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Replanting and yield increase strategies for alleviating the potential decline in palm oil production in Indonesia

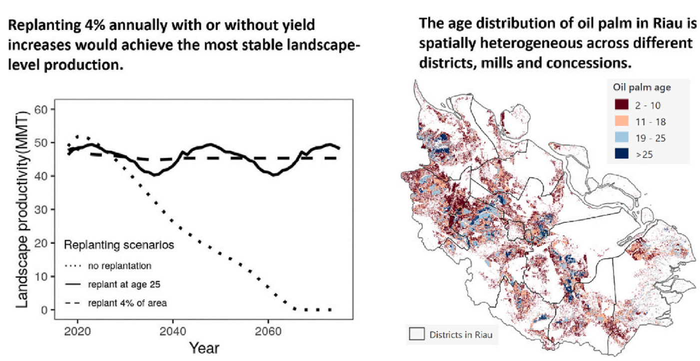
Jing Zhao [a], Andrew J. Elmore [a,b], Janice Ser Huay Lee [c,d], Izaya Numata [a], Xin Zhang [a,*], Mark A. Cochrane [a,*]

[a] Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD, United States of America
[b] National Socio-Environmental Synthesis Center (SESYNC), Annapolis, MD, United States of America
[c] Asian School of the Environment, Nanyang Technological University of Singapore, Singapore, Singapore
[d] Earth Observatory of Singapore, Nanyang Technological University of Singapore, Singapore, Singapore

HIGHLIGHTS

- Maintaining stable and high level of palm oil production within current oil palm extent is vital for multiple stakeholders.
- We designed scenarios based on replanting rates and yield improvements to show the impacts of replanting strategies.
- The age distribution of oil palms in Riau is spatially heterogeneous among districts, mills and concessions.
- Replanting 4% annually with or without yield increases would achieve the most stable landscape-level production.
- Combining replanting with yield improvements could more quickly overcome potential declines in regional production.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Maintaining stable and high levels of palm oil production within the current oil palm extent is a potential strategy to relieve deforestation pressure. Recent exponential growth of oil palm plantation area has led to significant carbon emissions and biodiversity loss. However, halting palm oil expansion may have adverse effects on palm oil production and the impact on the palm oil industry has not been well studied.
OBJECTIVES: We developed quantitative methods to assess the potential decline of regional oil palm productivity given the landscape-level age-distribution structure on existing oil palm plantation land and evaluated strategies to alleviate this potential decline. These could provide guidance to multiple stakeholders, including mill owners, plantations, farmers, and regional governments, interested in improving and stabilizing palm oil yield.
METHODS: We developed a model of palm oil production for Riau, Indonesia, where two decades of extensive industrial and smallholder oil palm expansion has occurred. Using established age-related rates of production, we investigated how palm oil productivity in current plantation areas would change over time if existing oil palm trees were cut and replanted at 25 years. We also designed scenarios based on replanting rates and yield

* Corresponding authors.
E-mail addresses: xin.zhang@umces.edu (X. Zhang), mark.cochrane@umces.edu (M.A. Cochrane).

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improvements (better management practices or adopting more productive cultivars) to show the different impacts of replanting strategies. For each scenario, the production level was projected to 2075.
RESULTS AND CONCLUSIONS: We found that the production of fresh fruit bunches from oil palm could fluctuate around 45 million metric tons if all current oil palm was replanted at 25 years with no further planted-area expansion. Replanting 4% annually, with or without yield improvements, would achieve the most stable landscape-level production. With yield improvements, the regional production could be increased to higher levels under any replanting rate. However, improving yields alone would be insufficient to prevent declining productivity trends in current plantation areas. Combining replanting with yield improvements could more quickly overcome potential declines in regional production. The age structure of oil palms in Riau is spatially heterogeneous across different districts, mills and concessions, posing increased challenges for replanting efforts to stabilize landscape-level yields.
SIGNIFICANCE: Our study provides important information about the policy implications from different replanting and yield increase strategies on landscape-level palm oil production. Our findings demonstrate the need for collaborations among multiple stakeholders to maintain steady high levels of palm oil production in Riau, however varying stakeholder interests present major challenges for enabling and facilitating collaborations.

1. Introduction

The recent rapid growth of oil palm plantation area in Indonesia and its adverse impact on deforestation, carbon emissions and biodiversity are well known (Meijaard et al., 2020). Oil palm area in Indonesia has dramatically increased, from 0.3 million ha in 1980 to 14.8 million ha in 2020 (Directorate General of Estate Crops, Ministry of Agriculture, 2020). Oil palm expansion has played an important role in the loss of Indonesian old-growth primary forests (Gaveau et al., 2022), resulting in significant carbon emissions and biodiversity losses. However, it is critical for Indonesia to maintain high levels of palm oil production since the oil palm industry has a broad impact on economic development, poverty alleviation, and rural employment (Qaim et al., 2020). Reaching these societal goals, while also reducing the environmental impacts of oil palm production, is a key challenge for the region.

One strategy for slowing the expansion of an agricultural system into natural habitats is to focus on increasing the average yield and total production of extant areas (Pradhan et al., 2015). For example, average oil palm yields across Indonesia were only 15.3 and 19.7 tons FFB per hectare for smallholders and large plantations in 2020, which is far lower than the attainable yield of 30.6 ton FFB per hectare (Monzon et al., 2021). Palm oil yield declines with age after approximately 18 years (Woittiez et al., 2017), therefore old oil palms identified in survey and satellite data as being established in the 1980s (Danylo et al., 2021; Mariyah et al., 2018) are expected to drive further declines of average palm oil yields in the next decade. Thus, replanting aging oil palm in a timely manner is a vital and necessary strategy for improving average yields that could enhance total palm oil production within extant areas, reducing pressures to expand development into sensitive and diminishing natural forest areas.

Multiple studies have investigated optimal replanting ages, which depend on various factors such as palm oil price, cost to establish new palms, discount rate, availability of labor, availability of other income sources during the replanting period, period of time before new plantings can be harvested, and capital costs associated with replanting (Ismail and Mamat, 2002; Nurfatriani et al., 2019). However, few studies have investigated the actual rates of replanting of oil palm on existing landscapes. Faeid et al. (2020) examined the optimal replanting rate for long term production in Malaysia using a system dynamics approach which incorporated the dynamic interaction of palm oil supply and demand, new plantation area, and crude palm oil price. Wahid and Simeh (2010) found low rates of replanting (only 1.18% per annum) caused by higher prices could eventually lead to a “rush to replant”, which would affect the overall supply chain, including seedlings, milling, refining, and exporting. These studies approached replanting strategies from different perspectives, such as maximizing net revenue over productive life (Ismail and Mamat, 2002), decisions of farm households (Mariyah et al., 2018), and an interaction of supply and demand via price (Faeid et al., 2020). However, sustainable management of oil palm thus far has focused on the improvement of yields at the farm-level but has not considered how optimizing replanting rates could affect landscape-level productivity.

Here, we took a regional perspective and leveraged a robust remote sensing approach to map the initial oil palm age distribution, which was heavily influenced by the rapid growth of oil palm area over the last decade (Danylo et al., 2021). Our approach allowed us to predict the impacts of replanting rate on yields beyond the farm scale, across heterogeneous landscapes, and at scales relevant to regional policy and management. Increasing palm oil production without expanding the area of production could help reduce development pressure on biodiverse natural ecosystems, such as forests and peatlands (Monzon et al., 2021; Khor et al., 2023).

We used Riau, Indonesia as a case study, where a large amount of industrial and smallholder oil palm expansion has recently occurred over carbon rich peat soils. The research aim is to demonstrate future production trends based on the current (year 2017) age structure of extant oil palm and the impact of different replanting strategies. We also investigated how progressive improvements of maximum palm oil yields could affect future production trends.

2. Data and method

2.1. Study area

Our analysis focused specifically on the oil palm area in Riau Province on the island of Sumatra for several reasons. First, given its rapid oil palm expansion, Riau is now the province with the largest area of oil palm planted in Indonesia, 2.86 million ha in 2020 (Directorate General of Estate Crops, Ministry of Agriculture, 2020). Second, oil palm expansion is a major driver of deforestation in Riau (Ramdani and Hino, 2013). Third, it is critical for Riau to improve production within existing oil palm areas since little forest area remains for potential oil palm expansion (Purwanto et al., 2020; Zhao et al., 2022). Fourth, 21% of oil palm expansion area has recently occurred over high-carbon content peat soils in Riau, based on the spatial distribution of peatland (Indonesia Ministry of Agriculture) and oil palm map (Danylo et al., 2021). However, a relatively large peat swamp forest area remains, the protection of which is important for carbon sequestration and continued storage (Miettinen et al., 2012; Posa et al., 2011).

Riau has a longer history of oil palm compared to most other provinces in Indonesia. As the demand for oil palm continues to grow, these provinces may follow the same path and face similar challenges as Riau. Therefore, understanding oil palm development in Riau could be beneficial for provinces and countries beyond Riau.

2.2. Data

This study used the Riau portion of the 2017 oil palm (~2 million hectares) map from Danylo et al. (2021). The regional oil palm maps were developed based on a stratified unsupervised classification algorithm applied to the Copernicus Sentinel-1 microwave backscattering time series. Plantation stand ages were estimated using the bare soil index based on the time series data from the Landsat 5 and Landsat 7 image collections since 1984. The map does not distinguish between industrial plantations and smallholder oil palms. The overall accuracy of the map for Sumatra was 84.8% with a confidence interval of 82.8–86.7%. For reference oil palm pixels, 90.21% were correctly identified as "oil palm", while 78.5% of areas identified as "oil palm" in the classification were actually oil palm. Errors were partly attributed to the temporal availability of very high-resolution satellite imagery. Danylo et al. (2021) found oil palm to be first detectable at 2 to 3 years of age, therefore the most recent detection of oil palm after previous clearing is treated as being 2 years old in this study. We calculated the ages of oil palms and the area by different age classes across the landscape in 2017 for all of Riau based upon the year of first detection.

The list and spatial locations of oil palm mills in 2017 are from Center for International Forest Research (CIFOR) website (https://www.cifor.org/knowledge/dataset/0098/). Travel time data is from Weiss et al. (2020), which provides a global friction surface based on road networks from OpenStreetMap, Google Maps and academic experts. We used these data to calculate 2-h isochrones around each mill. About 98% of oil palms in Riau are within 2 h travel time of a mill (Fig. S1). We used a clustering analysis to summarize the variability in oil palm age distributions within 2-h travel time of mills in Riau.

2.3. Method

Oil palm is a perennial crop with 25–30 years of productive life. The actual yield of palm oil is strongly related to a tree's age (Fig. 1). Approximately three years after planting, oil palms start to bear a few fruits. Annual yields increase very quickly thereafter and peak when around 8–9 years old (Woittiez et al., 2017). Peak yields are typically maintained until reaching 18 years old. From 19 years old onward, yields of palm oil decline gradually (Soliman et al., 2016). Age-based yield curves (Fig. 1), based on work by Woittiez et al. (2017), Monzon et al. (2021) and Khiabani and Takeuchi (2020), show the general trends for fresh fruit bunch yields during the productive life of oil palm trees, but considerable uncertainty remains due to variation in inputs, management, weather (Woittiez et al., 2017).

We first investigated how productivity in existing areas of oil palm will change over time, given the current oil palm age structure and a typical replanting age of 25 years old. Then, we designed several scenarios to investigate how different replanting strategies may affect the level and stability of total palm oil production through 2075. The replanting strategies considered in this study include different annual replanting rates and distinct yield improvements from use of improved cultivars, fertilization, and other management practices. At the field scale, there is evidence that industrial oil palms are typically replanted at 25 years old (Monzon et al., 2021), however, we observed that some areas have oil palm trees as old as 32 years (Fig. 2). For an even-aged field, these ages suggest a replanting rate near 3%. In Riau, we suggest that considering spatial variation in farmer decisions about when to replant results in an average replanting rate close to 4%, which we adopt as our baseline scenario. Lower replanting rates (perhaps 2–3%) might occur in some cases, such as when current palm oil prices are very high (Wahid and Simeh, 2010). In this case, farmers might have an incentive to reduce replanting rates and thus avoid potential near-term income losses. Conversely, if palm oil prices are very low, farmers may prefer to replant at higher rates, such as 5%. Therefore, we designed scenarios with four annual replanting rates of 2%, 3%, 4%, and 5% for replacing the oldest oil palm trees each year. Under each scenario, the oldest 2–5% of oil palm area was annually replanted and the corresponding yield curve for the location was restarted from 1 year old, while the ages of the remaining 95–98% of oil palm area was advanced by one year.

Using the resulting age distribution and the yield curve (Fig. 1), we calculated the total potential production for each year within the 2017 oil palm extents in Riau. We calculated the production trends for the entire landscape out to 2075 under the various replanting rates and compare the cumulative production of each replanting rate to the 4% baseline scenario. We also considered the effect of yield increases for replanted oil palm (e.g., due to improved cultivars, fertilization, and other management practices) against the base case of no yield increase. We designed scenarios to examine yield increases at the level of 0%, 10%, 20%, and 30% (Table 1). Scenario 1 assumes no yield increase for replanted oil palm. Scenario 2–4 assumes that the replanted oil palm increases yield by 10%, 20%, 30% respectively, potentially due to better cultivars, inputs (e.g. fertilizer), and management (Kome and Tabi, 2019; Lee et al., 2014; Purba, 2019). For each scenario in Table 1, the production was quantified as fresh fruit bunches (FFB) and was projected out to 2075 in Riau using a static plantation area equal to what was measured in 2017.

Detailed data on the various costs, including detailed yield and FFB prices, were unavailable for the Riau oil palm industry, therefore, we were not able to evaluate more specific production indicators, such as profitability.

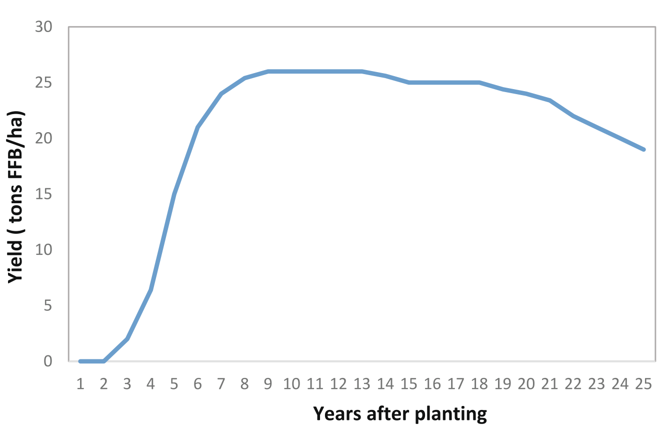

Fig. 1. Typical fresh fruit bunch yield by oil palm tree age (Woittiez et al., 2017; Monzon et al., 2021; Khiabani and Takeuchi, 2020; *http://www.yieldgap.org/indonesia-oil-palm*).

3. Results

3.1. Age structure of oil palm in Riau and future production trend

The uneven annual expansion rates of oil palm in Riau during recent decades have resulted in a skewed distribution of oil palm ages across the landscape (Fig. 2a). As of 2017, 8% of the extant area of oil palm (175,750 ha) in Riau was older than 24 years. These areas are overmature, with decreasing productivity, and should be replanted soon. A boom period of oil palm expansion occurred from 2004 until 2014 (3 to 14 years old in 2017), accounting for 61% of total oil palm area in 2017, and the average annual expansion rate of oil palm area from this period was higher than 4% of the 2017 area (the dashed line Fig. 2a; 4% was used as the baseline annual replantation rate because it achieves the most stable and productive landscape for oil palm). By 2035, all current extents of planted oil palms would be older than 20 years and beyond peak yield rates with declining productivity. Without replanting, the FFB production could peak in 2020 at 52 MMT and drop to 0 MMT in 2075 (Fig. 2b). Therefore, timely replanting is essential for stable palm oil production in Riau.

If replanting at a typical age of 25, the production of FFB could peak

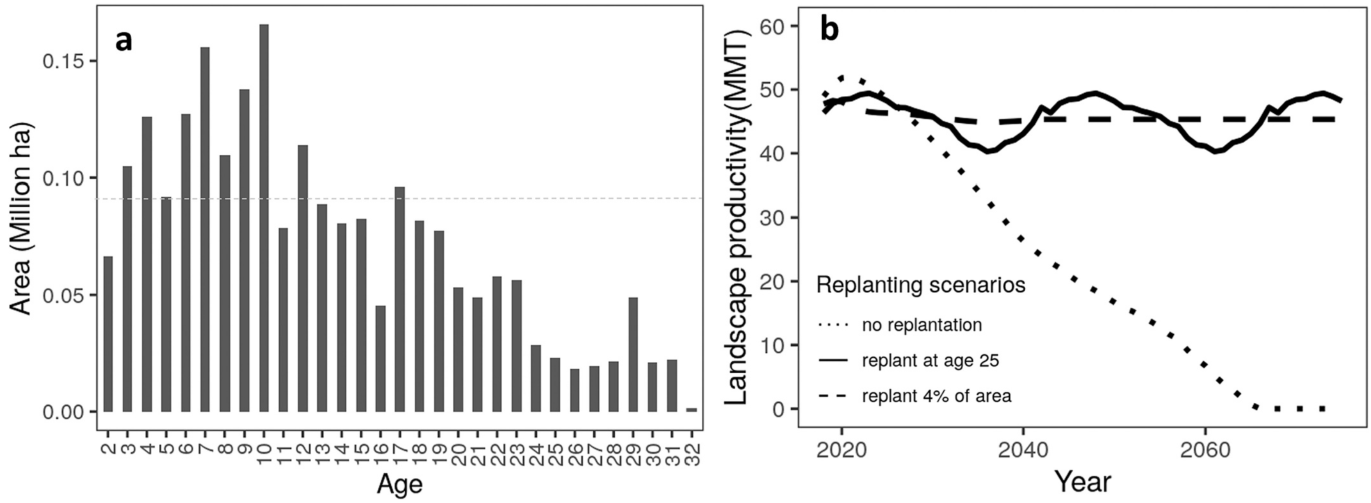

Fig. 2. Oil palm area by age in Riau in 2017 (Danylo et al., 2021) and future production trend. Panel a shows the oil palm area by age in Riau in 2017. Dashed line shows the 4% level of total oil palm area if evenly distributed in 2017. Panel b shows the landscape productivity trend (FFB production) under 3 different replanting scenarios, including no replantation, replant at age 25, replant 4% of the area each year. Under the scenario of no replantation, from age 35 to age 50, the yield is 10 tons per hectare, and becomes 0 after age 50 due to difficulties in harvesting.

Table 1
Scenario design based on replanting rate and yield improvement.

Scenarios for Replanting rate	Scenarios for yield improvement			
	0%	10%	20%	30%
2%	A1	B1	C1	D1
3%	A2	B2	C2	D2
4%	A3	B3	C3	D3
5%	A4	B4	C4	D4

in 2023 at 49 MMT, decrease by over 18% to 40 MMT in 2036, and then continue to fluctuate between 40 and 49 MMT between 2037 and 2075 (Fig. 2b). While this replanting strategy avoids the long-term decline observed in the no replantation scenario, it does not actively change the skewed age distribution of oil palm in the landscape, and consequently has large interannual fluctuations in replanting area. For example, with this replanting strategy, 620,000 ha of oil palm area would need to be replanted during a five-year period (2033–2037), which accounts for 27% of the current 2017 area (Fig. 3a). In contrast, only 20% of the current 2017 area needs to be replanted every five years if replanting 4% annually.

In contrast to replanting at a typical age, steadily replanting 4% of the area annually will lead to a more stable production level over the long term. If this replanting strategy was implemented after 2017, the FFB production would peak in 2019 at 48 MMT and then gradually decrease to about 45 MMT by 2035, remaining relatively stable thereafter (Fig. 2b). But it is important to note that, with this replanting strategy, 93,713 ha oil palm would need to be replanted before age 25 during the 2018–2027 period (Fig. 3a), which could lead to short-term production losses compared with replanting at age 25. Therefore, annual FFB production in the existing oil palm production area is projected to decline from 2023 to 2026, if oil palm is replanted by 4% per year. These two replanting strategies (i.e., replanting at age 25 and replanting at the rate of 4% annually) also show substantial differences in the spatial distribution of replanting area (Fig. 3b and d). The replanting time could be very different for the same trees under the two different replanting strategies (Fig. 3c and e). For example, the red color in Fig. 3e shows that oil palm trees would be replanted over 2038–2042 if replanting 4% each year, most of which would be replanted between 2033 and 2037 if replanted at age 25 (Fig. 3c).

3.2. Spatial distribution of aging plantations

The age structure of oil palm varies among regions in Riau due to the history of expansion, and consequently affects the spatial pattern of replantation (Fig. 4a). First, the aging oil palm density in northern Riau is much higher than that in southern Riau. Second, aging oil palms are highly concentrated in some districts, such as Kamper, Rokan Hilir, Siak (Fig. 4a). Third, some districts have high concentrations of young oil palms, such as Rokan Hulu, Rokan Hilir, while young oil palms are widely spread in the other districts, expanding around previous oil palm plantations.

The spatially heterogeneous age structure may pose challenges for oil palm mills located in regions dominated by aging oil palms, since they may have to confront sharp temporary declines in FFB production during replantation (Fig. 4), versus continuous but slower rates of decline without replanting. The oil palm mills inside oil palm concessions and surrounded by aging oil palms (light blue and dark blue in Fig. 4a) would see a decline in productivity due to aging plantations in the next five years. Moreover, mills are also highly concentrated in a few districts, especially in Siak, Kampar, Rokan Hilir, and Pelalawan. Therefore, mill owners should be aware of the risk of yield decline and increasing competition for FFB due to aging plantations in the surrounding area, especially within a radius of 25 km (Zhao et al., 2022). In addition, it is critical to match the FFB production and overall mill capacity at the landscape level. The oil palm production could confront different replanting challenges inside and outside oil palm concessions. Since the majority of old oil palms in 2017 are inside oil palm concessions (Fig. S3), in the short run, oil palm within concessions is most affected by age-related production losses and insufficient replanting rates. However, the majority of young oil palms in 2017 are distributed outside oil palm concessions (Fig. S3). Several districts have large areas of 2–10 year old oil palms outside of concessions, such as Rokan Hulu, Rokan Hilir (Fig. 4b). Moreover, small-medium farmers are more likely to own the areas of young oil palms outside of concessions, which would need strategic planning for replanting by policymakers at the district level to avoid the substantial landscape productivity decline in the future.

In addition, age distribution of oil palms within 2 h travel time to each mill varies considerably. Clustering analysis identified 4 groups of mills with similar oil palm age distributions (see supplementary Fig. S6). One large cluster centered on Rokan Hilir and Kota Dumai will need to increase mill capacity to satisfy rising palm oil production levels due to a

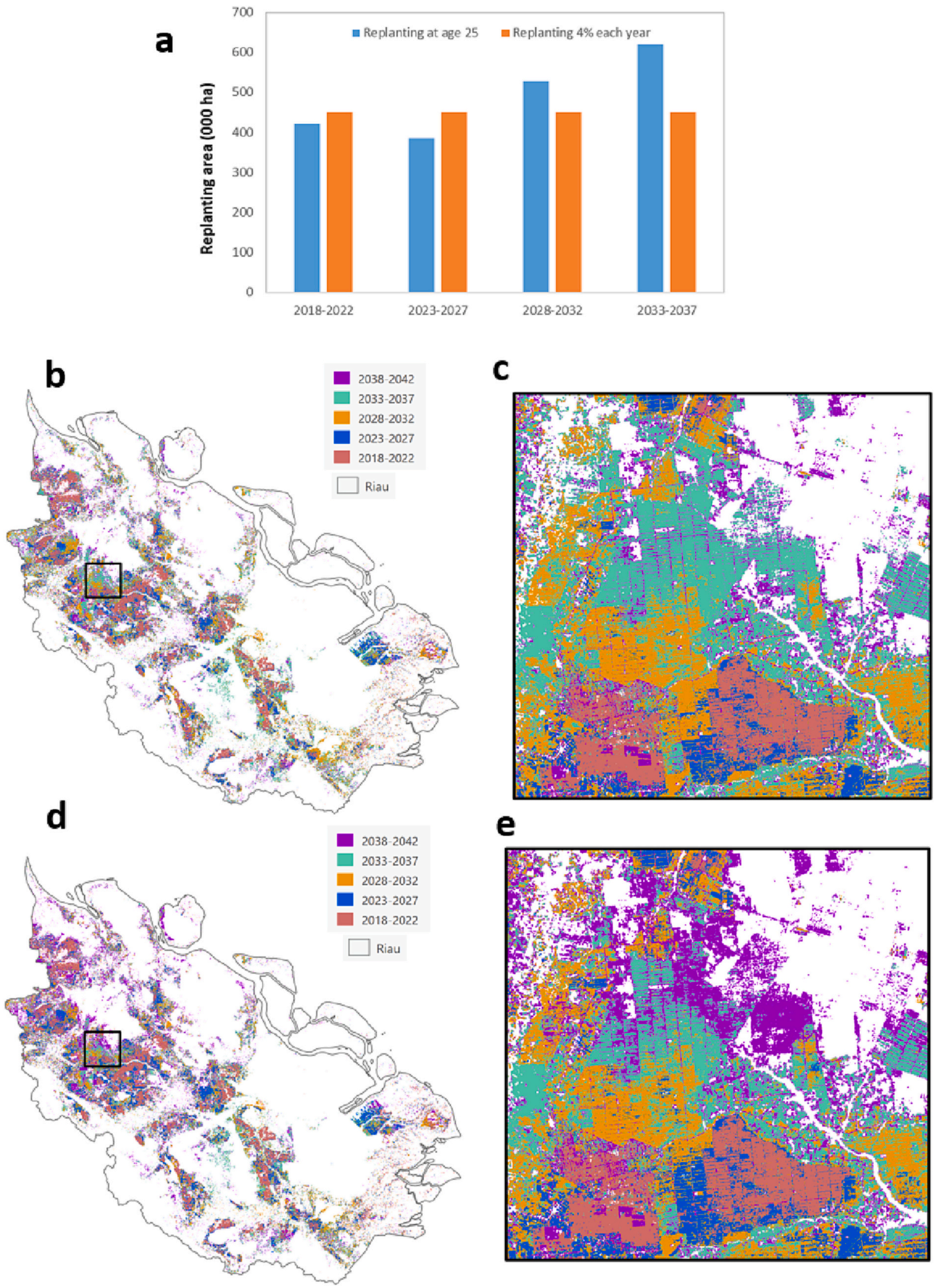

Fig. 3. Temporal and spatial patterns of oil palm replanting in Riau. The replanting area under two scenarios over time, summarized in 5-year bins (a). Maps of projected replantation areas under the 25-year scenario, provided for five future time periods for all of Riau (b) and a small region to show detail (c). Similarly, maps of replantation area under the 4% annual replanting scenario (d and e). The 4% selected for annual replanting in each age-group is assumed to be random.

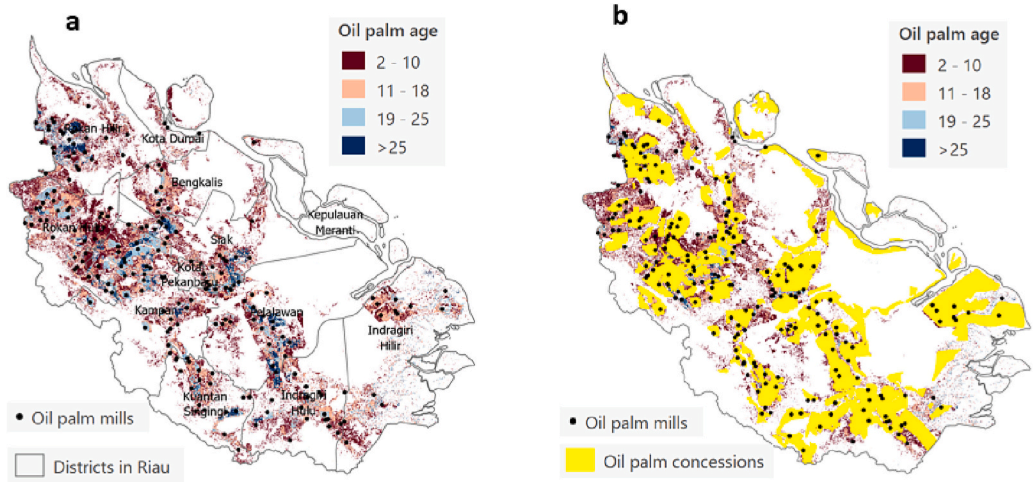

Fig. 4. Spatial distribution of oil palm by age, and the locations of mills and oil palm concessions in Riau in 2017.

currently high fraction of young oil palm (<10 years) relative to older oil palm. In contrast, some mills in Indragiri Hilir are facing declining FFB availability due to a high fraction of aging oil palms. A cluster of mills in the southwestern region would be expected to have relatively stable palm oil production with appropriate replanting rates.

3.3. The impacts of different replanting rates

With current yield levels and the 2017 age composition, lower replanting rates would yield higher near-term (e.g., before 2025) palm oil production in Riau (Fig. 5a). Replanting 2% each year leads to peak production of 50 MMT in 2020, which would be 4% higher than production if 4% were replanted each year. Moreover, in terms of cumulative palm oil production across all of Riau, replanting 2% each year would continue to have a higher total cumulative production than replanting 4% each year until 2037 (Fig. 5a).

However, in the longer run (i.e., after 2040) replanting 4% each year (when compared with the other scenarios) would maximize palm oil production over the existing oil palm area (Fig. 5a). Palm oil production would eventually stabilize at 45 MMT per year, which would be 28% higher than the production in 2075 if only replanting 2% each year.

Overall, replantation rates <4% a year achieve better short-term yields, but at disproportionate costs, in terms of reduced yields, thereafter. Conversely, replanting at a greater rate such as 5% will lead to reduced yields for all years compared to the 4% rate. Even if replanted trees had enhanced productivity, replanting 4% each year out to 2075 would still be the optimal choice for stabilizing productivity and maximizing productivity over the long term because it maximizes landscape-level palm oil production (Fig. 5b-d).

3.4. The impacts of yield improvement

If there were no yield improvements, total oil palm production would decline and/or stabilize at the maximum production rates unique to the different replanting rates (Fig. 5a). If replanting 2% per year, the fresh fruit bunch production in 2075 would decline to 35 MMT from a peak production of 50 MMT in 2020. Ultimately, replanting 2% or 3% would result in having 50% or 24% of extant oil palm >25 years old, respectively, reducing total landscape-level productivity. Conversely, cutting and replanting 5% a year would lead to a maximum oil palm age of 20 years across Riau. Replanting at the higher rate of 5% would require replacing still-productive 21–25 years old trees, increasing the

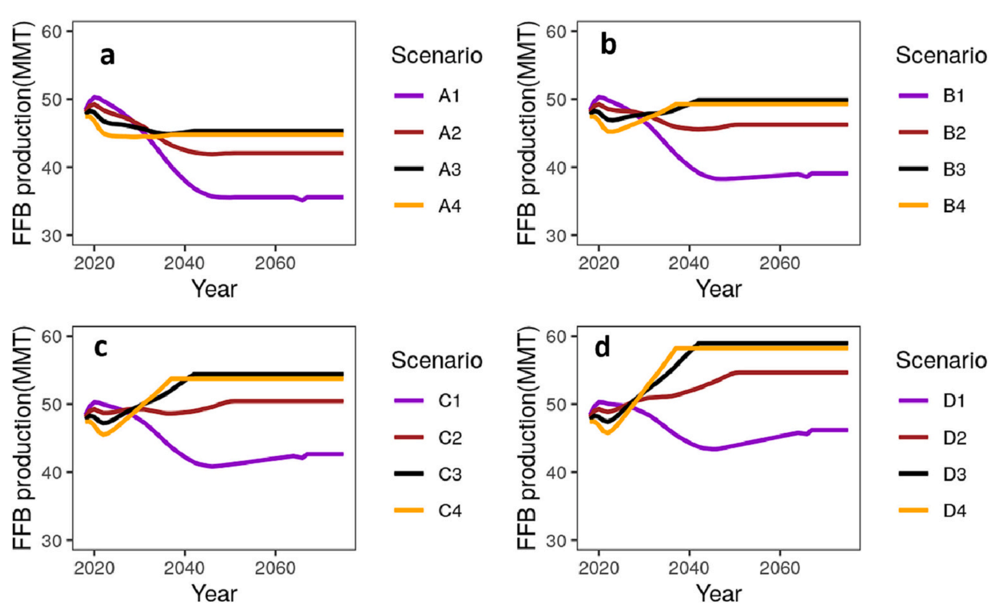

Fig. 5. Projection of fresh fruit bunch (FFB) production (million metric ton) by year. Scenarios are as shown in Table 1.

representation of young oil palm with little or no production, and slightly reducing landscape-level yields of palm oil.

If yields for replanted areas could be improved (e.g., with better choice of cultivars, fertilization, and other management practices), the regional palm oil productivity could be increased to higher levels under any replanting rate. The dynamics of improved yields at the different replanting rates would be similar but the cumulative production differences would be exacerbated/reduced for replanting rates lower/higher than 4%. Improved yields would reduce the number of years until both annual and cumulative palm oil yields for the 4% replanting rate exceed those of lower rates (Figs. 5 and 6). Conversely, at replanting rates of 5%, improved yields could result in some middle years of FFB production exceeding those at 4% but cumulative production by 2075 is still greatest for the 4% rate. Therefore, a combined effort of replanting 4% annually with yield improvement could generate the highest and most stable oil palm production in Riau.

4. Discussion

4.1. Optimal replanting strategies for landscape-level production

Our results show that replanting at 4% each year in Riau is the optimal landscape-level strategy for the highest and most stable long-run production, exceeding those of other replanting rates or simply replanting the current landscape when oil palms reach 25 years old. Importantly, this approach would achieve stable, high palm oil production levels without abrupt distortions to annual production levels.

Although several studies have explored approaches for improving oil palm yield and production (Faeid et al., 2020; Monzon et al., 2021; Varkkey et al., 2018), our approach is unique in demonstrating the impacts of intensification through different replanting strategies on landscape-level productivity without new deforestation or expansion of planted areas. For example, our study differs from Faeid et al. (2020) in several aspects. First, our model identifies an optimal replanting strategy for landscape-level production within the current age-structure of the oil palm area. Faeid et al. (2020) employed a system dynamic optimization model to identify the optimal replanting rate to obtain maximum FFB yield in 2075. Second, our constraints did not allow for new oil palm expansion scenarios or linkages between the crude palm oil (CPO) price to supply and demand, as they did. Third, we quantified differences between replanting by age or by annual replanting rate (the ratio of replanted area over current plantation area). Their assessment had replanting rates prescribed by the number of hectares per year. Our results identify how stable, high-levels of production can be achieved with implementation of a landscape-level replanting rate, regardless of yield improvements. This result contrasts with work by Faeid et al. (2020), who found that higher replanting rates improve yields, but would cause increased interannual volatility in production for Malaysia. In fact, they did not find any replanting rate that could achieve stable FFB outputs over the long run. Faeid et al. (2020) focused on the interactions of multiple factors from supply and demand sides of oil palm that could influence farmer decisions to replant at a particular rate. We, on the other hand, showed how the historic planting influences extant age-structure that would influence outcomes of different replanting rates. These differences in scale and variables led to different results. The combined findings from these two studies could be used to help develop strategies to encourage farmers to replant at an optimal rate.

4.2. The potential production cycle and deforestation risk

Without planned replanting cycles, annual palm oil production on existing planted areas could be reduced by 10%–30% compared to peak production levels in 2020. This reduction would grow over time due to declining yields from aging trees (Fig. 5a). Farmer response to declining production has a strong influence on sustainability. Our results show that choices of replantation rates can either contribute to or detract from sustained oil palm production levels over the long term. Production declines would increase incentives for farmers to expand planted areas of oil palm. Forest area in Riau has been vastly reduced and remnants are mainly peat swamp forest. If the landscape's aging palm oil structure, resulting from the 2004–2014 planting boom period, is not addressed with managed replanting strategies, it will likely result in increased deforestation risk for remaining peat swamp forests. This would be to the detriment of global carbon storage and biodiversity. As of 2019, only 940,000 ha of peat swamp forest remains in Riau, which could emit 65–110 million tons CO_2 eq yr^{-1} if converted to oil palm plantations

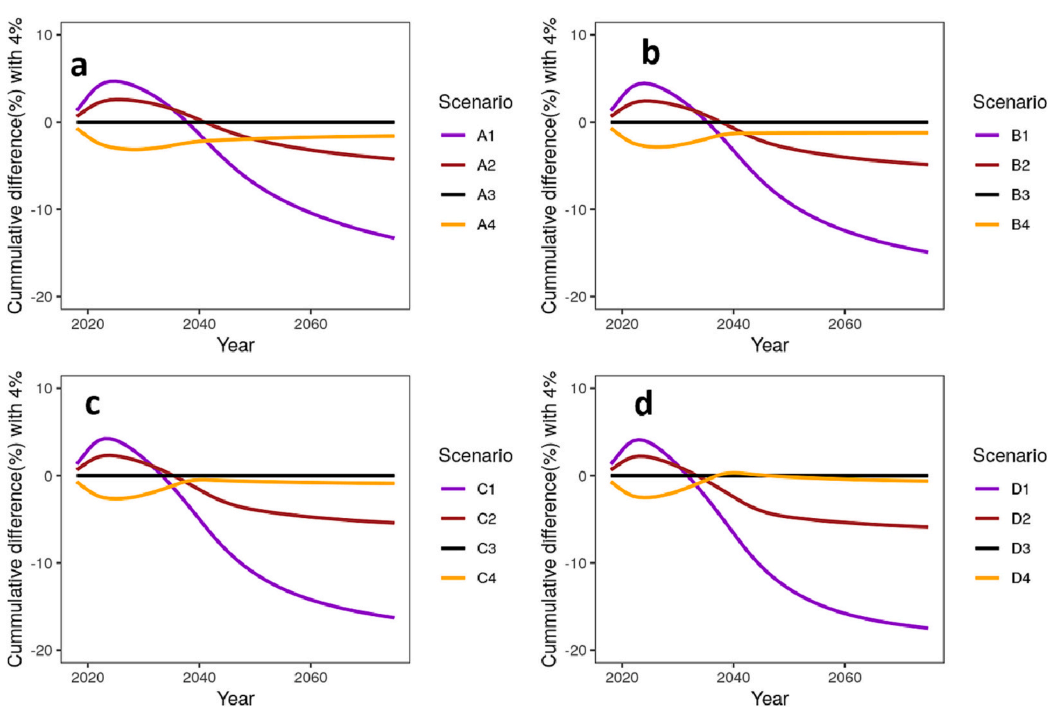

Fig. 6. Cumulative fresh fruit bunch production expressed as the difference (%) with the 4% replanting rate. Scenarios are as shown in Table 1.

(Cooper et al., 2020). This is equivalent to the annual carbon emissions from 14 to 24 million passenger vehicles. However, only 21% of the remaining peat swamp forests are within protected areas (Zhao et al., 2022).

4.3. The role of government in maximizing palm oil production within existing landscapes

Our results show that replanting 4% of older oil palm areas each year is the optimal strategy for achieving high and stable landscape-level productivity. Since industrial plantations usually replant old oil palms at age 25, the replanting rate of 4% is not difficult to achieve by the private sector. However, smallholder farms are likely to delay replanting of aging oil palms for multiple reasons. As of 2017, 2.4 million hectares of smallholder oil palm plantations in Indonesia needed replanting (Nurfatriani et al., 2019). Although the Indonesian government already has some policies, such as the *Peremajaan Sawit Rakyat* (PSR) program, to help smallholder farmers to replant trees, realization of PSR program goals have remained far from their targets, leaving aging and unproductive oil palm areas in Indonesia (Ardana et al., 2022). Legal issues with land tenure rights have also been a barrier to farmers gaining access to necessary replanting services and funds (Nurfatriani et al., 2019). Replanting could also be constrained by planting materials, labor or capital, especially for smallholders. The government needs to design and implement policies that account for the challenges faced by smallholder farmers to more effectively improve their oil palm replanting rates.

Current government policy precludes replanting in some areas such as Kawasan hutan, which contains a large area of oil palm (Purwanto et al., 2020). Should this or future government regulations prevent replanting on peatlands, then total oil palm area would eventually shrink by 21%, as compared to 2017. This could result in a significant drop of palm oil production, which would require an effective policy response from government to improve replanting rates and yields.

Both government and mills could provide support for replanting and get benefits from increasing palm oil production. If there are high punishment costs for deforestation while higher returns exist from replanting, both private and smallholder would prefer replanting. Moreover, through replanting and increasing yield, mills could better manage the risk and challenge of yield decline posed by spatially heterogeneous age structure.

4.4. The potential impact of recent high palm oil prices

It is clear from these analyses that achieving a stable replanting rate of 4%, with or without yield improvements, would result in the highest and most stable rate of landscape-level palm oil production among the scenarios tested in this study. While this may be an optimal outcome for Riau Province or the Indonesian government, achieving this across a spectrum of privately-held individual plantations of different ages and sizes, ranging from smallholders to large commercial operations, who operate with differing time preferences within a system of shifting regulations, commodity price fluctuations and variable weather events will be challenging. Wahid and Simeh (2010) found that low oil palm replanting rates in Malaysia were closely linked to periods of high CPO prices when most oil palm growers delay decisions to replant so as to maximize current profits. Faeid et al. (2020) also stated that high crude palm oil prices would lead to low replanting rates. For example, palm oil prices jumped from 577 USD/MT in May 2020 to 1717 USD/MT in May 2022 (prices data from World Bank), an increase of 200%. With palm oil prices this high, especially if the spike in prices is expected to be temporary, farmers will have great incentive to maximize near-term production rates and therefore defer replanting of many aging palms, even if the original intent had been to do so. Thus, periods of relatively high palm oil prices may result in lower rates of replantation of older oil palm, thereby setting in motion a process whereby age-structure distortions result in future reductions in potential landscape-level production, increasing pressure for additional oil palm expansion. For example, the production difference in 2075 between replanting rates of 2% and 4% each year, under current yield levels, would be 9.79 MMT, around 20% of total peak production, which is roughly equivalent to production from 0.4 million hectares of mature oil palm. Market values of 9.79 MMT ranged from 5.6 billion USD to 16.8 billion USD, based on prices between May 2020 and May 2022. The extent to which replanting rates are influenced by commodity, fertilizer or other prices will lead to increased volatility in palm oil production that can last for decades, leading to limited effectiveness of palm oil yield intensification efforts to stabilize the deforestation frontier in Riau.

4.5. Limitations

In this study, we focused on identifying replanting strategies that could stabilize and maximize palm oil production at the landscape-level over the long term. We acknowledge that different replanting strategies also have profound impacts on the productivity and profits of individual households or farmers, and such impacts need to be investigated in future studies. Our analysis is based on yield curves generated according to Woittiez et al. (2017), Monzon et al. (2021) and Khiabani and Takeuchi (2020), and the yield curves reflect an averaged status of yield change during the lifetime of an oil palm tree. Indeed, yield curves may vary among different trees and locations. For example, some trees may have longer peak periods or more rapid senescence. Nevertheless, our analysis focuses on the averaged status, and demonstrate the impacts of different replanting strategies. In addition, the average yield decline after 18 years may reflect management choices in confronting increased labor costs for harvesting, such as reducing input levels. This analysis could be improved in the future as more location-, cultivar- and management-specific yield information and age of mills become available, but it is beyond the scope of this study.

5. Conclusions

Based on the age composition of oil palm in 2017, we analyzed the production of palm oil in Riau under different replanting rates and yield improvement scenarios and found that replanting rates $<$4% a year increase short term production amounts at the cost of long-term landscape-level productivity. Moreover, future yield improvements for replanted areas would significantly shorten the number of years until both annual and cumulative palm oil production for the 4% rate of replanting exceeds those of lower replanting rates. Replanting 4% annually while improving yields with better management practices or better cultivars could be the optimal choice for increasing landscape-level palm oil production while maintaining the region's remaining forests.

Our results provide important insights for sustainably managing and improving palm oil production in the existing oil palm plantation area at a landscape level. However, although replanting 4% per year may be an optimal outcome for Riau Province, achieving this could be very challenging across a spectrum of privately-held individual plantations and smallholder farms. Collaboration among local governments, farmers, extension specialists, plantation owners, mill owners, and environmental conservationists are imperative and essential to achieve optimal palm oil productivity within the current plantation area so as to minimize pressure for additional deforestation-based expansion.

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Declaration of Competing Interest

Authors have no competing interests to disclose.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103714.

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