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LETTER

Land rents drive oil palm expansion dynamics in Indonesia

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Abstract

Increasing global demand for oil palm drives its expansion across the tropics, at the expense of forests and biodiversity. Little is known of the dynamics that shape the spread of oil palm, limiting our potential to predict areas vulnerable to future crop expansion and its resulting biodiversity impacts. Critically, studies have not related oil palm expansion to the role of agricultural rent and profitability in explaining how and where oil palm is expected to expand. Using a novel land rent modelling framework parameterised to oil palm expansion across Indonesia between 2000 and 2015, we identify drivers of crop expansion and evaluate whether Indonesia's Forest Moratorium might reduce the rate of future oil palm expansion. With an overall accuracy of 85.84%, the model shows oil palm expansion is driven by price changes, spatial distribution of production costs, and a spatial contagion effect. Projecting beyond 2015, we show that areas under high risk of oil palm expansion are mostly not protected by the current Forest Moratorium. Our study emphasises the importance of economic forces and infrastructure on oil palm expansion. These results could be used for more effective conservation decisions to manage one of the biggest drivers of tropical biodiversity loss.

Introduction

As the most widely traded vegetable oil and biofuel, oil palm (*Elaeis guineensis* Jacq.) is an important driver of land-use change across the tropics [1]. Globally, there has been a rapid increase in extent of oil palm plantations from 10.9 Mha in 2000 to 20.2 Mha in 2015 [2], with expansion linked to extensive deforestation, biodiversity loss, and environmental degradation, especially in Southeast Asia [3–5]. As global palm oil demand grows [6], we can expect greater pressure on remaining tropical forests and biodiversity. A crucial question, however, is which areas are most likely to be the focus of further oil palm expansion, and at what costs to the environment and biodiversity. To answer this, it is essential that we first understand the drivers that explain oil palm expansion across time and space.

Our understanding of oil palm expansion has largely been based on environmental crop suitability and accessibility [7–10]. We also have an extensive understanding of spatial variation in oil palm suitability [1, 11, 12], and potential palm oil yields pantropically [13]. Studies examining oil palm expansion within the Neotropics also account for the influence of socio-economic factors or trade impacts on oil palm expansion across time and space [14, 15], relating expansion to market incentives and profits. A key research unknown is the role of agricultural rent—the potential economic returns from converting land to agriculture [16]—in explaining and predicting oil palm expansion. Land-use change for expansion of commercial crops is fundamentally economic [17] and driven by profitability, and it is thus important we have a better understanding of this relationship across both space and time. Knowing which areas are susceptible to land-use change and crop expansion could also inform conservation policies. Efforts managing oil palm expansion typically involve protecting vulnerable areas with high conservation value, via state intervention (e.g. establishing protected areas), or corporate action under certification schemes (e.g. the Roundtable on Sustainable Palm Oil).

Here, we focus on Indonesia as the world's largest producer and exporter of palm oil. The extent of oil palm plantations increased from 2 Mha in 2000 to 8.6 Mha in 2015 [2], and concurrently, Indonesia experienced 6 Mha loss of primary intact and degraded lowland dipterocarp forests and peatland forests during this period, with annual deforestation steadily rising [18]. In 2010, Indonesia passed legislation protecting over 69 Mha of primary forest and deep peatlands from land-use change under a Forest Moratorium, while allowing oil palm expansion across primary forests already licensed and forests degraded by logging [19, 20]. Incorporating an agricultural land rent approach, in relation to commodity prices, establishment costs and profitability into models of oil palm expansion, allows us to uniquely: (i) explain the factors driving the recent spread and current distribution of oil palm plantations across Indonesia; (ii) predict future oil palm expansion and any associated forest loss; and (iii) evaluate how effective Indonesia's Forest Moratorium is at restricting future oil palm expansion into dryland and peat swamp forests.

Methods

Overview

Using distribution maps of oil palm plantations across Indonesia for different time points spanning 2000–2015, and spatial variation in potential oil palm yields, we built a model explaining oil palm expansion using an agricultural land rent approach. This model allows us to examine the spread of oil palm plantations both spatially—from variations in crop yields and market accessibility—and temporally—according to changes in palm oil prices and production costs. We then projected the extent of further oil palm expansion beyond 2015 based on hypothetical projections of future prices, and from which we predict the effectiveness of Indonesia's Forest Moratorium.

Data collection

We obtained spatially explicit distributions of oil palm plantations, other land-use types and vegetation classes across Indonesia in 2000, 2010 and 2015 [21, 22]. These were mapped as grid cells, each representing an area of 250 m by 250 m. For each cell, we obtained information of potential palm oil yield across space [13] (table S1 available online at stacks.iop.org/ERL/14/074024/mmedia). We also obtained information on the areas across Indonesia set aside for conservation from Indonesia's Forest Moratorium [23], legally protected areas [24] and locations of oil palm concessions [25]. We restricted our analyses to cells with positive potential palm oil yields, and cells available for conversion to oil palm plantation from 2000, i.e. existing oil palm plantations, concessions and all vegetation types across lowlands [22]. Our model therefore did not permit oil palm expansion into cells within protected areas and other plantations. Because the spatial distribution of oil palm plantations was not distinguished from other plantations in the map for the year 2000, we determined the distribution of oil palm plantations in 2000 as cells that were classified as plantations in 2000 and as oil palm plantations in 2010.

We based yearly production costs attributed to labour on annual reports of mean monthly national minimum wages [26]. We also obtained yearly national prices of fuel [27], fertilisers, oil palm fresh fruit bunches and timber [2]. Prices were deflated to USD 2015 values, and yearly prices were used where available: when prices were not available, we assumed constant prices from the previous year (table S1).

Explaining the spread and current distribution of oil palm plantations

We based our crop expansion model on variation in agricultural rent across space and time [16]. Here, the decision to convert a cell for palm oil production is based on whether the amount earned from agricultural and timber harvests outweighs the costs involved to convert and manage a plantation, and, exceeds a minimum threshold. This threshold represents the opportunity costs of other land uses, including conversion to other crops: rent exceeding this threshold indicates a cell is more likely to be converted into oil palm plantation over other land uses. Rent for a cell i in a single year is calculated as

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

where y_i is the potential yield per hectare in cell i, p is the price of oil palm fruit bunches, and w represents revenue from sale of timber from first clearing the land, given a set timber harvest of 23.1 m^3 per hectare [28]. f and l represent capital costs attributed to fertiliser and labour per hectare respectively, with labour requirement set constant at 43.6 man days per hectare [29]. $\frac{y_i}{c} v d_i$ represents the cost (per hectare) of transporting fresh fruits, which we calculated from the number of trips needed given the yield y_i and the maximum capacity of oil palm fruit bunches a truck can carry (c, assumed as 18 m^3), fuel cost per driving hour v, and the travel time d_i to the nearest large city (with at least a population of 50 000), therefore a measure of accessibility (S1).

For every cell i, we evaluated the rent net present value (NPV), i.e. the discounted sum of yearly agricultural rents across the lifespan of an oil palm plantation. The rent calculation from (1) is embedded within the formula for NPV given in equation (2), where t is a time index $t \in [0, T]$, with $t = 0$ as the base year for the plantation and T the final year in a crop cycle, and r is the discount rate.

$$\mathrm{NPV}_i = \sum_{0}^{T} \frac{\mathrm{Rent}_{i,t}}{(1 + r)^t}. \quad (2)$$

NPV was calculated based on a typical 25 year life cycle ($T = 25$) of an oil palm plantation, accounting for time taken for crops to mature: oil palm crops typically start producing fruits after the third year, therefore we only considered returns from the harvest of fruits ($y_i p$) from the fourth to twenty-fifth years. Because our analyses relied on spatial variation of potential yields, we were limited to assuming constant yearly agricultural output upon maturity to maintain average values, instead of varying with age. Timber sales (w) were recorded as a one-off gain in the first year ($t = 0$).

Rent for each year t was discounted annually by a discount rate r, set at 10% following [30, 31], and NPV was derived from the summed discounted rents across all 25 years (2). We calculated the equivalent annual costs (EAC) of each cell i, i.e. the equivalent constant annual revenue that leads to a similar NPV value. Having calculated NPV and EAC for each cell in a given year, we then adjusted the EAC (EACadj), based on additional factors that could potentially influence the distribution and spread of oil palm plantations across time and space.

$$\mathrm{EACadj}_i = \mathrm{EAC}_i - P_i - S \times A_{i,t-1} - K \quad (3)$$

K represents the minimum threshold rent needed to establish plantations, set constant across space and time. This includes the opportunity cost of capital, recognising the capital could have been invested elsewhere achieving some baseline profit. P_i adjusts EAC_i based on soil type, allowing for additional costs incurred from draining peat swamps prior to conversion. Finally, S accounts for adjustments in rent associated with the location of the cell in relation to existing oil palm plantations. This parameter captures the impact of local resources, labour skills and transport systems which result from having existing plantations in the area and which result in lower costs on the basis that the necessary infrastructure already established from neighbouring plantations would reduce costs of further expansion [8, 9, 32]. S therefore relates to the proportion of cells devoted to oil palm surrounding each cell. $A_{i,t-1}$ refers to the percentage of plantation area within a buffer (set at 0.1°) for cell i in period $t - 1$ to capture this potential accelerating factor in crop expansion, where higher percentages of existing plantations surrounding a cell relate to reduced establishment costs for that cell.

We fitted our model to land-use maps in 2000 and 2015, simulating spatial predictions of Indonesian oil palm expansion every year from 2001 to 2015 based on yearly changes in agricultural rent across space from 2001 to 2014. We assumed a one-year time lag between changes in prices and establishing a plantation. Although we incorporated yearly changes in prices, we assumed that investment decisions were based on expectations of future prices, allowing current prices to represent future expectations in real terms. Starting from 2001, we calculated EACadj for cells not classified as oil palm plantations, based on deflated prices of oil palm fruits, labour, fertiliser and fuel in that year. Cells with agricultural rent exceeding the minimum threshold K (i.e. $\mathrm{EACadj}_i > 0$) were considered economically viable for oil palm agriculture, and we simulated conversion to plantation. We then updated prices and distribution of existing plantations to re-evaluate agricultural rent across the remaining unconverted cells the following year (2002). We repeated this process every year until 2015 (S1).

We determined parameter values that returned an outcome of oil palm expansion by 2015 with closest resemblance to the known distribution of oil palm plantations via an optimisation approach (S1), and across multiple iterations we selected as our fitted model the combination of parameter values that returned the highest recall, i.e. the highest average proportion of cells correctly predicted across both classes of oil palm plantations and non-plantations. This selects the model that produced the highest average proportion of both correctly predicted converted and unconverted cells. To determine magnitudes of the parameters and relationship of the spatial contagion effect, we repeated the optimisation process across different sets of models (i.e. ways of evaluating EACadj) and selected the model with the highest average recall as the final, best performing model (S1). We also compared our analyses with oil palm expansion models that only account for suitability and yield (S1).

Due to computational limitations, models were fitted on a subset of cells stratified-randomly sampled across the total dataset (~24000 of 25 111 235 cells), ensuring the same proportion of cells across all provinces. Given the limitations of this single-crop expansion model, we did not model displacement of other crops by oil palm and, therefore, cells classified as other plantations were excluded from this analysis except where oil palm concessions had been awarded. Additionally, we did not account for oil palm abandonment due to the lack of spatial information of area and extent of abandoned fields. We validated our final model against a larger subset of the overall data (10%, ~2 400 000 cells), and model performance was similarly evaluated by comparing the predicted with the observed distribution of oil palm.

Projected future oil palm expansion and effectiveness of Indonesia's Forest Moratorium

Using projected palm oil prices from 2016 to 2025 [2, 33], while keeping all other costs at 2015 values, we ran our model forwards to determine areas susceptible to future expansion as palm oil prices vary and identified areas that become economically viable for oil palm expansion each subsequent year. In keeping other prices constant in real terms, our projections show the direct impact of oil palm prices on future oil palm expansion. Given our model only focuses on the spread of oil palm plantations, we do not examine future displacement of other crops by oil palm, and

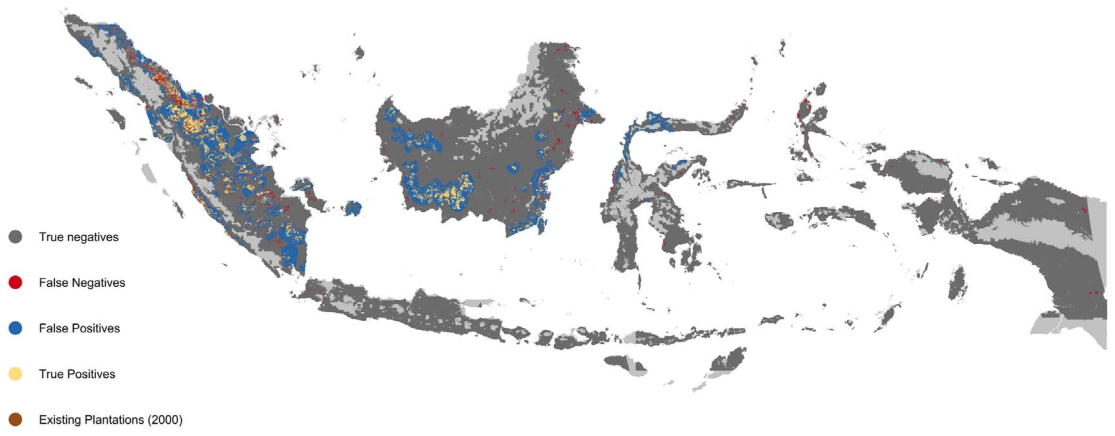

Figure 1. Performance of oil palm expansion model across Indonesia between 2000 and 2015, validated against a stratified random sample (10%) of cells (250 by 250 m) spanning all provinces ($n = 2\ 242\ 417$). Across known oil palm plantations, the model was 70.07% successful in identifying cells as economically viable/profitable to convert into plantation (yellow), while 29.93% of the oil palm plantations (red) were not identified as having rents high enough to be converted. Of the cells not classified as oil palm plantations in 2015, the model predicted 13.53% were profitable for oil palm expansion during that time (blue): these cells were either converted to other plantations (S1) or remained as forests and peatlands. The remaining cells (grey) were correctly identified as not having rents high enough to establish plantations.

excluded other plantations from projections of oil palm expansion beyond 2015. From these projections, we identified the proportion of areas vulnerable to crop expansion that fall under protection by Indonesia's 2011 Forest Moratorium.

Results

Explaining the spread and current distribution of oil palm plantations

A land rent framework was more effective in explaining Indonesia's oil palm expansion than just relying on suitability (S2). Of the models run, Model 4 performed best (average recall = 75.8%; S2) and was used for validation and projection. This model included a minimum threshold K of USD10,053 per hectare before a new plantation is established, adopting a discount rate of 10%. We also captured a spatial contagion effect in relation to agricultural rent: lower costs are incurred ($S =$ USD987 per hectare) as the percentage of existing surrounding plantations increases, following a square-root relationship. We excluded additional costs of establishing plantations on peat soils in this model (i.e. $P =$ USD0 per hectare). Considering an overall relationship across fifteen years, our model showed gradual increase in the area cleared for oil palm each year. As prices of oil palm fruits (relative to other costs) increased from 2000 to 2010, so did the extent of oil palm expansion into forests and peatlands. Additionally, with the spatial contagion process, even with the slight drop in fruit prices beyond 2011, the extent of oil palm plantations continued increasing.

Against our validation data-points (10% of the total area), our model showed an overall accuracy of 85.84%. We correctly identified 70.07% of cells converted to plantations in 2015 (58 483 out of 83 460 cells). Our model performed particularly well in Kalimantan, Jambi, Riau, North and West Sumatra (figure 1). The model also correctly identified 79.23% of peat swamps converted into oil palm plantations by 2015, particularly in Riau, North and West Sumatra (S4). The model could not identify 29.93% of the converted cells (24 977 out of 83 460 cells) as having agricultural rents high enough to establish plantations. Of these cells, 17 286 (69.2%) had been classified as other plantations in 2000 but converted to oil palm by 2015, thus had not been detected by our model. Other cells were located within areas and provinces (e.g. West Papua, East Kalimantan) with no detected oil palm plantations in 2000 (figure 1).

Our model also had a false positive rate of 13.53%, i.e. cells predicted to be economically profitable for conversion into plantations but were not classified as oil palm plantations in 2015 (figure 1). These cells were mainly located within proximity to existing plantations, especially across provinces in Sumatra and Kalimantan. Of these cells, 50.49% were classified as plantations: while the returns from oil palm expansion was high, these areas had been converted to other crops instead (figure S1). Provinces such as West Papua, Bengkulu, Jambi, and Southeast Sulawesi, for instance, showed high false positive rates (>65%, S4).

Projected future oil palm expansion and effectiveness of Indonesia's Forest Moratorium

Keeping other costs constant at 2015 values and assuming no other land-use changes, the extent of oil palm plantations based on projected annual prices of oil palm fruits could grow by as much as 4.5 times by 2020 (figure 2), and six times by 2025 (S5). Areas economically viable for further crop expansion were mainly located near existing oil palm plantations.

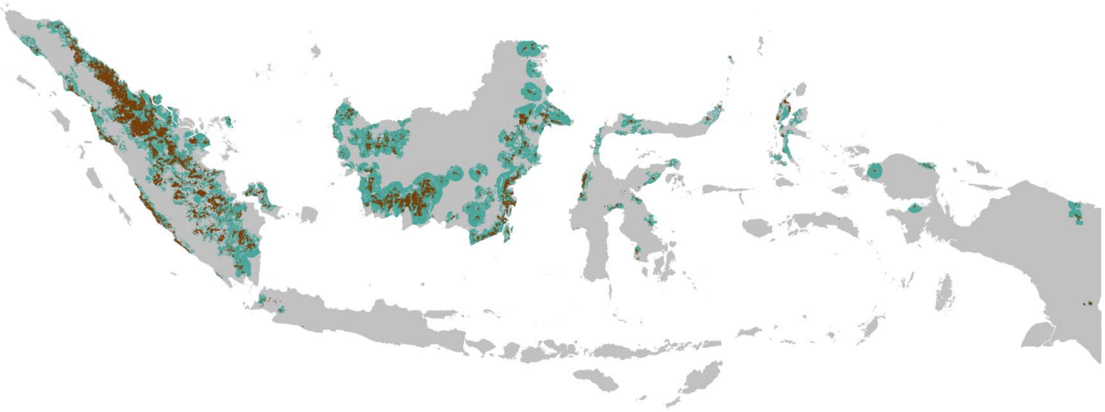

Figure 2. 2020 Model projections of areas susceptible to further oil palm expansion as prices of oil palm fruits increase, based on agricultural rents and spatial distribution of oil palm plantations in 2015. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations, natural areas and other plantations. Agricultural rents were evaluated from projected prices of palm oil from 2016 to 2020, while keeping other costs constant at 2015 values.

Projected oil palm expansion was therefore highest across Sumatra and Kalimantan. Only 9.79% of the areas susceptible to oil palm expansion by 2020 (10.27% by 2025) fall within Indonesia's Forest Moratorium. 80.67% of natural areas (i.e. forests, peatlands and mangroves) vulnerable to oil palm expansion by 2020 (83.9% by 2025) were not protected by the Forest Moratorium (table S5). Provinces like Riau, Papua and West Papua were better protected against oil palm expansion, with a higher proportion of areas with high agricultural rents by 2025 falling within the Forest Moratorium areas (0.22–0.27, table S6). Conversely, within Kalimantan, large proportions of natural areas susceptible to expansion by 2025 were not protected by the Forest Moratorium ($\geqslant$0.89, table S6).

Discussion

Understanding oil palm expansion is key for improving environmental management via spatial planning. Studies have focused on oil palm suitability in explaining oil palm distribution and expansion, e.g. [10, 12], or incorporated the influence of socio-economic factors [15] and trade [14]. Expansion is, however, fundamentally economic [17], and we uniquely show how variations in agricultural rent—the costs and benefit from converting forestland as a factor of crop expansion—and a spatial contagion effect influence Indonesian oil palm expansion. Our approach accounts for both costs of plantation establishment and economic returns from agricultural harvests [16] through incorporating spatial variation in potential oil palm yield [13] and temporal variability in commodity prices. This provides a means of explaining oil palm expansion, i.e. companies (and smallholders) respond to changes in agricultural rent and profitability of conversion [16, 34]. Our findings emphasise the importance of economic forces and infrastructure on oil palm expansion, and provide a method for spatial zoning to manage oil palm expansion.

Building on the land rent framework [16], we found a high overall minimum threshold (K) needed to establish plantations, accounting for initial set-up costs and opportunity costs of other land uses. The rate and extent of oil palm expansion could, therefore, be influenced by the ability to withstand the initial losses incurred before plantations reach maturity. While we have kept the threshold (K) constant, we acknowledge that it could vary spatially and across years, as well as between companies and smallholders—some might be able to withstand initial losses more easily than others. We also identified an economic-driven spatial contagion process of oil palm expansion in proximity to existing plantations across Indonesia since 2000, supporting patterns of spatial dependence and clustering observed from remotely sensed data [22]. Other studies also emphasised the strong influence of proximity to existing plantations, typically including distance to the nearest existing plantation as a predictor for crop expansion [8, 9]. The spatial contagion effect builds on the von Thünen land rent approach [16], capturing fine-scale changes in agricultural rent associated with the presence of existing plantations, such as established infrastructure and an existing labour force. Spatial clustering of agricultural expansion is characteristic of agricultural expansion, via a positive feedback between prices, access to resources and possibly land-use rules, increasing agricultural rent and likelihood of conversion at the local scale [32]. While we have kept this effect constant, it could vary across provinces and across companies.

Despite additional costs incurred from draining waterlogged peat swamps and other establishment costs [35, 36], there was little evidence of a large effect on overall costs incurred to convert peat swamp forests into plantations. Land concessions on peat soils are awarded to large-scale oil palm estates [18, 35], and therefore, the additional establishment costs associated with peat soils might incur less of a cost barrier than expected. Clearing and draining peatlands for agriculture is associated with higher carbon emissions [3, 10] and increased risk of fire. As Indonesia launches its new initiative to restore degraded peatlands, it is therefore important we also consider which peatlands are at greater risk of conversion and require increased protection.

Against our model projections, only a small proportion of forests vulnerable to future expansion due to high land rents would be protected under Indonesia's Forest Moratorium. These results confirm Sloan *et al* [37] who identified low additionality of dryland (dipterocarp dry) forest conservation from the Forest Moratorium due to low association with areas of heavy land use, and Sumarga and Hein [8] that noted minimal contribution from the Forest Moratorium to reduce oil palm expansion and loss of ecosystem services within Kalimantan. The Forest Moratorium was established as a means of reducing land-use change in the immediate future, but with little overlap with areas susceptible to oil palm expansion, it fails to protect remaining forests and peat swamps against immediate crop expansion, suggesting its additionality is questionable.

Our oil palm expansion model has three core limitations. First, our model is dependent on spatial and temporal accuracies of past and present oil palm distribution, potential yield, yearly national data of prices and costs. Inaccuracies in the data could manifest in erroneous predictions of expansion. For instance, while we have used the most accurate land-use maps of Southeast Asia to date [21, 22] and reliable predictions of potential palm yield [13], we are unable to distinguish between industrial plantations and smallholders.

Second, the model excludes factors related to land tenure (including property rights), subsidies, land management, spatial variations in governance, aspects of the political economy, and company-level capital assets [5, 38]. Crop expansion attributed to regional-level effects, e.g. government decisions, were not considered in this study [39]. We also did not consider infrastructure of palm oil mills, road-building decisions and government policies of investment in new areas (e.g. Papua). This likely explains why our model could not identify oil palm expansion in regions without prior plantations in 2000, and the increased probability of forest conversion across Papua. Institutional decisions to begin establishing plantations within a region are difficult to predict and not determined by land rent or spatial contagion effect. Similarly, due to data paucity, we could not account for fine-scale responses to local policies, tax and tenure regimes, local-scale management, and company-level capital assets that determine the extent to which a company can afford to pursue longer-term goals and tolerate short-term losses across space and time. This suggests we might underestimate the capacity of actors with high capital assets to invest and expand in remote areas where rents would be initially low.

Third, we only modelled expansion of a single crop without considering competing land-uses. Our projections of future expansion only considers a single land use, keeping all other costs constant. Accounting for displacement and leakage of other crops would help us to better understand the overall extent of land-use change and environmental impacts. Quantifying and modelling displacement, however, is challenging, and requires establishing firm causal links between substitution of one crop in one place and its expansion in another [34]. Nevertheless, despite its simplicity, our model captures the salient dynamics of oil palm expansion in Indonesia.

As global demands for palm oil continue to rise with population and affluence, the probability of further oil palm expansion and forest loss is imminent. With oil palm estates expanding across Africa [40] and the Neotropics [11, 14, 15], our work offers a stepping stone for future studies to understand oil palm expansion in other regions and at a global scale. Given the role of commodity prices in explaining crop expansion, it is important that future studies also consider price feedbacks to changes in palm oil supply [41].

Conclusion

Using knowledge of the spatial distribution of oil palm plantations and temporal changes in costs and revenues, we show a land rent approach explains Indonesia's oil palm spread over a fifteen-year period. We also identified a spatial contagion effect: areas with greater extent of existing plantations might experience greater crop expansion. Considering the simplicity of our model, we were able to correctly predict 79% of past oil palm expansion. As global palm oil demands continue to rise, our model allows us to make spatially explicit projections of future crop expansion, highlighting provinces of immediate concern to forest loss. Importantly, we found little contribution from Indonesia's Forest Moratorium to protect forests from immediate oil palm expansion, exacerbating the global carbon and biodiversity crises. Understanding the economic forces driving this expansion, we can prioritise conservation interventions and reduce the impacts of crop expansion on carbon emissions and biodiversity loss.

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