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Land-use change from market responses to oil palm intensification in Indonesia

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Abstract

Oil palm is a major driver of tropical deforestation. A key intervention proposed to reduce the footprint of oil palm is intensifying production to free up spare land for nature, yet the indirect land-use implications of intensification through market forces are poorly understood. We used a spatially explicit land-rent modeling framework to characterize the supply and demand of oil palm in Indonesia under multiple yield improvement and demand elasticity scenarios and explored how shifts in market equilibria alter projections of crop expansion. Oil palm supply was sensitive to crop prices and yield improvements. Across all our scenarios, intensification raised agricultural rents and lowered the effectiveness of reductions in crop expansion. Increased yields lowered oil palm prices, but these price-drops were not sufficient to prevent further cropland expansion from increased agricultural rents under a range of price elasticities of demand. Crucially, we found that agricultural intensification might only result in land being spared when the demand relationship was highly inelastic and crop prices were very low (i.e., a 70% price reduction). Under this scenario, the extent of land spared (~0.32 million ha) was countered by the continued establishment of new plantations (~1.04 million ha). Oil palm intensification in Indonesia could exacerbate current pressures on its imperiled biodiversity and should be deployed with stronger spatial planning and enforcement to prevent further cropland expansion.

KEYWORDS

agricultural expansion, *Elaeis guineensis*, equilibria analysis, market feedbacks, partial-equilibrium model, price elasticities, rebound effect

Cambios en el uso de suelo causados por la reacción del mercado a la intensificación de la palma aceitera en Indonesia

Resumen: La palma aceitera es una de las principales causas de la deforestación. Una intervención importante propuesta para reducir la huella de esta palma es la intensificación de la producción para que el suelo sobrante sea usado por la naturaleza, pero se sabe muy poco sobre las implicaciones del uso indirecto de suelo de la intensificación a través de las fuerzas del mercado. Usamos un marco de modelos de renta de suelo espacialmente explícito para caracterizar la oferta y demanda de la palma aceitera en Indonesia bajo varios escenarios de mejoras en la producción y elasticidad de demandas y exploramos cómo los cambios en el equilibrio del mercado alteran las proyecciones de la expansión agrícola. La oferta de palma aceitera fue susceptible a los precios de los cultivos y a las mejoras en la producción. La intensificación elevó la renta agrícola y redujo la efectividad de la reducción de la expansión agrícola en todos nuestros escenarios. El aumento en la producción bajó los precios de la palma, pero estas caídas no fueron suficientes para evitar la expansión agrícola a partir de las rentas agrícolas elevadas bajo un rango de elasticidad de precios de demanda. Más importante, descubrimos que la intensificación agrícola puede sólo resultar en que sobre el suelo cuando la relación de demanda casi no sea elástica y los precios de las cosechas sean muy bajos (una reducción del 70% en los precios). Bajo este escenario, la extensión de suelo sobrante (~0.32 millones de ha) fue contrarrestado por el establecimiento continuo de nuevos sembradíos (~1.04 millones de ha). La intensificación de la palma aceitera en Indonesia podría agravar las presiones existentes sobre su biodiversidad en peligro y debería implementarse con una mayor planeación espacial y aplicación para prevenir una expansión agrícola superior.

PALABRAS CLAVE

análisis de equilibrios, efecto rebote, elasticidad de precios, expansión agrícola, modelo de equilibrio parcial, retroalimentación mercantil, *Elaeis guineensis*

印度尼西亚油棕农业集约化的市场反应导致土地利用变化

油棕农业是热带森林砍伐的主要原因。许多研究提倡集约化农业生产以减少土地使用, 但我们并不清楚市场反应如何间接影响土地使用。我们使用空间显式经济租金模型来了解印度尼西亚油棕的供需情况。我们分析了在不同的需求的价格弹性,农业生产率的提高如何改变市场均衡以及我们对种植园扩张的预测。油棕的供应对价格变化和生产力的提高非常敏感。在我们所有的模拟中, 集约化增加了经济租金, 从而增加了扩张的可能性。在不同的需求价格弹性下, 油棕产量的增加导致价格下降。 但由于经济租金上涨, 我们仍然看到农业扩张。我们需要需求的价格弹性非常缺乏弹性, 并降低油棕价格(70%)以减少土地使用。然而, 在该模拟中, 节省的土地面积(约 32 万公顷)仍然被不断建立的新种植园(约 104 万公顷)所抵消。印度尼西亚油棕农业的集约化可能会对生物多样性产生负面影响, 需要谨慎实施, 以防止种植园进一步扩张。

土地节约和土地共享, 农业扩张, 市场均衡分析, 市场反应, 反弹效应, 部分平衡模型, 需求价格弹性, 油棕

INTRODUCTION

Land-use change for agricultural expansion is driving the accelerated global loss of forests and natural areas (Chaudhary & Kastner, 2016; Gibbs et al., 2010). In seeking to reduce forest loss from agricultural expansion and the associated impacts on biodiversity, intensification to improve crop yields is often promoted as a means of meeting expanding agricultural demands with minimal land-use impact (Balmford et al., 2018; Phalan et al., 2016). Researchers have examined the direct benefits of agricultural intensification on carbon stocks and biodiversity within retained forests (Edwards et al., 2010; Gutiérrez-Vélez et al., 2011; Phalan et al., 2011; Williams et al., 2018).

Market feedbacks (i.e., responses to changes in policies or practices driven by market dynamics) are important to consider in conservation because associated land-use changes could undermine regional efforts to reduce biodiversity losses (Armsworth et al., 2006). However, researchers tend to overlook that agricultural practices altering land use will have an effect on the overall market via the supply relationship (Lim et al., 2017). This relationship describes how crop prices might vary with changes in the quantities produced and available to the market. Although potential market feedback effects of conservation interventions are highlighted in the literature (Armsworth et al., 2006; Larrosa, et al., 2016; Lim et al., 2017), studies linking the specifications of supply and demand of agricultural and forest commodities with spatial patterns of land-use change are scarce (Busch et al., 2022).

Studies examining the role of markets in land-use change for agricultural production typically rely on equilibrium models to characterize market dynamics. These include general-equilibrium models that characterize the supply and demand of multiple crops, trade, and other sectors of the economy (Dissanayake et al., 2017; Hertel, 2012; Hertel et al., 2014; Taheripour et al., 2017). A simpler approach involves partial-equilibrium models that characterize the supply and demand of commercial crops without considering external sectors and markets (Bouët, et al, 2014; Jafari & Othman, 2016; Lattaet al., 2013; Tyner & Taheripour, 2008). Although these partial-equilibrium models do not consider trade at the global scale, they offer much simpler parameterization (Baldos & Hertel, 2012; Walsh, 2000). However, the majority of equilibrium model-based studies are not spatially explicit and thus overlook the specifics of where crop expansion and its resulting deforestation and species losses would likely occur. This points to the need to incorporate crop production across landscapes in analyses of production and supply (Walsh, 2000) to allow explicit consideration of the spatial variation in crop suitability and accessibility, key factors influencing crop expansion (Angelsen, 2010). This shortcoming hinders the use of agricultural market modeling for biodiversity conservation, for which spatial information is paramount.

Oil palm (*Elaeis guineensis* Jacq.) represents a key crop for which knowledge of its market behavior has particular conservation importance. As global palm oil demands continue to rise (OECD/FAO, 2021), plantation expansion encroaches into tropical forests pantropically (de Almeida et al., 2020; Margono et al., 2014; Ordway et al., 2019) and is having large impacts on global biodiversity and carbon loss (Dislich et al., 2017; Meijaard et al., 2020). As the world's top palm oil producer and exporter (FAO, 2021), Indonesia's rapid oil palm expansion has resulted in ~2 million ha of forest loss, 23% of the country's deforestation since 2001 (Austin et al., 2019).

Agricultural intensification and yield enhancements are often seen as an effective means to meet oil palm demands with reduced impacts on biodiversity and the environment (Barcelos et al., 2015; Khatiwada et al., 2021). Current yields across Indonesia are lower than in Malaysia, the world's second-largest producer of oil palm (Khatiwada et al., 2021; Woittiez et al., 2017), and it is believed that agricultural demands can be met using less land via improved management practices (Donough, Witt, & Fairhurst, 2009) and higher-yielding varieties (Barcelos et al., 2015; Sime Darby, 2020). Referred to as the Borlaug hypothesis, this belief forms the primary argument of the land-sparing framework, whereby land can be spared for nature and biodiversity if crop yields of existing plantations increase through technological improvements (Feniuk et al., 2019; Folberth et al., 2020; Green et al., 2005). Studies have highlighted the potential of increasing land-use efficiency for oil palm agriculture (Afriyanti et al., 2016; Euler et al., 2016), and new crop varieties are expected to increase oil palm yields (Sime Darby, 2020).

Whether oil palm intensification is effective in protecting forests and biodiversity across Indonesia remains a key question. Although agricultural intensification could reduce conversion pressures, it could also result in a rebound effect (Alcott, 2005; Villoria et al., 2014) that exacerbates land conversion and the biodiversity crisis (Wilcove et al., 2013). There are multiple instances across the tropics in which agricultural intensification did not reduce deforestation rates, resulting in an increase in cropland area (Ceddia & Zepharovich, 2017; Goulart et al., 2023; Pratzer et al., 2023). Often referred to as Jevons paradox, these patterns are prevalent across low- to middle-income countries that produce commercial, nonstaple crops (Pratzer et al., 2023) and may be due to, for example, spatial patterns of land rights, land-use policies (Kubitza et al., 2018; Stevenson et al., 2013), and market feedbacks that challenge projections of the effectiveness of changing land-use practices (Taheripour et al., 2019). The effectiveness of yield improvements on reducing deforestation also depends on demand characteristics, such as elasticity (i.e., the sensitivity of quantity demanded to price changes) (Hertel, 2012).

To fill this knowledge gap, we constructed a novel modeling framework that includes a partial-equilibrium model for oil palm in Indonesia integrated with a spatially explicit land-rent-based crop expansion model. Specifically, we aimed to assess whether oil palm intensification reduces the extent of crop expansion in Indonesia and evaluate how yield increases and demand elasticity influence the potential to reduce land-use change.

METHODS

Outline of methods

We based our simulations of land-use change and oil palm expansion on known distributions of oil palm plantations in 2015 (Miettinen et al., 2016). First, we used a land-rent modeling approach to construct a supply relationship of palm oil production with prices across Indonesia. With this approach, we assessed the amount of oil palm fruits supplying the market as crop prices varied across known oil palm plantations in 2015 and newly established plantations that we identified using an oil palm expansion model based on agricultural rent (Lim et al., 2019). We used this approach to then construct and characterize three other supply relationships that simulated nationwide yield enhancements of 15%, 50%, and 100%. We also constructed four demand curves spanning a range of elasticities. By comparing the interactions between supply and demand curves across scenarios, we examined the market feedbacks under different scenarios of agricultural intensification and price elasticities of demand (shocks to the market). Based on the shifts in market equilibrium prices, we assessed the expected changes in land use and the extent of newly converted and abandoned plantations. We also examined market feedbacks and resulting impacts on land use with increases in the overall demand (Appendix S3) and the impacts of global market responses on land use and palm oil production in Indonesia (Appendix S4).

Data collection

We used maps of oil palm plantations and other land-use and vegetation classes across Indonesia in 2015 (Miettinen et al., 2016). Plantations were mapped as grid cells, each representing an area of 250 × 250 m. Because information on actual oil palm yields was restricted to existing plantations, we estimated potential palm oil yields per cell based on information on oil palm suitability (Pirker et al, 2016). We also obtained information on the areas across Indonesia set aside for conservation under Indonesia's Forest Moratorium (WRI, 2017), on legally protected areas (Ministry of Forestry, 2010), and on locations of oil palm concessions (WRI, 2012). We used national prices per ton of oil palm fresh fruit bunches in 2015 and 2016 (FAO, 2021), deflated to 2015 USD values as a baseline for our analyses. We obtained national-level information on other production costs, such as fuel (GIZ, 2014), fertilizer (FAO, 2021), and timber prices (FAO, 2021). We also considered variations in wages among provinces (Wage Indicator, 2022). For provinces where minimum wages for 2015 were not available, we used the national minimum wage (ILO, 2017). Because prices for 2015 were not available for a few variables, we used prices from the previous year (inflated to 2015 USD values) based on the assumption that previous prices are taken as given when producers make plans to undertake crop expansion.

Constructing supply curves via a land-rent model

We constructed supply relationships for Indonesian oil palm fruit for 2016. Rather than use production functions to construct supply relationships (e.g., Bouët et al., 2014; Jafari & Othman, 2016; Jafari et al., 2017), we built our supply curves from a spatially explicit land-rent model (Lim et al., 2019). This approach emphasized the spatial aspect of the supply relationship (i.e., crop expansion) and the influence of commodity prices on production across existing and new plantations (Walsh, 2000). Our supply curve had two components: supply within existing plantations and supply from the establishment of new plantations (Appendix S1). We used a land-rent approach (Lim et al., 2019) to evaluate the capacity of oil palm plantations established by 2015 to supply the market as prices of oil palm fruit vary. We calculated the agricultural rent of maintaining production in existing plantations in a single year as a function of the price of oil palm fruits (U.S. dollars per ton). Rent for a given cell i was calculated as:

$$\text{rent}_i = y_i\, p - \left(f + l + \frac{y_i}{c} v d_i \right), \tag{1}$$

where y_i is the potential yield per hectare; p is the price of oil palm fruit bunches; f is costs attributed to fertilizer per hectare; l is labor costs per hectare (labor requirement set constant at 43.6 person days per hectare and year [Corley & Tinker, 2015]); and $\frac{y_i}{c} v d_i$ is the cost per hectare of transporting fresh fruits. The latter was derived from the number of trips needed given y_i, maximum capacity of a truck (c) (set at 18 m^3), fuel cost per driving hour (v), and travel time to and from the nearest large city (d_i) (population $\geq$ 50,000) as a measure of accessibility.

To construct our supply relationship across existing oil palm plantations, we calculated agricultural rents with Equation (1) and varied prices of oil palm fruits from USD0 to USD250 per t). At a given price of oil palm fruits, we considered a plantation was capable of supplying the market if the annual revenue was higher than the production costs. If, however, the plantation incurred negative rents at that price, we assumed, conceptually, that it was abandoned (i.e., the area might be available for forest regeneration or conversion to other land uses, but does not contribute to the total supply). We evaluated the extent of plantations capable of supplying the market and calculated the expected amount of oil palm fruits produced across these cells under different prices.

We then considered the potential supply from newly established plantations based on an oil palm expansion model that used a land-rent approach to predict oil palm spread (following Lim et al., 2019) (Appendix S1). This model allowed us to predict and simulate the spread of oil palm plantations across Indonesia from spatial variations in prices and profitability. We evaluated the agricultural rent across the average lifespan of a typical oil palm plantation (25 years) based on net present values. This involved summing up rents across years (Equation 1) based on a yearly discount rate of 10% (Irawan et al., 2013; Sumarga et al., 2015). The crop expansion model included a spatially dependent contagion effect, which further adjusts the agricultural rent for a new plantation based on the proportion surrounding area occupied by existing plantations because establishment costs are likely to be lower in areas with existing plantations and infrastructure (Garrett et al., 2013; Lim et al., 2019) (details of the crop expansion model are in Appendix S1).

We ran the crop expansion model across cells that were suitable and available for oil palm expansion. Areas already converted for other use (e.g., settlements and other plantations) and protected areas were excluded from conversion. We calculated agricultural rents across cells while increasing the price per ton of oil palm fruits from USD0 to USD250 and identified cells with agricultural rents at each price step exceeding the minimum value needed to establish and maintain a new plantation. From there, we calculated the extent of area converted to new plantations and the amount of oil palm fruits produced across these new plantations. Given computational limitations, we ran our analyses on a stratified-random sample of the data (i.e., random sample of 10% of the cells within each province) and scaled up the extent of areas and quantity produced accordingly. We also assumed that all existing and newly established plantations would operate at maximum productivity.

To construct our base supply curve, we ran simulations assuming the current estimated potential oil palm yields across plantations. From the results of our simulations, we then fitted equations to describe how the quantity supplied varies as we increased oil palm prices. We did this separately for new and existing plantations before combining both equations to form an overall supply function for our partial equilibrium model (details on supply functions in Appendix S2). We then repeated this process to construct multiple supply curves simulating nationwide increases in potential yields. We simulated a 15% yield increase across Indonesia from higher-yielding varieties (Sime Darby, 2020). Furthermore, because palm oil yields were expected to double with new varieties (Barcelos et al., 2015), we ran two additional scenarios in which potential yields increased nationwide by 50% and 100%. Across our simulations, we assumed nationwide uptake of new varieties and consistent proportional increases in yield. The varieties could be developed by large companies and then distributed to smallholders through partnership programs or through government support and agricultural extension services. In ensuring that we only adjusted a single variable (i.e., yield) across our supply curves, we kept all other factors in our simulations constant; the only changes in production costs came from direct changes in yields.

Constructing demand curves

We constructed four demand curves for 2016. These describe the relationships between oil palm price and the total amount demanded by the market in that year. We first set, as our reference point of equilibrium, the price of oil palm fruits in 2016 (USD112.70 [FAO, 2021]) and the amount of oil palm fruits supplied across existing and new plantations at that price, based on our baseline supply relationship. From this reference price-quantity point, we then constructed the demand curve to explain the relationship between price per ton (P) of oil palm fruits and quantity demanded Q:

$$Q = A \times P^{E}, \tag{2}$$

where A is a coefficient and E is the price elasticity of demand (i.e., the sensitivity of the demand quantity to price changes). If E is >1 in absolute value, demand is said to be elastic. Conversely, the demand curve is said to be inelastic if the absolute value of E is <1. The more elastic the demand (the larger the absolute value of E), the greater the expected fluctuation in demand for a given price change. We assumed constant elasticity of demand across prices. To capture a range of demand elasticities representative of the market, we constructed four demand curves with varying price elasticities of demand taken from recent studies on Indonesian palm oil: $E = -0.38$ (Jafari et al., 2017), $E = -0.54$ (Abdullah, 2011), $E = -0.57$ (Rifin, 2010), and $E = -1.01$ (Villoria et al., 2013). These elasticities are the best available estimates in the literature. The elasticity is consistently similar for studies focused on Indonesia, but noticeably larger in a global study (Rifin, 2010). Each demand curve intersected with our baseline supply curve at the reference price-quantity point, where the market is at equilibrium. The price at market equilibrium denotes the price at which the quantity supplied matches the quantity demanded.

Scenarios

We set our baseline equilibrium price based on the 2016 price (FAO, 2021) and evaluated the amount of oil palm produced at that price from existing and newly established plantations. Our baseline scenario assumes potential yields are met across existing and newly established plantations. We then evaluated the shift in market equilibrium from this baseline, for each of our three intensification scenarios, while considering each demand relationship. Using the shift in equilibrium price in each scenario as increased yield shifts supply to a new equilibrium with a given demand characterization, we examined the change in extent of newly converted and abandoned plantations compared with the expected extent of oil palm expansion at our baseline equilibrium. Using the same approach, we then considered a set of scenarios where we simulated shifts in the demand curves (i.e., representing increases in the overall demand) (Appendix S3). Finally, we projected our supply curve to consider global supply and demand and explored the impacts of global market responses on land use and oil palm production in Indonesia (Appendix S4).

RESULTS

Linking land-use change with variation in crop prices and yield improvements

From our model simulations, crop expansion was concentrated across the areas with the largest extents of existing plantations: Sumatra and Kalimantan (Figure 1). Areas closer to existing plantations had higher rents and, therefore, were converted more readily when oil palm prices were low, assuming current estimates of potential yields. With all else held constant, the rate of expansion increased as the price of fruit gradually increased (Figure 2a), spreading outwards from existing plantations (Figure 1). At our baseline (FAO) price of USD112 per t of fruit (FAO, 2021), our model simulated cropland expansion 5.18 million ha from 2015 (Figure 2a).

Increasing oil palm prices also reduced the extents of spared land among existing plantations. At current yields and with low oil palm prices (≤USD40 per t), agricultural rents across all existing plantations were insufficient to maintain plantations, and one might assume they would be abandoned. At USD50, 1.5 million ha of existing plantations had sufficiently high rents, and as prices continued increasing, more areas had sufficient rents and the extent of plantations abandoned decreased sharply at USD70 per t (Figure 2b).

Yield enhancements translated to an overall rise in agricultural rents across the remaining area and, therefore, an increase in areas profitable for conversion to plantation at the same prices (Figure 2a). For instance, a nationwide increase in yields by 15% led to a notable shift in the price−area relationship for new and existing plantations (Figure 2a), resulting in a rightward shift in the overall supply curve (Figure 3). At the same baseline price per ton of fruit (USD112), a total of 231 million t would supply the market. This was attributable to the expected 15% increase in productivity within existing plantations and the increased extent of area (7.1 million ha) profitable from conversion (Figure 2a).

Increasing yields by 50% and 100% resulted in even greater initial rates of expansion with rising prices. These increases slowed down as prices approached USD250 per t of fruit (Figure 2a). Concurrently, the points at which we saw sharp declines in land abandonment of existing plantations occurred at lower prices with increasing yields (Figure 2b). Across all yield scenarios, land abandonment of nonprofitable plantations occurred only at lower prices of oil palm fruits (≤ USD80) (Figure 2b).

Shifts in market equilibria from yield improvements and varying demand elasticities

In our baseline scenario, the market equilibrium price of USD112 per t of fruit corresponded with a total supply of 174.14 million t of oil palm fruits to market (Figure 3). This was composed of 71.55 million t from newly established plantations

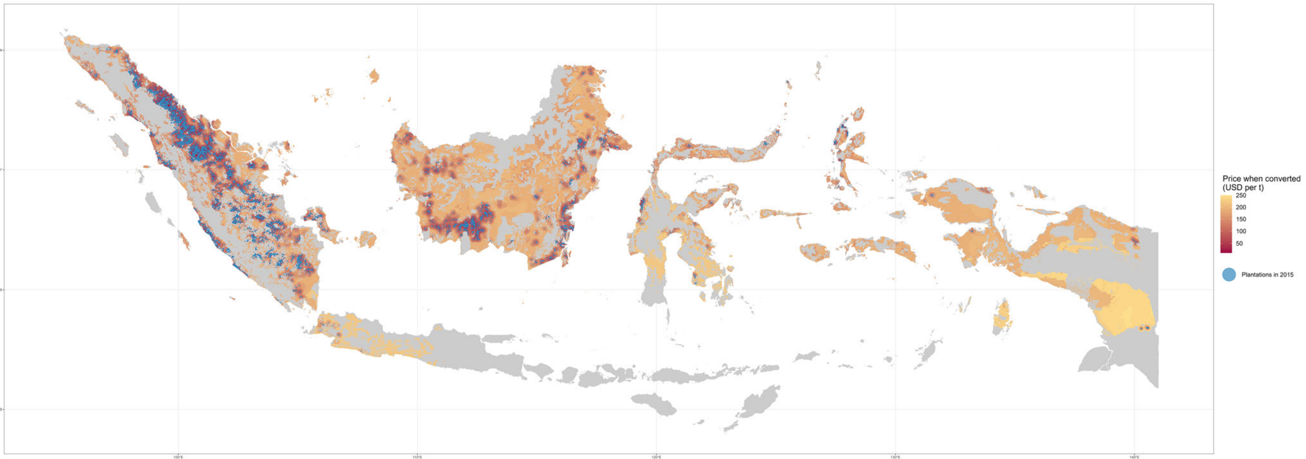

FIGURE 1 Land area converted to oil palm plantations as the price (based on crop expansion model) of oil palm fruit increases at current potential yields.

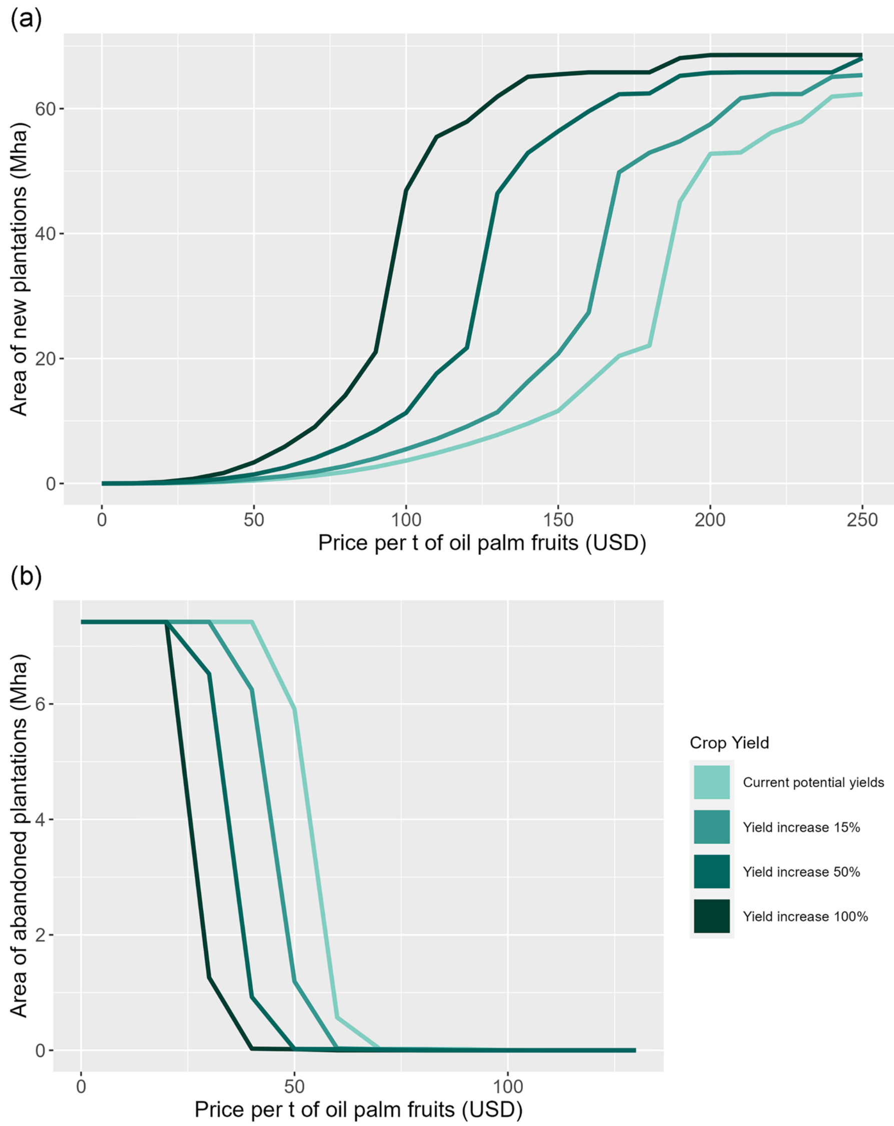

FIGURE 2 Extents of (a) newly converted oil palm plantations and (b) plantations abandoned due to negative rents as prices of oil palm fruits vary and under different scenarios of yield improvements.

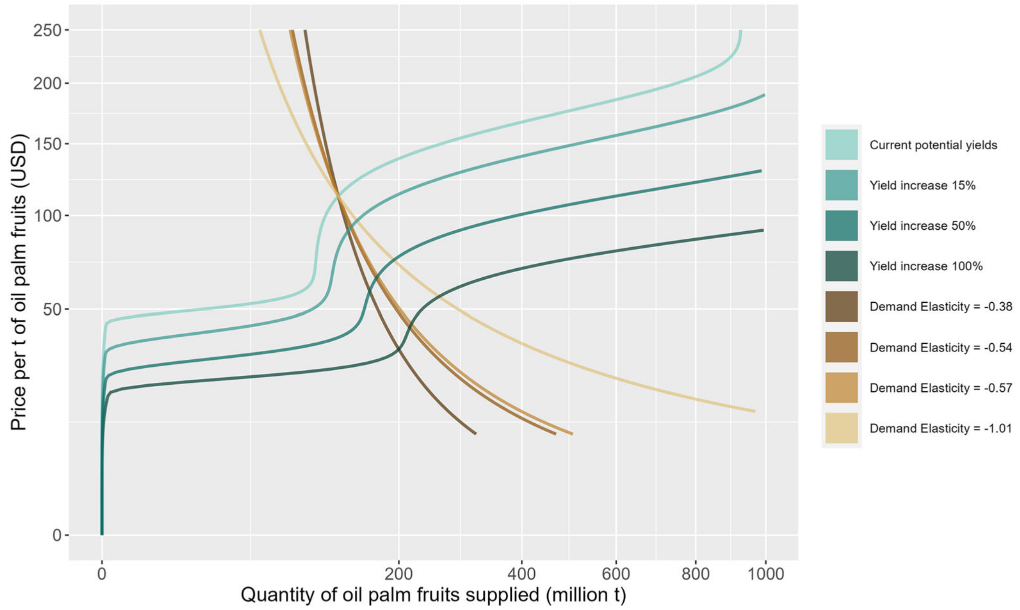

FIGURE 3 Supply and demand of oil palm fruit across yield and demand elasticity scenarios. Supply curves constructed based on 2015 distribution of oil palm plantations. Demand curves centered on 2016 prices (FAO, 2021).

(spanning 5.18 million ha) (Figure 4b) and the production from existing plantations.

The extents of crop expansion and plantation abandonment were primarily determined by the reduction in equilibrium price, which in turn was influenced by demand elasticities and yield increase. Across our scenarios, yield improvements reduced equilibrium prices (Figure 3). The establishment of new plantations was lower than in the baseline scenario (Figure 4a), but the extent of existing plantations abandoned due to low rents was marginal and present only when equilibrium prices dropped below USD70 per t of fruit.

Assuming a constant demand elasticity of −1.01 (Villoria et al., 2013), price changes from yield improvements were small and reductions in the extent of new plantations were marginal compared with the baseline. A 15% increase in yields reduced the equilibrium price to USD 97 (Figure 3). At this price, there was a 4.1% decrease in extent of new plantations (4.97 million ha); total production was 14% higher than the baseline (197 million t).

Increasing yields by 50% resulted in a drop in equilibrium price to USD74, corresponding with a 6.8% decrease in new plantations from the baseline. Total production was 254 million t. Doubling yields (100% increase) reduced equilibrium prices to USD56, and 335 million t were produced. New plantations spanned 4.7 million ha, 9.2% lower than the baseline (Figure 4b). In this scenario, 0.011 million ha were spared in (0.15% of the 2015 plantation extent).

Demand curves with more inelastic relationships (i.e., less negative) resulted in more dramatic shifts in market equilibria from the baseline and, therefore, sharper drops in equilibrium prices (Figure 3). Considering a more inelastic demand curve (elasticity = −0.38, [Jafari et al., 2017]), for instance, our simulations resulted in larger reductions in equilibrium prices, ranging from USD91 (15% yield increase) to as low as USD34 when yields improved by 100%. Prices were low enough to allow land sparing among existing plantations, particularly with 50% (sparing 0.019 million ha, 0.26% of the 2015 crop extent) and 100% (sparing 0.32 million ha, 4.3% of the 2015 crop extent) yield improvements (Figure 4b). Expansion of new plantations still occurred, although it was considerably lower than the baseline (Figure 4b). The extents of new plantations were 21−79% lower than the baseline, ranging from 4.08 million ha with 15% yield improvements to 1.04 million ha when yields were doubled.

Considering yield improvements and changes in demand elasticities, the scenario with the best outcome for minimizing land-use changes came from the scenario with the greatest increase in crop yields (100%), coupled with highly inelastic demand relationships (−0.38), resulting in the sharpest price reduction to USD34 (a 70% reduction from FAO reported price). In this scenario, the total amount of oil palm produced (226 million t) was 30% higher than the baseline scenario and corresponded with a 108% increase from 2015 plantations. The total oil palm extent spanned 8.15 million ha, achieved through establishing new plantations (1.04 million ha) and a reduction of 2015 crop extent (0.32 million ha).

DISCUSSION

The supply relationship of an agricultural commodity is directly related to land use; crop prices are determined by the interaction between demand and supply, and, in turn, they affect potential rents and influence the extent of land-use change and

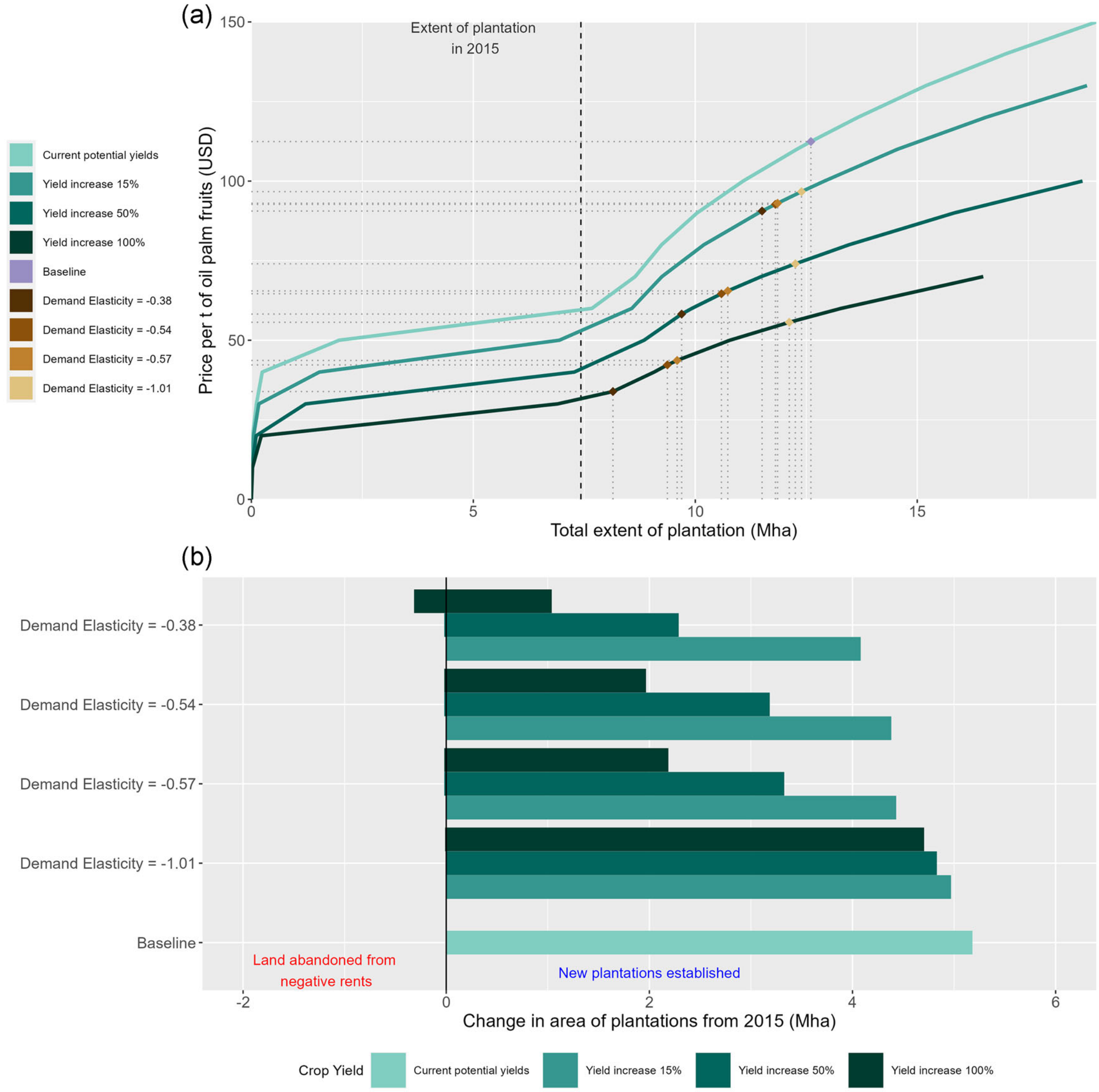

FIGURE 4 Extent of (a) oil palm plantations across Indonesia as crop prices (measured in U.S. dollars per t of oil palm fruits) increase and at each new equilibrium price and (b) newly established oil palm plantations and plantations abandoned due to negative rents based on the new equilibrium prices in each supply and demand scenario (negative values, land spared across existing plantations [i.e., a reduction in production area]; baseline scenario, current potential yields and equilibrium prices [FAO, 2021]).

agricultural expansion (Angelsen, 2010; Armsworth et al., 2006). The spatial aspect of the supply relationship (i.e., crop expansion) is instrumental in linking land-use change with market responses, yet it is rarely emphasized in the literature, and, to our knowledge, few researchers have constructed supply relationships acknowledging the influence of commodity prices on production across existing and new plantations (Walsh, 2000). Studies typically rely on production functions to construct supply relationships (Bouët et al., 2014; Jafari & Othman, 2016; Jafari et al., 2017). Notably, these studies focus on other aspects of the market, such as shifts in export demands, rather than land-use change, but doing so removes an important determinant of the market supply. Linking spatially explicit patterns of crop expansion with supply of a commercial commodity addresses this innate, yet often overlooked, link between market feedbacks and land-use change and could inform biodiversity conservation decisions.

The discussion around land-sparing versus land-sharing frameworks is fundamentally economic because it centers on trading land use as a scarce resource (Fischer et al., 2014). Here, the main inputs included labor and transport costs, land, and oil palm varieties, and oil palm fruit represented the primary output (Appendix S1). Land use and crop expansion relate directly to the forest and biodiversity loss, but these costs are largely ignored by the market (therefore, considered an externality). Improving crop yields does not directly resolve or internalize the externality (e.g., make farmers take into account biodiversity effects associated with their decisions), but, because the intensive use of existing cropland is more profitable than expansion, it can potentially result in the damaging action (further crop expansion) not being selected, thereby avoiding losses associated with the externality. By increasing productivity without excessive additional costs, agricultural intensification also reduces the amount of land needed per unit of oil palm production. Coupled with a demand that is not perfectly inelastic, we expect the demand of palm oil to increase from the increased productivity, resulting in increased plantation expansion. By addressing the interactions between markets and land-use change, we explored the influence of market feedbacks on the expansion of a highly commercial crop and highlighted the complexities around assessing the efficacy of agricultural intensification in reducing crop expansion and sparing land.

Across our simulations, oil palm expansion was highly sensitive to price changes and yield improvements: increasing yields extended the area profitable from crop expansion. Agricultural intensification did not automatically lead to land sparing. Rather, the reduction of land use was primarily driven by the drop in crop prices, which, in turn, was determined by the sensitivities of supply and demand curves. Additionally, the market was sensitive to price elasticity of demand, and market shifts (or price drops) from yield improvements increased as the demand relationships became more inelastic. Our simulations also suggest that the long-run elasticity of substitution between yield and land use depended on the elasticity of demand (Figure 4). For agricultural intensification to be effective in sparing land for nature, high yield improvements (e.g., 100% increase) need to be coupled with highly inelastic demand relationships (elasticity = −0.38) to trigger a sharp market shift and major reduction in oil palm price (Figure 4).

Yield improvement and crop expansion

By considering how improving crop yields shift the supply relationship, our work challenges the notion that agricultural intensification leads to a reduced extent of cropland. With oil palm plantations across Indonesia exhibiting crop inefficiency (Sari et al., 2021), the land-sparing framework (Green et al., 2005) has been repeatedly promoted as an effective means of increasing agricultural output on less land to meet these demands while protecting forests and biodiversity (Luskin et al., 2018). However, while agricultural intensification undoubtedly increases outputs within existing plantations and improves overall land-use efficiency, it also raises profit margins, making crop expansion more attractive across a larger area and resulting in a notable shift in the supply curve, at least in the short term. This sensitivity to crop prices and yields suggests that intensification vastly increases the extents of land profitable, thereby increasing the likelihood of expansion (Phelps et al., 2013). Additionally, large-scale abandonment of existing plantations only occurred at lower crop prices (≤USD70), with the extent of abandoned land available for reforestation at a given price decreasing as yields increased. Agricultural intensification might spare land for crops that are primarily consumed locally, but could exacerbate land conversion for highly commercial or substitutable crops with rapidly growing global demands (Lambin & Meyfroidt, 2011). Across Indonesia, oil palm expansion has, in part, been incentivized by intensification (Varkkey et al., 2018), and land-owner decisions are heavily influenced by crop prices (Wibowo et al., 2021). This rebound effect (Alcott, 2005) is prominent because of the large amount of land available for conversion to plantations (Varkkey et al., 2018).

Changes in demand relationships and projections of land-use change

Our study highlights the sensitivity of the market to changes in demand elasticity. This sensitivity needs to be considered when assessing the effectiveness of agricultural intensification. Margin growth and expansion associated with yield improvements might be countered by falling crop prices, but the extent to which this occurs is determined by the interaction of demand and supply. Studies focused on meeting static production targets do not acknowledge the dynamic nature of markets and, thus, underestimate the impacts of changing agricultural practices: market feedbacks could undermine these changes in land-use practices for conservation (Taheripour et al., 2019). Across our simulations, yield improvements facilitating the reduction of plantation extents only occurred when demand was highly inelastic (i.e., little change in demand despite falling prices) and market shifts resulted in large drops in commodity prices, allowing only the most profitable and efficient areas to maintain production. The Borlaug hypothesis—that demands are met on less land via high-intensity farming practices, thus sparing land for nature—is based on the assumption that demand is sufficiently inelastic (Hertel, 2012; Salles et al., 2017; Villoria et al., 2014). This assumption that the demand relationship varies little despite large price fluctuations is likely unrealistic (Salles et al., 2017), especially when considering a highly commercial commodity, such as oil palm.

Our range of estimates for demand elasticities (Abdullah, 2011; Jafari et al., 2017; Rifin, 2010; Villoria et al., 2013) and our use of a constant elasticity of demand functional form offers a useful starting point for constructing better-informed and more in-depth analyses of the demand relationship. Simulating increased demands for Indonesian oil palm also resulted in further shifts in market equilibrium toward higher prices and quantities of oil palm and the establishment of new plantations (Appendix S3). Because we did not include anticipated global rises in demand (OECD/FAO, 2021), our projections offer a very cautious understatement of the output expansion for any given assumption about demand elasticity. Given crop prices are projected to continue rising (OECD/FAO, 2021), conservation policies that rely solely on agricultural intensification to decrease land use need to be wary of the potential for this to backfire. Because intensification alone does not fully internalize the externality, market responses could make production cheaper, leading to higher demand and greater externalities, and making matters worse, as suggested by economic theory (Lipsey & Lancaster, 1956). Changes in the demand relationship in response to increasing global population and affluence, plus resource substitution (from other oils), could further shift market equilibria toward higher prices and traded quantities, exacerbating forest loss by increasing demand elasticity (OECD/FAO, 2021; Taheripour & Tyner, 2020).

Although it might appear that intensification scenarios could reduce the overall extent of cropland while increasing production and efficiency, without additional land protection of areas vulnerable to expansion, benefits that might come from forest regeneration following land abandonment are potentially outweighed by the continued increase in plantation expansion from yield improvements. Further, plantation abandonment due to low rents does not automatically reduce the externality from the initial conversion, even if it reduces the aggregate supply. Loss of natural areas from the new expansion is irreparable, and regenerated forest on abandoned plantations would be of comparatively poor quality for biodiversity (Edwards et al., 2021; Sodhi et al., 2010).

Limitations and future directions

Rather than provide predictions of market feedbacks and impacts on land use and biodiversity over time, we set out to examine the dynamics of this system under different scenarios. Therefore, we removed time-dependent factors, such as the assumption of time lag between establishing plantations and first harvest of fruits. We also used potential yields rather than actual yields across plantations, due to the lack of data for newly established plantations. Our model does not include interactions between oil palm and other land uses: oil palm could displace other crops that are not as profitable (e.g., rice and rubber) (Saswattecha et al., 2016; Susanti & Maryudi, 2016). Our study and results, therefore, offer a lower estimate of aggregate oil palm supply and total cropland expansion. If one were to consider the potential knock-on impacts on land use from crop displacement, the extent of total cropland might be higher within or even outside of Indonesia (Jayathilake et al., 2023).

Because equilibrium prices are path-dependent, we restricted our analyses to market responses over a single period, focusing on the impacts of supply and demand scenario changes on land-use change purely from a baseline. The supply curves did not match quantities produced in 2016, and end-supply levels are an underestimation of actual amounts traded (FAO, 2021). Further, while our partial equilibrium model focused on the oil palm market, supply curves could also vary depending on the opportunity costs of the land across space and time. Enhanced assessments that account for opportunity costs of the land would allow greater insight into the other economic and political drivers of market feedbacks and land use. Nevertheless, we provide a straightforward analysis that clearly highlights the risks of yield enhancements in the supply relationship. Partial-equilibrium models also impose limitations. We varied a single variable while other parameters (e.g., labor wages and production costs) remained constant, although they might vary with changes in demand and supply. This simplification could lead to underestimates of equilibrium prices from market shocks, but it allowed us to uniquely analyze the sensitivity of the market to changes in a single factor. Given the scale of expected yield changes, other price changes are likely to have less of an effect (Jafari et al., 2017).

Linking spatially explicit patterns of crop expansion with supply of a commercial commodity addresses the innate, yet often overlooked, link between market feedbacks and land-use change and biodiversity impacts. Compared with studies describing country-level market feedbacks, our modeling approach (i.e., constructing the supply curve from a spatially explicit land-rent model) allows investigation of how other aspects of agricultural intensification affect production and supply across space. Our crop expansion model and supply curves highlight the sensitivity of regions across central and eastern Indonesia (e.g., Kalimantan, Sulawesi, and Papua) to further crop expansion and the potential for forest and biodiversity losses in these regions as oil palm prices increase. With continual improvements in spatial information of oil palm plantations across Indonesia (Austin et al., 2017; Danylo et al., 2021), our method has the potential to make finer-scale predictions of land-use change that take market feedbacks into consideration. Additionally, methods that can distinguish smallholder from industrial plantations (Pribadi et al., 2023) could refine future spatial supply models and offer predictions of plantation expansions or abandonments from both smallholders and large corporations.

Our partial equilibrium model illustrates how increasing crop productivity without additional costs, by reducing the amount of land needed per unit of oil palm production, could result in greater conversion of land for low-input agriculture (Lambin & Meyfroidt, 2011). In examining market feedbacks, it is also worth considering how other market-based mechanisms might influence the opportunity costs of land expansion for oil palm. Accounting for how this market interacts with other substitute markets (i.e., alternative vegetable oils) would further projections of land-use change and market feedbacks: changes in the supply relationship from agricultural intensification could result in a further demand shift from other oil crops (Lim et al., 2017). General-equilibrium models suggest that restricting consumption of palm oil from Malaysia and Indonesia (which collectively produce >80% of the world's supply) might restrict expansion locally, but does not reduce the extent of oilseed plantation expansion globally (Taheripour et al., 2017; Taheripour et al., 2019). Considering the overall demand shifts in response to substitute markets would provide a fuller picture of market feedbacks, including leakage and displacement of trade internationally and across substitute markets (Carrasco et al., 2014; Santeramo & Searle, 2019; Taheripour & Tyner, 2020).

Current developments in the political and economic sectors put increased pressure on agribusinesses to internalize their externalities on nature (i.e., to account for the external impacts on nature), and understanding the responses to these pressures and policies could improve assessments of land-use changes. Voluntary carbon markets, which are expected to increase under Article 6 of the Paris Agreement, could incorporate carbon emissions from land conversion to oil palm, thus making land input to production more expensive and limiting oil palm expansion. Carbon credits are likely to be concentrated in areas of high carbon stocks, such as peat swamps and mangroves, thus limiting oil palm expansion (Richards

& Friess, 2016). These changes could contribute to reducing the negative impacts of high-yielding new varieties on land use. The increased scrutiny and expectations of environmental, social, and governance (ESG) reporting could also influence the actions of large agribusinesses (Galaz et al., 2015). However, it is unclear how the likely increase in ESG reporting will affect eventual land-use dynamics, especially among smallholders. Ongoing research on supply-chain traceability for large corporations and smallholders is key to advancing this area of research and understanding the influence of carbon markets and ESG on overall oil palm markets and expansion (Zu Ermgassen et al., 2022).

Our study contributes to discussions of the efficacy of land-sparing as a conservation tool. Understanding the market dynamics surrounding yield improvements and land-use change is especially important for a commercial crop system, such as oil palm in Indonesia, where crop expansion is strongly driven by profit and has been a major driver of deforestation. Indonesia's palm oil supply is sensitive to crop prices and yield enhancements, and changes in agricultural rents greatly influenced crop expansion. With palm oil demands rising, agricultural intensification is still seen as a major contributor to meeting these demands while adhering to no-deforestation commitments (Meijaard et al., 2020). Crucially, we found that yield improvements did not automatically lead to land sparing, unless prices dropped low enough to eliminate the most inefficient areas from supplying the market. Without these significant drops in crop prices, there could be greater cropland expansion. Given that further oil palm expansion is the most likely outcome of oil palm intensification, intensification should be accompanied by efforts to prevent further expansion (e.g., zoning), improved legal protection of forests, and enhanced enforcement, especially in areas most susceptible and profitable.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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