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Shortening harvest interval, reaping benefits? A study on harvest practices in oil palm smallholder farming systems in Indonesia

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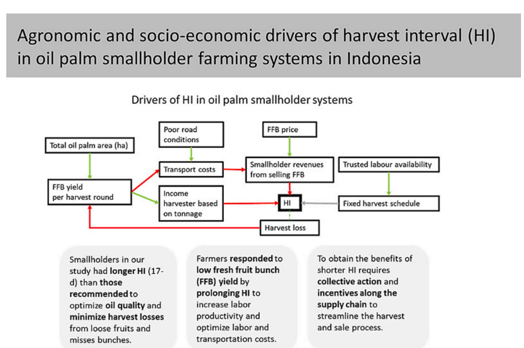
HIGHLIGHTS

- Timely harvesting of oil palm through short harvest interval (HI) can help to enhance oil quality and reduce harvest loss.
- We studied agronomic and socio-economic drivers of HI for Indonesian smallholders via surveys, interviews and field audits.
- The oil palm smallholders in our study had longer HIs than recommended to minimize harvest losses and optimize oil quality.
- Farmers responded to low yield by prolonging HI to increase labor productivity and optimize labor and transportation costs.
- To benefit from shorter HI requires yield-increasing measures, and collective action and incentives along the supply chain.

GRAPHICAL ABSTRACT



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A B S T R A C T

CONTEXT: Smallholders are responsible for a large share of global palm oil production. Yet, in Indonesia, the main palm oil producing country, smallholders' yields remain low. Better management practices, including short harvest interval (HI, the number of days between two harvest rounds), could help to raise smallholder yields. However, at present, HI is long in smallholder fields and the drivers underlying this phenomenon are poorly understood.

OBJECTIVE: We explored agronomic, socio-economic, and institutional factors that underlie harvesting practices in independent oil palm smallholder farming systems in Indonesia to assess scope for sustainable intensification through shorter HI and reduced harvest losses.

METHODS: Combining methods from agronomy and anthropology, we followed harvest interval of 950 farmers in six representative locations across Indonesia via farmer diaries over a period of two years to establish a correlation with yield. To quantify this relationship, we conducted post-harvest field measurements, and to explain which underlying factors impact HI we did qualitative interviews and surveys.

RESULTS AND CONCLUSIONS: The HI of smallholders in our study ranged from 10 to 39 days (average: 17-d). Half of the farmers followed long HI (>16-d). Key factors impacting HI include annual fresh fruit bunch (FFB) yield, total palm area per farmer, trusted labor availability, plantation accessibility, and FFB price. Farmers responded to low yield by prolonging HI to increase labor productivity and optimize labor and transportation costs.

SIGNIFICANCE: This study contributes to a better understanding of the relation between HI and yield in smallholder farming systems, by uncovering how socio-economic and institutional factors sometimes override agronomic considerations. Long HI can potentially lead to harvest loss from loose fruits and missed bunches, and reduce oil quality from overripe bunches. However, to obtain the benefits of shorter HI requires collective action and incentives along the supply chain to streamline the harvest and sale process.

1. Introduction

Smallholders are responsible for a large share of the total global palm oil production. In Indonesia, the largest producer of palm oil, smallholders account for approximately 40% of total palm oil acreage (BPS, 2021). However, independent smallholders, who are defined as palm oil producers with a total land size of maximum 25 ha and not formally tied to mills as outgrower, experience large yield gaps (e.g., Euler et al., 2016; Lee et al., 2014; Monzon et al., 2023; Woittiez et al., 2017). Closing this yield gap is considered crucial to meet global palm oil demands without further crop land expansion to avoid deforestation and greenhouse gas emissions (Austin et al., 2017; Monzon et al., 2021), as well as strengthening rural economies through higher incomes for farmers (Santika et al., 2019).

Oil palm smallholder yield gaps are rooted in a combination of factors, including suboptimal harvest and nutrient practices (Lim et al., 2023; Monzon et al., 2023; Sugianto et al., 2023). Previous studies have suggested that harvest interval (HI), i.e., the number of days (d) between two harvesting rounds, is a key factor to determine annual fresh fruit bunch (FFB) yield (Euler et al., 2016; Lee et al., 2014). To maximize both FFB and oil yield, it is important to conduct the harvest when bunches are ripe, but before they become overripe with too many detached fruits, which are commonly referred to as 'loose fruits' (Corley and Tinker, 2015). Loose fruit collection is time consuming and costly, and loose fruits deteriorate quickly, or sprout into weeds (Mohanaraj and Donough, 2016). Additionally, overripe bunches bruise more easily during transport and have lower oil quality (Lovely et al., 2015; Morcillo et al., 2013). Mills may pay a lower price for FFB that is overripe or damaged (Anggraini and Grundmann, 2013). In addition, as longer HI allows for more bunches to ripe, harvesters will find a field with bunches at various ripeness status, and they may miss more ripe bunches, reducing effective crop recovery, defined as the harvested FFB relative to that that could be attained without harvest losses. Large-scale plantations typically maintain a HI of 7–10 days to maximize bunch and oil yield (Donough et al., 2010). In contrast, independent smallholders in Indonesia often maintain a HI of 14—30 days (De Vos et al., 2021; Jelsma et al., 2019; Lee et al., 2014). Similarly, Rhebergen et al. (2018) reported an average HI of 17-d on smallholdings in Ghana, and Somnuek et al. (2016) found that smallholders in Thailand harvested once a month.

It may be difficult for smallholders to shorten HI. Multiple challenges may hamper harvesting, such as poor maintenance of harvest paths (Rhebergen et al., 2020), lack of pruning (Maat, 2018), limited accessibility due to poor infrastructure or weather conditions (Jelsma et al., 2019), and labor shortages (Habibi, 2022). For example, Jelsma et al. (2019) found that smallholder fields in remote locations were less frequently harvested in the rain season due to poor infrastructure conditions. In addition, harvesting decisions may be influenced by the uptake capacity of middlemen, quota set by mills, and estimations of costs in relation to benefits of selling FFB at a certain price (Anggraini and Grundmann, 2013). Hence, the room that exists to reduce HI, and expected benefits, need to be assessed from both an agronomic and socio-economic perspective.

Here we hypothesize that short HI is a potential management practice that smallholders can implement to increase harvested yield and profit by increasing crop recovery. However we also suspect that these potential benefits will be influenced by socio-economic factors determining smallholders' abilities and preferences in adopting shorter HI. The objective of this study is to identify agronomic, socio-economic, and institutional factors that underlie harvesting practices of independent oil palm smallholders in Indonesia. To do so, we followed an interdisciplinary research approach, combining methods from agronomy and anthropology, seeking to understand smallholders' HI decisions and the structural factors influencing their harvesting practices. We used a database including farmer survey data collected across six sites representing main oil palm regions in Indonesia to correlate HI with yields and explanatory factors. We complemented the analysis with field audits assessing post-harvest losses, and qualitative interviews to understand factors affecting harvesting practices.

2. Materials and methods

2.1. Research setting

This study is part of a research project about sustainable intensification on existing oil palm plantations, focusing on the role of management practices at explaining yield gaps in smallholders' fields in Indonesia. The goal of the project is to develop cost-effective intensification practices to increase yield, raise rural incomes, and reduce the need to expand plantations into new areas. Study sites were in mineral soil across six provinces in Indonesia: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), Central Kalimantan (CK), and East Kalimantan (EK). Hereafter, sites are referred to using the name of the province where they are located.

At each site, we selected 200 farmers to follow in terms of practices, input use, yield and FFB sale, hereafter referred to as 'non-field trial' (NFT) farmers. Moreover, we selected a subgroup of six farmers per site (30 in total) to participate in an experiment consisting of paired fields, one of which is managed according to best management practices (BMP) and the other as farmers' current practice (REF). The BMP farmers were asked to harvest their plots every ten days, whereas the REF and NFT farmers continued their normal HI. BMP farmers also altered fertilizer management, and all applied adequate pruning and weeding practices (see Sugianto et al., 2022). To select farmers for this study, we excluded intercropped fields, very small (<0.1 ha) or very large fields (>25 ha), and immature (< 3 years) or very old plantations (> 25 years). Following quality control of data, and after validation with local partners, we excluded fields with average HI > 40-d, because this suggests fields were abandoned and also those with average yield (per ha per harvest round) > 2 t FFB because this suggests pooling of FFB from multiple fields. Likewise, observations from WK between Nov 2019 and March 2020 were excluded as there was a major flood preventing access to smallholder fields at this site. The final data set includes 950 respondents, and 50,143 harvest rounds over the period between Jan 2020 and June 2022. Detailed description of study sites, field selection, and quality control measures is available in Monzon et al. (2023).

2.2. Research methods

We used seven different data collection methods to assess impact and drivers of HI decisions in independent smallholder fields (Table 1). Briefly, we collected data from baseline, land, and harvest surveys, as well as from a farmer diary from all six sites. We complemented these databases with qualitative interviews and post-harvest field audits in two sites (RI and WK).

At each site, we conducted a baseline survey across ca. 200 smallholders to collect data on farmers' socio-economic background, plantation characteristics, and agronomic management. Additionally, we mapped the borders of a designated field to determine associated palm density, palm age, dura contamination, and soil type. Thereafter, we followed respondents via a farmer diary in which they reported all activities related to plantation management and FFB sale for the designated field between Nov 2019 and June 2022. We used data from the baseline survey, land survey, and farmer diary to identify sources of variation in HI.

After a first round of data analysis from the surveys and farmer diaries, fieldwork was conducted for six months between Jan 2022 and July 2022 in RI and WK, primarily using qualitative in-depth interviews. We selected RI and WK as case studies to represent the two main palm oil producing islands and because HI at these sites was significantly different, including a more regular two-week HI in RI and a longer, more variable HI in WK. Respondents for the qualitative interviews were purposefully selected from the list of NFT respondents, based on having medium to long HI (>16 days). We selected respondents with total oil palm area < 6 ha and palm age > 7 years. On some occasions when the oil palm field owner was not available, the plantation supervisor, or the harvest worker was interviewed. We interviewed 14 NFT farmers in RI and 16 NFT farmers in WK. In addition, we interviewed smallholders who participated in the BMP trials (seven in RI and five in WK). Subsequently, we used insights from the previous methods to design a survey focused on harvesting practices for all ca. 200 respondents at each site.

To further investigate yield losses in relation to long HI, we conducted a harvest loss audit in RI and WK for three field classes: BMP, REF, and NFT. We selected 14 (RI) and 13 (WK) NFT fields with long HI (> 16-d), and 7 (RI) and 5 (WK) BMP and REF fields, with palm age ranging from 7 to 20 years. These audits were conducted after each harvest during a 3-month period: from January to March in RI and May to July in WK. Data gathered each audit were: harvested bunches (HB), un-harvested ripe bunches (UHB), harvested bunch left in the field (HBL), and loose fruits (LF). Two conditions were followed during each audit: (i) at least half of all harvest paths were sampled, and (ii) at least 20 harvested bunches were audited. Following these criteria, audits included 25% to 100% of total harvested bunches, and 33% to 100% of total productive palms per harvest occasion across sites.

Table 1
Overview of research methods used for our assessment of agronomic and socio-economic drivers of harvest interval decisions in smallholder fields in Indonesia.

Research method	Site	Respondents	Observations available for data analysis	Time period
Baseline survey	all sites	1200 NFT	950	Oct 2019 – April 2020
Land survey	all sites	1200 NFT	950	Oct 2019 – April 2020
Farmer diary	all sites	1200 NFT	50143 harvest rounds	Jan 2020 – June 2022
Harvest survey	all sites	1132 NFT	1132	May – July 2022
Interviews NGOs	all sites	6	6	Jan 2022
Qualitative interviews	RI, WK	RI: 7 BMP / REF; 14 NFT. WK: 5 BMP/ REF; 16 NFT.	42	Jan- March (RI) May – July (WK) 2022
Field audits	RI, WK	RI: 7 BMP / REF; 14 NFT. WK: 5 BMP/ REF; 13 NFT.	39	Jan- March (RI) May – July (WK) 2022

RI: Riau; WK: West Kalimantan, BMP: trial plot following best management practices; REF: trial plot following current farmers' practice; NFT: non field trial.

2.3. Quantitative data analysis

We explored farmers' characteristics (e.g., education, level of training, experience with oil palm, dependency on oil palm for income, and labor source), plantation characteristics (e.g., total size of oil palm area, palm density, palm age), and harvesting practices (frequency, criteria, and method of FFB selling). We calculated average HI as the average HI over the period from Jan 2020 to June 2022 for a given field. Average FFB yield was calculated as the accumulated harvested FFB yield per field over the study period divided by the field area, whereas the FFB price was the price per kg FFB received by the smallholder as reported for each harvest round. Total oil palm area (ha) cultivated per smallholder was retrieved from the baseline survey. Palm density was calculated as number of palms per ha, retrieved from the land survey. Following analysis of variance (ANOVA), after checking for homoscedasticity via plotting residual versus fitted values and normal Q-Q plots, we used Tukey's test to evaluate differences in average HI and FFB yield among sites. Also, we analyzed differences in average yield between short, medium, and long HI categories at each site. All quantitative data were analyzed in RStudio and plotted using GGPlot (GGPLot package; Wickham, 2016).

We analyzed the relationships among HI and farmer and field characteristics to identify sources of variation in HI at each site. Because our data did not follow any explicit statistical design, and given the variation in climate, soil, and management background across fields, we used non-parametric statistical methods to establish relationships between HI and other factors. First, we used random forest regression (RandomForest package in R; Breiman, 2001) to quantify the importance of each variable at explaining variation in HI (Fig. S3). As site was identified as the most important variable in the analysis of pooled data, we ran separate random forest regression analysis for each site, except SS where there was little variation in HI (average: 15 ± 0.4 days). Then, we used linear regression to explore whether factors that fluctuate over time, such as yield per harvest round and FFB price, correlated with HI. For the latter analysis, we used each harvest round as reported in the farmer diary, to capture variations in HI per respondent over time. We did not observe a seasonal pattern in monthly FFB yield over the study period; hence season and month were not included as independent variables in our statistical analyses. Finally, we visualized the relationships between total oil palm area, and FFB yield, and average HI, as well as the relationship between FFB price and HI including each reported harvest round via linear regression lines fitted to scatterplots.

Lastly, we used data from the post-harvest field audit to estimate loose fruits (kg ha^{-1}) and missed bunches (kg ha^{-1}) per field per harvest round within each site. In contrast to our expectation, there were very few loose fruits left in the field after harvest, due to collection by harvesters or farmers. According to the harvest survey, 96% and 93% of the smallholders in RI and WK, respectively, indicated that loose fruits are usually collected. This means that in our study sites there was no significant harvest loss from loose fruits. Hence, we focused our analysis on the missed bunches.

2.4. Qualitative data analysis

The qualitative dataset contains 42 verbatim transcribed interviews in Bahasa Indonesia, conducted in the case study areas in RI and WK, as well as 6 interviews with representatives of our partner NGOs in each site. We analyzed data using software for qualitative data analysis (ATLAS.ti Scientific Software Development GmbH, 2023, Atlasti.22 version 22.2.5.0; Friese, 2019). We coded data line-by-line, using an inductive thematic coding approach (Gibbs, 2012). This means that we assigned descriptive codes to quotations as we read the text, and then categorized codes into general analytical codes which reflect themes that are relevant to our research question, such as labor relations, transportation, field conditions, and FFB sale. Finally, we compared results of the qualitative analysis to results from the quantitative analysis. Quotations presented in Section 3.4 illustrate key themes that were identified from the coding of interview transcripts.

3. Results

3.1. Agronomic and socio-economic background

Across smallholders, average total oil palm area was 2 (±3) ha, with an average plantation age of 12 (±4) years. Most smallholders planted non-certified planting materials. Thus, plantations comprised a mix of dura and tenera palms with an average of 51% dura. Average FFB yield varied between 12 (JB) and 17 t ha^{-1} y^{-1} (CK), with an overall average of 14 t ha^{-1} y^{-1}. Oil palm accounted for >50% of total annual household income for half of our respondents. Around half of our respondents used external labor for harvesting; the rest relied exclusively on family labor. The majority of our respondents (80%) sold their FFB through local middlemen who collect FFB from multiple smallholder fields before selling to the mill; 14% sold collectively through a farmer groups, and only 6% sold directly to the mill. Smallholders received an average price of IDR[1] 1849 per kg FFB, equivalent to USD$0.12.[2]

3.2. Estimating harvest losses through field audits

Contrary to our expectation, we could not find a statistically significant relationship between missed bunches per harvested round and HI (Fig. 1), although the highest observed values of missed bunches per round over the range of HI tended to increase with longer intervals.

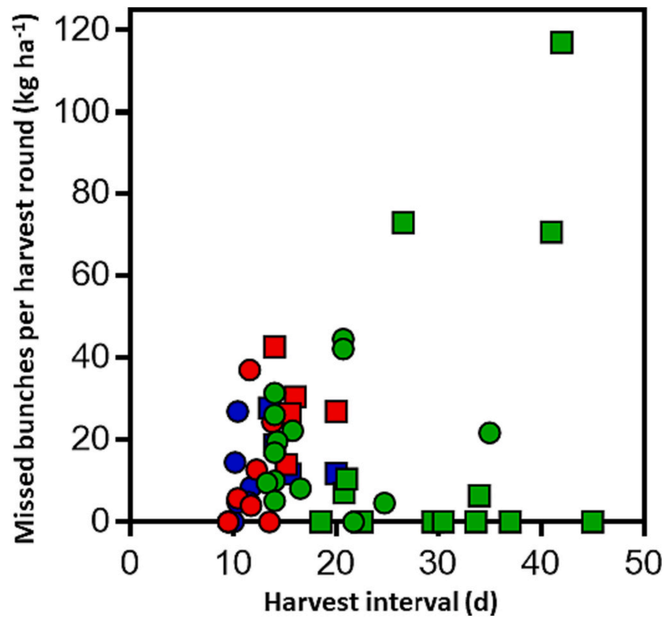

Fig. 1. Relationship between missed bunches per harvest round (in kg ha^{-1}) and harvest interval across fields under three treatments in Riau (RI, circles) and West Kalimantan (WK, squares): field trials adopting best management practices (BMP, blue), field trials not adopting BMP (REF, red), and non-field trials (NFT, green). Each symbol corresponds to the average for a given field per harvest round $^{-1}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Perhaps more importantly, for a given HI, there was wide variation in missed bunches. For example, for a 14-d HI the range of missed bunches was between 5 (NFT in RI) and 43 kg ha^{-1} (REF in WK). This may be explained by differences in total oil palm area owned by the smallholder, labor availability, or the FFB price which influences the economic value of missed bunches. Given an average HI and annual yield of 17 days and 14 t ha^{-1}, respectively, and the highest value of missed bunches around that HI (ca. 40 kg ha^{-1}), we estimated a maximum harvest loss from missed bunches equivalent to 6% of the total harvestable FFB.

3.3. Exploring factors of influence on harvest interval through survey data

The overall average HI including every harvest round reported in the

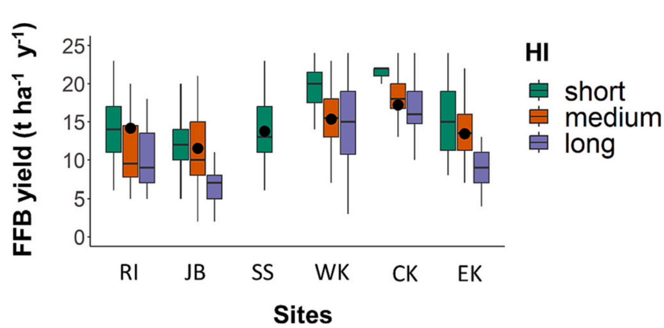

Fig. 2. Box plots for average FFB yield across six sites in Indonesia for three lengths of harvest interval: short (<16 days), medium (16—22 days) and long (>22 days). Data were collected from 950 smallholder fields. In the box plots, the upper and lower boundaries of boxes indicate 75th and 25th percentiles, respectively. Vertical bars indicate 5th and 95th percentiles. Horizontal lines within boxes are the median values, and black dots are average FFB yield per site. Analysis of differences among sites and treatments can be found in Supplementary Table S1, S2. Sites are named according to the sites where they are located: Riau (RI), Jambi (JB), South Sumatra (SS), West Kalimantan (WK), Central Kalimantan (CK), and East Kalimantan (EK).

[1] Indonesian Rupiah
[2] At a conversion rate of IDR 1 = USD$0.000067.

farmer diary was 17 days; 20% harvested every 16–22 days; ca. one third had HI longer than 22 days (Fig. 2). All sites significantly differed from each other in relation to average HI, except RI and SS where HI was ca. 2 weeks. In relation to variation in productivity, CK and WK had a significant higher average yield compared with other sites ($p < 0.001$) (Fig. 2). This yield difference is attributable to overall better field management, especially better plant nutrition, at these two sites as reported elsewhere (Lim et al., 2023; Monzon et al., 2023; Sugianto et al., 2023). Within each site, FFB yield was significantly higher on fields with short versus long HI, or alternately, HI was significantly longer on fields with lower FFB yield (Fig. 2, Supplementary Table S1, S2).

Results from random forest analysis showed that site, FFB yield, and total palm area were the most important factors explaining variation in HI among fields (Fig. 3). Indeed, there were statistically significant relationships between HI, FFB yield and total palm area (Figs. 4–5). It is likely that FFB yield and total palm area influence HI *through* other factors which are difficult to quantify, such as labor availability. We also found palm density to have a strong influence on HI in WK. However, palm density in WK is negatively correlated with palm area. Presumably, farmers aim to maximize yield in small plots by using higher densities in such plots. As small palm areas correspond to longer HI, we presume that palm area explains the observed relationship between palm density and HI found in WK (Supplementary Fig. S1).

Despite that yield per harvest round was positively correlated with HI as a consequence of allowing more time for bunches to ripe (Supplementary Table S3), we found small variation in FFB per harvest round because farmers adjusted HI aiming to harvest relatively the same amount of FFB per harvest round. For example, if one looks at fluctuations in FFB yield per harvest round for 2021 across sites, we see that coefficient of variance (CV) was only 49 kg for an average of 692 kg ha^{-1} per harvest round.

At question is how these relationships may be influenced by FFB

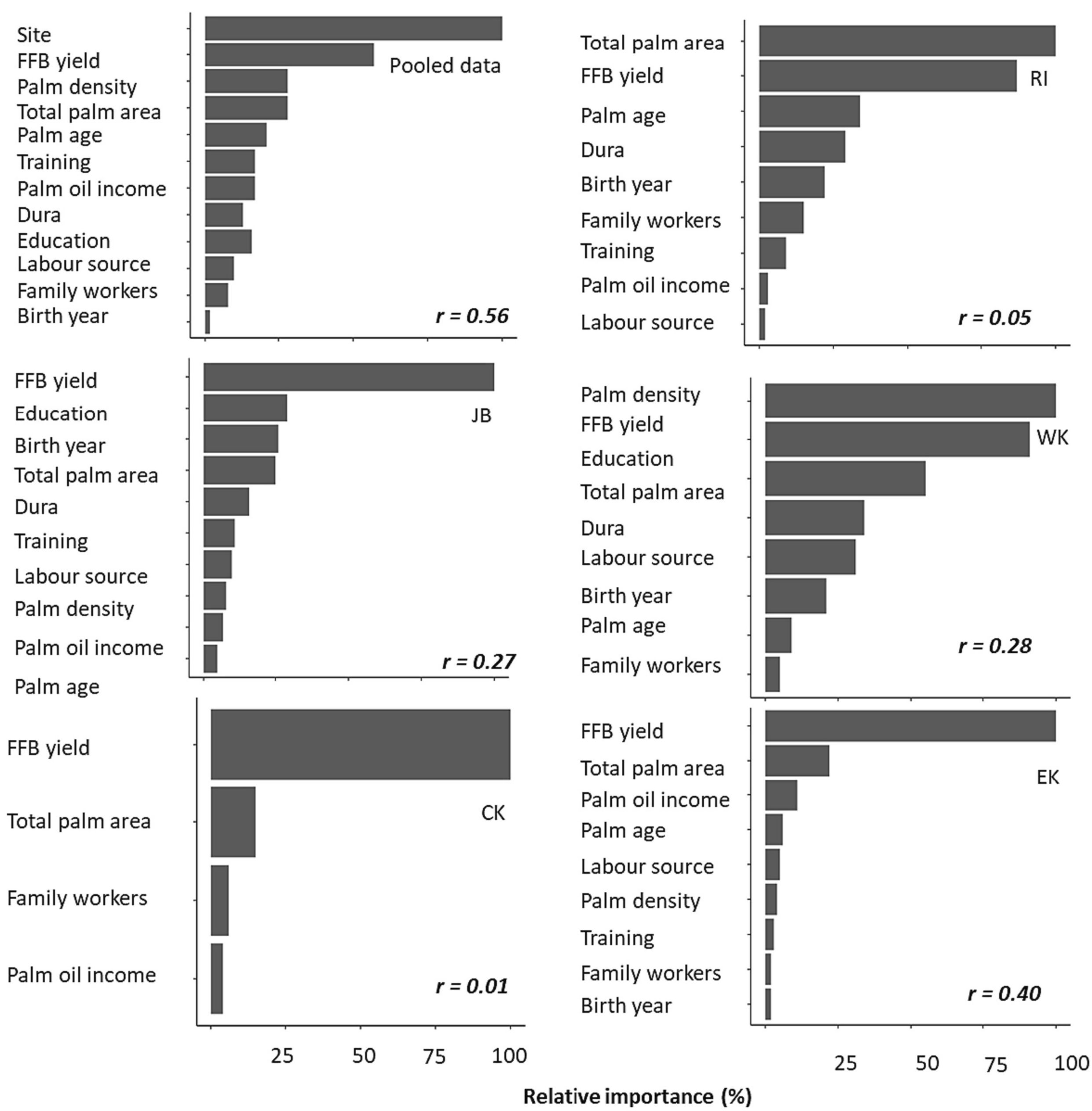

Fig. 3. Importance of variables from random forest analysis for predicting average harvest interval. Relative importance was calculated by comparing the relative contribution of each variable with the most important variable. Analysis was based on survey data from 863 farmers across five sites. Pooled data, excluding SS. See caption to Fig. 2 for site names.

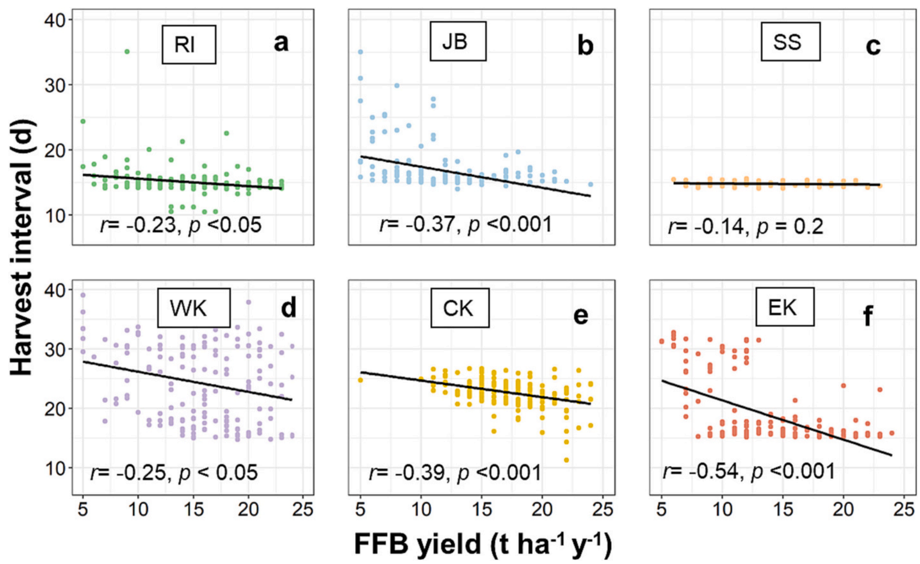

Fig. 4. Harvest interval as influenced by fresh fruit bunch (FFB) yield across six sites in Indonesia based on data collected from 950 smallholder fields. Fitted linear regressions and associated Pearson's correlation (r) and statistical significance (p values) are also shown. See caption to Fig. 2 for site names.

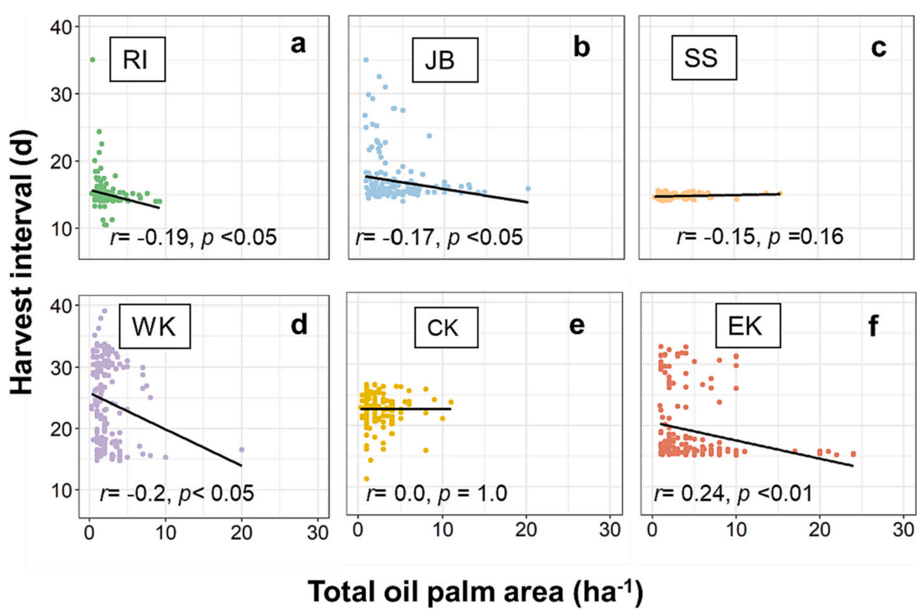

Fig. 5. Harvest interval as influenced by total oil palm area across six sites in Indonesia based on data collected from 950 smallholder fields. Fitted linear regressions and associated Pearson's correlation (r) and statistical significance (p values) are also shown. See caption to Fig. 2 for site names.

price. We found that HI is negatively correlated with FFB price when data were pooled and for five sites (RI, JB, SS, WK, CK) when relationships were assessed separately for each site (Supplementary Fig. S2, Supplementary Table S3). In other words, HI tends to be shorter with higher prices and vice versa, although these relationships were weaker compared with those between HI, FFB yield, and total oil palm area. Indeed, HI remained relatively insensitive to price during a period of extremely low FFB price due to a temporary export ban on palm oil from May to Aug 2022 (Supplementary Fig. S5).

3.4. Explaining long harvest intervals through interviews

We used case studies from RI and WK to further explore how factors identified in Section 3.3 influence smallholders' harvesting practices. These case studies were complemented with data collected through the harvest survey which helped us explain similarities and differences in HI, and its drivers, across the six sites. Farmers in RI and WK grew oil palm independently on generally small fields (2.5 ha on average in both sites). Farmers in RI and WK had significant different average HI (14 versus 24 days) and HI in WK was more variable. In RI, most respondents depended for >75% on their independent oil palm fields for their total annual household income. Yet, some respondents described themselves as "farmers with many trades," working on other farms or having small businesses in addition to oil palm. This was different in WK, where many worked on a company plantation, and 75% of the respondents depended for <25% on their own oil palm fields for their income. In RI most (86%) hired workers to conduct the harvest, but in WK more than half of the farmers harvested themselves. In both areas, harvesters were paid per ton of harvested FFB, with an average wage of USD$11.38 (171.000 IDR) per kg in RI, and USD$14.20 (208.000 IDR) per kg in WK.

The case studies, complemented with the data from the harvest survey, revealed multiple interrelated factors that influence HI. First, respondents indicated that their HI was based on total FFB yield obtained from all their fields per harvest round. The harvest survey revealed that not obtaining enough FFB tonnage per harvest round was a barrier to shorten the HI for 38% of all respondents across six sites (Fig. 6). Indeed, 82% of respondents with average HI longer than 16 days indicated low FFB yield as a barrier for shortening HI. Likewise, interviewees from both RI and WK explained that a short HI of 10 days would not generate sufficient FFB per harvest round, while longer HI would lead to loose fruits. Meanwhile, 70% of all respondents indicated that they would respond to a high yield season by shortening HI, although we did not observe this response in the farmer diary, as HI was quite regular in most sites (Supplementary Fig. S4e).

The influence of yield on HI can be explained through multiple mechanisms. First, total FFB yield influenced HI because of the tonnage payment system, in which harvesters are paid per ton of harvested FFB. In this system, a shorter HI would reduce their income per harvest round, as less bunches can be harvested per round. Both in RI and WK respondents said that if yields were structurally low, for example when palms were still young, or when little fertilizer was applied, the HI was sometimes lengthened to 21 days or once a month. For example, one respondent from RI explained that his harvester proposed to lengthen the HI to 21 days because his yields were low:

"In the past, I harvested my palms every two weeks. However, the yield was too low, so I changed to a three weeks schedule. When I harvested twice a month, I only got 200 kg. The harvest worker said, lets' harvest every three weeks. I agreed. He also needs to make a living."

Second, yield influenced HI through transportation costs and efficiency. In both RI and WK, middlemen collected FFB from road-side collection points to transport it to the mill, deducting transportation costs from the revenues for the smallholder. Although respondents from RI and WK said that middlemen were always available to buy their produce, relative transport costs increased when trucks drove back and forth half empty. For example, a respondent from RI who harvested every three weeks said:

"If we harvest once a week, the yield will not be much. The consequence is that operational cost will be high. The price for the truck will be the same no matter if we harvest 2 or 4 ton. If I harvest every two weeks, I can fill one truck and the transportation cost are in line with the yield."

Similarly, a respondent from WK explained that middlemen sometimes required a minimum FFB tonnage to fill their trucks before transport. This also impacted one of the BMP plots: harvested FFB was only collected after 3–4 days, because the middleman wanted to pick it up together with the fruits from adjacent fields to increase the volume. In the harvest survey, 12% of our respondents indicated that uptake capacity of middlemen was a barrier to shorten HI, mostly in JB. The local NGO explained that middlemen in this site have fixed schedules to collect FFB and it is difficult for an individual farmer to change this schedule.

Poor road conditions due to excessive rain, or fields in remote areas, increased relative transportation costs and effort to collect FFB. In JB, RI and CK ca. half of the respondents said that HI were longer when an oil palm field was in a remote location (Supplementary Fig. S4d). Bad weather conditions and poor road conditions were reported as a reason to postpone the harvest by 69% and 23% of all respondents, respectively, with poor road conditions selected as reason to postpone the harvest mostly in WK (45%) (Fig. 6). The NGO in WK explained:

"It depends on the condition of the field, sometimes FFB can be harvested, sometimes not. When there is a flood, the middleman cannot collect FFB. The field is not flooded, but the road is inaccessible. It can last two weeks to a month."

Third, total FFB yield per harvest round is related to total oil palm area. According to 21% of all our respondents, small total palm areas were related to longer HI (Supplementary Fig. S4a). For example, a respondent from RI with 1.6 ha of oil palm land explained:

"If I had four hectares, I could shorten the HI. But a farmer like me, how could I do it? I generate at most 300-400 kg. This is tiresome for the harvest worker. When you have a small oil palm field, it is better to harvest every three weeks."

Likewise, one respondent from WK who harvested every 20 days, said that he could not harvest every ten days, because his oil palm field was too small (0.75 ha).

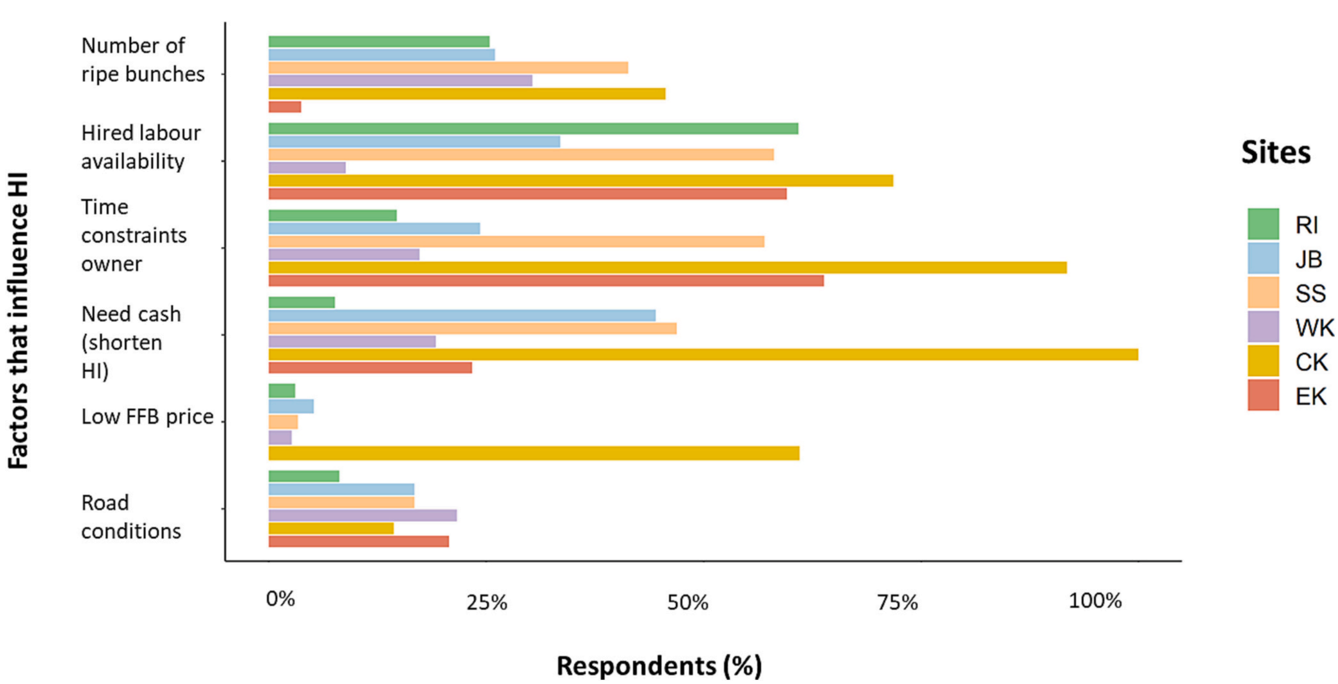

Fig. 6. Bar plot showing the frequency of respondents per site that identified a specific factor influencing harvest interval as determined by the harvest survey based on data collected from 1132 oil palm smallholder farmers across six sites. See caption to Fig. 2 for site names.

"If my land were 2-3 hectares, I could harvest every 10 days. My field is not even one hectare, so of course I harvest every 3 weeks. To harvest every 10 days, you must at least get one ton per harvest. I harvest 2.5 ton every 20 days in the good yield season."

In RI, some respondents addressed the problem of small land sizes by finding a "harvest companion," which meant they organized harvesting and FFB collection together with owners of neighboring fields. Respondents from RI said that the possibility to further shorten HI depended on making an agreement with their neighbors about collective harvesting.

Another factor of influence on HI was labor availability. In the harvest survey, 72% indicated that labor availability was a barrier to shorten HI, for farmers who outsourced harvesting (61%), as well as for those who harvested themselves (39%) (Fig. 6). The nature of limited labor availability was different in WK compared to RI. In WK, respondents said that harvesters were difficult to find, because people worked on company plantations in addition to managing their own plantations. For example, one respondent with 15 ha of oil palm explained:

"It is difficult to find workers here. All people from the village work on the company plantation, nobody is unemployed. Only on Sundays they seek additional income."

In consequence, many harvested themselves, in which case some respondents said that their harvest schedule was flexible, depending on the number of ripe bunches and their time availability. In contrast, in RI nearly all (96%) indicated that harvest schedules were pre-determined and fixed (Supplementary Fig. S3). Oil palm harvesters typically had multiple oil palm fields under their care, which they harvested on a rotation base (*ancak* system, see Habibi, 2022). When asked whether it was possible to shorten the HI by hiring more or other workers, respondents indicated that they preferred to use the same worker whom they trusted. A trust relation was considered important, because workers were responsible for the FFB sale, and they kept an eye on the plantation to prevent theft. The need to maintain a trust relation is illustrated by the following quotation:

"There are many harvest workers here, but sometimes our trust...well, as I explained before, the disappearance of fruits from the plantation. There are harvest workers available, but I do not want to change my harvest worker. If we frequently change our harvest worker, what would our trust relation be like? I rarely change my harvest worker."

To thank workers, farmers sometimes let their harvesters collect loose fruits as a bonus. For example, one oil palm owner explained:

"I do not collect loose fruits; these are collected by the family of the harvest worker. He built a small house on my plantation. To thank him because he stays there and guards my plantation, he can take the loose fruits for his children."

Giving loose fruits to harvesters as a bonus was also a way to make sure they were collected and would not sprout into weeds, as illustrated by the following quotation from RI:

"The loose fruits are for the harvester, as a little extra for him. For us, it means they will not sprout everywhere as a weed. He can just take them. I don't have the time to collect them, I have other jobs to do."

Trusted workers were also considered important to warrant the quality of harvested bunches by avoiding harvesting underripe or overripe fruit bunches. As workers were paid per ton of harvested FFB, there was an incentive to increase the weight by harvesting unripe bunches. This was confirmed by a respondent from WK who said that although it is difficult to find workers, he did not want to change his trusted worker because he was afraid others might harvest underripe bunches to increase their income.

Finally, although long HI is significantly correlated with low FFB price (Supplementary Fig. S2), just 14% of all respondents said that a low FFB price was a reason to postpone the harvest, mostly in CK where HI was long (23-d) (Fig. 6). Also, in WK some interviewees who had long HI, said that when the FFB price was high, they harvested at the first sign of palm fruits becoming ripe. In contrast, when the price was low, they waited until bunches started to drop fruits. This is explained in further detail by the following interview excerpts:

"Farmers postpone because the price goes up and down. That is of influence. When the price is high, they will not wait until two weeks to harvest, so that they can benefit from the price. Interviewer: and when the price is low? The other day, I was also thinking about it. My friends did not harvest for a month, because the price was low."

"I have a fixed schedule of 15 days when the price is high. When the FFB price is low, I don't harvest for one or two months. It's not worth it. I wait for the price to go up."

The response to price in WK is also visible from HI as reported in the farmer diary. Although data from the period Jun-Aug 2022 does not show a low yield season, the average HI for this period was significantly higher (25-d) compared to the period of Jan-May 2022 (20-d). (Supplementary fig. S4). While this could have multiple causes, interviewees explained that the price drop was the reason. In contrast, in RI we did not observe a response to price in this period. In this site, the harvest interval was more regular, and although some farmers remember that in the past, they postponed the harvest due to low price, this only happened when the price was extremely low (400 IDR, USD$0.026).

Regardless of price, respondents indicated that a need for cash could be a reason to harvest ahead of schedule (Fig. 6). This was explained by a respondent from WK who harvested once a month:

"Sometimes you want to buy something, but you are short of cash. When some fruits can be harvested, even enough for some hundreds of thousands of rupiahs (IDR 100.000 is USD$6.73), they will be harvested. I experienced this in the past, when I wanted to buy something like school supplies, I tapped some rubber. Other people do the same, this makes their schedule flexible. The key is the need to cover some costs."

Harvesting ahead or behind schedule is also facilitated by the lack of quality control at the level of middlemen. At least in CK and WK, NGOs confirmed that middlemen do not sort FFB based on quality. The incentive for farmers and harvesters to prioritize weight over quality in FFB sale hampers implementation of short and regular HI:

"Now we are talking from a farmer's perspective: what matters is that fruits are yellowish or red, for farmers this means that they are ripe because what matters to us is the weight. The company looks for four fallen fruits. When there is only one fallen fruit, the fruit is underripe. For us, it's the weight. It is too much hassle to look out for the fallen fruits."

4. Discussion

Sustainable intensification on oil palm smallholder fields can be achieved through implementation of better management practices (BMPs), one of them being short HI. However, our field audit showed huge variation in harvest losses at any HI and, indeed, we could not detect a clear relationship between harvest losses and HI (Fig. 1). We estimated that, given current HI and yield levels, harvest losses from missed bunches can be up to 6% in smallholders' fields, which is similar with those reported in a food loss and waste (FLW) standard case study based on large plantations (Maire and Lee, 2019), but much larger than that reported by Donough et al. (2010) who estimated a harvest loss of 1% in large plantations with shorter HI and strict BMP measures. As mentioned previously, losses from loose fruits were small, because loose fruits were collected prior to the audit (Section 2.3). In most cases, this was done by oil palm field owners, or harvesters, but in some cases, loose fruits provided a source of income to third persons (see also Koczberski, 2007). Although collecting loose fruits is highly labor intensive (Teo et al., 2021), the benefits of loose fruit collection seem to outweigh labor costs and effort. This may particularly be the case when FFB price is high, increasing the economic value of loose fruits. However, in areas with labor shortages, especially when combined with larger land sizes, loose fruits may be more problematic, as it may not be economically attractive to collect them, but they will sprout into weeds. Similarly, more bunches may be missed when land sizes are larger. Mohanaraj and Donough (2016) point out that there is a risk that loose fruits will not all be collected, or lost on the way to the mill, and they will lose oil content quicker than when fruits are still in bunches. Moreover, the oil quality of overripe fruits and loose fruits is lower, and mills may pay a lower price for inferior quality of FFB (Anggraini and Grundmann, 2013).

However, our study also revealed several socio-economic factors that override agronomic considerations, leading to long HI in smallholder fields (Fig. 7). Our study shows that a two-weekly harvest cycle is the preferred HI for smallholders in Indonesia, which is longer than the agronomically optimal range of 7—10-d (Corley and Tinker, 2015; Donough et al., 2010). Our study confirmed earlier studies that HI is correlated with yield (Fig. 4). However, while long HI has mostly been considered as a cause for low yields (e.g., De Vos et al., 2021; Euler et al., 2016; Lee et al., 2014), the nature of cause-and-effect relations was not yet examined. This study demonstrates that oil palm smallholders also extend their HI in response to low yield and small total oil palm area (Figs. 4–5). This suggests that HI is at least partly determined by the total amount of FFB that can be obtained from all fields owned by a smallholder during one harvest round: smallholders wait until enough FFB is ripe to justify harvesting costs and effort. From the case studies, we also learned that harvest workers and FFB collectors required a minimum tonnage of FFB to harvest and collect harvest round to be cost effective and generate sufficient income. This minimum threshold in turn depended on factors such as FFB price, of which respondents said that it was influenced by worker availability, the wage of workers; and location of the oil palm field, road conditions, or other factors that impact transportation costs. Smallholders valued trust relations with their harvesters, who were also responsible for the FFB sale, so they did not want to change their harvest worker in order to harvest more frequently. Last, we found that some smallholders respond to FFB price fluctuations, especially in sites were HI was not fixed according to a harvest rotation schedule wherein harvesters have multiple plots under their care.

The scope to shorten HI as part of a sustainable intensification strategy depends on smallholders' ability to achieve a sufficient tonnage per harvest round for efficient harvesting and transportation of FFB. On average, smallholders in our study sites harvested 706 kg FFB ha^{-1} per harvest round, harvesting every 17-d, and achieved a total yield of 14 ton ha^{-1} per year. At this yield level, if one would harvest every 10 days (37 harvests y^{-1}), the average yield per harvest round would be 366 kg ha^{-1-1} and 544 kg when harvesting every 14-d (26 harvests y^{-1}) (Supplementary Table S4). With an average land area of 2 ha, this would generate an income of IDR 200.000 (USD$13.7) per harvest round. Based on personal communication with NGO partners, we estimate that <500 kg ha^{-1} per harvest round is insufficient to provide a good income to the harvest worker, although this depends on wage agreements between workers and field owners. Smallholders that have long HI (>16-d) may be able to implement a two-week harvest schedule if they can meet the threshold of 500 kg. However, even when the average yield per harvest round is around 500 kg, it may be that during the low yield season, yield per harvest round is lower. For this calculation, we did not account for better crop recovery when palms are harvested every ten days as we did not collect data on this effect. Hence, meeting the FFB tonnage requirement can either be achieved by increasing productivity, for example through improved nutrient management, or, by re-organizing the harvesting process so that multiple fields can be harvested together, and trucks can be filled in one harvest round. Our findings contribute to a better understanding of the potential of better management practices to address yield gaps, by showing how the benefits of yield intensification for farmers are conditioned by other factors, including labor and transport efficiency and costs. This is in line with Cock et al. (2022) who argue that increased labor productivity is crucial for achieving higher crop yields.

Finally, we want to highlight the agronomic and anthropological approach to study how farmers manage their fields and explore the conditioning factors which shape management practices in a local context. The benefits of this interdisciplinary research approach are that it enables an iterative research process in which results from one method can inform research methods in the next round of data collection. Second, we could triangulate different data sources to better understand observed trends and to assess similarity and difference across sites, as well as consistency between what people said and what actions people reported. A difficulty that we encountered was that sometimes there were discrepancies between data obtained through different methods. For example, in CK respondents said that they postponed the harvest in response to the low FFB price, but the farmer diary did not show a higher number of respondents with long HI during this period. In contrast, in WK, some respondents said in interviews that price was not of influence on their harvest schedule, but the researcher who did the case studies observed that farmers were delaying the harvest. Although there may be discrepancies between what people say and what people do, interview-based methods have their strength in obtaining a better understanding

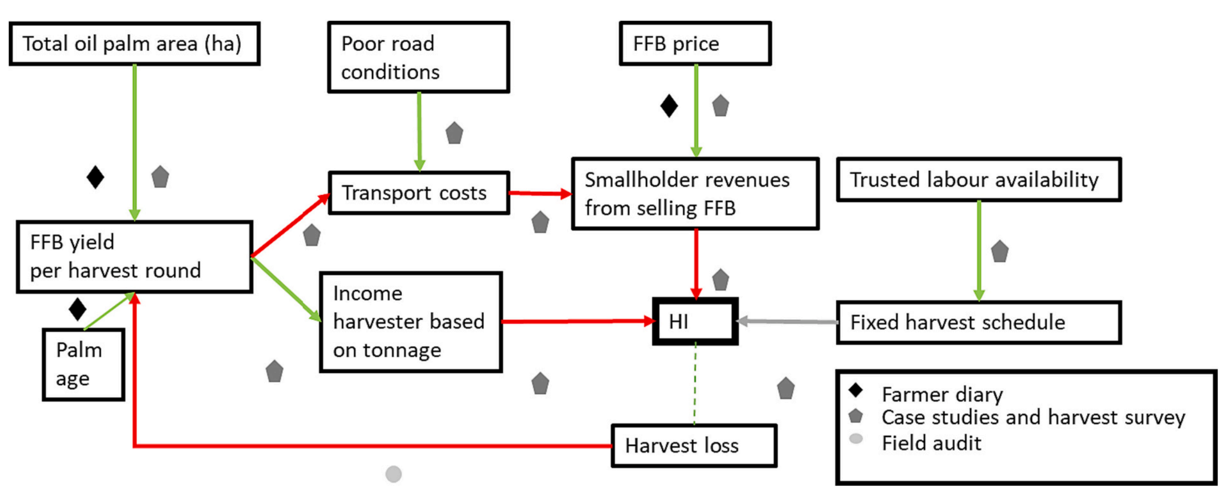

Fig. 7. Overview of factors positively (green) and negatively (red) influencing HI based on the farmer diary, case studies, harvest survey and field audits. The grey arrow means this factor is fixing the HI. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of people's motivations for doing things, while observations, or reported actions may provide a more accurate insight in what people do, as well as show trends over time. More research based on both agronomy as well as anthropology research approaches can contribute to a better understanding of farmers' realities, enabling context specific and realistic support programs for farmers.

5. Conclusions

Independent smallholders in our study harvested their fields every 17 days on average. Farmers responded to low yield by prolonging HI to increase labor productivity and optimize labor and transportation costs. This can potentially lead to increased harvest losses from loose fruits and missed bunches, and reduced oil quality from overripe bunches. Key barriers to shorten HI are availability of trusted harvest workers, minimum FFB tonnage requirements to guarantee sufficient income for harvesters, and poor road conditions. We conclude that increasing harvest frequency makes more sense to farmers when coupled with yield-improvement management practices, such as fertilizer application and weed control, to increase volume per harvest. In turn, increasing harvest frequency requires collective action, involving oil palm field owners, harvest workers, FFB collectors, and mills to streamline the harvest process and increase uptake security, also in times of low FFB prices. Moreover, farmers need financial incentives to improve harvest quality by harvesting according to standard.

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.agsy.2023.103753.

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