

Agronomy explains large yield gaps in smallholder oil palm fields

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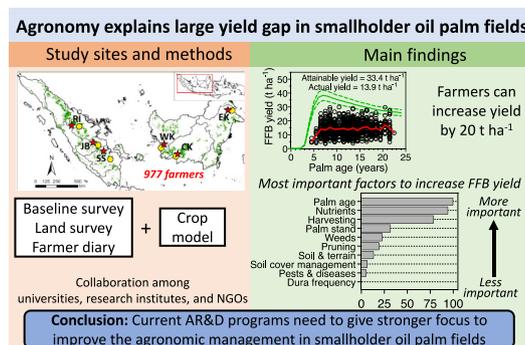
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HIGHLIGHTS

- The role of agronomic management for explaining yield gaps in smallholder oil palm fields has received little attention.
- We assessed yield gaps in smallholder oil palm fields using a crop model, survey data, and field measurements.
- Average farmer yield was low, representing 42% of the attainable yield as determined by local weather and soil.
- Among management practices, nutrients, harvest interval, weeds control, and pruning have largest influence on yield gaps.
- Improving agronomic management can increase smallholders oil palm yield and profit on existing plantation area.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Palm oil production is a major source of income for millions of smallholders in Indonesia. However, actual yield remains low in relation to the attainable yield. While emphasis has been given to planting material as a factor explaining low yield in smallholder fields, the role of agronomic management has received less attention. **OBJECTIVE:** We assessed the role of agronomic management in explaining low oil palm productivity in independent smallholder fields in Indonesia.

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Yield gap
Agronomic management

METHODS: We quantified yield gaps and their causes using data on fresh fruit bunch (FFB) yield and management practices collected over two years across 977 fields. The yield gap was estimated for each field as the difference between actual and attainable yield. The latter was estimated using a crop model, local weather and field-specific soil and palm age. Statistical techniques were used to identify factors explaining yield gaps.

RESULTS AND CONCLUSIONS: Average yield represented 42% of the attainable yield, with largest yield gaps occurring in young plantations. Our analyses identified agronomic practices explaining yield gaps, including nutrient management, harvest interval, weed control, and pruning. Improved agronomic management can help smallholders increase yield and profit on existing plantations.

SIGNIFICANCE: There is an opportunity to produce more palm oil on current plantation area via better agronomy, generating a positive economic impact at local to national levels, while reducing pressure to clear new land for cultivation. Research & extension programs should be re-oriented to give more emphasis to agronomic management.

1. Introduction

Oil palm is a perennial crop grown in tropical environments and the largest source of vegetable oil in the world (OECD, 2020). Oil extracted from the palm's fresh fruit bunches (FFB), typically referred to as crude palm oil (CPO), is used for cooking, processed food, cosmetics, cleaning products, and biodiesel. Indonesia is the main CPO producing country in the world, accounting for 60% of global production (2019/20, FAOSTAT, 2023). Revenue from CPO is a major source of income for Indonesia, accounting for 10% of national exports, and to >2.5 million smallholder households (Statistical Yearbook of Indonesia, 2022; Statistical of National Leading Estate Crops Commodity [WWW Document], 2020). Additionally, it provides a significant and affordable source of calorie for the people of Indonesia and elsewhere in Asia (FAOSTAT, 2023; OECD, 2020). The CPO output has increased six-fold from 2000 to 2020, which was driven by a sharp increase in plantation area in Indonesia (+10.7 M ha). In contrast, average yield, reported here as tons of FFB per hectare per year, has remained unchanged during the same period (FAOSTAT, 2023; Statistical of National Leading Estate Crops Commodity [WWW Document], 2020). Given growing global demand for vegetable oil and recent national mandates on CPO-based biodiesel in Indonesia (OECD, 2020; Ungku and Munthe, 2021), concerns exist about further land conversion for oil palm cultivation and associated biodiversity loss and greenhouse gasses (GHG) emissions (Curtis et al., 2018; Gaveau et al.,

2016; Wilcove et al., 2013). Increasing yield on existing plantation area can help Indonesia to produce more palm oil, benefiting smallholders and the country as a whole, while avoiding conversion of natural ecosystems.

Total oil palm area in Indonesia was ca. 15 M ha by year 2021, with smallholders and large plantations accounting for 40% and 60% of the area, respectively (Statistical of National Leading Estate Crops Commodity [WWW Document], 2020). Nearly two thirds of the smallholder area corresponds to independent farmers who are not connected to a large plantation, while the other third is managed by farmers that have a contract with a large plantation company (commonly referred to as "plasma") that provides technical and financial assistance (Euler et al., 2016; Jelsma et al., 2017a; Molenaar et al., 2013). Using a process-based crop model and high-quality weather and soil databases, Monzon et al. (2021) showed that actual farmer FFB yield (Y_a) is lower in smallholder fields compared with large plantations, with average FFB yield representing 53 and 62% of the attainable yield, respectively. The attainable yield (Y_{att}) was calculated as 70% of the simulated yield potential. Unfortunately, official statistics does not show yield data separately for independent and plasma smallholders, which is expected to be lower in the case of independent farmers (de Vos et al., 2021; Euler et al., 2016; Molenaar et al., 2013; Woittiez et al., 2017). To our knowledge, there has been no explicit effort to assess the magnitude of the yield gap for independent smallholders in Indonesia. This information is crucial to

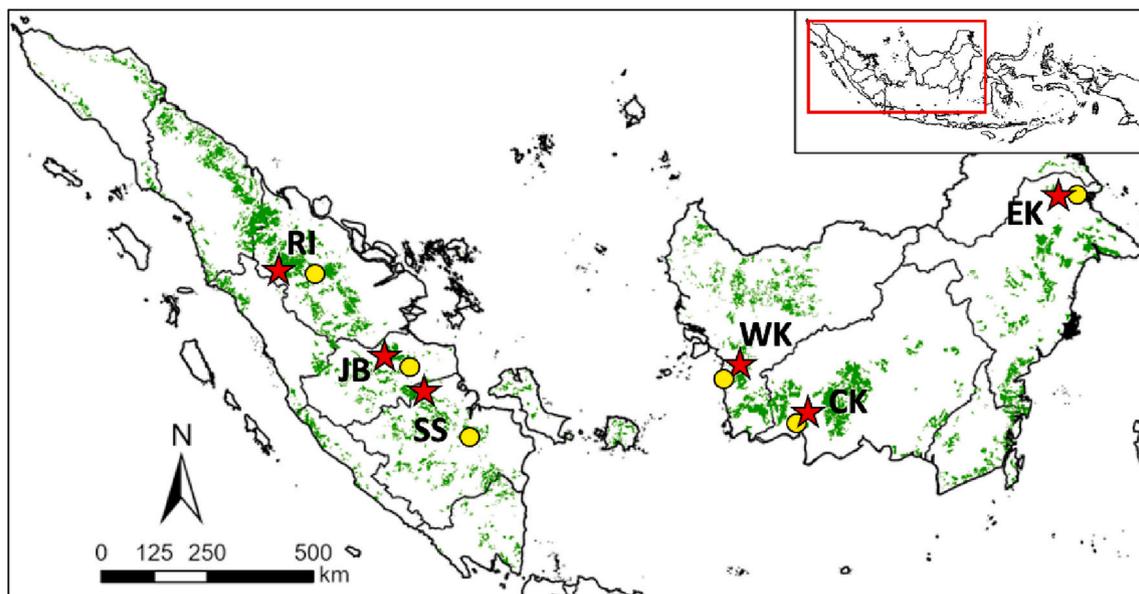


Fig. 1. Map of the six study sites in Indonesia (stars) and nearest meteorological stations with available daily weather data (yellow circles). Sites are refer according to the name of the provinces where they are located: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), Central Kalimantan (CK), and East Kalimantan (EK). Oil palm area distribution in mineral soils is shown in green (Harris et al., 2018). Inset shows location of the study area within Indonesia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

determine the potential impact that yield improvement in independent smallholder fields can have at local, regional, and national levels, and associated potential benefits on land savings and climate change mitigation (Euler et al., 2016; Molenaar et al., 2013; Monzon et al., 2021).

Current efforts to increase oil palm yield in independent smallholder fields focus on replanting programs, in which farmers are encouraged to replant their fields with certified planting material (www.ekon.go.id, www.gapki.id, Ardana et al., 2022; Molenaar et al., 2013; Woittiez et al., 2017). Typically, large plantations are planted with certified planting material with high frequency (>98%) of Tenera palms (Sidhu et al., 2020). In contrast, smallholder fields are commonly planted with non-certified planting material containing higher frequency of Dura palms (Molenaar et al., 2013). Oil extraction rates (OER) are different between the two palm types, in Tenera palms OER is generally 25–30% higher than in Dura palms (Corley and Law, 2001; Ooi et al., 2016). Hence, oil yield is expected to increase when smallholder fields, originally planted with non-certified planting material, are replanted at the end of the plantation cycle with certified Tenera planting material. Besides socio-economic barriers limiting adoption of new planting material (e.g., lack of financial resources and incentives, access to technical information), the associated timeline for impact is long given the usual replanting cycle of 25 years. Hence, at question is what smallholder farmers can do *now* with their *existing plantation and planting material* to improve their yield and profit. In connection to this question, Jelsma et al. (2017b), Molenaar et al. (2013), and Euler et al. (2016) associated low FFB yield in smallholder fields, even in those planted with certified planting material, with poor agronomic management. Hence, it is important to assess the potential impact that better agronomic practices can have on yield in independent smallholder fields, as an approach to increase productivity of current plantations and those replanted with certified planting material.

There is a dearth of research in relation to the role of agronomic management at explaining low productivity in independent smallholder fields. To fill this gap, we performed a rigorous evaluation of the current yield gap and its causes in independent oil palm smallholder fields across six sites in Indonesia. To do so, we used data on FFB yield and management practices, complemented with in-situ field measurements, collected from 977 independent smallholder fields located in mineral soils. We used crop modeling to establish the size of the yield gap, and statistical techniques of diverse complexity, ranging from tercile comparison to random forest regression to determine the underlying causes. Implications of our findings for orienting crop intensification in independent smallholder fields and informing policy are discussed.

2. Materials and methods

2.1. Field selection and mapping

Our study focused on six sites located within the oil palm producing area in Sumatra and Kalimantan islands in Indonesia (Fig. 1). Sites were selected based upon availability of local partners to collect the data and included only independent smallholder fields in mineral soils. We note that ca. 80% of oil palm area in Indonesia is located in mineral soils. Selected sites were located in five climate-soil domains, as defined by Agus et al. (2023), that represent 87% of oil palm area in mineral soils in Indonesia. In selecting farmers for this study, we excluded those with fields where oil palm was intercropped with other crops (e.g., banana, cassava, etc.), home gardens (<0.1 ha), and immature (< 3 years) or very old plantations (> 25 years). Following these criteria, we selected 200 independent smallholders at each site, totaling 1200 farmers across sites. For simplicity, we referred to the sites using the names of the provinces where they are located: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), Central Kalimantan (CK), and East Kalimantan (EK).

Yield and management data were collected from individual fields, defined as the parcel of land that was planted, managed, and harvested

as a unit. One third of the farmers have more than one field; in those cases, we only considered the largest field for our study. We partnered with local non-governmental organizations (NGOs) to collect farmer data: World Resources Institute-Indonesia in RI (<https://wri-indonesia.org/>), Setara Jambi in JB and SS (<https://www.setarajambi.org/>), Bentang Kalimantan in WK (<https://bentangkalimantan.org/>), Posyantek in CK, and Plan B in EK (<https://planb.co.id/tentang-kamiin>). Farmers do not necessarily know their field size and, even if they do, small inaccuracies can lead to large biases given the small size of their fields (average: 2 ha). On the other hand, mapping field boundaries of smallholder fields can be challenging given their irregular shapes and fuzzy boundaries with other adjacent fields. We minimized these sources of error by mapping each field in the presence of farmers and with the aid of GPS devices and drones. Additionally, we performed independent audits to re-check the mapped field boundaries and adjusted them whenever discrepancies were found.

2.2. Collection of yield and management data and quality control

We collected data following three complementary approaches: (i) baseline survey, (ii) land survey, and (ii) farmer diary. Baseline and land surveys were conducted once at the beginning of the project (between Oct 2019 and April 2020). The baseline survey was performed by trained NGO personnel via personal interviews with each farmer. This survey included a structured questionnaire containing questions on agronomic and socio-economic variables, such as experience at growing oil palm, previous agronomic training, and sources of labor (Supplementary Table S1). Additionally, we performed a land survey to collect detailed field information, such as palm density, frequency of Dura palms (hereafter referred as ‘dura frequency’), weed infestation, and soil depth and texture (Supplementary Table S2). We also scouted for abnormal palms (unfertile palms, mainly Pisifera palms), palms infected with *Ganoderma* spp. and supply palms (young palms in their unproductive phase that were planted some years after the field was planted to replace dying palms). The sum of these three categories (abnormal, *Ganoderma* infected, and supply palm) is hereafter referred as “low productive palms”.

The land survey was performed by trained personnel from the Indonesian Oil Palm Research Institute (IOPRI, <https://www.iopri.org/>) following a standard protocol that aimed to cover field variability. Collected soil data was further verified with assistance from personnel from the Indonesian Soil Research Institute (ISRI) using available soil maps for the sites (Indonesian Soil Map Scale 1:250,000, 2012). Additionally, based on the mapped field boundaries, the mean topographic wetness index (TWI) was calculated for each field to determine the likelihood for runoff and run-on (Sørensen et al., 2006). Fields with high TWI values are more likely to receive runoff water from adjacent areas and vice versa. TWI was calculated using the *rsaga.wetness.index* package in R (R development Core team, 2016) based on a 5-m resolution Digital Elevation Model (DEM) retrieved from MAPZEN (<https://www.mapzen.com/data/elevation/>).

Following the baseline and land surveys, we implemented a ‘farmer diary’. Each farmer was asked to keep records on harvested FFB and prices, applied inputs, field upkeep activities, and associated timing, cost, and labor (Supplementary Table S3). We asked farmers to keep records of prices and amount of FFB associated with each harvest round. The amount of FFB was weighted at the field edge by farmers and FFB collectors before being loaded to the truck and transported to the mill. Diary data were collected monthly by the local NGO partners and put into a digital database. Quality control measures were implemented to detect erroneous data entries, typos, outliers, etc. To do so, we established protocols specifying acceptable ranges for data entries for each variable. Data were rechecked by local partners and corrected as needed. In general, smallholders do not know their production and applied inputs on a per-hectare basis, but rather on a per-field basis. To overcome this limitation, smallholders were requested to periodically

report their data on production and applied inputs on a field-basis. Subsequently, we estimated yield and input rates (per-hectare) according to the mapped field size and the accumulated amount of FFB and input reported during each year. Following this approach allowed us to retrieve robust estimates of FFB yield, fertilizer rates, and other variables on a per-hectare basis for each field. In the present study, we used diary data collected over two consecutive years, starting on Jan 1, 2020 and ending on Dec 31, 2021.

Despite our efforts to minimize sources of error in mapping field and collecting farmer data, there were still fields exhibiting unrealistic values. For example, in some fields, annual FFB yield exceeded 35 t FFB ha⁻¹, suggesting that the reported harvested FFB may have included bunches from other adjacent fields. In other cases, yield was extremely low (<3 t FFB ha⁻¹) and/or average harvest interval was too long (>45 days) suggesting that the field was quasi-abandoned and/or subjected to prolonged flooding. In connection to this point, there was an unusual long flooding event in WK during 2020, which impeded access to some of the fields for a long period of time. These fields were excluded from the database after verification with local partners, field visits, and cross-checking with other variables reported by farmers. Similarly, even though data collection started in late 2019, we excluded data collected before Jan 1, 2020 to avoid possible mistakes in data collection at the beginning of the project. After the quality control, the final database used for the analyses contained 977 fields. Despite a full cross-validation of the database was not possible given lack of data from independent sources, we made efforts to evaluate the level of uncertainty. For example, our estimated average FFB yield was not statistically different (two-tailed *t*-test; *p* = 0.65) from reported FFB verified *in-situ* by our project auditors across 30 independent field trials located in five of the six sites during the same period (Sugianto et al., 2022) (Supplementary Fig. S1). Overall, we believe that the data collected in this study are accurate and provide a good representation of the yield and management background of independent smallholder fields in Indonesia.

2.3. Estimation of water-limited yield potential and attainable yield

Crop yield potential is determined by solar radiation, CO₂ level, temperature, and crop traits influencing capture of solar radiation and its conversion into dry matter (Evans, 1993; Fairhurst and Griffiths, 2015). Yield potential of oil palm is also influenced by age as plantations start to produce two to three years after planting, which is followed by a sharp yield increase until reaching a peak, and a subsequent gradual decline in productivity over time until replanting (Fairhurst and Griffiths, 2015; Goh et al., 1994; Ng et al., 1990). In the case of rainfed fields, as it is the case of oil palm in Indonesia, water supply and soil properties that influence the soil water balance impose another upper limit to yield potential, hereafter referred to as ‘water-limited yield potential’ (Yw) (van Ittersum et al., 2013). In the present study, we estimated Yw using PALMSIM v2.0 crop simulation model (Hoffmann et al., 2014; Hekman et al., 2018). The model provides estimates of Yw on a field-scale level at a daily time resolution and requires specification of climate and soil properties. The model has been used to benchmark yields in large plantations and smallholder fields in previous studies (Hoffmann et al., 2015, 2017; Monzon et al., 2021). When simulating Yw, PALMSIM assumes no limitation by nutrients and no yield reductions due to incidence of weeds, pathogens, insect pests and excess water. Details on model calibration and evaluation are provided elsewhere (Hekman et al., 2018; Monzon et al., 2021).

In the present study, we estimated Yw in 2020 and 2021 for each field based on local weather, palm age, and soil properties such as depth and texture. Precipitation was measured at each site using rain gauges while daily measured data on incident solar radiation, minimum and maximum temperature, relative humidity, and wind speed were retrieved from the nearest meteorological station to each site (BMKG; <http://www.bmkg.go.id/>) (Fig. 1). Palm age and soil properties needed for crop simulations were retrieved from the data collected via the land

survey. Following Monzon et al. (2021) and references cited therein, the attainable yield (Yatt) was calculated as 70% of the simulated Yw for each field-year. Reaching 70% of Yw is a realistic goal for farmers with adequate access to inputs, markets, and technical information (Donough et al., 2010; Hoffmann et al., 2017) and consistent with previous studies on oil palm (Hoffmann et al., 2017) and other crops (Lobell et al., 2009). For each field, Yatt was estimated as the average over the two years (2020–2021).

We validated our approach to estimate Yatt using an original FFB yield database collected from large plantations, provided by two private oil palm companies. The database included annual FFB yield from a total of 207 commercial blocks located in mineral soils in Sumatra and Kalimantan between 2010 and 2020 (total of 1908 block-year observations), with palm age ranging from seven to 25 years. Detailed description of the database is provided elsewhere (Agus et al., 2023). We compared these FFB yield data against the average Yatt estimated for our six study sites, separately for the entire yield database and for the top 10 highest-yielding blocks for each palm age. The evaluation served two purposes: (i) to validate model predictions of Yatt over the range of palm age and (ii) to provide proof of concept for the assumption of 70% of Yw as the Yatt with proper agronomic management.

2.4. Data analysis

We averaged data from the farmer diary on actual FFB yield (Ya), fertilizer use and harvest interval, over the two years, for each field to minimize the impact of episodic reporting errors and/or transitory changes in management practices. To enable cross-site comparisons we normalized the data to field-specific Yatt, *i.e.* average (2-y) Ya for each field was expressed as a percentage of the associated Yatt (Yatt%). Low and high Yatt% values indicate respective low and high Ya in relation to Yatt in each field, providing an indication of the magnitude of the yield gap. Along this article, Ya and Yatt are expressed in metric tons of FFB per hectare per year.

We performed three independent statistical analyses, with diverse level of complexity, to identify causes of yield gaps: (i) comparison of terciles of Yatt%, (ii) conditional inference tree, and (iii) random forest regression analysis. These approaches have been used in previous studies aiming to identify causes of yield gaps (Mourtzinis et al., 2018; Rattalino Edreira et al., 2017; Tenorio et al., 2021). Identifying the same causes of yield gaps using three approaches would give confidence about the robustness of the results. In our analyses, we considered Yatt% as the dependent variable while all the management collected through the baseline and land survey and farmer diary variables (*e.g.*, applied inputs, weed infestation, frequency of Dura palms, etc.) were treated as independent variables (Supplementary Table S4). Measured terrain and soil properties were also included in our analyses to identify possible interactions between management practices and soil types. Following Cock et al. (2016), we analyzed if TWI, soil texture (fine, medium, coarse) and water table (shallow, intermediate, deep) were correlated or clustered into different combinations separately for each site. Since we did not detect any statistically significant difference in Ya and Yatt% among these variables, we decided to include TWI, soil texture, and water depth as individual independent variables in our statistical analyses.

For the tercile comparison analysis, we compared management practices between fields in the upper (UT) versus lower tercile (LT) of the field Yatt% distribution. Statistical significance was evaluated using *t*-tests or chi-square tests for continuous and categorical variables, respectively. Conditional inference trees estimate the relationship among several variables by binary recursive partitioning in a conditional inference framework using distributional properties of variables (Hot-horn et al., 2006). Here, we performed conditional inference tree analysis using the *partykit* package in R (R Development Core Team, 2016). Briefly, the algorithm tests the null hypothesis of independence between the response variable (Yatt%) and any of the independent variables. To

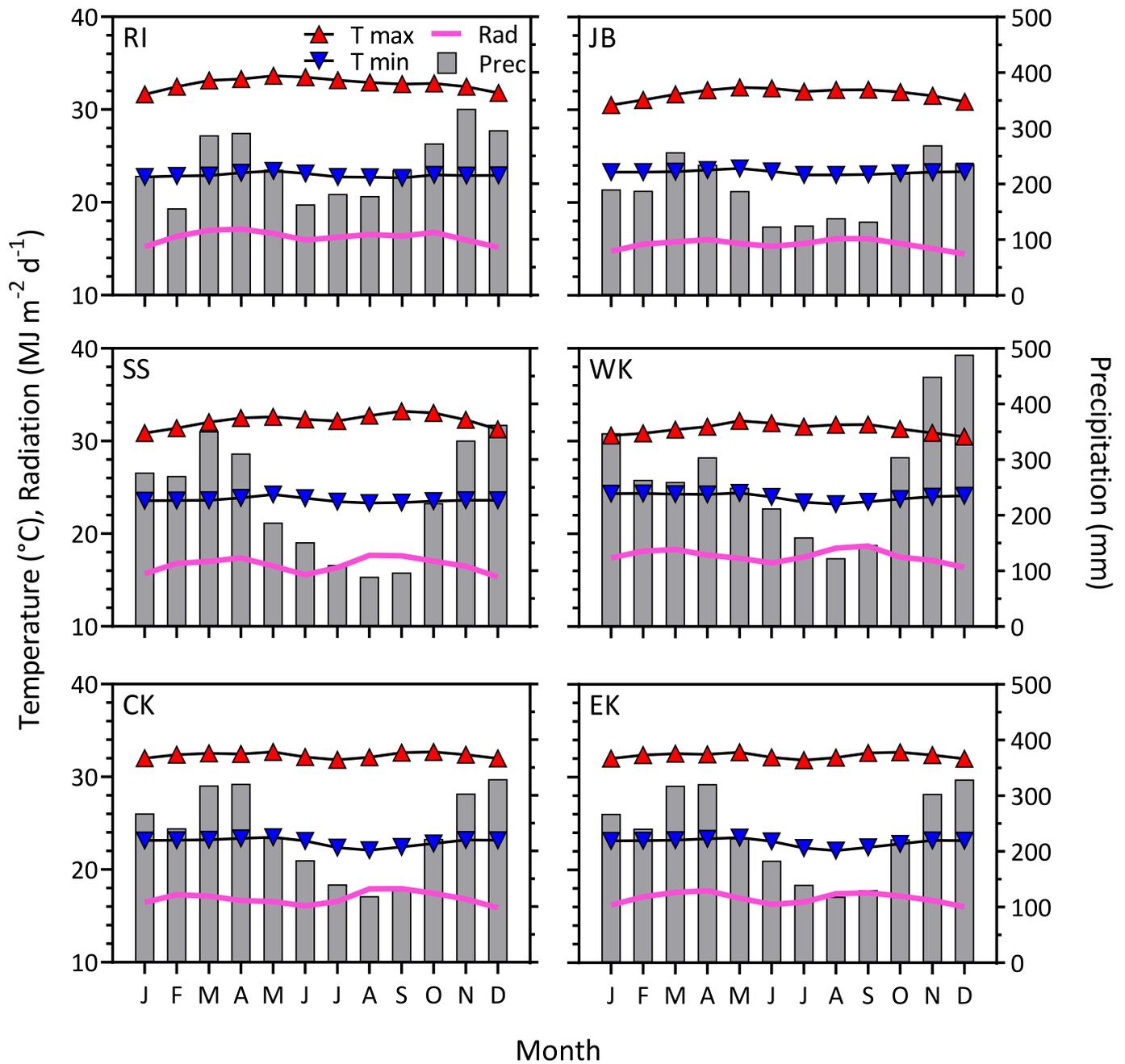


Fig. 2. Long-term (1990–2020) monthly average minimum and maximum temperature (Tmin and Tmax, respectively), incident solar radiation (Rad), and total precipitation (Prec) across the six study sites. Data were measured in weather stations located in proximity to our study sites. See caption to Fig. 1 for province acronyms.

ensure adequate power, besides the *p*-value, we ensured that each intermediate node account for a minimum of 33% of total observations, and a terminal node should contain a minimum of 11% (one third of observations in an intermediate node). All these criteria must be met at every step of the algorithm so that a variable can qualify for a split. To avoid overfitting and enhance interpretability, the maximum tree depth was set to 10 nodes. Explanatory power of the conditional inference tree was calculated with the coefficient of determination (*r*²) and root mean square error (RMSE). Finally, random forest regression is a machine-learning technique, that operates by constructing multiple conditional inference trees (Ho, 1995). Here, random forest regression analysis was performed using *randomForest* package in R (Breiman, 2001) to quantify the importance of each independent variable, which was based on how much the mean accuracy of the prediction decreases

when a variable is excluded. We note that ca. 200 fields per site would provide a sample size that is reasonable to identify yield constrains using farmer-reported data (Mourtzinis et al., 2018).

To synthesize information provided by the three analyses (*i.e.*, tercile comparison, conditional inference trees, random forest regression), we computed the appearance frequency of each agronomic factor (Eq. (1)). To do so, we grouped variables into ten categories: nutrients (*i.e.*, N, P and K rates), pruning (*i.e.*, method, schedule, fronds per palm and pruning quality), harvest practices (*i.e.*, interval and criteria), palm age, palm stand (planting pattern, density, and frequency of low productive palms), dura frequency, soil and terrain (TWI, soil depth, water table depth, texture), soil and water management (cover crop, empty bunches application, artificial drainage, terracing, and pruned frond arrangement), weed (*i.e.*, degree of infestation and weed type), and incidence of

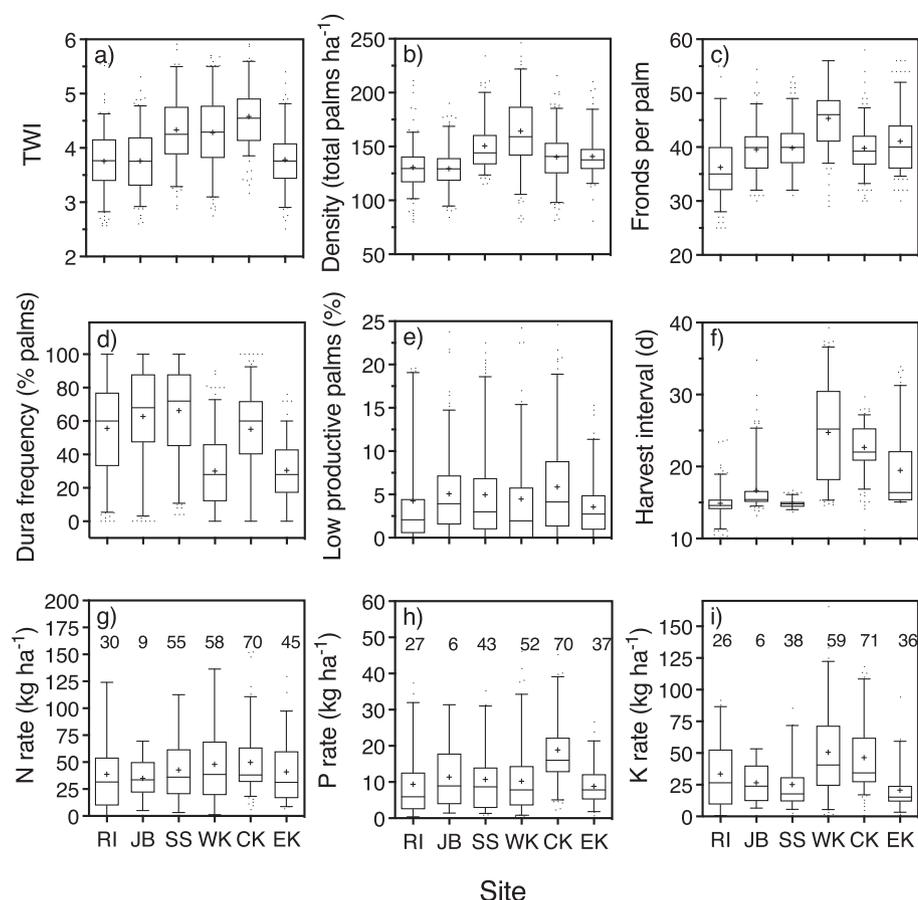


Fig. 3. Box plots for selected variables in independent smallholder fields located in sites across six provinces in Indonesia, including (a) topography wetness index (TWI), (b) palm density, (c) fronds per palm, (d) dura frequency, (e) low productive palms, (f) harvest interval, and (g-i) nitrogen (N), phosphorus (P) and potassium (K) fertilizer rates in treated fields. Lower and upper whiskers represent 5 to 95th percentiles, respectively. Means and medians are shown with crosses and horizontal lines inside boxes. Numbers inside panels (g-h) indicate frequency of fields receiving nutrient fertilizer application. See caption to Fig. 1 for province acronyms.

pest and diseases (Table 2). Following this approach, we estimated the frequency of appearance of each category across the three analyses as follows:

$$F_j = \frac{\sum_{i=1}^N J_i * W_i}{N} \times 100 \tag{1}$$

where F_j is the frequency of appearance of the j category among statistical methods (expressed in %) and w is the weight of each factor. Factors were weighted from one to zero according to their importance. To do so, weights were calculated based on (i) degree of statistical significance of the UT-LT difference for a given factor as determined through the tercile analysis, (ii) level at which the variable appeared within the conditional inference trees, and (iii) variable rank as determined using random forest regression. Following this approach allowed us to determine the overall impact of each factor at explaining the observed variation in $Yatt\%$ across sites. For example, a value of 100% for a given factor means that it was the most important one at explaining variation in $Yatt\%$ according to the three methods.

Table 1
Selected socio-economic and soil variables located in six sites in Indonesia. Also shown are the overall means. See caption to Fig. 1 for site acronyms.

Variables	RI	JB	SS	WK	CK	EK	Mean
<i>Socio-economic</i>							
Total oil palm area (ha)	2.0	4.6	3.3	1.5	2.1	4.8	3.1
FFB income (% total household income)	62	41	48	22	51	76	50
Experience growing oil palm (years)	13	10	9	6	13	11	10
Middle school or higher education (% farmers)	68	42	59	58	53	38	51
Adequate access to fertilizer (% farmers)	91	62	84	10	99	35	63
Adequate access to labor (% farmers)	9	19	21	21	25	2	16
Technical information sourced from own experience or neighbors (% farmers)	61	78	100	65	54	100	76
<i>Field variables</i>							
Steep terrain (%fields) [†]	14	37	15	9	5	5	14
Shallow soil depth (% fields) [†]	2	1	20	5	0	1	5
Shallow water table (% field) [†]	2	1	27	14	2	4	8
Coarse soil texture topsoil (% fields) [‡]	0	1	1	10	1	1	2

[†] Soils and water tables were considered shallow when <0.5 m, whereas terrain is considered steep when slope > 8%.

[‡] Following FAO soil textural classification (Soil texture, 2023).

2.5. Economic analysis

Inter-relationships between $Yatt\%$ and net profit were assessed. Only data for year 2021 was used for this specific analysis due to incomplete labor data in year 2020. Additionally, there was a big fluctuation in FFB price in Indonesia during 2022 due to CPO export bans (<https://setkab.go.id/en/govt-bans-palm-oil-export-starting-april-28/>). Hence, using data from 2021 provides a better representation of the economic outcome in smallholder fields. Gross income was calculated based on reported FFB yield and associated price received by farmers (as reported in the farmer diary). Production costs were estimated based on the farmer reported data on inputs, labor used for harvest, fertilization, and field upkeep, and associated prices. In the case of unpaid labor, mostly

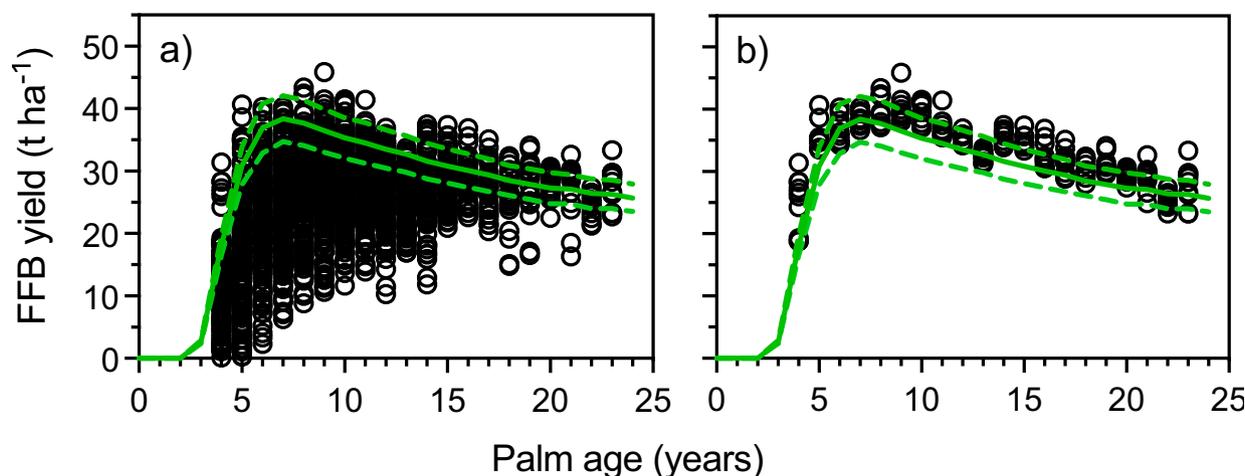


Fig. 4. Comparison between modelled attainable yield (green solid line) and measured fresh fruit bunch yield (FFB) in large plantations over the range of plant age (circles). Data from large plantations was provided by two major private oil palm companies; each circle corresponds to an individual block-year observation ($n = 1908$). The comparison is shown separately for (a) the whole database and (b) a subset that includes only the ten highest-yield blocks for each palm age. Solid lines represents the average attainable yield across the six study sites, with dashed lines representing \pm one standard deviation based on simulations with long-term measured weather data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

associated with farmer or family labor, we used the minimum wage for Indonesia for year 2021 (ca. 2 USD h^{-1} , <https://take-profit.org/en/statistics/minimum-wages/indonesia>). Finally, net profit was calculated as the difference between gross income and production costs.

3. Results

3.1. Biophysical, socio-economic, and agronomic background

Annual precipitation averaged 2801 mm across sites (1990–2020 weather data), ranging from 2305 (JB) to 3313 mm (WK). Precipitation is highest during Oct–April and lowest in May–Sept (Fig. 2). Probability of water deficit is relatively low at RI, JB, CK, WK and EK, where monthly precipitation exceeds, on average, 100 mm all year round. In contrast, risk of water deficit is higher in SS, where monthly precipitation is lower than 100 mm during two consecutive months (Aug–Sept). In contrast, risk of water excess seems higher in WK, where monthly precipitation exceeds 400 mm in Nov–Dec. Radiation and temperature varied little across sites and months, with highest and lowest values during the dry and wet season, respectively. Weather conditions during the study period (2020–2021) were comparable to the long-term means. Fields in RI, JB, and EK were prone to lose water through runoff, as inferred from their low TWI (average: 3.7), while fields in SS, WK, and CK exhibited higher TWI (4.3–4.7) indicating a higher probability for water accumulation (Fig. 3, Table 1). The majority of fields had good internal drainage, deep soils (>1 m) with fine-to-intermediate soil texture, except for 20% of fields in SS with shallow soils, 10% of fields in WK with coarse texture, and 27% and 14% of fields in SS and WK with shallow water tables.

On average, independent smallholders managed 3.1 ha of oil palm, ranging from 1.5 ha in WK to 4.8 ha in EK (Table 1). These values are well below the 25-ha threshold used in Indonesia to categorize an oil palm farmer as a smallholder (Molenaar et al., 2013). Despite the small area, income derived from oil palm cultivation accounted for half of the annual household income, ranging from 22 to 76% across sites. On average, farmers have been growing oil palm for 10 years, which means that all fields included in our study are still within their first plantation cycle, and farmers do not have any previous experience growing oil palm beyond the current cycle. Nearly half of the farmers only attended elementary school and relied on their own (or other farmers) experience as source of agronomic information. Most farmers (>60%) in RI, JB, SS and CK reported reasonable access to fertilizer, but this was not the case

in WK and EK (<35%).

One third of fields exhibited total palm densities below or above the optimal range of 140–160 palms ha^{-1} (Fig. 3). Majority of fields in RI and JB exhibited sub-optimal densities, while half of fields in WK had supra-optimal densities (Fig. 3b). Depending on frond number and palm age, one can infer if palms have been properly pruned (von Uexküll et al., 2003). Based on data on observed fronds across sites, we estimated that one out of four fields were pruned properly, while remaining fields were under- or over-pruned. In relation to harvest practices, mean harvest interval was 19 d, ranging from 15 d (RI) to 25 d (WK) (Fig. 3f). Most farmers followed a fairly fix harvesting schedule in RI, JB and SS, harvesting every two weeks. In contrast, harvest interval was longer and more variable in WK, CK and EK. Fertilizer was applied in half of the fields (Fig. 3g–i), with CK and JB exhibiting highest (69%) and lowest frequency (10%) of fertilized fields, respectively. Considering only those fields that received fertilizer, average nutrient rate was 42 kg N, 12 kg P, and 44 kg K per ha per year.

Dura frequency was high (mean: 51%) indicating widespread use of non-certified planting material in smallholder fields (Fig. 3d). Indeed, dura frequency was below 2% in only 5% of the fields, a threshold that is typically used for certified planting material (SNI, 2015), indicating that most fields were planted with non-certified planting material. Widespread use of non-certified planting material, together with likely poor management of nursery and early plantation, led to a high frequency of low-productive palms, which, on average, accounted for ca. 5% of total palms per field across sites. Supply and abnormal palms accounted for most of the low productive palms, with only four fields showing significant incidence of *Ganoderma sp* (> 5% palms). In contrast, 80% of fields had visual evidence of severe weed infestation.

3.2. Validation of modelled attainable yield using data from large plantations

Our average Yatt compared well with the highest yields measured over the entire range of palm age in large plantations (Fig. 4). Modelled Yatt reached a peak around 5–10 years after planting, and gradually declines afterwards. We did not find evidence to believe that the shape of the Yatt-age relationship could be an artifact derived from differences in field management. Indeed, we note that the database from large plantations that we used for the Yatt validation included the same set of blocks over time (field were not abandoned or replanted) and harvest interval remained constant, and even decreased slightly with age.

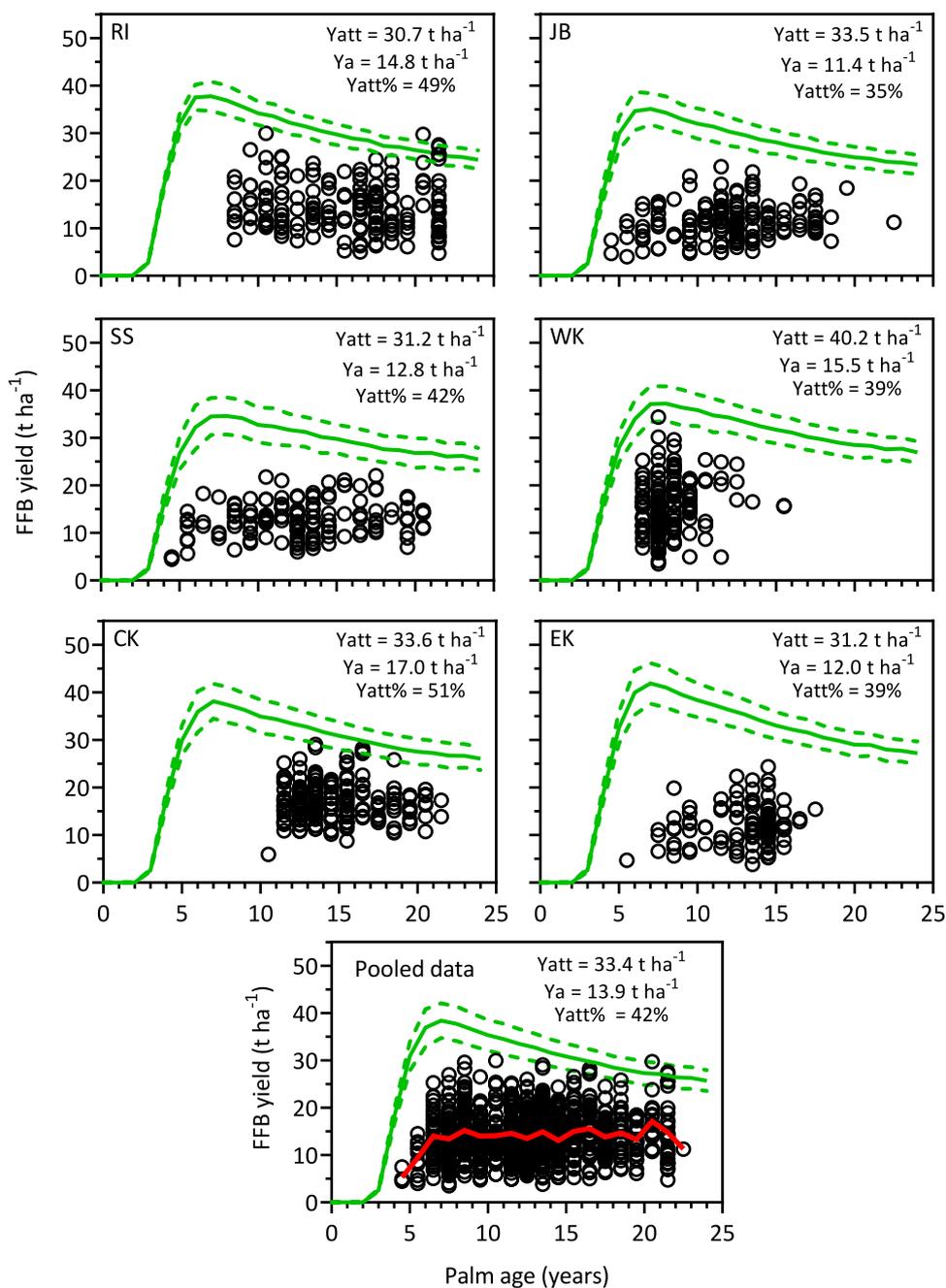


Fig. 5. Assessment of farmer yields in independent smallholder oil palm fields based on sites located in six provinces in Indonesia. Green solid line shows attainable yield (Yatt) as a function of palm age estimated for each province, with dashed lines indicating \pm one standard deviation based on simulations with long-term weather data, while circles represent the 2-y (2020–2021) average yield in individual smallholder fields (circles). The horizontal distance between a circle (individual field) and the green solid line represents the exploitable yield gap. Also shown are means for Yatt, average farmer yield (Ya), and average yield as percentage of Yatt (Yatt%). Bottom panel shows the pooled data across the six sites, with red line connecting the average yield estimated for each palm age. See caption to Fig. 1 for province acronyms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Hence, our evaluation gives confidence about the robustness of our simulated Yw and the assumption of 70% of Yw as a meaningful estimate of Yatt, indicating that our modelled Yatt provides a proper benchmark to calculate exploitable yield gaps over the entire range of palm age.

3.3. Exploitable yield gaps in independent smallholder fields

Average Yatt was 33.4 t ha^{-1} across the six sites, ranging from 30.7 t ha^{-1} in RI to 40.2 t ha^{-1} in WK (Fig. 5). Variation in Yatt across sites was associated to differences in palm age ($p < 0.01$) and, to a lesser extent, variation in climate and soil. For example, Yatt was highest in WK where plantations were at age of peak yields (mean: 8 years). Average Ya in independent smallholder fields was 13.9 t ha^{-1} , well below national average FFB yield of 18 t ha^{-1} (FAOSTAT, 2023), representing only 42% of Yatt. The exploitable yield gap, estimated as the difference between Yatt and Ya, averaged $19.5 \text{ t FFB ha}^{-1}$ across sites, with largest and

smallest gaps in JB and CK, respectively. The data scattering in Fig. 5 illustrates the wide variation in yield gaps across independent smallholder fields. A very small number of fields (ca. 1%) achieved yields comparable ($\pm 5\%$) to Yatt but most of them were well below. The exploitable yield gap was larger in younger plantations (5–10 years) because they were close to the peak Yatt. In contrast, the yield gap was smaller in older plantations because of a simultaneous decline in Yatt and increase in Ya over time after the peak in Yatt.

3.4. Explanatory causes for yield gaps

Our comparison of upper and lower terciles of the field yield distribution revealed consistent differences in nutrient, pruning, harvest, and weed management between fields with small and large yield gaps (Table 2). An exception was the lack of differences in nutrient inputs between UT and LT fields in JB and EK, because frequency of fertilized

Table 2

Means for selected variables, including palm age, management, and soil properties, for lower (LT) and upper terciles (UT) of the field yield distribution, expressed as % of attainable yield across six sites in Indonesia. Also shown are UT-LT differences. See caption Supplementary Tables S1-S3 for detailed explanation of each variable.

Category	Variable	UT	LT	UT-LT
Palm age	Palm age (y)	14	12	2**
Nutrients	N (kg ha ⁻¹)	28	13	15**
	P (kg ha ⁻¹)	7	3	4**
	K (kg ha ⁻¹)	24	8	16**
Pruning	Separate pruning (% fields) [†]	78	70	8**
	Pruning frequency (months)	6	6	nil
	Proper pruning (% fields)	73	75	-2
Harvesting	Harvest interval (d)	18	21	-3**
	Inappropriate criteria (% fields) [‡]	58	46	12**
Palm stand	Triangular pattern (% fields)	66	61	5
	Density (palms ha ⁻¹)	145	138	7**
	Low-productive palms (% palms)	5	4	1**
Planting material	Dura frequency (% palms per field)	49	51	-2
Soil & terrain	TWI	4.2	4.1	0.1*
	Shallow soil (% fields)	20	16	4
	Shallow water table (% fields)	20	21	-1
	Coarse texture topsoil (% fields)	2	4	-2
	Cover crop (% fields)	20	14	-6
	Empty bunch application (% fields)	8	4	-4**
	Artificial drainage (% fields)	9	9	nil
Soil and water management	Terracing (% fields)	0	2	2
	Pilled-up pruned fronds (% fields)	86	79	7**
	Severe weed infestation (% fields)	82	87	-5*
Weeds	Weed categories (n)	1.1	1.2	-0.1**
	Insect presence (% fields)	79	81	-2
Pest & diseases [§]	Disease presence (% fields)	71	68	3

Asterisks indicates statistically significant difference at ** $p < 0.05$ and * at $p < 0.10$ using T-test or chi-square test for continuous and categorical variables, respectively.

N: nitrogen; P: phosphorous; K: potassium; TWI: topographic wetness index.

[†] Pruning can be done together or separate from harvest time and, depending on the frond number, one can infer whether pruning was appropriate or not.

[§] Farmers-reported incidence of pest and diseases in that field in previous years.

[‡] Number of loose fruits is considered here as the proper harvest criteria while others are not (e.g., bunch colour).

fields and fertilizer rates were the lowest at these two sites, not allowing a proper comparison of fields with contrasting fertilizer inputs (Fig. 3). There were other variables showing differences between UT-LT classes such as palm age, palm density, and frequency of low-productive and dura palms, but we note that there is limited room to manipulate these variables within the current plantation cycle. Findings were consistent when analyses were based on the pooled data versus the data for each site (Supplementary Table S4). We note that farmers reported incidence of pest and diseases during previous years in a high frequency of fields (Table 2), but this factor explained little of the variation in Yatt%. Indeed, very few farmers (<2%) applied insecticide/fungicide during the two years of our study. Moreover, we did not observed incidence of pests and diseases in 30 field trials conducted at the same sites and we also note that farmers tend to confound diseases with nutrient deficiencies (Sugianto et al., personal communication). Altogether, these findings support the conclusion that pest and diseases are not major factors explaining yield gaps in smallholder fields in Indonesia.

Because results from conditional inference trees and random forest regression were consistent across sites (Supplementary Figs. S2-S7), and influence of weather, climate, and palm age on yield potential was accounted for by expressing yield as percentage of Yatt, we showed the

results derived from the analysis using the pooled database (Figs. 6). Findings were consistent with those derived from the UT-LT tercile comparison, with the added value of providing a rank of the factors based on their relative explanatory power at explaining yield gaps. For example, nutrient fertilizer, in particular K, was a key factor explaining variation in yield gaps. Similarly, conditional inference tree analysis was useful to identify suites of management practices leading to consistent high yields in each site and revealed interactions among them (Supplementary Figs. S2-S7). For example, highest Yatt% in RI was obtained with a combination of short harvest interval and large N fertilizer rates. The group of fields following these practices achieved a Ya that represented ca. 70% of the Yatt. Combining the results from the three statistical analyses shows that the main messages from the individual statistical analyses remain the same: palm age and agronomic practices such as nutrient, pruning, harvest, and weed management accounted for largest portion of observed variation in yield gaps (Fig. 7). Instead, pest and diseases and dura frequency have comparably small explanatory power.

3.5. Relationship between yield gap closure and farmer profit

Average annual net profit was 1960 USD ha⁻¹ across sites, ranging from 360 to 4602 USD ha⁻¹ across fields (Fig. 8). Costs were highly variable and depended mostly on differences in fertilizer use, which, in turn, accounted for ca. half of the total production cost. There was a positive strong correlation between net profit and Yatt% ($r^2 = 0.85$; $p < 0.01$) indicating that yield gap closure leads to better economic output. In contrast, net higher profit was not associated with lower costs, and, indeed there was a weak, but still statistically significant, positive correlation between net profit and production costs ($r^2 = 0.16$; $p < 0.01$).

4. Discussion

Our study revealed a large exploitable yield gap for independent smallholder fields in Indonesia, with only a handful of fields approaching the Yatt (Fig. 5). On average, current yield represented 42% of the attainable yield. This value is within the range of Yatt% (40–50%) reported by previous local studies based on a relatively small number of smallholder fields (Euler et al., 2016; Molenaar et al., 2013). Our study adds value to these previous studies by showing the prevalence of large yield gaps across the oil palm production region in the country, using field-level data collected across many sites and years using consistent protocols, and rigorously screened to avoid biases due to reporting errors or inaccuracies in field size. Moreover, our study estimates the yield gap for each individual field using a well-validated process-based crop model coupled with local weather and field-specific soil and palm age. The exploitable yield gap estimated for independent smallholders farmers is larger than that reported for large plantations in Indonesia (Hoffmann et al., 2017; Monzon et al., 2021; Rhebergen et al., 2019) and even larger than for smallholder oil palm farmers in Ghana (Rhebergen et al., 2018). Our yield gap estimate is also larger than that reported for smallholders in Indonesia by Monzon et al. (2021), probably because the latter study did not disaggregate between independent and plasma smallholders. Larger yield gaps are expected in independent versus plasma smallholders due to differences in access to technical information and inputs (Jelsma et al., 2019; Jelsma et al., 2017a, 2017b). Finally, the estimated yield gap in our study (mean: 19.5 t ha⁻¹) can be used to estimate the *ex-ante* impact that improved agronomic management could have at national level. For example, considering the mature area of oil palm located in mineral soils in Indonesia that is managed by independent smallholder farmers (3.0 M ha), closing the current yield gap can add 60 MMT FFB at national level. Considering an OER of 20%, this is equivalent to 12 MMT CPO, which represents one quarter of current palm oil production in the country. Closing the yield gap through better agronomic management would not only generate additional income for the country but also improve the

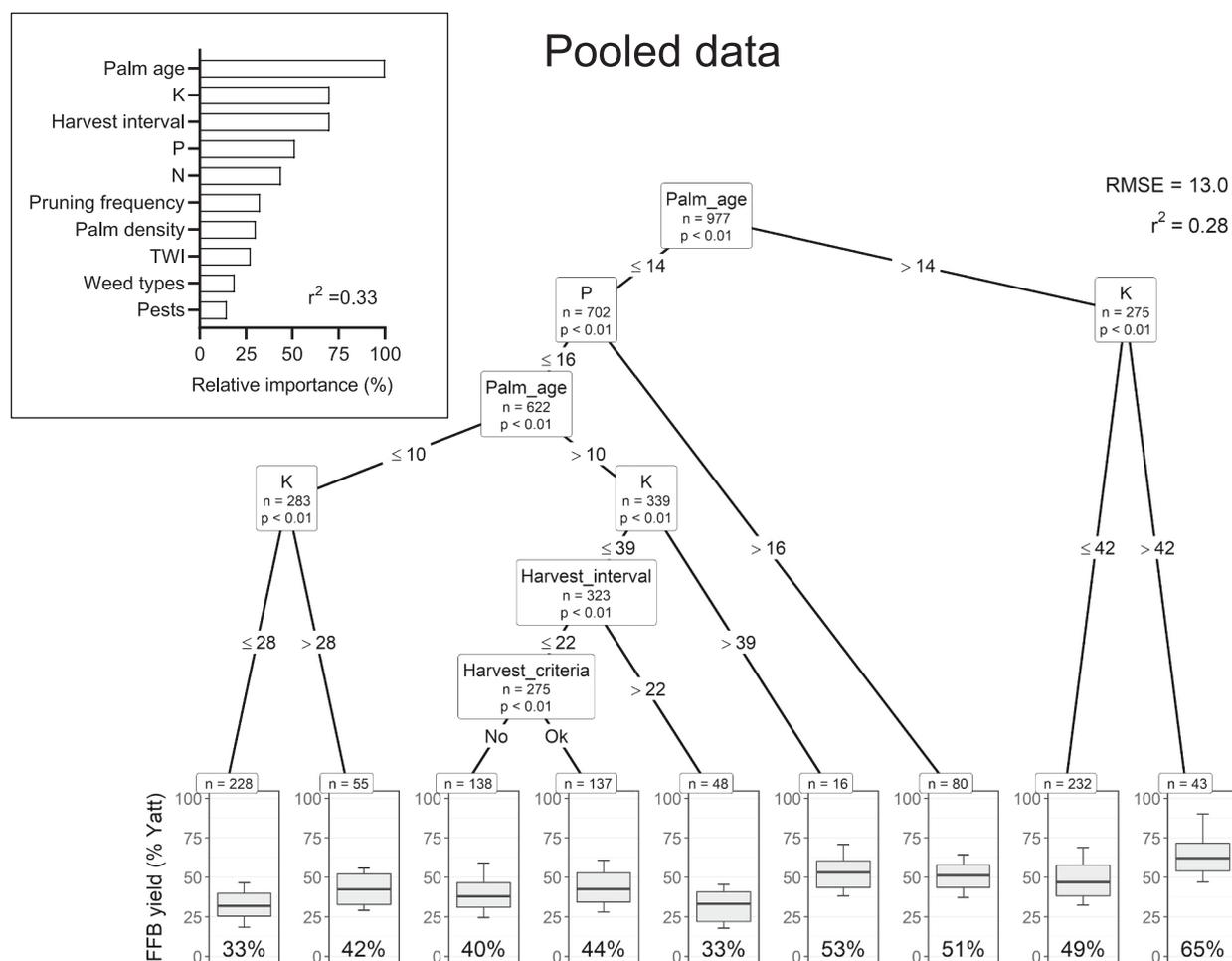


Fig. 6. Conditional inference trees assessing variation in farmer yield (as % of the attainable yield) in smallholder fields using the pooled data collected across six sites. Boxes indicate 25th and 75th percentiles, whiskers represent the 10th and 90th percentiles, and medians are shown with horizontal lines inside boxes. Also shown are, root mean square error (RMSE; %) and coefficient of determination (r^2) of the overall analysis, number of fields (n) at each node, and means for terminal nodes. Inset shows results from the random forest regression analysis and associated r^2 . Separate regression trees for each site are shown in Supplementary Fig. S2-S7. See also Supplementary Table S4 for full list of variables included in the analysis.

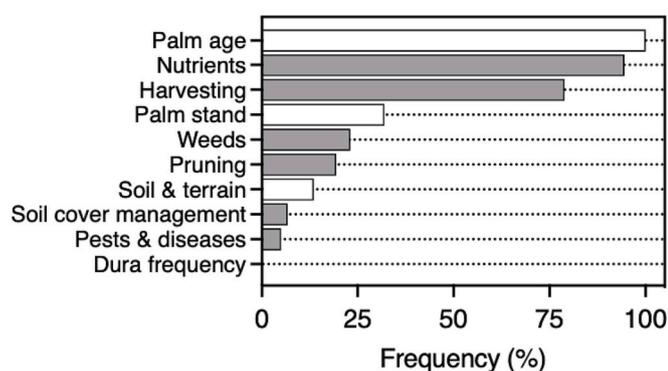


Fig. 7. Summary of results from three statistical methods (tercile comparison, conditional inference trees, and random forest regression) used to identify causes for yield gaps in independent smallholder fields. Variables were grouped in different categories following the classification shown in Table 2. A value of 100% means that the variable was identified as the most important one at explaining yield gaps across statistical methods. Colors in bars represent variables that can be manipulated (solid) or cannot be modified substantially (empty) during current plantation cycle.

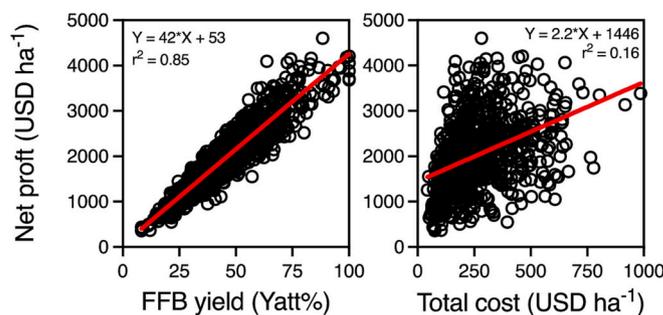


Fig. 8. Relationship between farmer net profit and fresh fruit bunch yield, expressed as percentage of attainable yield (Yatt%) and total production costs (left and right panels, respectively). Also shown are the fitted linear regression models, and associated parameters and coefficient of determination (r^2). All relationships were statistically significant ($P < 0.01$). Each data point corresponds to a farmer field.

livelihood of millions of smallholders. Indeed, our findings suggest that higher expenditures on yield-improving practices, such as fertilizer, weed control, and regular pruning and harvest, lead to higher farmer profit whilst minimizing costs at expense of reducing yield does not seem to be compatible with high profits (Fig. 8).

We note that assessing cause-effect relationships in oil palm is challenging as FFB yield is determined over a long period of time, taking approximately 39 months from initiation of a bunch primordia to harvest (Breure and Menendez, 1990; Monzon et al., 2022). Hence, there will be a delay between implementation of management practices, such as nutrient application and pest and weed control, and the associated impact on yield (Rhebergen et al., 2020). In our analyses, we assumed that field ranks, in relation to productivity, input application, and management level, are persistent over time. In other words, fields exhibiting high (low) yield and/or input rates in a single year will also be the ones showing high (low) yield and input rates in other years. Our assumption is reasonable considering the high rank correlations we found for yield and nutrient fertilizer rates between the two years ($p < 0.001$). Likewise, some of the variables that we detected influencing oil palm yield may have some co-linearity with other factors. For example, our analysis may tend to overestimate the effect of harvest interval on FFB yield because field size and yield may also influence harvest frequency. A more detailed analyses of the factors influencing harvest interval is needed (de Vos et al., 2023). Similarly, while high weed infestation was taken as an indication of poor weed control, it can also be taken as a consequence of nutrient deficiencies and sub-optimal plant density via reduced canopy size and low solar radiation interception. Despite these sources of uncertainty, our analysis is useful to highlight the importance of agronomic management as a factor explaining yield gaps and provides a roadmap to future studies assessing opportunities to overcome yield constraints.

Improving agronomic management is imperative for narrowing the current large yield gap that exists in smallholder fields (Fig. 6-7). The yield-gap explanatory factors identified by our study can be categorized into two groups: one that includes those variables that cannot be manipulated by smallholders within the current plantation cycle (e.g., palm age, palm density and arrangement, dura frequency), and another group that consists of management practices that can potentially be improved to increase current productivity (e.g., harvest, nutrient application, pruning, and weed management). In relation to the first group, it was remarkable the consistent impact that age had at explaining yield gaps. The largest yield gaps occurred during early years of the productive phase of the plantation (around 5–10 years after planting), reflecting the yield penalty that smallholders incurred into by missing the productivity peak that, with good management, would occur during that timeframe, as one can observed in well-managed large plantations (Figs. 4-5). Our finding is consistent with Molenaar et al. (2013) who reported wider gaps in early years of the plantation cycle. Together with the evidence of sub-optimal palm density and arrangement, and widespread use of non-certified planting material, this finding highlight the importance of judicious selection of planting material, proper land preparation and plantation establishment, and good management of seedlings and plantations during the first years. We conclude that programs directed to increase productivity in smallholder fields should not only focus on management of mature plantations but also direct efforts to ensure proper establishment and management of the plantation in early years.

Fortunately, our analysis also identified a number of management practices that farmers can consider to increase the productivity and profit of their fields during the current plantation cycle (Fig. 6-7). Among those variables, nutrient, harvest, pruning, and weed management explained the largest portion of the yield gap. The effect of nutrients was not surprising considering the small number of farmers applying fertilizer and associated small amount and widespread nutrient deficiencies observed in farmer fields (Sugianto et al., 2023; Lim et al., 2023). In relation to harvest practices, farmers follow sub-optimal harvest practices: most farmers harvested two times per month and half of them used inappropriate harvest criteria (for example, bunch colour instead of loose fruits). We found a consistent benefit of shorter harvest intervals (10–15 d), which is consistent with the evidence that frequent harvests reduces harvest losses, not affecting OER while increasing oil

quality (Lee et al., 2014; Mohanaraj and Donough, 2016). On the other hand, we note that farmers may harvest depending on their yield level and field size to ensure a minimum amount of FFB that would justify harvest and meet requirement of FFB collectors. So, farmers may shorten harvesting interval when yields are higher and lengthen them when yields are lower (de Vos et al., 2023). Still, we note that fertilized fields will likely have higher yield and therefore, for a given field size, would need to be harvested more often as shown by the conditional inference tree analysis for CK and RI. Hence, promotion of management practices needs to be done from a system perspective, in which multiple practices are combined to exploit their synergies, rather than from the conception of individual practices.

Increasing both FFB yield and OER is important for the palm oil industry. However, current efforts to increase smallholder yield focus mostly on a replanting program promoting use of certified planting material with low dura frequency and higher OER (www.ekon.go.id, www.gapki.id). Over the long term, given current average dura frequency of 50% (Fig. 3), replanting independent smallholder fields with certified planting material would lead to a large increase in oil yield via higher OER as shown by Sugianto et al. (2023). The management practices discussed in the present study have little or no impact in OER, but have the potential to increase oil yield substantially via higher FFB yield. Hence, improved agronomic practices, especially improved plant nutrition, coupled with replanting of certified seed, can increase both FFB and OER. In turn, increase in FFB yield and OER will benefit smallholders, local economies, and the entire country. Likewise, when complemented with strong institutions and proper enforcement, higher CPO production on existing cropland can help relieve pressure on land conversion for oil palm cultivation. To achieve this end, current prioritization on research and extension programs would benefit from a more balanced perspective that recognizes the need to improve current agronomic management to increase smallholder yields.

5. Conclusions

There is a large exploitable yield gap in independent smallholder fields, where current average FFB yields represents 42% of the attainable yield. A large portion of the yield gaps is associated with poor agronomic management, including insufficient nutrient application of fertilizer, long harvest interval, poor weed control, sub-optimal palm density. Inadequate palm density and arrangement also explain part of the yield gap, and use of non-certified planting material further reduces oil yields. Additionally, poor management of the early plantation resulted in large yield gaps during the potentially most productive years. We conclude that, to be effective at increasing smallholder yields and profit, current AR&D programs need to give stronger focus to improve the agronomic management in smallholder fields.

Declaration of Competing Interest

The authors declare no conflict of interest. The paper contents have not been previously published nor are under consideration for publication elsewhere. All co-authors have contributed to the paper and have agreed to be listed as co-authors.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agry.2023.103689>.

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