent smallholdings are managed entirely by smallholders, and the fresh fruit bunch produced are sold to any oil palm mill with the best fresh fruit bunch price, often through the hands of an oil palm middleman.

2.2 Household surveys

Two preliminary surveys were conducted in August 2010 and in April 2011 for this study. The former was carried out with 83 different oil palm stakeholders using semistructured interviews while the latter was carried out with 15 oil palm smallholders to test the survey questionnaire. The final study was conducted between June and July 2011 using a standardized questionnaire which consists of two sections: (1) socio-economic background of the smallholder household and (2) characteristics of their oil palm plantations. The unit of our sample is a household.

A two-stage clustered sampling was carried out where villages were selected based on distance from main roads, accessibility to markets as well as smallholder palm oil management schemes present in the village. Next, the research team (which consists of the lead author and three other trained enumerators from Indonesia) held a meeting with the village head to request for permission to conduct research in the village and a map of main roads and landmarks (e.g., mosques, local schools) within the village. These objects were labeled with numbers as starting points in the village for enumerators to begin their transect sampling. At the beginning of each sampling day, a starting point for the transect line was randomly selected for each enumerator, and households along that transect line were sampled (Magnani 1997). Households which declined to be interviewed were passed over and the next household was visited. Enumerators spoke to the head of the household present in the house, often the men of the household. In some cases, women were in charge of the household or took over answering questions as the men were away. In other cases, both men and women helped in answering questions. Altogether, we collected a total of 379 smallholder interviews from 15 villages across the study sites and plantation management data on 611 smallholdings. Majority of the interviews were conducted with men (76 %), some with women (21 %), and a handful where both men and women jointly participated in the survey (3 %).

2.3 Data analysis

Data collected from surveys were double-checked with the enumerator for any missing entries or misinterpretations and translated into English by the lead author. Ambiguous data or unreliable respondents were removed from the dataset. Responses from interviewees had to be coded and regrouped (Table 1). There were two main datasets collected from the household surveys—smallholder plantation (number of smallholdings=528) and smallholder household background (number of smallholders=375).

To investigate the most important factors influencing smallholder yield and income from oil palm agriculture, we applied an information-theoretic approach which provides a framework that allows for multiple model comparisons and identifies the most parsimonious model which best explains variation in the response variable (Burnham and Anderson 2002). This approach requires the construction of a set of a priori candidate

Table 1 Coded responses from the questionnaires were pulled together to construct factor levels for several categorical variables used in our data analysis. Here, we present a detailed description of all variables used in our yield and income analyses

Variable	Type of data	Unit/factor levels	Description
Yield analysis			
Soil type (soil)	Nominal	Mineral	"Mineral" refers to mineral soil.
		Swamp	"Swamp" refers to peat soil or waterlogged soil since smallholders tend to group both types of soils under the Indonesian word *gambut*.
		Mixed	"Mixed" refers to a mix of soil type from categories mentioned above.
Area of smallholding (area)	Continuous	ha	Area of smallholder oil palm plantation
Seedling quality (seed)	Nominal		Seedling quality is based on where smallholders source their seedlings from.
		High	"High" refers to seedlings sourced from a certified nursery, from the government or from a private oil palm company.
		Medium	"Medium" refers to seedlings sourced from local shops, traveling salesmen, and local nurseries.
		Low	"Low" refers to sources like family and friends, or produced locally by smallholders from loose fruits.
		Mixed	"Mixed" refers to mixed sources from different categories mentioned above.
Number of essential nutrients used as fertilizer (fertilizer)	Ordinal	All	Oil palm trees require five essential nutrients for productivity (nitrogen, phosphorous, potassium, magnesium, and boron). Fertilizer usage here refers to the number of essential nutrients used as fertilizer and not the quantity.
		Sufficient	"All" includes application of all 5 nutrients.
		Insufficient	"Sufficient" includes application of 3–4 nutrients.
		Organic	"Insufficient" includes application of 1–2 nutrients.
		None	"Organic" includes livestock waste and empty fresh fruit bunches.
Volume of herbicides applied per hectare per application (herbicide)	Continuous	l/ha	We only considered herbicides used against grasses (common trade names include paraquat and Gramaxone).
Density of oil palms within smallholding (density)	Continuous	Palms/ha	Number of oil palms planted per hectare
Harvesting rotation per month (harvest)	Ordinal	Once	"Once" refers to harvesting of fresh fruit bunches carried once a month.
		Twice	"Twice" refers to harvesting carried out at a 15-day interval.
		Thrice	"Thrice" refers to harvesting carried out at a 10-day interval.
Start-up capital (capital)	Nominal	Informal	"Informal" sources of capital include smallholder's personal savings, money borrowed from family and friends as well as from people in the village.
		Formal	"Formal" sources of capital include money borrowed from banks and companies.
		Mixed	"Mixed" sources of capital include money borrowed from both informal and formal sources.
Accessibility to mills (d.mill)	Continuous	km	Distance of smallholding to nearest available oil palm mill
Accessibility to roads (d.road)	Continuous	km	Distance of smallholding to nearest main tarred road
Management of smallholding (manage)	Nominal	Independent	"Independent" refers to smallholdings managed entirely by smallholders with no agronomic inputs and technical assistance from companies.
		Scheme	"Scheme" refers to smallholdings managed with agronomic inputs and technical assistance from companies.
Land tenure security (land)	Ordinal	Minimum	"Minimum" land tenure security for smallholding is where there are no land titles to the land where smallholding is located on, there is only a verbal agreement to the land, or the land is protected by customary laws.
		Moderate	"Moderate" land tenure security for smallholding is where land titles such as the *SKT*, *SKGR*, *Sopradik*, *Segel*, and *SPH* are available for the land.
		Maximum	"Maximum" land tenure security for smallholding is where land titles such as the *BPN* land certificate are available or the smallholder is in the process of obtaining his *BPN* certificate.

Table 1 (continued)

Variable	Type of data	Unit/factor levels	Description
Income analysis			
Number of years of experience (experience)	Continuous	Years	Smallholder's number of years of experience working in oil palm production (e.g., within oil palm companies, nurseries, and as hired laborers).
Total area of smallholdings (area)	Continuous	ha	Total area of oil palm plantations owned by smallholder
Accessibility to oil palm mill (d.mill)	Continuous	km	Distance of smallholder household to closest available mill
Accessibility to main road (d.road)	Continuous	km	Distance of smallholder household to main tarred road
Type of management for smallholder (type)	Nominal	Independent	"Independent" smallholders manage their plantations on their own and are not bound to sell their produce to one mill.
		Scheme	"Scheme" smallholders manage their plantations with the support of oil palm companies and are required to sell their produce to the same company's mill at least for a certain time period.
		Managed	"Managed" smallholders allow full management of their plantations by oil palm companies and all production is sold to the company's mill.
Level of participation in cooperative (coop)	Ordinal		The level of participation by smallholders in a cooperative is based on the frequency of participation in meetings and cooperative activities.
		Very active	"Very active" refers to smallholders who participate in cooperative activities either every day, every week, once in 2 weeks or every month.
		Active	"Active" refers to smallholders who participate in cooperative activities once in 3 to 6 months.
		Member	"Member" refers to smallholders who participate in cooperative activities once a year or only when there are invitations.
		Not involved	"Not involved" refers to smallholders who are not part of an oil palm cooperative.
Price of fresh fruit bunch (price)	Continuous	IDR/kg of fresh fruit bunch	Average price of fresh fruit bunch offered to smallholders, expressed in Indonesian rupiah (IDR).
Education of smallholder (education)	Nominal	Nonschool	"Nonschool" covers smallholders who did not go to school and did not graduate from primary school.
		Primary	"Primary" covers smallholders who graduated from primary school *SMP*.
		Secondary	"Secondary" covers smallholders who graduated from secondary school *SMA*.
		Tertiary	"Tertiary" includes education levels *SMK* (high school) and *S1* (college).
Migrant status of smallholder (migrant)	Ordinal	Local	"Local" refers to smallholders who were originally from the village they resided in.
		Migrant	"Migrant" refers to smallholders who were originally from a different village, district, or province.

models using existing knowledge and logic about the hypothetical relationships regarding factors that influence smallholder yield and income from oil palm agriculture (World Bank 2010). Assessment of the models was based on the index Akaike's information criterion corrected for small sample sizes (AIC*c*). This index measures the Kullback–Leibler information loss which can be conceptualized as a "distance" between full reality and the model (Burnham and Anderson 2002). Hence, the best model is seen as losing the least information relative to other models within the model set and is the model with the lowest AIC*c* value. The AIC*c* can be used to calculate Akaike weights, *w*AIC*c*, which represent the relative probability of each model being the best model within the model set. Akaike weights are used to create evidence ratios which provide quantitative information about the support for one model relative to the other (Burnham and Anderson 2002).

A set of eight candidate models were generated to represent competing hypotheses of which group of smallholder variables (agronomy, supply chain for production and sale of oil palm fruits, and/or enabling environment of smallholder development) were most important in accounting for variations in annual yields of fresh fruit bunch per hectare for smallholder plantations (Table 2) and in gross monthly income derived from smallholder plantations (Table 2) (See Table 1 for a detailed description of each variable). Under the yield analysis, variables associated with agronomy practices include the type of soil where the smallholding was located on (soil), area of smallholding (area), quality of seedling used (seed), number of essential nutrients used as fertilizer (fertilizer), volume of herbicides applied per hectare during each application (herbicide), density of palm trees within 1 ha of smallholding (density), and labor efficiency of harvesting oil palm trees (harvest); variables associated with the supply chain for production and sale of the oil palm fruit include start-up capital used by smallholders (capital), accessibility to mills (d.mill), and main roads (d.road), while variables associated with the enabling environment of smallholder development include management of smallholding (e.g., independently managed or supported by a company) (manage) and land tenure security of smallholding (land). Under the income analysis, variables associated with the agronomy of smallholder oil palm plantations include the number of years of experience working in oil palm production (including previous experiences working in oil palm companies, oil palm nurseries, and as hired laborers) (experience) and total area of smallholding (area); variables associated with the supply chain for production and sale of oil palm fruits include accessibility of smallholder household to mills (d.mill) and main roads (d.road), while variables associated with the enabling environment of smallholder development include the type of management smallholders are involved in (type), the level of active participation in a smallholder cooperative (coop), the price of fresh fruit bunch offered to smallholders (price), the level of education of smallholders (education), and the migrant status of smallholders (migrant).

As the data for both our yield and income analyses are hierarchically structured (households in villages within districts), we used generalized linear mixed-effect modeling (GLMM) to account for these dependencies within hierarchical groups through the introduction of random effects (Pinheiro and Bates 2000). Each hypothetical relationship was fitted as a specific GLMM using the lmer function of the lme4 library in the R Package (http://www.r-project.org/). For the yield analysis, candidate GLMMs were fitted with annual yield of smallholder plantation per hectare as the response variable, and each candidate model included age of plantation as a continuous control variable (age) and identity of smallholder, village and district (village nested in district) of smallholder plantations as random effects. Each candidate model was fitted to a normal-error distribution and an identity-link function. For the income analysis, candidate GLMMs

Table 2 Candidate models constructed to account for variations in smallholder oil palm yields and income

Model no.	Candidate models	Analytical theme
Yield analysis		
1	Yield ~ 1+age	Null
2	Yield ~ soil+area+seed+fertilizer+herbicide+density+harvest+age	AG
3	Yield ~ capital+d.mill+d.road+age	SC
4	Yield ~ manage+land+age	EE
5	Yield ~ soil+area+seed+fertilizer+herbicide+density+harvest+capital+d.mill+d.road+age	AG+SC
6	Yield ~ soil+area+seed+fertilizer+herbicide+density+harvest+manage+land+age	AG+EE
7	Yield ~ capital+d.mill+d.road+manage+land+age	SC+EE
8	Yield ~ soil+area+seed+fertilizer+herbicide+density+harvest+capital+d.mill+d.road+manage+land+age	AG+SC+EE
Income analysis		
1	Log(income) ~ 1+yield	Null
2	Log(income) ~ experience+area+yield	AG
3	Log(income) ~ d.mill+d.road+yield	SC
4	Log(income) ~ type+coop+price+education+migrant+yield	EE
5	Log(income) ~ experience+area+d.mill+d.road+yield	AG+SC
6	Log(income) ~ experience+area+type+coop+price+education+migrant+yield	AG+EE
7	Log(income) ~ d.mill+d.road+type+coop+price+education+migrant+yield	SC+EE
8	Log(income) ~ experience+area+d.mill+d.road+type+coop+price+education+migrant+yield	AG+SC+EE

Model 1 (or null model) represents no relationship between the response variable (annual yields and gross monthly income from oil palm) and predictor variables associated with agronomy (*AG*), supply chain for the production and sale of oil palm fruit (*SC*), and enabling environment for smallholder development (*EE*). *Models 2–4* represent models with variables only from *AG*, *SC*, or *EE*. *Models 5–7* represent different combinations of models while *model 8* represents the full model with variables from all three groups

were fitted with log-transformed gross monthly income from oil palm plantation as the response variable, and each candidate model included total annual yield per hectare of plantation as a continuous control variable (yield) and village and district (village nested in district) of smallholder plantations as random effects. Each candidate model was fitted to a normal-error distribution and an identity-link function. All continuous variables were standardized to improve model convergence of the fitting algorithm and comparability of effect sizes from estimated coefficients which are now on the same scale (Rhodes et al. 2009). After excluding samples with incomplete information ("NA"), the sample size for the yield and income analyses were 426 and 313, respectively.

To assess multi-collinearity among predictor variables within the model, the variance inflation factor (vif) function of car library in the R package was applied. vifs can be used to detect multi-collinearity among predictors by quantifying how much the variance of each predictor is inflated due to the presence of high collinearity with other predictors. As vif does not work with lmer function, we used a lm function to check for any large vif values (vif>10) and removed variables with the highest vif values (Montgomery and Peck 1992). We removed the predictor type of smallholder scheme (e.g., Members' Primary Credit Co-operative or *KKPA* and the estate-transmigration program *PIR-TRANS*) since it was highly collinear with management of smallholding.

3 Results and discussion

3.1 Background of smallholder households and plantations

Our smallholder household dataset (n=313) consisted of oil palm smallholders who owned only independent smallholdings (173 independent smallholders, 55.3 %), smallholders who owned scheme smallholdings (115 scheme smallholders, 36.7 %), and smallholders who owned managed smallholdings (25 managed smallholders, 8 %). Approximately 60 % of scheme and managed smallholders owned an additional independent smallholding. The average area of oil palm ownership by smallholders was 2.97 ha and ranged between 0.25 and 25 ha. When broken down into different types of smallholders, the average area of oil palm ownership under independent, scheme, and managed smallholders was 2.3±2.5 (SD), 3.9±3.1, and 3.8±2.4 ha, respectively. Our oil palm smallholding dataset (n=426) consisted of 281 independent smallholdings and 145 scheme smallholdings. The average area of an independent and scheme smallholding in our dataset was 1.8±1.9 and 2.0±0.7 ha, respectively. We excluded all managed smallholdings from our dataset as they are managed entirely by the oil palm company, and oil palm smallholders have no information regarding agronomic practices within these smallholdings.

The mean age of our survey respondents was 43.7±11.2 years. More than half of our respondents were migrants (54 %), of which 14 % came from a different village or subdistrict, 10 % came from a separate district, and 74 % came from a different province. Of the smallholders who were migrants, 10 % married into the village and settled down, 37 % were part of the transmigration program or were second-generation transmigrants, while 46 % migrated to eke out a living (*merantau*). Respondents came from a range of ethnic backgrounds, the most common were the Melayu (29 %) and Javanese (26 %), followed by Mandailing (15 %), Sundanese (9 %), and Minang (7 %). The remaining respondents came from a mixed ethnic background, and a few individuals identified themselves as Batak (3 %). Islam was the dominant religion among our oil palm smallholders surveyed (308 smallholders, 98 %).

Average smallholder household size was 4.3±1.7 people, and the average number of children under 17 years of age for each household was 1.6±1.2 children. The majority of oil palm smallholder households had at least two sources of income including oil palm cultivation (59 %). Smallholder households that relied on oil palm cultivation as their only source of livelihood made up 21 % of our survey, while 20 % had three or more sources of income including oil palm cultivation. Out of the smallholder households surveyed, 42 % owned an additional agricultural system such as rubber plantations, rice, corn, cacao, or vegetable farms. Majority of our respondents received basic education, with 37 % having a primary school education and 22 % who did not finish school or did not attend school. Around 15 % received secondary school education, and about one quarter (25 %) received tertiary education or were pursuing a tertiary education.

3.2 Yields from oil palm smallholdings

The overall mean annual yield of smallholdings from our surveys was 15.4±7.5 t/ha, close to the mean annual yields reported by the Indonesian Ministry of Agriculture for the smallholder oil palm sector (~14 t/ha) (Molenaar et al. 2010). At an early stage of oil palm development (5–8 years), the mean annual yield of independent smallholdings (14.2±0.6 t/ha) was 25 % lower compared to scheme smallholdings (17.8±1.1 t/ha). At a later stage of oil palm development (9–17 years), the mean annual yields of independent smallholdings (15.9±0.7 t/ha) were 38 % lower compared to scheme smallholdings (22.1±0.5 t/ha).

From our analysis, the best model for predicting variations in annual yield per hectare for oil palm smallholdings included variables associated with the agronomy practices within smallholder plantations and the enabling environment for smallholder development (Table 3). This model accounted for 86.3 % of the Akaike weights in the model set but had a very low percentage deviance explained, 1.35 %. The second best model was the full model which included variables associated with the agronomy, supply chain for production and sale of fresh fruit bunch, and the enabling environment for smallholder development. This model accounted for 13.1 % of the Akaike weights in the model set and had an equally low percentage deviance explained of 1.35 % (Table 3). Altogether, these two models represent more than 99 % of the Akaike weights present in the model set. The best fit model is represented by the following equation:

$$Yield \sim 1,864.66 \times soil_{mineral} + 2,464.79 \times soil_{swamp} - 129.06 \times area + 1,960.08 \times seed_{high} + 282.29 \times seed_{medium} - 279.87 \times seed_{low} + 6,489.58 \times fertilizer_{all} + 2,763.34 \times fertilizer_{sufficient} + 1,182.76 \times fertilizer_{insufficient} + 94.77 \times herbicide + 658.57 \times density + 818.95 \times manage_{scheme} + 2,878.41 \times land_{maximum} + 2,954.30 \times land_{moderate} + 9,997.47 \times harvest_{thrice} + 5,937.37 \times harvest_{twice} + 3,313.98 \times age - 104.71$$

Within the above model, the coefficients represent the effect sizes of individual predictor terms and were used to make yield predictions of oil palm smallholdings under a 10,000 iteration bootstrapped model (Fig. 2). All terms within

Table 3 Results of model selection using the AIC*c* (Akaike's information criterion corrected for small sample sizes) as an index for comparing models in the yield and income analyses

Model no.	Candidate models	Analytical theme	LL	K	ΔAIC*c*	*w*AIC*c*	Evidence ratio	%DE
Yield analysis								
6	Yield ~ soil+area+seed+fertilizer+herbicide+density+harvest+manage+land+age	AG+EE	−4,276	12	0.000	0.86300	1	1.35 %
8	Yield ~ soil+area+seed+fertilizer+herbicide+density+harvest+capital+d.mill+d.road+manage+land+age	AG+SC+EE	−4,275	14	3.776	0.13061	6.607	1.35 %
4	Yield ~ manage+land+age	EE	−4,283	10	9.959	0.00594	145.377	1.19 %
7	Yield ~ capital+d.mill+d.road+manage+land+age	SC+EE	−4,282	13	15.074	0.00046	1,876.237	1.20 %
5	Yield ~ soil+area+seed+fertilizer+herbicide+density+harvest+capital+d.mill+d.road+age	AG+SC	−4,308	4	48.874	<0.00001	40,997,706,674	0.59 %
2	Yield ~ soil+area+seed+fertilizer+herbicide+density+harvest+age	AG	−4,307	7	52.854	<0.00001	3.00E+11	0.62 %
3	Yield ~ capital+d.mill+d.road+age	SC	−4,319	6	74.445	<0.00001	1.46E+16	0.35 %
1	Yield ~ 1+age	Null	−4,334	5	102.339	<0.00001	1.67E+22	0.00 %
Income analysis								
6	Log(income) ~ experience+area+type+coop+price+education+migrant+yield	AG+EE	−301.682	11	0.000	0.79065	1	20.57 %
8	Log(income) ~ experience+area+d.mill+d.road+type+coop+price+education+migrant+yield	AG+SC+EE	−300.841	13	2.658	0.20935	3.77	20.79 %
2	Log(income) ~ experience+area+yield	AG	−339.93	6	65.893	<0.00001	2.03E+14	10.50 %
5	Log(income) ~ experience+area+d.mill+d.road+yield	AG+SC	−338.675	8	67.582	<0.00001	4.74E+14	10.83 %
7	Log(income) ~ d.mill+d.road+type+coop+price+education+migrant+yield	SC+EE	−337.368	11	71.373	<0.00001	3.15E+15	11.17 %
4	Log(income) ~ type+coop+price+education+migrant+yield	EE	−340.33	9	73.014	<0.00001	7.16E+15	10.39 %
1	Log(income) ~ 1+yield	Null	−379.811	4	141.511	<0.00001	5.35E+30	0.00 %
3	Log(income) ~ d.mill+d.road+yield	SC	−378.321	6	142.675	<0.00001	9.58E+30	0.39 %

LL log likelihood, *K* number of parameters, *ΔAICc* difference between the AIC*c* value and the minimum AIC*c* value within the model set, *wAICc* refers to the weight of the model which represents the relative probability of each model being the best model within the model set, *Evidence ratios* provide model weight assessments to the best fit model , *%DE* percentage deviance explained quantifying the amount of variation in the response variable explained by the model itself, *AG* agronomy practices, *SC* supply chain for production and sale of oil palm fruit, *EE* enabling environment for smallholder development the categorical variables predicted the annual yield per hectare within the observed bootstrapped 95 % confidence intervals of annual yields from oil palm smallholdings although plantations which were harvested only once a month predicted annual yields which were slightly above the lower limit of our bootstrapped 95 % confidence interval (Fig. 2(f)). Once-a-month harvesting predicted the lowest annual fresh fruit bunch yields (14.82 t/ha) from our bootstrapped model. Variables which predicted lower annual yields per hectare from oil palm plantations include mixed (mineral and swamp) soil type, low and mixed seed quality, insufficient use of fertilizer types and organic fertilizers, smallholdings which were managed independently, and minimum land tenure security (Fig. 2(a–e)). Increasing the area of smallholdings resulted in slightly decreasing yields while increasing the density of palm plantings led to increase in yields. Increasing the volume of herbicide applied led to only minimal increase in oil palm yields (Fig. 2(g–i)).

3.3 Household income from oil palm cultivation

Oil palm is a major source of income for rural communities visited in our survey. The mean percentage contribution to total income from oil palm agriculture in our study, 77 %, was slightly higher compared to 63 % reported by Susila (2004), and fell within the range of 63–78 % from Budidarsono et al. (2012). Mean gross monthly income from oil palm cultivation of an oil palm smallholder household was 4.74±5.82 million Indonesian rupiah (IDR) or 555.03 US dollars (USD) (1 USD =8,540 IDR for July 2011) and ranged widely from 50,400 IDR to 45.9 million IDR.

The best model for predicting variations in gross monthly income from oil palm cultivation was a combination of variables associated with the agronomy practices within smallholder plantations and the enabling environment for smallholder development. This model accounted for 79.1 % of the

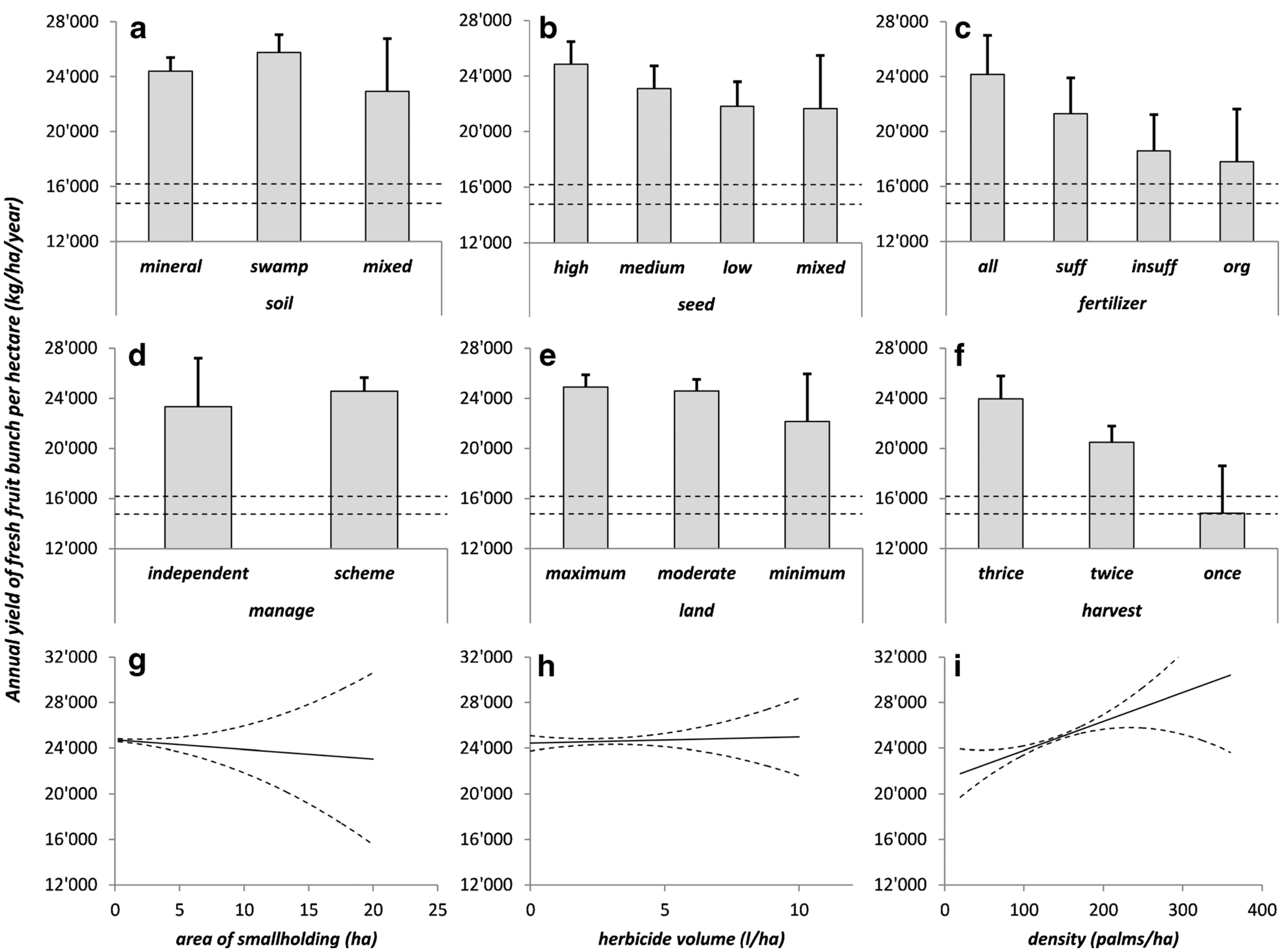

Fig. 2 Predicted annual yield of fresh fruit bunch for each variable considered in the generalized linear mixed-effect modeling (GLMM) incorporating soil type (*a*), seed quality (*b*), fertilizer sufficiency (*c*), management of smallholding (*d*), land tenure security (*e*), harvesting rotation (*f*), area of plantation (*g*), herbicide volume (*h*), and density of palm plantings (*i*). The observed annual yield of fresh fruit bunch 95 % confidence interval (*dotted horizontal lines*) was determined by a 10,000 iteration bootstrap predicted by the "best" model that included a combination of variables from agronomy practices within smallholder plantations and the enabling environment for smallholder development. *Error bars* represent the 10,000 iteration bootstrapped upper 95 % confidence limits. *Suff* sufficient, *insuff* insufficient, *org* organic. See Table 1 for description of variables

Akaike weights in the model set, and the percentage deviance explained was 20.57 % (Table 3). The second best model was the full model which included variables associated with the agronomy, supply chain for production and sale of fresh fruit bunch, and the enabling environment for smallholder development. This model accounted for 20.9 % of the Akaike weights in the model set, and the percentage deviance explained was 20.79 % (Table 3). Altogether, these two models represent more than 99 % of the Akaike weights present in the model set. The best fit model is represented by the following equation:

$$Log(income) \sim 0.09383 \times experience + 0.42447 \times area + 0.40545 \times type_{manage} + 0.25387 \times type_{supported} + 0.05429 \times coop_{veryactive} + 0.36285 \times coop_{active} + 0.26448 \times coop_{member} + 0.39055 \times price - 0.11941 \times education_{primary} - 0.09423 \times education_{secondary} + 0.02579 \times education_{tertiary} - 0.09006 \times migrant_{migrant} + 0.35979 \times yield + 14.58404$$

Within the above model, the coefficients represent the effect sizes of individual predictor terms and were used to make income predictions of oil palm smallholder households under a 10,000 iteration bootstrapped model (Fig. 2). All terms within the categorical variables predicted gross monthly income from oil palm cultivation within the observed bootstrapped 95 % confidence intervals except for independent smallholders (Fig. 3(a–d)). Independent smallholder households predicted the lowest gross monthly income from oil palm cultivation (2.17 million IDR) from our bootstrapped model. Active participation in smallholder cooperatives predicted higher gross monthly income although very active participation in cooperatives predicted similar gross monthly income as smallholders who were not involved in cooperatives. Migrant status and highest education level attained by smallholders showed no clear trends in predicting gross monthly income. Unsurprisingly, increasing the number of years of experience working in oil palm cultivation, the total area of oil palm plantation owned, and the price of fresh fruit bunch predicted increasing gross monthly income of smallholders (Fig. 3(e–g)).

3.4 Improving yields and benefit sharing for oil palm smallholders

Improving smallholder oil palm yields has been given increasing attention by the Indonesian government (Yulisman 2011) and international organizations (World Bank 2011; Fitriyardi 2012). While fertilizer and good seedlings are the basis of high yields for oil palm cultivation, best management practices within plantations can help reduce the oil palm yield gap (Donough et al. 2010). Our results provide empirical support for the importance of optimal harvesting towards increasing smallholder oil palm yields. Within our study, harvesting once a month predicted the lowest yields in smallholder oil palm plantations (Fig. 2(f)). Harvesting rotation within an oil palm plantation has a strong impact on the productivity of the oil palm, and short harvesting intervals (7–10 days) have shown to improve fresh fruit bunch productivity of oil palm crops (Donough et al. 2010).

From an environmental perspective, it is interesting to note the response of smallholder fresh fruit bunch yields to organic fertilizers and increasing volume of herbicide used. While organic fertilizers predict lower annual yields than the use of all types of mineral fertilizers (17.8±3.8 t/ha compared to 24.2 ±2.8 t/ha, Fig. 2(c)), the predicted yields from organic fertilizers fell within the range of our observed bootstrapped values from our best predictor model. Therefore, organic fertilizers are feasible as an alternative nutrient source for oil palm smallholdings though they do not lead to maximum yields. On average, 2.4±1.8 l of herbicide (e.g., glyphosate) is used per application to remove weeds in smallholder plantations. Increasing the volume of herbicides does little to increase yields within oil palm smallholdings (Fig. 2(h)). Based on our interviews, some smallholders have the impression that blanket spraying of herbicides is “cleaner” and therefore better for their oil palm plantations. As shown from our results, increasing herbicide use leads to minimal increases in yields and may instead be an additional operational cost for smallholders.

Improving benefit sharing within the oil palm smallholder sector is important given that over the last two decades, there has been a growing socio-economic gap among oil palm smallholders in Indonesia (McCarthy 2010; McCarthy et al. 2012). Our results show that independent smallholders who are not tied to any oil palm company receive the lowest gross monthly income from oil palm cultivation. While yields for independent and scheme smallholdings do not show large differences (Fig. 3(d)), the difference in gross monthly income is most likely related to the price received by independent smallholders for their fresh fruit bunch. At an early stage of oil palm development, the mean fresh fruit bunch price received by independent smallholdings (1,221±15 IDR/kg) was 10 % lower compared to scheme smallholdings (1,345±39 IDR/kg). At a later stage of oil palm development, the mean fresh fruit bunch price received by independent smallholdings (1,303±21 IDR/kg) was 6 % lower compared to scheme smallholdings (1,382±20 IDR/kg). Disadvantages in fresh fruit bunch prices for independent smallholders were also reported in a case study

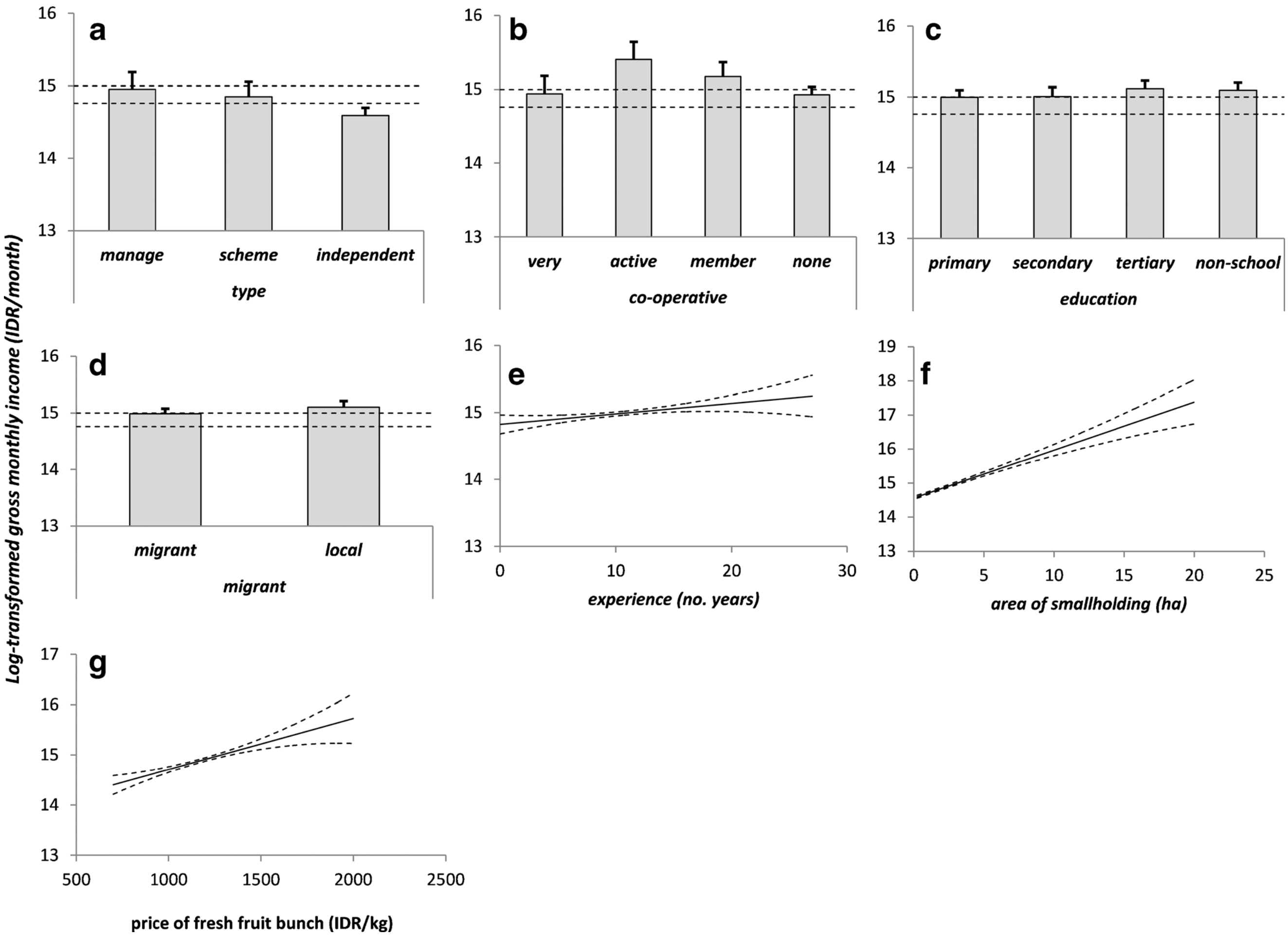

Fig. 3 Predicted gross annual income derived from oil palm cultivation for each variable considered in the generalized linear mixed-effect modeling (GLMM) incorporating type of management for smallholders (*a*), level of participation in cooperative (*b*), highest education level of smallholder (*c*), migrant status of smallholder (*d*), years of experience working in oil palm cultivation (*e*), total area of smallholding owned (*f*), and price of fresh fruit bunch (*g*). The observed gross annual income 95 % confidence interval (*dotted horizontal lines*) was determined by a 10,000 iteration bootstrap predicted by the "best" model that included a combination of variables from agronomy practices within smallholder plantations and the enabling environment for smallholder development. *Error bars* represent the 10,000 iteration bootstrapped upper 95 % confidence limits. *Very* very active, *none* non-involved. See Table 1 for description of variables

in Riau where marketing costs for independent smallholders was 94 IDR/kg, approximately twice that for scheme smallholders in the vicinity (Rifal et al. 2008). The costs of marketing fresh fruit bunch for independent smallholders is higher since smallholders could not access oil palm mills directly without a letter of entitlement such as a delivery order or *Surat Pengantar Buah (SPB)*. Indeed, the oil palm middlemen we came across in all our study districts noted that owning a SPB is mandatory for selling their fresh fruit bunch to any processing mill, and an individual SPB is needed for individual processing mills. Oil palm middlemen who did not possess a SPB will have to borrow another middleman's SPB, and this may incur borrowing costs which are then passed on to independent smallholders. However, scheme smallholders may not always have fairer prices for their fresh fruit bunch as shown in Kalimantan where unrelated costs (e.g., oil palm mill depreciation costs, oil palm company's bank interest rates) are transferred from the oil palm company to their scheme smallholders (Gillespie 2011).

Variables under agronomy and the enabling environment for smallholder development were most important in predicting variations for both annual yields from smallholder plantations and gross monthly income from oil palm cultivation. Interestingly, factors under the supply chain for production and sale of oil palm fruit did not appear in both yield and income best models but did appear under second best models. While distance to public roads and mills are important in accounting for the full weights (>99 %) in the model set, on-time and efficient transportation services were perhaps sufficient to make up for long distances from roads and mills. For example, smallholders sampled in Musi Banyu Asin were located more than 30 km away from an oil palm mill but were capable of arranging timely and efficient transportation of the fresh fruit bunch to the mill. Hence, taking into consideration the quality of transportation services may have been more representative for our analysis. The percentage deviance represented by our models in the yield analyses was very low (0.35–1.35 %; Table 3), suggesting that the effects from our predictor terms were weak. One of the main caveats of our yield analysis was the use of the number of essential fertilizers instead of the quantity of fertilizers used as a variable. Previous research has shown that quantity of fertilizers greatly influences fresh fruit bunch yields within oil palm plantations (Corley and Tinker 2003). Although we did capture data on the amount of fertilizers used by smallholders, this measurement was not complete for our entire dataset and had to be excluded. We recommend that future studies looking into smallholder oil palm yields include quantity of fertilizer usage as an important variable for consideration.

4 Conclusion

Our results indicate that a combination of factors under the agronomy of oil palm smallholdings and the enabling environment for smallholder oil palm development best explain variations in both smallholder oil palm yields and household incomes. Good practices in agronomy within oil palm smallholdings are a result of smallholders' own experience and knowledge in oil palm agriculture and smallholders' enabling environment which defines the level of support smallholders receive in terms of access to training and agricultural inputs. From our model predictions, we highlight two specific variables, harvesting rotation and type of smallholder management, which were shown to constrain smallholder oil palm yields and incomes, respectively. Improving smallholder yields and income to increase productivity and benefit sharing within Indonesia's oil palm industry therefore require both intensive agricultural extensions to smallholders in Indonesia and state intervention policies to ensure smallholders have an enabling environment for oil palm development. Based on the main findings of our study, we recommend (1) prioritizing agricultural extension on best management practices for independent smallholders and (2) improving access to oil palm mills to lower marketing costs of fresh fruit bunch for independent smallholders. While agricultural extension and state intervention policies continue to be important for smallholder yields and income, the approach taken should be considered in light of Indonesia's past agricultural extension policies for smallholder tree crop development. Some lessons drawn from Indonesia's experience with smallholder oil palm and rubber projects in Sumatra and Kalimantan include the need for stronger institutional structures, greater mobilization of farmers into cooperatives, and better resources to manage credit for smallholders (ADB 2005; IEG 2012).

At present, Indonesia's smallholder oil palm sector is more influenced by market-driven processes following government decentralization and a withdrawal of state engagement in supporting smallholder programs (McCarthy 2010). Without active involvement of a developmental state to ease constraints for oil palm smallholders, the *laissez faire* approach may leave poor oil palm smallholders, especially independent smallholders, vulnerable to global market processes (McCarthy 2010). Given that the Indonesian government is considering further expansion of oil palm estates to increase crude palm oil production, it is crucial to empirically assess how much of this desired growth can be met sustainably through increasing smallholder yields and developed in a way where smallholder incomes can be improved (Ministry for Economic Affairs 2011). Understanding variations in smallholder oil palm yields and income is a useful first step in this direction.

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