Unanticipated land-use changes from market responses to conservation interventions in the tropics

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Thesis Summary

Commercial agriculture is the main driver of global forest and biodiversity loss. While research and policies focus on implementing sustainable, cost-efficient agricultural practices to reduce deforestation rates whilst meeting rising global food demands, they often overlook market responses and indirect impacts on land-use change. As forest loss for agriculture is primarily market-driven, not accounting for these market responses could lead to grossly underestimating the extent of forest and biodiversity impacts.

This thesis focuses on the unanticipated land-use changes from market responses to our conservation interventions. By integrating theoretical economic concepts with spatial land-use models, I investigated how perverse market outcomes arise from common conservation interventions and policies. I first developed a framework describing the economic underpinnings of unintended consequences via market responses to our conservation efforts. Following this, I further explored market responses to land-use changes and conservation efforts, focusing on oil palm agriculture across Indonesia. I developed a model that explains and predicts oil palm expansion and deforestation across Indonesia, in relation to crop prices, production costs and profitability. Using this model, I constructed a partial-equilibrium model characterising market dynamics, and, finally, evaluated the unanticipated land-use impacts of projected crop expansion, under various land-management and conservation scenarios, on forests and biodiversity.

A land-rent approach provided more realistic assessments of land-use change oil palm spread compared to just using crop suitability. Equilibria analyses from this model highlighted the sensitivity of supply relationships to changes in agricultural practices: changes in yield resulted in resulted in sizeable shifts in supply and market equilibria. Importantly, from the crop-expansion model, agricultural intensification increases the likelihood of further expansion into forests. Land-use policies in place offer little protection to remaining forests, given minimal overlap with areas vulnerable to oil palm expansion. This study emphasises the potential risks conservation efforts being undermined by market feedbacks; it is imperative we account for these potential market-driven responses and develop more effective conservation decisions with minimal counteractive feedbacks.

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Statement of contribution

The research presented in this thesis is my own. This thesis has not been submitted for any other award at this or any other institution. In addition to myself (F.K.S.L), other collaborators in this research include (in alphabetical order): David Edwards (D.P.E.), Jolian McHardy (J.M.) and L. Roman Carrasco (L.R.C.).

Chapter 1

Thesis introduction.

F.K.S.L. wrote the chapter.

Chapter 2

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The manuscript is reproduced in full in this thesis, with minor formatting alterations. The overall contribution of authors was as follows: F.K.S.L. and D.P.E. conceived the study and planned the layout of the review. F.K.S.L. and J.M. developed the economic framework. F.K.S.L. wrote the article, with contributions from D.P.E., J.M. and L.R.C.

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Chapter 4

Building a partial equilibrium model for oil palm in Indonesia: insights from equilibria analysis.

The overall contribution of authors was as follows: F.K.S.L., J.M. and L.R.C. conceived the study. F.K.S.L performed all analyses, with contribution from J.M. F.K.S.L. wrote the chapter, with contributions from D.P.E., L.R.C. and J.M.

Chapter 5

Oil palm intensification generates indirect land-use impacts that drive biodiversity loss in Indonesia.

The overall contribution of authors was as follows: F.K.S.L., D.P.E., J.M. and L.R.C. conceived the study. F.K.S.L. developed the methods with contributions from L.R.C., and performed all analyses. F.K.S.L. wrote the chapter, with contributions from all authors.

Chapter 6

Thesis discussion.

F.K.S.L. wrote the chapter.

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Chapter 1

Thesis introduction

1.1 Introduction

1.1.1 Environmental impacts of forest loss and agricultural expansion across the tropics

With the continual increase in both population and affluence globally, the surge in global demand for food and agricultural products are at the forefront of reasons driving global land-use change (DeFries, Rudel, Uriarte, and Hansen, 2010). While the increase in global resource demand is often attributed to rising global population, per capita resource consumption is also rapidly increasing, particularly in areas of affluence and high standards of living (Tilman, Balzer, Hill, and Befort, 2011; Godfray et al., 2010), and the rise in global land-use change is more strongly related with global urban population than it is with total population (DeFries et al., 2010).

Agricultural expansion to meet these demands is especially high across the tropics (Gibbs et al., 2010). Many of the world's major crops, including rice, soy, maize and oil palm, as well as pastureland for livestock, are widespread across the Neotropics, Asia and Africa (Monfreda, Ramankutty, and Foley, 2008; Ramankutty, Evan, Monfreda, and Foley, 2008, Figure 1.1). This continual pan-tropical agricultural expansion comes at the expense of forests and biodiversity (Phalan et al., 2013). Tropical forests have been rapidly cleared, primarily for agriculture and pastureland for livestock, over the last few decades (Gibbs et al., 2010) and, as demands for these crops continue rising with population and economic growth, we can expect greater pressure on tropical forests.

A large proportion of the world's biodiversity is concentrated within the tropics (DeFries et al., 2010), and with the accelerating loss of forests pan-tropically, negative impacts on biodiversity are undoubtedly increasing (Tollefson, 2019). Deforestation leads to contractions of species ranges, particularly forest specialists, exacerbated by increased fragmentation of remaining forests and habitats and additional human pressures (e.g., Maxwell, Fuller, Brooks, and Watson, 2016; Symes, Edwards, Miettinen, Rheindt, and Carrasco, 2018). Species composition and diversity, as well as other aspects of biodiversity important for maintaining ecosystem function and forest health in the long run are also negatively impacted by continual habitat loss and fragmentation (Haddad et al., 2015). Additionally, the continual forest loss for agriculture exacerbates the global carbon crisis. Forest cover loss, disturbance and degradation, are a major source of carbon emissions (Baccini et al., 2017), with forest loss for agricultural expansion being responsible for a third of global greenhouse gas emissions (Vermeulen, Campbell, and Ingram, 2012). As regions of high terrestrial biodiversity and carbon sinks, the

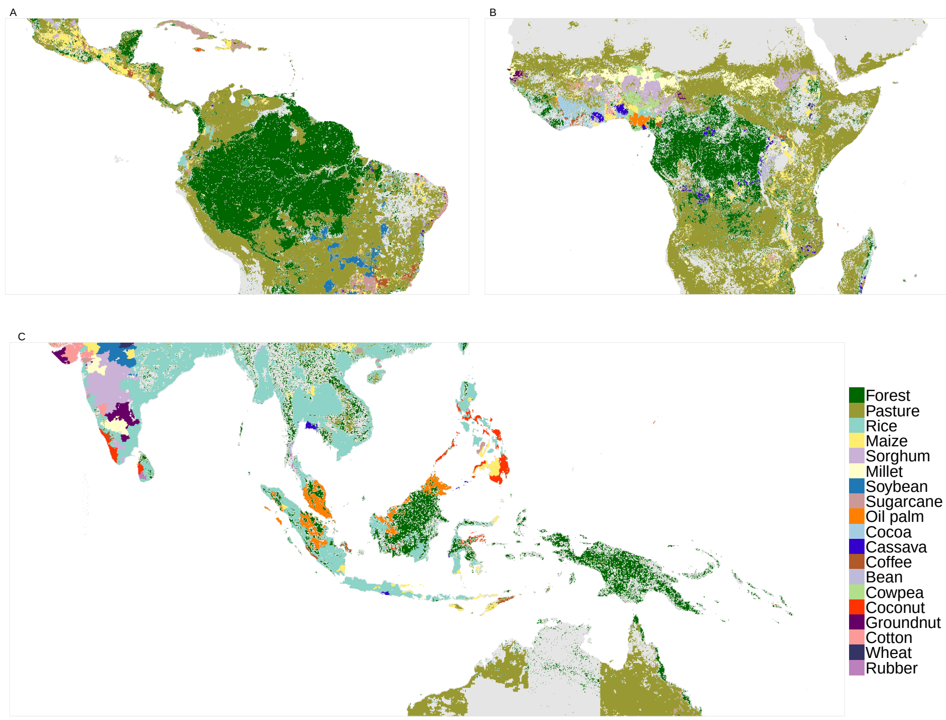

Figure 1.1: Extent of natural forests, pastures and the top 17 most frequently cultivated tropical crops across (A) the Americas, (B) Africa and (C) Asia-Pacific. Crop and pasture distribution in 2000 were averaged across 1997-2003 (Monfreda, Ramankutty, and Foley, 2008; Ramankutty, Evan, Monfreda, and Foley, 2008). The dominant crop/pasture of each cell with the highest proportion was displayed, provided harvest area exceeded 10% of each cell. Information on the extent of forests across tropics was obtained for 2009, including all forest types. Cell were mapped at a resolution of 5 by 5 arc-minutes (approximately 10 by 10 km along the equator)

impact of agricultural expansion on biodiversity and carbon emissions is therefore a biodiversity catastrophe in the tropics (Brook, Sodhi, and Bradshaw, 2008). With the urgent need to manage land-use practices more sustainably, striving to meet rising global demands while keeping social and environmental costs minimal is a focus of many studies and policies, and there is a heavy reliance on conservation interventions to achieve this.

1.1.2 Conservation interventions to manage land use sustainably across the tropics

Conservation efforts have been put in place to minimise habitat, biodiversity and carbon losses and other environmental impacts, while still regulating agricultural output to meet the rising global demands (Erb et al., 2016). Legal restrictions on land use and resource extraction — such as establishing protected areas (PAs) and enforcing limits on resource extraction within designated areas (e.g., timber harvest quotas) — or economic-based initiatives — including Payment for Ecosystem Services (PES) schemes and sustainability certification schemes (e.g., Forest Stewardship Council, FSC) — represent two key approaches to regulating land-use. Additionally, improving crop yields through agricultural intensification is often proposed as a means of reducing pressure on remaining forests while increasing overall agricultural output. The land-sparing framework (Green, Cornell, Scharlemann, and Balmford, 2005, much like the Borlaug hypothesis, argues that high-intensity farming practices on existing land while minimising additional clearing of forested areas is a more effective strategy for protecting overall biodiversity and retaining carbon stocks than adopting low-intensity farming techniques (i.e., land-sharing, Green et al., 2005). Given a large proportion of existing agricultural land is not operating at their optimal potential capacity, i.e., not producing at their maximum potential yield, there is room to increase agricultural output and close yield gaps on existing farmland (Foley et al., 2011; Licker et al., 2010; Tilman et al., 2011). This framework is increasingly promoted as a means of increasing overall agricultural supply to meet demands without having to convert more farmland, thus relieving pressure on remaining forests and reducing the negative impacts of agriculture on biodiversity and the environment (e.g., Phalan, Green, and Balmford, 2014; Tilman et al., 2011). A number of recent studies have since called for a shift in research focus shift beyond a land-spring vs sharing dichotomy, and to consider other aspects like the spatial scale, type of system and perspectives that influence both land-use strategies (e.g., Ekroos et al., 2016; Kremen, 2015; Salles, Teillard, Tichit, and Zanella, 2017). Additionally, measures need to be taken within land-sparing framework to ensure sustainable intensification, or land-use and biodiversity could still be negatively affected (Phalan et al., 2016). Nevertheless, with this framework gaining both traction and inertia, more policies are adopting high-intensity agricultural methods.

1.1.3 Unintended feedbacks to conservation interventions from perverse market outcomes

However, very often studies that explore the direct benefits of agricultural intensification and other conservation interventions do not consider the potential indirect and unintended consequences of these conservation efforts (Larrosa, Carrasco, and Milner-Gulland, 2016). In particular, little attention is paid to how markets might respond to these conservation policies. Fundamentally, forest loss for agricultural expansion is driven by markets and demand for resources. Therefore, regardless of the approach they take, as conservation efforts and policies regulate supply of agricultural produce and land use, we can expect trade-offs and market feedbacks in response to land-use change and conservation actions (Armsworth, Daily, Kareiva, and Sanchirico, 2006; DeFries, Foley, and Asner, 2004). Overlooking these market feedbacks could result in reduced efficacy of our conservation efforts, and policies could potentially even backfire. For instance, establishing protected areas could result in leakage of land-exploitation efforts (Ewers and Rodrigues, 2008; Renwick, Bode, and Venter, 2015). Similarly, imposing regulations on deforestation and logging could result in an increased import of illegal timber from neighbouring countries (Meyfroidt and Lambin, 2009). The drivers of these unintended feedbacks of conservation efforts can be economic-based. It is crucial that we have a deeper focus and understanding of how markets react to conservation interventions aimed at reconciling agricultural expansion and biodiversity conservation, and the often-overlooked, indirect impacts on the land-use, forest and biodiversity. If we wish for more effective land-use policies, it is critical we identify and incorporate potential market feedbacks into our analyses and predictions of land-use change. Indirect environmental and ecological impacts of both land-use change and conservation actions typically occur over longer time-scales and larger distances than directly measured outcomes. Importantly, compared to more localised conservation efforts, these perverse market outcomes and impacts span longer time frames and larger spatial scales, especially exacerbated by the role of international trade in an increasingly tele-connected world (Carrasco, Chan, McGrath, and Nghiem, 2017). Focusing on a policy change or intervention as a localised one-off shock might be inadequate, since the shock could set off a chain of feedbacks which extend geographically and temporally.

1.2 Case study: conservation efforts surrounding oil palm agriculture

The issues surrounding deforestation for agricultural expansion across the tropics are well-encapsulated within global oil palm (*Elaeis guineensis* Jacq.) agriculture. As the world's most widely traded oil crop, oil palm agriculture is one of the key crops driving lowland and peat forests and biodiversity loss across the tropics (Phalan et al., 2013). Global demands for palm oil continue to grow, with an estimated 240 Megatonnes of palm oil needed by 2050, given previous expected population growth rates (Corley, 2009). The global extent of oil palm plantations more than doubled between 2000 and 2017, from 10.86 Mha to 21.35 Mha (FAO, 2019), Figure 1.2A), with Indonesia and Malaysia producing more than 80% of the world's palm oil (Figure 1.2B).

Oil palm agriculture has been a major driver of both economic development and environmental issues within Indonesia, the world's top producer and exporter of palm oil. Oil palm expansion and palm oil production across Indonesia continue to grow exponentially since 2000 (Figure 1.3): while rice plantations remain the dominant crop across Indonesia's landscape, the rate of oil palm expansion in the country has far exceeded any other crop (FAO, 2019, Figure 1.3). This increase in oil palm extent happens at the expense of primary and secondary forests, peatlands, other plantations and, ultimately, biodiversity across Indonesia (Margono, Potapov, Turubanova, Stolle, and Hansen, 2014). The biodiversity impacts of oil palm agriculture have been extensively studied and well-documented (Dislich et al., 2017). Oil palm plantations support lower biodiversity than primary and secondary forests (Fitzherbert et al., 2008). Additionally, forest carbon stocks and carbon sequestration potential are reduced with continual forest loss for oil palm plantations (Guillaume et al., 2018; Kotowska, Leuschner, Triadiati, Meriem, and Hertel, 2015). Carbon emissions are also known to increase with draining of carbon-rich peat soils for agriculture (Carlson et al., 2013; Kurnianto et al., 2015).

Current conservation efforts to minimise the impacts of oil palm agriculture on forests and biodiversity have been extensive and increasing. Notably, the land-sparing framework is largely agreed as an effective means of meeting palm oil demands with reduced environmental and biodiversity impacts. More studies are arguing in favour of intensification via high-intensity agricultural practices and new crop varieties with

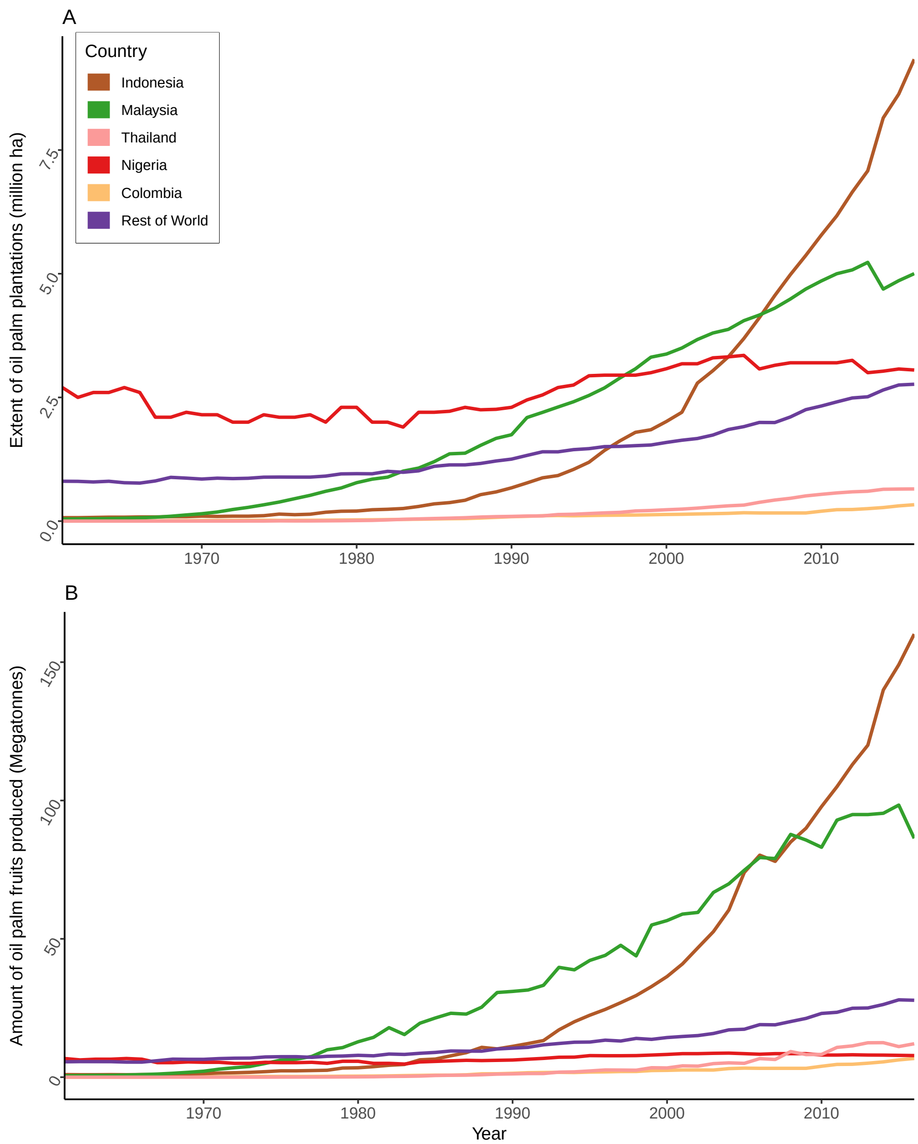

Figure 1.2: (A) Area occupied by oil palm plantations and (B) amount of oil palm fruits produced across the top 5 producing countries and the rest of the world collectively, from 1961 to 2016 (FAO, 2019).

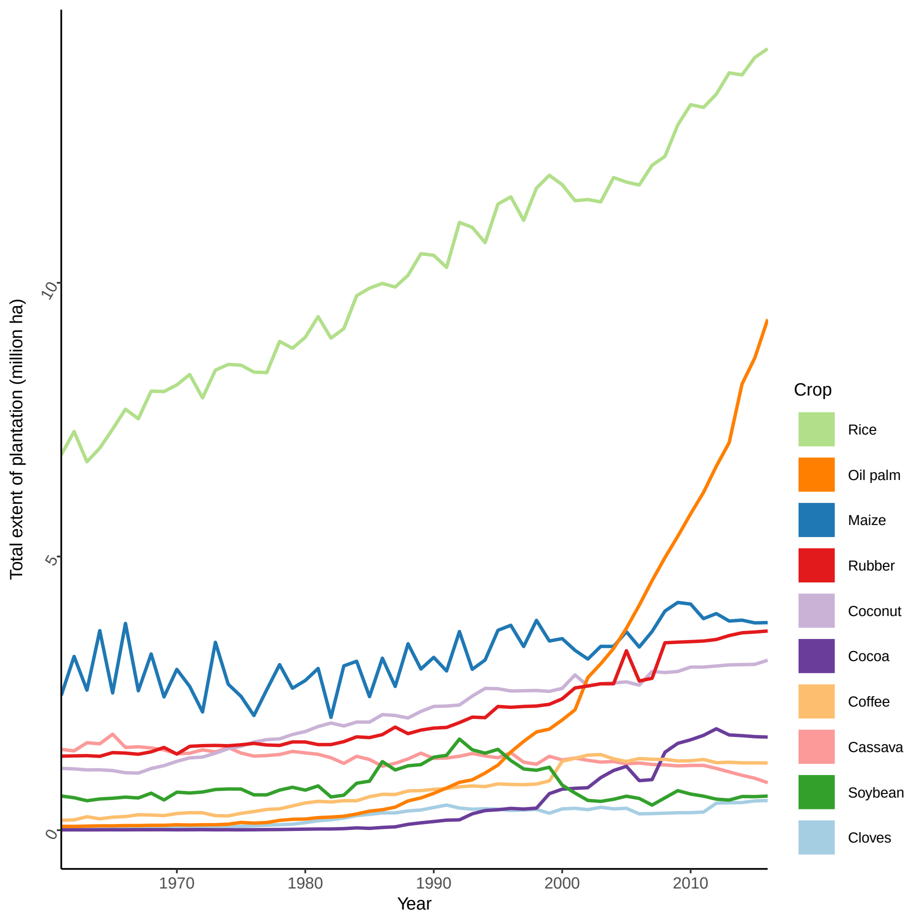

Figure 1.3: Changes in area across Indonesia occupied by the top ten crops from 1961 to 2016 (FAO, 2019).

higher crop yields to reduce pressures on forests. Research has also placed focus on identifying and closing yield gaps (Woittiez, van Wijk, Slingerland, van Noordwijk, and Giller, 2017), especially among smallholders (Euler, Hoffmann, Fathoni, and Schwarze, 2016; Soliman, Lim, Lee, and Carrasco, 2016), to increase total palm oil production across existing plantations. Additionally, land-use restrictions are being put in place to restrict deforestation. For instance, Indonesia implemented a Forest Moratorium in 2011, protecting over 69 Mha of forests and peatlands against land use, while issuing concessions allowing sustainable agriculture in remaining areas (Sloan, 2014). Regulated certification schemes like the Roundtable for Sustainable Palm Oil (RSPO) have also been introduced across a number of plantations, ensuring that resource extraction and agricultural production are managed within guidelines that incentivise sustainable practices.

While the top priority research agenda surrounding oil palm sustainability typically lies in biodiversity and conservation (Padfield et al., 2019), little, however, is known about how markets respond to these conservation efforts and policies. Given that these land-use policies and changes in farming practices directly impact on Indonesia's (and therefore the global) palm oil supply, they need to be approached with extreme caution to ensure they do not backfire. We need a deeper understanding of the role of economic forces in oil palm expansion, supply and demand, and, therefore, how perverse market outcomes might arise from agricultural intensification and other conservation interventions. As a highly commercial cash-crop widespread across the top producer, Indonesia's oil palm agriculture provides an excellent case study to better understand how market feedbacks could undermine our efforts at reducing deforestation and biodiversity impacts. This should allow us to make better-informed projections of land-use change and biodiversity impacts and, ultimately, develop more effective conservation policies.

1.3 Thesis aims and overview

The overall aim of the thesis is to study the unanticipated land-use changes from market responses to our conservation interventions across the tropics and emphasises the importance of accounting for economic forces in understanding land-use change and improving biodiversity conservation efforts. By focusing on different aspects of the market responses to conservation efforts and the potential impacts on forest and biodiversity, this thesis seeks to shed light on the crucial yet often overlooked relationship surrounding policies and practices aimed at reducing forest and biodiversity loss.

In Chapter 2, I first provide a general framework of perverse market outcomes from biodiversity conservation, through succinct explanations for leakage effects and changes in market equilibria and links to examples across various types of conservation interventions. The thesis then focuses on specific economic drivers of land-use change and market feedbacks to conservation efforts surrounding oil palm agriculture and expansion using Indonesia as a case study (Chapters 3–5). The concepts surrounding agricultural expansion and intensification, nonetheless, apply to other agricultural systems globally. I developed an integrated spatial economic model to explain how market prices, new agricultural technologies and conservation policies all affect distribution of plantations, and therefore land-use and deforestation. By combining economic theory with land-use models and projections, the model identifies areas vulnerable to future agricultural expansion and the resulting impacts on biodiversity and the environment. Using this model, I then further explore the full implications of different policies aimed at sustainable agricultural production.

Chapter 2: Perverse market outcomes from biodiversity conservation

Chapter 2 highlights a common problem of unanticipated market feedbacks in conservation that research and policies often overlook, but could severely reduce the effectiveness of conservation measures. Conservation policy analyses tend to focus only on the direct impacts of the policy, and often fail to account for indirect consequences that could potentially reduce, and in some cases even reverse, the intended outcomes of our conservation efforts. Using fundamental economic principles, I constructed a conceptual framework explaining the economic underpinnings of how conservation interventions could, instead, lead to an overall increase in environmental resources being exploited. Through various examples from the wider literature, I emphasise how market regulations in response to our conservation policies can lead to such leakage effects. I also discuss the critical knowledge gaps that need to be addressed to strengthen our understanding of market feedbacks. By bringing forward the awareness of perverse market outcomes, this chapter stresses the need for a deeper understanding of market responses to conservation, and aims to provide a platform for exploring market feedbacks, encourage better-integrated assessments and improve conservation goals.

Chapter 3: Land rents drive oil palm expansion dynamics in Indonesia

Rising global demand for palm oil continues to threaten forests, biodiversity and livelihoods across Indonesia, and while studies and policies focus on minimising these negative environmental impacts, there remains a critical need to explain the drivers of oil palm expansion and distribution to better inform predictions and policies. Ensuring cost-effectiveness of our conservation policies is dependent on our ability to identify areas more vulnerable to future oil palm expansion. Projections of future oil palm expansion in Indonesia, however, focus on environmental suitability of crops, overlooking the role of socio-economic drivers of crop expansion. Building on existing work that includes agricultural suitability, in Chapter 3, I incorporate spatial economic drivers into a land-use model to better understand and explain oil palm spread and distribution. Using a land rent modelling framework, I constructed a novel crop expansion model explaining the spread of oil palm plantations across Indonesia in relation to economic forces, crop suitability and other factors such as accessibility, proximity to other plantations and areas under protection. I then identified areas vulnerable to future crop expansion and assessed the effectiveness of Indonesia's Forest Moratorium in protecting forests and peatlands against agricultural expansion.

Chapter 4: Building a partial equilibrium model for oil palm in Indonesia

To better assess the socio-economic implications of conservation policies aimed at regulating oil palm production and land use, we need a better appreciation of the market dynamics surrounding oil palm. While current economic models are effective in explaining impacts of conservation policies on oil palm trade (e.g., Jafari and Othman, 2016; Taheripour, Hertel, and Ramankutty, 2019), the link between economic models and land-use change is seldom emphasised across studies. Chapter 4 focuses on better understanding the market dynamics surrounding agricultural expansion and intensification by focusing on the interaction between supply and demand of a highly commercial commodity.

Using the spatial economics (land rent) modelling approach described and developed in Chapter 3, I constructed spatially explicit aggregated supply curves describing how palm oil production relate to palm oil prices and profitability. I then constructed a partial equilibrium model to evaluate the sensitivity of Indonesia's oil palm supply and demand to exogenous shocks brought about by changes in agricultural practices, and assess how such shifts in market equilibria, in turn, affect land use and deforestation.

This chapter thus serves as a proof of concept of the supply relationship spatially, and calls to attention the importance of considering market feedbacks when assessing the efficacy of our conservation policies. Understanding the sensitivity of markets to changes in agricultural policies allows us to make better-informed assessments of the efficacy of agricultural intensification, land-use policies and restrictions and even certification policies.

Chapter 5: Oil palm intensification generates indirect land-use impacts that drive biodiversity loss in Indonesia

Various conservation interventions and land-use policies have been proposed and implemented to reduce negative impacts of oil palm agriculture and expansion on forest carbon and biodiversity. These range from protecting areas through policies like the Forest Moratorium (Sloan, 2014), to promoting high-intensity farming to increase crop yields and output. The land-sparing framework is quickly gaining traction across studies and greater emphasis placed on promoting the direct benefits of agricultural intensification improving crop yields. There, however, lies great uncertainty as to how markets might respond to these interventions, and many studies unfortunately ignore this underlying issue surrounding land-use and conservation. However, where studies compare effectiveness of opposing land-use strategies (e.g., land-sharing vs land-sparing), little emphasis is placed on the vulnerability of remaining forests to further expansion over time. This oversight means policies are blind to unanticipated land-use changes.

Chapter 5 therefore focuses on understanding how land-use changes are shaped by agricultural practices and policies over time. Building on Chapters 3 — which emphasises the role of socio-economic drivers in crop expansion — and 4 — which addresses the market dynamics surrounding agricultural expansion and intensification — I examine how future oil palm distribution in Indonesia varies as a result of changes in crop prices, yields, and land-use policies and conservation decisions, and the indirect impacts on deforestation, carbon stocks and biodiversity across Indonesia. In doing so, this chapter reinforces the links between land-use changes and economic forces, both across space and time, and addresses the indirect impacts on land-use changes often overlooked by studies.

Chapter Six: The role of market forces in managing forest loss from agriculture

Finally, Chapter 6 presents a summary of the previous chapters, with particular focus on the implications for current and future conservation policies and practices in Indonesia aimed at reducing forest loss from oil palm expansion. Drawing from key findings across Chapters 2 to 5, this chapter highlights the impacts of market feedbacks on the efficacy of current policies adopted to minimise land-use, and emphasises the importance of accounting for market responses when designing and implementing conservation actions. This chapter also discusses some approaches to managing these market feedbacks and minimising the impacts of perverse market outcomes on forest and biodiversity loss: by taking steps to account for these potential market outcomes before they occur, policies and land-use practices can be improved.

As we work towards minimising environmental impacts of land-use change and agricultural expansion via conservation policies and interventions, it remains crucial we consider the potential unintended feedbacks and perverse market outcomes of these conservation efforts. Market feedbacks to conservation actions are inevitable and, if overlooked, could undermine our conservation efforts. Through integrating economic theory with land-use models, emphasising different aspects of the markets and exploring the factors driving change across spatial and temporal scales, this project focuses on a significant component of an ongoing important environmental issue, and advances our understanding of the social and policy dimensions of global environmental change.

Chapter 2

Perverse market outcomes from biodiversity conservation interventions

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Abstract

Conservation interventions are being implemented at various spatial scales to reduce the impacts of rising global population and affluence on biodiversity and ecosystems. While the direct impacts of these conservation efforts are considered, the unintended consequences brought about by market feedback effects are often overlooked. Perverse market outcomes could result in reduced or even reversed net impacts of conservation efforts. We develop an economic framework to describe how the intended impacts of conservation interventions could be compromised due to unanticipated reactions to regulations in the market: policies aimed at restricting supply could potentially result in leakage effects through external or unregulated markets. Using this framework, we review how various intervention methods could result in negative feedback impacts on biodiversity, including legal restrictions like protected areas, market-based approaches, and agricultural intensification. Finally, we discuss how conservation management and planning can be designed to ensure the risks of perverse market outcomes are detected, if not overcome, and we address some knowledge gaps that affect our understanding of how market feedback varies across spatial and temporal scales, especially with teleconnectedness and increased international trade.

2.1 Introduction

With increasing global population and affluence, the global demand for timber, food and other natural resources is rising, with crop demands projected to increase by 100 – 110% from 2005 levels by 2050 (Tilman et al., 2011). Meeting this demand will drive further forest degradation from logging and deforestation for agriculture and timber plantations, especially in the tropics (Hansen et al., 2013). Habitat loss in the tropics is the biggest driver of biodiversity and ecosystem function losses (DeFries et al., 2004). There is thus an urgent need to better manage tropical land-use change to reduce the loss of biodiversity and ecosystem functions, whilst addressing the issue of rising timber and food demands, for instance via changing diets or reducing food waste (Erb et al., 2016).

Management strategies are commonly implemented to reduce conversion of natural habitats to other land uses, and therefore to stem the loss of biodiversity. These include legal restrictions on land-use by establishing protected areas (PAs) (Oliveira et al., 2007), economic-based conservation efforts such as certification and payment for ecosystem services (PES) schemes (Chobotová, 2013), and improvements in technology and agricultural intensification (Tilman et al., 2011).

Often, however, there are indirect and unintended consequences of conservation measures. Trade-offs are inevitable with changes in land use (DeFries et al., 2004), and this includes when implementing conservation efforts. Many unintended consequences are often overlooked when assessing the effectiveness of biodiversity conservation actions (Larrosa et al., 2016), in part because indirect environmental and ecological impacts of land-use changes and conservation actions typically occur over longer time-scales and larger distances than directly measured outcomes. Unintended consequences can have positive or negative effects on the overall (net) outcomes of interventions. Positive feedback effects include protection or restrictions on wildlife harvests diminishing demand (Pain et al., 2006) and unintended crowding-in effects from market-based conservation policies (Wunder, 2013). By contrast, negative feedbacks could include demand driving leakage of deforestation into unprotected areas in response to establishing PAs (Ewers and Rodrigues, 2008) and an increase in demand brought about by improving cost-efficiency of agriculture (Rudel et al., 2009).

Given that negative feedbacks compromise conservation efforts, we focus on their emergence via the influence of market forces. Knowledge of the socio-ecological system responses is crucial for decision makers to minimise negative unintended feedbacks. Typologies that classify feedbacks between deletion (removal of pre-existing feedbacks), addition, and flows (changes in magnitude of pre-existing feedbacks) have recently been developed (Larrosa et al., 2016). Under this typology, market feedbacks could be considered flow feedbacks and PAs establishment addition feedbacks.

Market feedbacks in response to the initial conservation intervention can undermine conservation efforts (Armsworth et al., 2006), and although important, they are often not considered in policies (Jantke and Schneider, 2011; Miller, Caplow, and Leslie, 2012; St John, Keane, and Milner-Gulland, 2013). Understanding how agents in a market respond to policy changes is very important in determining whether a certain scheme will have the intended consequences, or instead be counterproductive (Galaz, Gars, Moberg, Nykvist, and Repinski, 2015). Changes in policy typically affect the incentives of agents, resulting in changes in their behaviours. In many cases, the reaction of agents to the new incentives resulting from policies in biodiversity conservation will have a large influence over whether the policy is successful, or if perverse incentives will lead to damaging unintended consequences instead. Arguably, unintended consequences of environmental and conservation policies through these channels have not attracted sufficient scrutiny to date (Milner-Gulland, 2012). It is therefore essential to understand how a policy will alter the pattern of incentives of agents in the market. Indeed, successful policies will be designed to ensure the incentives of agents in the market are compatible with the intended aims of the policy.

In this review, we focus on the potential perverse market outcomes of conservation efforts. We first develop a theoretical model to explain how market regulations respond to conservation efforts. Reframing conservation in an economic context allows us to understand how market feedbacks could lead to perverse outcomes. We then apply the framework to different conservation interventions and discuss how conservation policies and management practices might be adapted to minimise the risk of negative consequences.

2.2 Economic underpinnings of unintended consequences via market feedbacks

2.2.1 Conservation places restrictions on resource use

Conservation interventions can be viewed as external impacts on the resource market (e.g., timber), which can result in a shift in the equilibrium or lead to disequilibrium. In many cases, conservation actions revolve around restricting access to a resource.

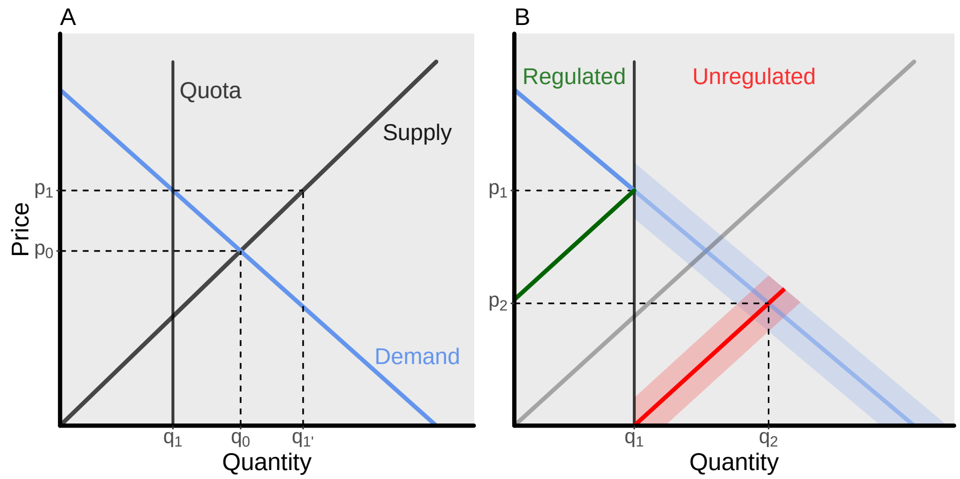

Figure 2.1: Conceptual framework describing possible effects of an output quota (A) on the creation of an illegal market (B). (A) The market is initially in equilibrium at (q_0,p_0). Setting a quota restricts the quantity of resource traded to q_1 raising the price to p_1. Firms can respond to this disequilibrium by creating an illegal market. Assuming, for simplicity, there are no additional costs to illegal supply relative to regulated supply, firms will expand supply through the illegal market moving up the supply curve beyond q_1 with total supply rising towards the pre-quota level, q_0. (B) If, for instance, the inefficient firms (green) supply the formal market, supplying q_1, and the efficient firms (red) supply the illegal market, supplying (q_2-q_1), the creation of the illegal market can result in an overall increase in the quantity traded ($q_2>q_0$) despite the quota. We might also expect shifts in demand and supply (shaded) within the unregulated market due to externalities.

Placing logging bans and quotas on timber harvests, for example, restricts trade of the commodity (i.e., timber). Establishing PAs also restricts land availability and access to resources. Imposing such restrictions limits the quantity of supply (q_1, Figure 2.1A), and the market is no longer in equilibrium. The market responds with a rise in the price to p_1, above the initial equilibrium level, at which suppliers would like to offer more than q_1 to the market . This represents the basic economic model of a quota (Goolsbee, Levitt, and Syverson, 2016).

However, there is some question about the effectiveness of such policies in practice. For instance, applications of this theory to include leakages (Murray, McCarl, and Lee, 2004; Jonsson, Mbongo, Felton, and Boman, 2012) involve the expansion of supply back towards the quantity at the free-market equilibrium. Related arguments of how illegal trade can expand consumption in the presence of import quotas have also been established in the international trade literature (e.g., Falvey, 1978). In other words, some of the restriction in quantity due to the quota may be undone by illegal trade. Perverse "illegal" (black) market incentives reduce the impact of the conservation policy.

The imposition of a quota also produces an artificially high price in the formal market, meaning that inefficient (i.e., high-cost or low-productivity) suppliers can co-exist with efficient ones. This presents the question — which suppliers supply the formal market and which supply the black market? In addressing this question, we highlight a novel further possible perverse impact of a quota policy. Compared to a free market where efficiency considerations determine which firms supply the formal market, the allocation of supply rights under a quota policy is now determined by the regulatory authority. With high prices within the formal market, there is less incentive to be efficient, and inefficient suppliers could end up supplying the market. If the regulatory authority does not observe efficiency and allocate supply rights to the most efficient firms, or, if the authority is able to exploit the power of allocating rights to pursue their own agenda (e.g. corruptly supplying rights to "friendly", possibly high-cost, firms), then one perverse result of the imposition of a quota might be a decline in market efficiency. In such a case, the inefficient firms supply the formal market and the efficient firms supply the unregulated market — there is a re-organisation of supply (Figure 2.1B) akin to the rationing rules on the demands side used, for instance, in Davidson and Deneckere (1986). The total output across the formal and black markets in this case could be greater than under the initial equilibrium before the quota was introduced (q_2, Figure 2.1B). The quota might be ineffective in terms of reducing trade, and may even result in an increase in trade.

The degree to which the quantity traded exceeds the quota will depend on which firms supply each market, as well as the costs and benefits to firms and consumers from trading in the illegal market. For instance, supply in the illegal market will shift downwards, reducing the leakage effect, if the costs associated with supplying the legal market are lower than supplying the illegal market. However, where the legal market has high costs associated with meeting regulatory standards, by avoiding these costs, firms trading in the illegal sector might offset extra costs associated with the illegal market (e.g. concealment costs).

2.2.2 Improving land-use practices and productivity to reduce land use

Conservation measures could also involve improving productivity and technology through agricultural intensification and new crop varieties, to reduce the pressure to convert more land. While the direct impact of such measures could be an increase in production with a reduced need for land, there may also be unintended consequences. Although there is uncertainty as to whether intensification would improve the cost-efficiency of production, if improved, it could lead to a decrease in the costs of resources: suppliers are willing to supply more at any given price. This is associated with a rightward shift in the supply curve and consequently, in the equilibrium (q_0,p_0 – q_2,p_2, Figure 2.2), resulting in an overall increase in resources being traded (e.g., Villoria, Byerlee, and Stevenson, 2014). The size of this shift in equilibrium does depend on the price elasticity demand of the product — with a more pronounced effect in the case of an elastic demand (where demand varies strongly with prices). Conservation measures aimed at regulating the supply of, for instance, agricultural production might instead put additional pressure on remaining available resources.

These perverse outcomes could be exacerbated in markets where the global demand is supplied though multiple substitutes, such as different types of vegetable oil crops (e.g., oil palm, rapeseed). Assuming markets for both commodities are the same (perfect substitutes), initial equilibria for both commodities should also be identical (q_0,p_0, Figure 2.3A). Improving yields in one crop lowers prices for any given quantity proportionally, represented by a shift in supply curve from $\mathrm{Supply_A}$ to $\mathrm{Supply_{A_{Int}}}$, and causes a shift in equilibrium from q_0p_0 to q_Ap_A (Figure 2.3B). Additionally, we can expect decreased demand for the less efficient substitute, denoted by the downward shift in $\mathrm{Demand_B}$, and a decrease in quantity of crop B (from q_0 to q_B): consumers are likely to favour the cheaper crop beyond price p_A. We can therefore expect higher quantities of crop A traded, and a surplus of crop B not traded. Overall, however, there could still be a net increase in agricultural land use (deforestation for crop A − forest recovery on abandoned land from crop B), and a net loss of old-growth forests across a larger region (Carrasco, Larrosa, Milner-Gulland, and Edwards, 2014).

2.3 Examples of conservation measures and market feedbacks

2.3.1 Legal restrictions on land use

Legal protection and restrictions on land use are widely implemented globally and include establishing PAs and regulating logging and other resource harvest quotas. Such conservation measures rely on regulation by an authority, usually governmental, to ensure the impacts on ecosystems and biodiversity are minimal, or at least compensated. However, legally enforced (i.e., sufficiently funded) conservation policies are often only

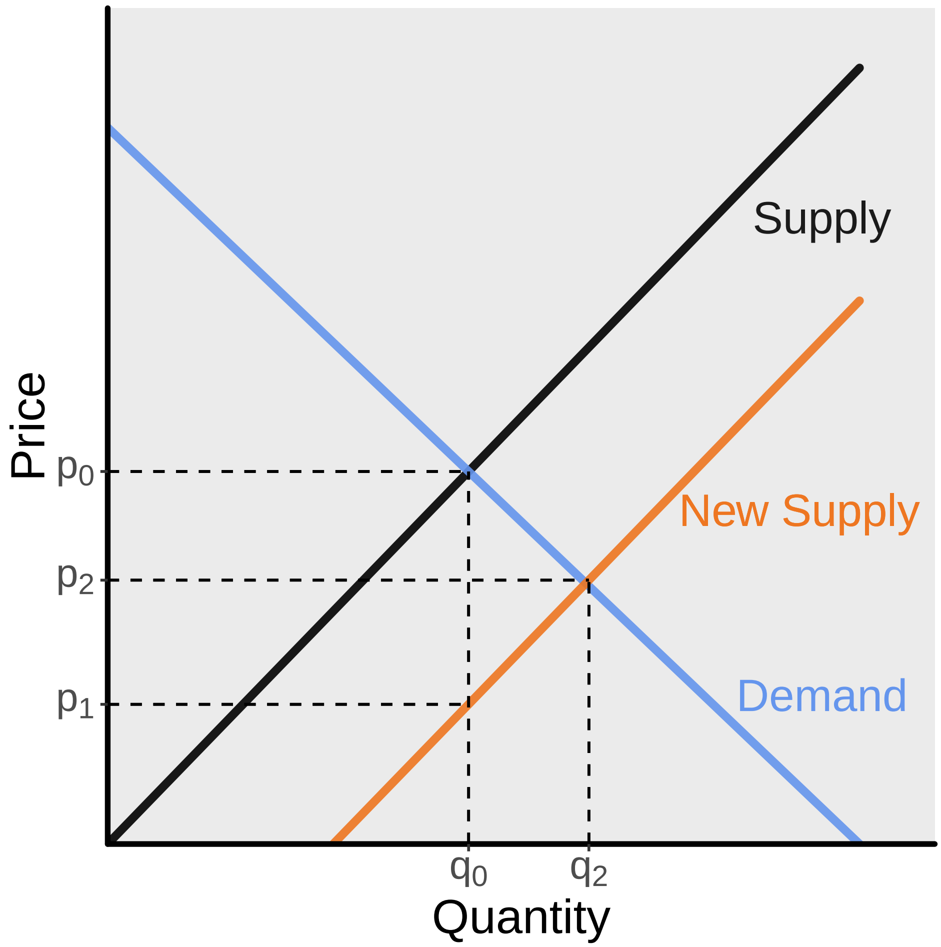

Figure 2.2: Conceptual framework describing how prices and quantities of resources traded vary when crops are improved. Agricultural intensification can shift supply rightwards (black to orange) resulting in an overall shift in equilibrium from (q_0,p_0) to (q_1,p_2).

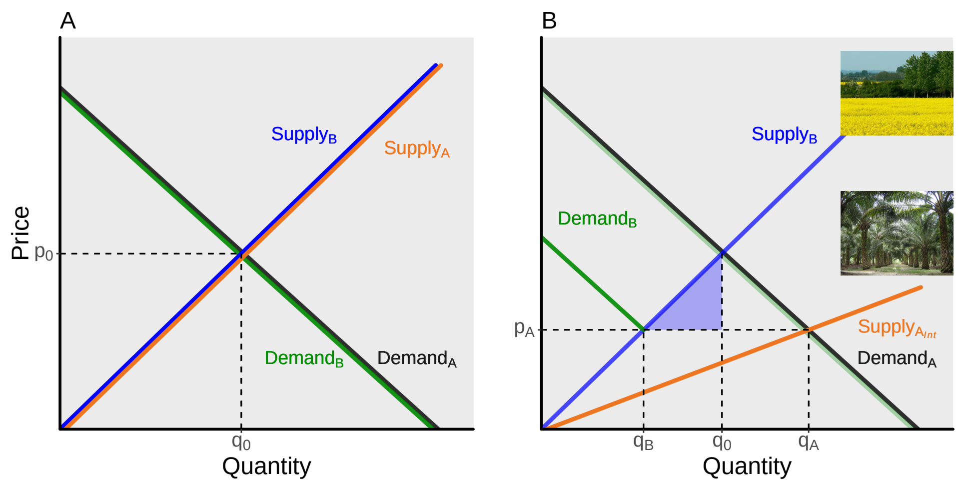

Figure 2.3: Conceptual framework describing the possible effects of agricultural intensification on demand and land-use of substitute crops (B). (A) Assuming, for simplicity, that demand and supply conditions of each commodity are identical, both markets will have the same initial equilibrium (q_0,p_0). (B) Agricultural intensification of one crop (A, orange) can increase amount traded, from q_0 to q_A. Additionally, demand for the substitute crop B could decrease (green), as consumers are likely to favour the cheaper substitute above price p_A. Amount of crop B traded decreases to q_B, resulting in either a surplus (shaded region) not traded. This surplus will ultimately lead to either innovation to use the surplus, or land abandonment from crop B. Improving oil palm yields (pictured lower inset) in the tropics, for example, could lead to a decreased demand in rapeseed oil (upper inset), allowing secondary forest regrowth in temperate regions, but the increased demand for palm oil could increase tropical deforestation.

effective within their designated areas, typically at local spatial scales, and could lead to a displacement of destructive activity and land use into unprotected and unregulated areas (Ewers and Rodrigues, 2008).

Establishing PAs could be effective in directly reducing human impacts within targeted forests, but in many instances might be driven more by markets than by conservation or ecological considerations (Rayner, Lindenmayer, Wood, Gibbons, and Manning, 2014). Many PAs lack additionality because they are situated in locations passively protected by their distance to markets, unproductive soils, steep gradients, etc. The establishment of PAs in economically valuable areas could increase land prices across remaining areas (Polasky, 2006), and shift deforestation and land-use changes into unprotected forests instead. This could create incentives for an unregulated market with consequences as outlined in the framework (Figure 2.1B).

In the tropics, such leakage effects result in high rates of clearing and degradation of forested areas surrounding PAs. For instance, while deforestation rates in the Peruvian Amazon were as low as 2% within PAs, they were up to 18 times higher outside PAs (Oliveira et al., 2007). Similarly, protection of mature forests in Costa Rica reduced the rate of mature forest loss by 50%, but resulted in cropland expansion redirected into unprotected natural habitats, including wetlands, native reforestation, and young secondary forests, due to the lack of legal protection of these areas (Fagan et al., 2013). Furthermore, import of timber and agricultural products into the country increased, displacing land-use change internationally (Jadin, Meyfroidt, and Lambin, 2016). Another potential perverse outcome is an acceleration of land-grabs before regulations are put in place. This situation was observed in Tanzania where accelerated land conversion occurred in anticipation of PA expansion (Baird, Leslie, and McCabe, 2009).

Legal restrictions against resource extraction, much like PAs, can also have displacement effects into unregulated areas, rather than decreased harvests as intended: a similar restriction to a quota is placed on resource quantity, which could result in an informal market arising with a re-organisation of supply and expansion of total output (Figure 2.1B). Reduction in deforestation rates across multiple countries was, for instance, associated with displacement via international trade (Meyfroidt, Rudel, and Lambin, 2010).

Basic economic principles can be used to show how endogenous market feedbacks (i.e., changes within the market, Figure 2.1) may undermine conservation efforts and benefits, and change conservation priorities (Murray et al., 2004; Armsworth et al., 2006). More recently, studies have integrated sub-models of resource extraction and biodiversity impacts, fluctuations in household utility and market prices, and spatially explicit distributions of biodiversity and resources to highlight the impacts on land-use change (Bode, Tulloch, Mills, Venter, and Ando, 2015; Renwick et al., 2015).

2.3.2 Market-mediated conservation measures

Market-based approaches to conservation policies are increasingly seen as efficient, effective means of managing resources, while promoting conservation (Chobotová, 2013). The impacts of biodiversity are controlled through use of markets, and practices that promote conservation are incentivised over practices with negative environmental outcomes. These could be used as complements to legally mandated conservation measures (Lambin et al., 2014). Nevertheless, as highlighted in our framework, these approaches still allow a quota to be set: a governing authority defines a formal, regulated market and determines who supplies within this market, potentially re-organising supply with possible perverse consequences (Figure 2.1B). Furthermore, market-based measures revolve around incentivising suppliers of the formal market, and do not necessarily penalise suppliers of the informal market. Much like legally mandated measures, market-based interventions could favour an unregulated market (with uncertified resources at lower prices, q_2p_2, Figure 2.1B) alongside the regulated market (with certified resources at higher prices, q_1p_1, Figure 2.1B). These perverse outcomes can occur at both local and transnational scales, because policies are typically narrowly focussed and do not account for their wider consequences.

PES schemes, such as the United Nations' Reducing Emissions from Deforestation and forest Degradation (REDD+), although not widely implemented, are increasingly popular (Wunder, 2013). They provide a means of internalising the externalities from loss of ecosystem services and enhancing conservation efforts by compensating suppliers who help improve or protect ecosystem services via habitat protection or restoration. PES schemes could promote more sustainable practices within the market, and allow authorities to decide who supplies the regulated market. However, this neither directly reduces the overall demand for a resource, nor does it penalise suppliers to the informal market. The incentive of supplying the informal market could therefore remain high (Figure 2.1B), and the market might favour suppliers of the informal market- we could ultimately witness a displacement of land-degrading activity into areas not regulated by the PES scheme. This leakage effect could be exacerbated as prices within the regulated market increase (p_1, Figure 2.1B).

Perverse incentives could also occur within PES schemes if they are not implemented and managed well (Wunder, 2013). When suppliers are only rewarded by favourable practices within designated areas (e.g., for additional management practices like afforestation), we could observe a leakage of effect, where destructive activity displaced into areas not enrolled in PES schemes but belonging to the same owner are neglected (Atmadja and Verchot, 2012). Managing PES schemes also becomes increasingly difficult in situations where a single approach is implemented to achieve multiple objectives: PES schemes are frequently also viewed as poverty alleviation and development tools (Daw, Brown, Rosendo, and Pomeroy, 2011).

Sustainability certification schemes (hereafter certification schemes) and eco-labelling (e.g., Rainforest Alliance, Roundtable on Sustainable Palm Oil) rely on consumer activism and pressure on companies to improve business practices and ethics, thereby promoting sustainability in the global supply chain. Forestry certification schemes like the Forest Stewardship Council (FSC) are among the most developed schemes (Auld, Gulbrandsen, and Mcdermott, 2008): the amount of FSC-certified forests has increased to over 186 Mha in the span of about two decades (FSC 2016), and some studies have reported improved forest health in FSC-certified forests (e.g., Kalonga, Midtgaard, and Eid, 2015). Certification schemes, however, have the potential to create similar effects in terms of a re-organisation of supply and associated consequences for expansion of output as those arising from a quota. For instance, if the scheme gives certified suppliers exclusive access to the consumers with a high willingness to pay (q_1, Figure 2.1), but is not tied to firm efficiency, then less efficient firms could end up amongst the suppliers in the certified market, displacing efficient firms into the uncertified market. Indeed, certification usually results in a rise in price of certified commodities (from p_0 to p_1, Figure 2.1B), thereby restricting access to wealthier consumers. Prices of certified timber within Malaysia, for instance, was up to 56% higher than uncertified timber (Kollert and Lagan, 2007). Therefore, only relatively wealthy consumers can afford certified products, while less wealthy purchasers continue buying unregulated and uncertified products (q_2p_2, Figure 2.1B). Additionally, if prices of certified-sustainable goods are too high, the market demand could be lower than the supply and we could observe lower uptake than expected (Edwards and Laurance, 2012). FSC schemes, for example, have increased in popularity over the last decade, but were concentrated in newly developed countries across the tropics, and usually do not include developing nations with larger native forests (Auld et al., 2008).

Importantly, because certification schemes do not penalise the informal market (i.e., no additional costs for supplying the unregulated market), we can expect the unregulated market to thrive. While certification schemes like FSC directly reduce poor logging practices within certified forests (formal market; from q_0 to q_1, Figure 2.1B), they could also result in leakage of (illegal) logging into unmanaged forests (from q_0 to q_2, Figure 2.1B), making the overall management of resources and deforestation more difficult. Indeed, illegal timber products account for 50–90% of forestry products across the tropics (Nellemann, 2012). Similar leakage effects could also emerge from other certification schemes. RSPO certification might be effective in promoting sustainable agricultural practices within certified oil palm plantations, but we could also witness a leakage effect not only affecting unprotected forests, but also production of other crops. RSPO certification across Indonesia led to increased conversion of existing rice cropland (Koh and Wilcove, 2008) and jungle rubber plantation (Warren-Thomas, Dolman, and Edwards, 2015) into oil palm plantations, resulting in an indirect displacement of efforts and habitat conversion in Indochina.

2.3.3 Biodiversity offsets and other trading schemes

Biodiversity trading schemes could be classified as market-driven measures to reduce biodiversity loss, but have also been passed as legislations in some countries. These are typically enforced on companies and developers to allow for economic growth and development, while indirectly reducing human pressures on biodiversity and the environment (Froger, Ménard, and Méral, 2015). Such schemes have been legislated in a number of countries (e.g., Australia) or regions (e.g., California), and widely embraced and adopted by private land developers and companies, including mining and oil companies (Edwards et al., 2014), as a means of measuring and reducing their impact on biodiversity loss.

Biodiversity offsets and trading schemes, in essence, place restrictions on some areas (reserves) while allowing others to be converted for use. Fundamentally, these methods mimic legally mandated conservation efforts (e.g., PAs), where the amount of land use is restricted (Figure 2.1A). Such offsets can only be effective at a very local level (i.e., within reserves themselves), and reserves need to have higher conservation values than areas being converted to achieve a no-net loss outcome. Enforcing restrictions on land-use, as with other conservation measures, does not affect the demand for land, timber or non-timber forest resources, and could result in a displacement of efforts outside the managed (regulated) area. Where reserves are of high economic value, land purchases in biodiversity offsetting programs could also alter supply and demand of resources, resulting in increased land rent and therefore biodiversity loss in unprotected areas (Armsworth et al., 2006).

2.3.4 Land sparing and high-yielding crop varieties

The land-sparing versus land-sharing framework, which considers the trade-offs between agricultural or timber demands and the desire to protect biodiversity, has been widely applied in the debate of how best to meet growing resource demands (Phalan, Onial, Balmford, and Green, 2011). Notwithstanding the limitations of both strategies (Fischer et al., 2011; Erb et al., 2016), a large number of data-based assessments suggest that the land-sparing approach of high-yield farming with habitat conserved elsewhere, if managed correctly with strong governance and effective protection of remaining forests, might be more effective in promoting biodiversity conservation whilst meeting demand (Phalan, Onial, et al., 2011; Erb et al., 2016). Agricultural intensification is a necessary condition for land-sparing, but not a sufficient condition for reducing the need to convert more forest to farmland (Erb et al., 2016).

Agricultural intensification, however, does not reduce the incentives associated with expansion; agricultural area has been observed on occasion to increase with intensification (Ewers, Scharlemann, Balmford, and Green, 2009; Rudel et al., 2009). Projections of land-use changes have also suggested the possibility of further loss of forests with improved crop yields (Kaimowitz and Angelsen, 2008; Phelps, Carrasco, Webb, Koh, and Pascual, 2013; Villoria et al., 2014). This is especially so in passive land-sparing scenarios, where remaining forests are not managed or protected effectively, and hence easily targeted for agricultural expansion (Phalan et al., 2016). A rebound effect known as Jevon's paradox could arise, where the increased productivity and reduced costs of crop production instead lead to increased demands. The magnitude of this effect could vary, depending on elasticity demand of the product (Hertel, 2011; Villoria et al., 2014). For agricultural intensification to be effective in reducing land-use change, an active land-sparing framework is necessary, with heavy reliance on the role of PAs and effective governance (Phalan et al., 2016), which many countries might lack (Fischer et al., 2011).

Increasing agricultural productivity could make crops cheaper and more profitable to produce over time, and increase its uses and demand as a cheaper substitute for other less cost-efficient crops (Villoria et al., 2014), even at transnational scales (Figure 2.3). If this results in favouring more cost-efficient tropical crops (e.g., oil palm), this could then exacerbate agricultural expansion across the tropics (Carrasco et al., 2014). There could be an increase in land abandonment and reforestation within low-profit areas i.e., a decrease in land use from q_0 to q_B (Figure 2.3), but this is coupled with increased expansion and deforestation (q_0 to q_A, Figure 2.3) within areas of higher market value. The benefits of increased forest regeneration in marginal areas for agriculture across the Neotropics (e.g., highlands), for instance, would be outweighed by the negative impacts on biodiversity from increased deforestation in the lowland tropical forest (Aide et al., 2013).

2.4 Managing the effects of market outcomes

Assessing perverse outcomes in studies

Conservation interventions need to work towards incorporating steps to monitor and minimise perverse outcomes (Larrosa et al., 2016), but little has been done to overcome these outcomes. Some studies have, however, looked into incorporating and evaluating unintended feedbacks into their analyses of PAs and incorporated spatial information, theoretical models and biodiversity maps to project spatially-explicit predictions of areas more vulnerable to leakage (Bode et al., 2015; Renwick et al., 2015). Others have identified and measured leakage of conservation policies such as REDD+, using econometric or general equilibrium models (e.g., Murray et al., 2004; Gan and McCarl, 2007). These models centre on identifying the market feedbacks incurred from the conservation action, and understanding how they translate into indirect impacts on resources i.e., through the unregulated market.

A number of factors also need to be considered when assessing, predicting and managing these perverse outcomes. Since costs associated with land-use change vary across space due to multiple factors (social, political and environmental), we would also expect the magnitude of market outcomes and impacts on biodiversity to vary between regions (Armsworth et al., 2006; Chaplin-Kramer et al., 2015) and across different spatial scales. While some studies acknowledge this, few have incorporated spatial information in their models (e.g., Bode et al., 2015). Not accounting for spatial variation results in often-erroneous assumptions of homogeneity across landscapes. Additionally, while policies, legislations and targets are often established at the national level, practices are often carried out at the local level. This decentralisation of land-use regulations and policies from national to local scales, alongside influence from the international markets, could result in gaps in policies that allow unintended consequences to arise from our conservation efforts.

As with spatial scales, actions tend to be implemented across short timescales, but the effects of land conversion and land use are long-term: time lags in responses and impacts on habitat and biodiversity (e.g., extinction debts and forest regeneration) might not be captured in static analyses (Ghazoul, Burivalova, Garcia-Ulloa, and King, 2015). Displacement costs of policies and actions could at times be intergenerational (Roca, 2003), and while the immediate effects of some measures might seem positive, by not making assessments over longer temporal scales we do not consider other socio-economic factors and market feedbacks that might be detrimental (Hill, Miller, Newell, Dunlop, and Gordon, 2015). The benefits of PES schemes and other long-term measures are also often based on the assumption that other conditions in the market are constant, but land-use regimes could be implemented alongside other regulations and socio-economic changes and shocks (Müller et al., 2014), which will impact on the effectiveness of the regime. More emphasis needs to be placed on dynamic effects in planning long-term measures.

Another aspect of market-based outcomes often not addressed in studies is the interaction between distant parts of the world (teleconnectedness; Carrasco et al., 2014). Given the importance of global markets and transnational trade, overlooking the effects of teleconnectedness could lead to a considerable underestimation of the indirect impacts on land-use change (Renwick et al., 2015): since legislations, policies and other conservation measures are usually localised, studies tend to focus only on local and national effects. The consequences of these conservation policies and actions are, however, usually spread across much larger spatial scales and between countries and continents (Liu et al., 2013). Reducing land-use in one area, without a reduction in resource demand, could lead to agricultural expansion and land conversion in another, and countries with large gains in forest cover might observe increases in imports of wood and agricultural products (Gan and McCarl, 2007; Meyfroidt, Lambin, Erb, and Hertel, 2013). For instance, regulations to increase forest regeneration within Vietnam (Meyfroidt and Lambin, 2009) and China (Vina, McConnell, Yang, Xu, and Liu, 2016) led to an increased import of timber products. Projections of land-use changes should also account for the possible influence of alternative and complementary markets. Oil palm, for instance, can be a cheaper substitute to other oil-producing crops, including soy and rapeseed, and changes in prices and quantities of one crop could affect demands of each substitute crop (Figure 2.3), and ultimately increase land-use across the tropics (Carrasco et al., 2014).

2.4.1 Reducing the risk of perverse incentives within formal markets

Our framework also helps highlight how policies might be designed to help mitigate these unwanted effects. Conservation policies should recognise where conditions and incentives exist for officials to be corrupt regarding the selection of suppliers and make this a focal point for anti-corruption investigation. Policies also need to implement mechanisms to increase transparency and address information asymmetries by employing competitive tendering mechanisms allowing the efficient firms to reveal themselves (Smith and Walpole, 2005). Third-party auditing, for instance, may be a potentially effective means of increasing transparency and minimising probability of leakage and of perverse behaviour within the formal market (Cook, van Bommel, and Turnhout, 2016). Measures like these would limit the potential for corruption to dictate the exploitation of land and resources.

2.4.2 Reducing the risk of informal markets emerging

Our framework also points at the emergence of an informal market as an important source of perverse outcomes from conservation efforts (Figure 2.1B). Conservation policies therefore need to be more inclusive of the entire market to identify and manage leakage effects; the quota-policy framework only pays attention to the formal market. Conservation policies that, for instance, incorporate and account for trade and import of agricultural and forestry products represent a step towards being more inclusive and could potentially minimise the likelihood and scale of leakage. Effective spatial planning and targeting specific areas to intensify agriculture, while ensuring designated areas are kept protected for conservation is another way to minimise leakage effects (Phalan et al., 2016).
Managing conservation efforts should also focus on minimising the risks of informal markets emerging. This involves a thorough understanding and projection of price and market condition changes in response to the initial conservation measure, as well as a working knowledge of the various actors in the formal and informal markets. Monitoring changes in prices of resources and understanding how they relate to emerging illegal markets is one way to better pre-empt and manage unintended feedbacks. Efforts towards better detection and punishment of illegal market operations will increase the costs of these trades and this will reduce the viability of suppliers in this market reducing the extent of the leakage (a downward shift in the supply curve in the unregulated sector in Figure 2.1B).

It is also important that we identify and monitor the key actors most likely to supply the informal market, and potential leakage sinks. This should allow for the more efficient detection of unintended and deleterious changes in land use. Measures to detect leakage should also focus on flows of unregulated or illegal products: trade flows may be used as a means of identifying transnational leakage and displacement of deforestation practices in response to conservation efforts (Meyfroidt and Lambin, 2011). Achieving this can be challenging: illegal timber for instance is often laundered through legal plantations and mills (Nellemann, 2012). Using satellite imagery could be another way of monitoring areas more likely to be cleared, and minimising displacement and leakage effects. Empirical studies suggest, for instance, that buffer zones and forested areas surrounding PAs are more prone to being cleared (Pfeifer et al., 2012), and focusing monitoring efforts in such areas could lower the chances of forest loss. Spatially explicit econometric analyses might also be effective in identifying key areas likely to undergo land conversion. Importantly, monitoring and management should not be restricted within national boundaries, but should also include transnational leakage.

2.5 Conclusion

Most conservation measures tend to focus only on the primary and direct outcomes on nature and biodiversity, while indirect consequences are overlooked. This could lead to an overestimation of the true effects of the intervention, and the promotion of conservation actions that yield minimal to no overall conservation benefit: rather than reducing biodiversity loss, they could instead be counterproductive. Applying economic principles, we highlight the possible perverse consequences that are often not accounted for. This allows us to acknowledge these counterproductive impacts and, ideally, to seek ways to mitigate these effects through further regulations or extending the spatial extent of action, working towards optimal management strategies. Appreciating, if not understanding, the vulnerability and sensitivity of biodiversity conservation efforts to market feedbacks is a first step towards designing and managing conservation interventions more effectively.

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Chapter 3

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 to 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.

Keywords

Agricultural rent, conservation planning, cropland expansion, deforestation, *Elaeis guineensis*, Forest Moratorium

3.1 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 (Meijaard et al., 2018). 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 (FAO, 2019), with expansion linked to extensive deforestation, biodiversity loss, and environmental degradation, especially in Southeast Asia (Dislich et al., 2017; Fitzherbert et al., 2008; Wilcove, Giam, Edwards, Fisher, and Koh, 2013). As global palm oil demand grows (Corley, 2009), 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 (Austin, Kasibhatla, Urban, Stolle, and Vincent, 2015; Austin et al., 2017; Carlson et al., 2012; Sumarga and Hein, 2016). We also have an extensive understanding of spatial variation in oil palm suitability (Gunarso, Hartoyo, Agus, and Killeen, 2013; Meijaard et al., 2018; Vijay, Pimm, Jenkins, and Smith, 2016), and potential palm oil yields pan-tropically (Pirker, Mosnier, Kraxner, Havlík, and Obersteiner, 2016). A number of studies examining oil palm expansion within the Neotropics have also accounted for the influence of socio-economic factors or trade impacts on oil palm expansion across time and space (Castiblanco, Etter, and Aide, 2013; Furumo and Aide, 2017), 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 (Angelsen, 2010) — in explaining and predicting oil palm expansion. Land-use change for expansion of commercial crops is fundamentally economic (Armsworth et al., 2006) 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

(FAO, 2019), 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 (Margono et al., 2014). 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 (Busch et al., 2015; Sloan, 2014). 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.

3.2 Methods

3.2.1 Overview

Using distribution maps of oil palm plantations across Indonesia for different time points spanning 2000 to 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.

3.2.2 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 (Miettinen, Shi, and Liew, 2016a; Miettinen, Shi, Tan, and Liew, 2012). 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, derived from information on oil palm suitability (Pirker et al., 2016) (Table A.1). We also obtained information on the areas across Indonesia set aside for conservation from Indonesia's Forest Moratorium (WRI, 2017), legally protected areas (Ministry of Forestry, 2010) and locations of oil palm concessions (WRI, 2012). 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 (Miettinen et al., 2016a). 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 (ILO, 2017). We also obtained yearly national prices of fuel (GIZ, 2014), fertilisers, oil palm fresh fruit bunches and timber (FAO, 2019). 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 A.1).

3.2.3 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 (Angelsen, 2010). 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

$$Rent_i = (y_i p + w) - (f + l + \frac{y_i}{c} v d_i) \tag{3.1}$$

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 (FAO, 2009). 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 (Corley & Tinker, 2015). $\frac{y_i}{c} v d_i$ 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 (A.1).

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 (3.1) is embedded within the formula for NPV given in equation (3.2), 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.

$$NPV_i = \sum_{0}^{T} \frac{Rent_{i,t}}{(1+r)^t} \tag{3.2}$$

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% as in other studies (Irawan, Tacconi, & Ring, 2013; Sumarga, Hein, Edens, & Suwarno, 2015), and NPV was derived from the summed discounted rents across all 25 years (3.2). 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.

$$EACadj_i = EAC_i - P_i - S \times A_{i,t-1} - K \tag{3.3}$$

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 (Austin et al., 2015; Garrett, Lambin, & Naylor, 2013; Sumarga & Hein, 2016). 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 degrees) 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 whose agricultural rent exceeded the minimum threshold K (i.e., $EACadj_i > 0$) 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 (A.1).

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 (A.1), 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 (A.1). We also compared our analyses with oil palm expansion models that only account for suitability and yield (A.1).

Due to computational limitations, models were fitted on a subset of cells stratified-randomly sampled across the total dataset (~24,000 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.

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

Using projected palm oil prices from 2016 to 2025 (FAO, 2019; OECD/FAO, 2018), 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 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.

3.3 Results

3.3.1 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 (A.2) Of the models run, Model 4 performed best (average recall = 75.8%; A.2) 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 3.1). The model also correctly identified 79.23% of peat swamps converted into oil palm plantations by 2015, particularly in Riau, North and West Sumatra (Table A.4). 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 3.1).

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 3.1). 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 A.1). Provinces such as West Papua, Bengkulu, Jambi, and Southeast Sulawesi, for instance, showed high false positive rates (>65%, Table A.4).

3.3.2 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 3.2), and six times by 2025 (Table A.5). Areas economically viable for further crop expansion were mainly located near existing oil palm plantations. 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 A.5). Provinces

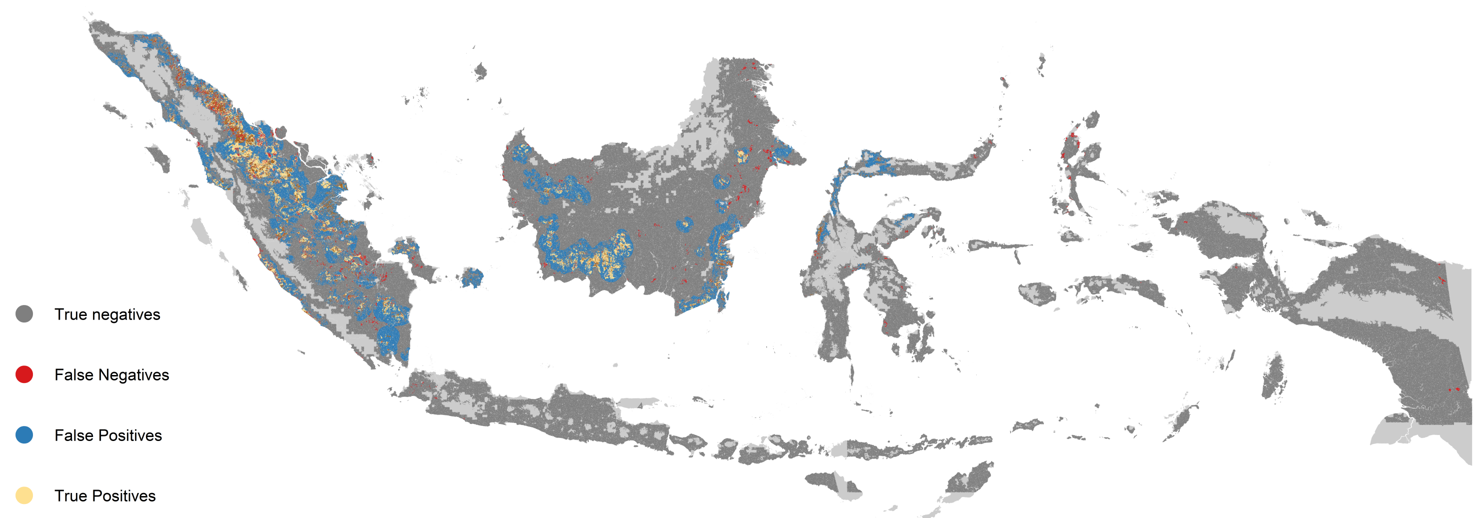

Figure 3.1: Performance of oil palm expansion model across Indonesia between 2000 and 2015, validated against a stratified random sample (10%) of cells (250 by 250 m) spanning all provinces (n= 2,242,417). Across known oil palm plantations, the crop expansion model was 78.97% successful in identifying cells as economically viable/profitable to convert into plantation (yellow), while 21.03% 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, the model predicted 14.07% were profitable for oil palm expansion during that time (blue): these cells were either converted to other plantations or remained as forests and peatlands (blue). The remaining cells (grey) were correctly identified as not having rents high enough to establish plantations.

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 A.6). Conversely, within Kalimantan, large proportions of natural areas susceptible to expansion by 2025 were not protected by the Forest Moratorium ($\geq$0.89, Table A.6).

3.4 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., (Carlson et al., 2012; Gunarso et al., 2013), or incorporated the influence of socio-economic factors (Castiblanco et al., 2013) and trade (Furumo & Aide, 2017). Expansion is, however, fundamentally economic (Armsworth et al., 2006), 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 (Angelsen, 2010) through incorporating spatial variation in potential oil palm yield (Pirker et al., 2016) 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 (Angelsen, 2010; Meyfroidt et al., 2014). 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 (Angelsen, 2010), 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 (Miettinen et al., 2016a). Other studies also emphasised the strong influence of proximity to existing plantations, typically including distance to

Figure 3.2: 2020 Model projections of areas susceptible to further oil palm expansion (shown in brown) as prices of oil palm fruits increase, based on agricultural rents and spatial distribution of oil palm plantations in 2015 (blue). 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.

the nearest existing plantation as a predictor for crop expansion (Austin et al., 2015; Sumarga & Hein, 2016). The spatial contagion effect builds on the von Thünen land rent approach (Angelsen, 2010), 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 (Garrett et al., 2013). 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 (Budidarsono, Rahmanulloh, & Sofiyuddin, 2012; Lee et al., 2014), 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 (Lee et al., 2014; Margono et al., 2014), 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 (Carlson et al., 2012; Dislich et al., 2017) 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, Edwards, and Laurance (2012) 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 (2016) 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 (Miettinen et al., 2016a; Miettinen et al., 2012) and reliable predictions of potential palm yield (Pirker et al., 2016), 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 (Fitzherbert et al., 2008; McCarthy & Cramb, 2009). Crop expansion attributed to regional-level effects, e.g., government decisions, were not considered in this study (Euler et al., 2016). 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 suggest 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. As our model did not consider expansion into areas of other land uses. it was not effective in identifying a proportion of converted plantations across regions with large extents of oil palm (e.g., East Kalimantan and South Sumatra). 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 (Meyfroidt et al., 2014). 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 (Strona et al., 2018) and the Neotropics (Castiblanco et al., 2013; Furumo & Aide, 2017; Vijay et al., 2016), 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 (Lim, Carrasco, McHardy, & Edwards, 2017).

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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Chapter 4

Building a partial equilibrium model for oil palm in Indonesia: insights from equilibria analysis

Abstract

Oil palm is a leading driver of tropical deforestation and biodiversity loss. However, the supply and demand curves of palm oil have not been characterised. This hinders analyses and assessments of the social and environmental implications of policies aiming to regulate the oil palm industry. To set the foundations of these analyses, in this study we characterise the supply and demand of oil palm in Indonesia, the top producer of palm oil. Specifically, we develop a supply curve for oil palm and analyse the partial equilibrium dynamics of the initial period and of an exogenous market shock from increased crop yields. Using an oil palm expansion model, we generated supply curves describing the land-use dynamics of production. We then constructed price-quantity demand relationships, and, interacting these functions, we evaluated how market equilibria shift in response to exogenous market shocks (e.g., increasing potential palm oil yields).We found that the supply of oil palm is elastic: small price changes led to large changes in quantities supplied. Equilibria analysis showed that small changes in productivity (i.e., a 15% in crop yields) could lead to dramatic potential conversion: considering a demand elasticity of -1.01, even with a drop in prices from USD 112.70 to USD 99.42, quantities increased from 168.07 to 195.87 million tonnes, and the extent of oil palm expansion increased by ~4%. Characterising supply and demand proves useful for understanding the both market and land-use dynamics, and allows us to make better-informed assessments of the efficacy of agricultural intensification, zonation and certification policies in minimising their environmental impacts.

Keywords

agricultural expansion, equilibria analysis, market feedbacks, oil palm, partial-equilibrium model, price elasticities

4.1 Introduction

Land-use change for agricultural expansion is spearheading the continual and accelerating loss of forests and natural areas worldwide (Chaudhary and Kastner, 2016; Gibbs et al., 2010). Deforestation, therefore, is linked to trade of agricultural commodities, and while potential market feedback effects of conservation interventions have been highlighted in the literature (Armsworth et al., 2006; Larrosa et al., 2016; Lim et al., 2017), studies linking shifts in supply and demand of crops, agricultural and forest commodities (e.g., timber) with spatial patterns of land-use change are scarce. The supply relationship between price and quantity of an agricultural commodity is directly dependent on land use, and policies and practices that alter land-use patterns inevitably affect total production. Additionally, crop prices are determined by the interaction between demand and supply, and will affect the potential profitability and therefore the extent of land-use change and agricultural expansion (Angelsen, 2010; Armsworth et al., 2006). If we wish for better economic analyses and understanding of the impacts of agricultural policy interventions on commodity prices, and ultimately, land use, we cannot overlook the interaction between demand and supply.

Few studies have attempted to characterise supply and demand. Studies have largely centred on general equilibrium models for major global crops. T One of the most commonly used general equilibrium model in these studies is the Global Trade Analysis Project (GTAP), which considers the whole economy (Hertel, 2012; Taheripour, Zhao, and Tyner, 2017). While general equilibrium models are effective in broad-scale analyses (Taheripour et al., 2017), characterising individual markets, however, becomes challenging due to data limitations. Developing a general-equilibrium model that incorporates a decision framework such as profit maximisation to estimate supply curves, however, can be extremely resource-intensive. There is, therefore, a reliance on partial-equilibrium economic models, as they present a simpler, more straightforward approach. Partial equilibrium models have been built for a number of commercial crops and commodities like timber and oil palm (e.g., Bouët, Estrades, and Laborde, 2014; Jafari and Othman, 2016; Latta, Sjølie, and Solberg, 2013; Tyner and Taheripour, 2008). While they do not consider trade (i.e., the interaction between demand and supply) at a global scale, these models include more intricate, direct relationships between supply and demand of resources, thereby facilitating simpler simulations of market shocks that are more direct and realistic (e.g., Walsh, 2000). However, there lacks the emphasis across studies to link these partial equilibrium economic models with land-use changes. Specifically, the supply relationship is primarily driven by land-use changes. Crop expansion, considering a land rent approach similar to von Thünen hypothesis:areas more accessible and profitable are more susceptible to conversion and therefore supplying the market (Angelsen, 2010). Conservation and agricultural policies alter land use will, therefore, affect supply, and ultimately markets. Despite this innate relationship, this is seldom a focus across studies. Given the important, fundamental relationship between land-use change and economic forces and market dynamics, both spatially and temporally, there is a need to make these links more explicit.

One key crop for which knowledge of its market behaviour would be especially useful for conservation is oil palm. Oil palm expansion continues to drive tropical deforestation as global palm oil demands continue to rise (Corley, 2009). As the world's top palm oil producer and exporter (FAO, 2019), Indonesia's oil palm expansion has been growing rapidly, at the expense of forests and biodiversity (Margono et al., 2014). Intensification and yield improvements have been proposed as an effective means to meet palm oil demands with reduced environmental impacts; much research has thus far focused on the direct co-benefits of agricultural intensification on carbon stocks and biodiversity within retained forests (e.g., Edwards et al., 2010; Gutiérrez-Vélez et al., 2011), as well as exploring the potential of closing palm oil yield gaps among smallholders (e.g., Afriyanti, Kroeze, and Saad, 2016; Euler et al., 2016; Soliman et al., 2016. Efforts to link land-use changes with markets and market behaviour, however, are lacking. Few studies have placed emphasis on the role of markets in understanding the impacts of oil palm agriculture. These studies have adopted market responses via general equilibrium models (e.g., Taheripour et al., 2019; Villoria, Golub, Byerlee, and Stevenson, 2013), as well as partial equilibrium models (e.g., Bouët et al., 2014; Jafari and Othman, 2016; Jafari, Othman, Witzke, and Jusoh, 2017). To our knowledge, however, no study has attempted to link market dynamics with land-use change and crop expansion, thus ignoring this potentially important relationship. Studies using general-equilibrium models (e.g., Taheripour et al., 2019) have also highlighted the importance of accounting for market feedbacks to changing land-use practices, but without considering the spatial extent of these feedbacks.

Concurrently, very few studies developing land-use models of oil palm expansion place focus on the role of market forces. Oil palm expansion models have alluded to the importance of economic forces (e.g.,Castiblanco et al., 2013; Furumo and Aide, 2017), but without explicitly accounting for them, while studies that incorporate these factors (e.g., Lim, Carrasco, McHardy, and Edwards, 2019) do not consider how market dynamics could cause shifts in land-use projections. As a highly commercial agricultural commodity with huge impacts on the environment, oil palm agriculture therefore presents a good case to characterise markets via a spatially explicit model, to ultimately understand how market feedbacks could impact on land-use changes.

In this study, we develop a partial-equilibrium model for oil palm in Indonesia based on a spatially explicit land-rent based crop expansion model. Specifically, this model seeks to (i) link supply relationships with land-use change; and (ii) explain how market equilibria shift in response to changes in market shocks brought about by changes in agricultural practices. By integrating economic concepts with land-use models, this study addresses the interactions between prices, markets, and ultimately land use, to provide better assessments of the impacts of changes in land use and agricultural practices on the scale and spatial distribution of forest loss.

4.2 Methods

4.2.1 Overview

We used 2016 as a base for our study, focusing on a single, exogenous market shock and the associated expansion of oil palm. Using a crop expansion model based on agricultural rent (Lim et al., 2019, Chapter 3), we ran simulations evaluating the extent of crop expansion at different commodity prices, thus constructing a supply relationship of palm oil production from newly converted plantations across Indonesia. We also built a separate supply relationship, simulating yield enhancements across Indonesia. From these simulations we fitted equations to obtain supply curves, and examined how supply of oil palm fruits varies with prices. We then constructed demand relationships, and from the interactions between the demand and supply curves, we evaluated how market equilibria shift following a change in yields, and how land-use change varies under different agricultural policies.

4.2.2 Using a land rent model to build a supply curve

We used a model that adopts a land-rent approach to explain oil palm expansion across Indonesia (Lim et al., 2019, Chapter 3). This model evaluates the extent of area that can be converted to oil palm, based on the potential amount earned from harvest of fruits relative to the costs to establish a plantation: at a given price, areas with high agricultural rents and profitability are deemed able to supply the market. This model also includes a spatially dependent contagion effect, which reduces production and establishment costs for new plantations setting up near existing plantations (Lim et al., 2019, Chapter 3). The model included known distributions of oil palm plantations in 2015 (Miettinen et al., 2016a). We used the estimated potential palm oil yields (Pirker et al., 2016) and costs of production, labour and transport in 2015 (FAO, 2019; GIZ, 2014; ILO, 2017) to evaluate the amount of additional palm oil available to the market in 2016 at varying prices of oil palm fruits. We calculated the agricultural rent of cells based on the oil palm expansion model over a range of market prices (USD 0–150 per tonne), and identified the cells with agricultural rents exceeding the minimum amount value needed for conversion (i.e., to be able to supply the market).

4.2.3 Variations in supply relationships under different agricultural policies

The use of a deterministic, spatially explicit model that accounts for the influence of economic forces on land-use change thus forms the basis of our supply relationship. Using this approach, we ran simulations to examine the extent of market feedbacks to exogenous shocks from agricultural intensification and improvements in crop yields via two key scenarios. We therefore have a model with two periods: the initial period before and after the market shock from yield enhancement.

First, we ran a set of simulations, assuming that all plantations were operating at current maximum potential yields. As a conservative baseline, we used current estimated potential palm oil yields (henceforth current yields) (Pirker et al., 2016); All existing plantations and newly converted plantations are assumed to operate at maximum productivity. Additionally, we assumed no additional land-use restrictions across Indonesia from oil palm expansion, other than existing protected areas (Ministry of Forestry, 2010) and private land (other plantations). This means that oil palm expansion in our model is permitted on all areas classified as public land or oil palm concession, given agricultural rents are sufficiently high. Our construction of the supply curve was constrained to newly converted plantations (in 2016), and additional to existing (2015) palm oil production. We also restricted crop expansion to areas with positive potential palm oil yields, and cells available for conversion to oil palm plantation from 2015 (i.e., only cells classified oil palm concessions or public land). Given computational limitations, we ran our analyses on a stratified-random sample of the data (i.e., random sample of 10% within each province), and scaled up the extent of areas and quantity produced accordingly.

We then repeated the process, assuming a nation-wide increase in estimated potential yields of 15% (henceforth referred to as increased yields). All other factors were kept constant, and the only changes in production costs were from direct changes to yields. For instance, we kept the amount of labour and fertiliser needed constant, but allowed transport costs to vary due to the increased agricultural output.

We then fitted supply curves to simulated data from each scenario, using the following equation:

$$Q = Q_{2015} + \beta \times P^{\alpha} \tag{4.1}$$

where the quantity of fruits Q supplied was a function of a given price P, adopting power-law relationship (α,) and a coefficient β, in addition to the amount of fruits produced within existing plantations in 2015 (Q_{2015}). Q is therefore directly dependent on crop prices. For each scenario, we fitted values of prices and quantities generated by our model simulations to Equation 4.1 and solved for coefficients β and α. Where we simulated increased yields, we adjusted Q_{2015} accordingly, to reflect yield increases within existing plantations.

4.2.4 Fitting demand relationships

We fitted demand relationships between prices and quantity of oil palm fruits for 2016. We first set as our first reference point of equilibrium the price of oil palm fruits in 2016 (FAO, 2019), and the amount of oil palm fruits supplied at that price, given the oil palm extent from the crop-expansion model (Chapter 3, Lim et al., 2019). From this reference price-quantity point, we then constructed a curve using Equation (4.2).

$$P = A \times Q^{ED} \tag{4.2}$$

where price per tonne of oil palm fruits (P), given the quantity available (Q), is affected by coefficient A and the price elasticity of demand (ED). We assumed constant elasticity of demand across prices ($ED = -1.01$, following Villoria et al., 2013). This curve therefore passes through the reference price-quantity point, and represents our baseline demand relationship. At the price-quantity point where the demand curve intersects with our baseline supply curve, market is considered to be at equilibrium.

We also fitted two more curves using Equation 4.2 that assume shifts in the demand relationship. We constructed a second curve where overall demand decreases by 10%, and a third where demand increases by 10% (where percentage changes are relative to quantity at the initial equilibrium). Each shift in demand curve represents a proportional change in the amount of oil palm fruits demanded at the same price. Like the baseline demand curve, both demand curves assumed the same elasticity of demand ($ED = -1.01$).

4.2.5 Shifts in market equilibria

Our analysis begins by identifying the market equilibrium price in each scenario, found at the intersection of the relevant supply and demand curves for that scenario. The baseline supply scenario is represented by a supply curve with current yields (current potential yields, and without additional land-use restriction. The baseline demand is one according to Equation (4.2) with $ED = -1.01$ passing through the supply curve at the 2016 price-quantity outcome outlined earlier. The new equilibrium for each scenario is identified at the intersection of the supply and demand curves. Using the new equilibrium price, we then ran the oil palm spread model, and evaluated the extent of newly converted oil palm expansion.

4.3 Results

4.3.1 Market equilibria at current crop yields

Assuming current estimated yields, increasing prices of oil palm fruits increased the extent of area with positive agricultural rents additional to existing plantations, and the total quantity of oil palm fruits available to the market increases ($\beta = 5.70 \times 10^{-05}$, $\alpha = 2.95$ from our fitted supply curve results, Figure 4.1). At our baseline equilibrium price of USD 112.70 (FAO, 2019), i.e., considering our baseline demand relationship, 4.74 Mha of area was profitable and therefore available for conversion into new plantation (Figure 4.2). A total of 168.07 million tonnes of oil palm fruits were available to the market, from both existing and newly converted plantations.

4.3.2 Shifts in market equilibria from improving crop yields

A 15% increase in palm oil yields nationwide resulted in a rightward shift in the supply curve (Figure 4.1). In addition to the 15% increase in productivity in-situ (i.e., within existing plantations), agricultural rent across the remaining vegetated area also increased, and we therefore observed a further rightward shift in the supply curve

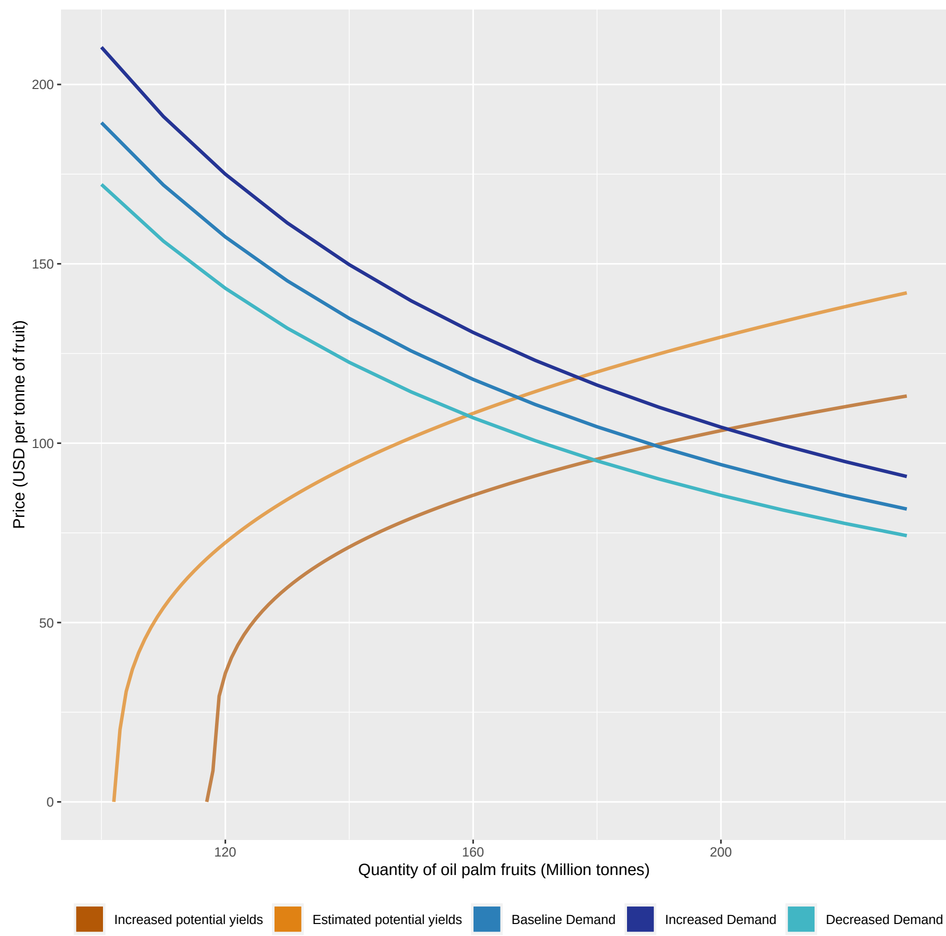

Figure 4.1: Supply and demand relationships across scenarios, illustrating shifts in market equilibria. Two supply curves were constructed: assuming (i) current estimated potential and (ii) improved potential crop yields. For each supply relationship, we calculated the amount of fruits produced at increasing prices (USD0–150) using a land-rent crop expansion model across newly established plantations at each price step. Palm oil production across existing plantations were assumed constant across prices, changing only with yield enhancements. Results of the simulated data were then fitted to equation 4.1. All simulations were conducted on an stratified random sample (10%) and values of quantity of fruits produced were scaled up accordingly. Three demand curves were built using equation 4.2, assuming a constant elasticity of demand of −1.01 (following Villoria, Golub, Byerlee, and Stevenson, 2013).

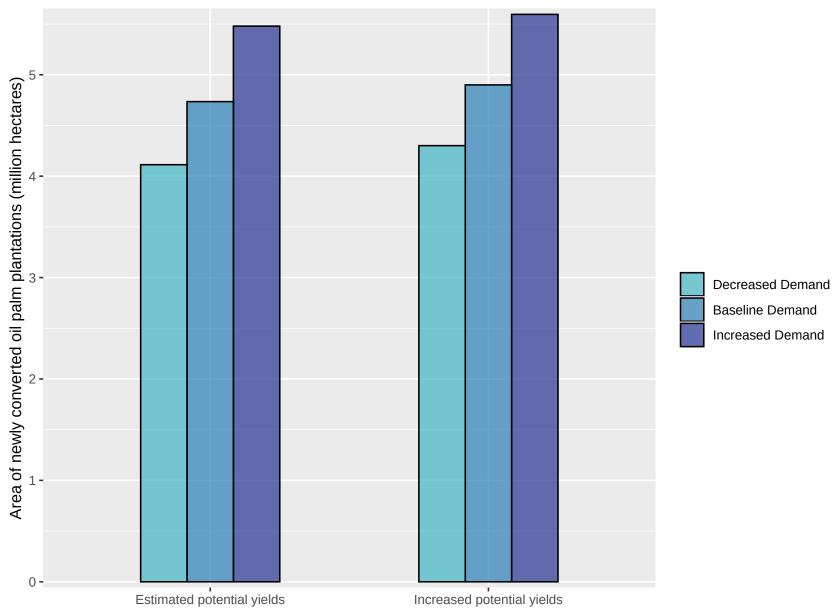

Figure 4.2: Extent of newly converted oil palm, based on the new equilibrium prices. Two supply curves and three demand curves were constructed, resulting in a total of six sets of equilibrium prices. From each market equilibrium price, we evaluated the area of extent converted to oil palm using the crop expansion model. Simulations were conducted on an stratified random sample (10%) and extents of area converted were scaled up accordingly.

(Figure 4.1). Per unit price, a greater amount of palm oil was supplied ($\beta = 7.38 \times 10^{-06}$, $\alpha = 3.50$). This rightward shift in supply curve from increasing crop yields resulted in a shift in market equilibrium, assuming constant elasticity of demand. Equilibrium price decreased from USD 112.70 to USD 99.42, while the quantity of oil palm fruits supplying the market at this price increased by 16.54% to 195.87 million tonnes. At this equilibrium price, the extent of newly converted oil palm was 4.90 Mha, a 3.48% increase in area compared to our baseline scenario (i.e., with current estimated crop yields).

4.3.3 Shifts in market equilibria from changes in demand

Assuming baseline supply (i.e., current potential oil palm yields), a 10% increase in demand resulted in an equilibrium shift favouring lower prices (USD 107.71, Figure 4.1). At this new equilibrium price, 5.48 Mha of new plantations would be established, and a total of 159.57 million tonnes of fruits would supply the market from both new and existing plantations. Simulating an increase in demand, conversely, led to a slight increase in equilibrium price (USD 118.23), at which 4.11 Mha would be profitable to convert, with a total of 178.25 million tonnes of fruits supplying the market.

Compared to the baseline demand relationship, a proportional decrease in demand while simulating improvements in crop yields nationwide (by 15%) resulted in a slight decrease in equilibrium price, from USD 99.42 to USD 95.33. At this price, 4.30 Mha of new plantations are economically viable to establish, with a total of 186.47 million tonnes of fruits supplying the market. An increase in the demand relationship, conversely, results in a shift in equilibrium favouring higher prices (USD 103.89). At this new equilibrium, 5.60 Mha new plantations would be established, with a total of 206.81 million tonnes of fruits would supply the market.

4.4 Discussion

Little focus has been placed on how market forces affect the efficacy of our conservation efforts (reviewed in Lim et al., 2017, Chapter 2). This study emphasises this innate relationship by linking spatially explicit patterns of crop expansion with supply of a commercial commodity through a land-rent model (Lim et al., 2019, Chapter 3). Additionally, using partial-equilibrium models, we show how variations in land use and agricultural practices cause shifts in markets, and impact on demand and supply, thereby challenging our projections of land-use change. Based on our model simulations, palm oil supply across Indonesia is highly elastic and sensitive to prices: yield enhancements to meet growing demands cause a shift in supply curves, and, depending on demand, could still result in increased extent of oil palm nationally.

4.4.1 Linking supply relationships with land-use change

The spatial aspect of the supply relationship in terms of land-use change and crop expansion, although seldom emphasised, is instrumental in linking land-use change with market responses and feedbacks. Fundamentally, conversion of forests and natural areas into cropland is largely influenced by the potential to profit from harvest (Angelsen, 2010; Lim et al., 2019). Aggregate supply is limited at low commodity prices, when production is constrained to areas with lowest costs. Increased commodity prices relative to costs means production is viable across a wider area (i.e., expansion into areas with lower suitability, accessibility and yields): more players can supply the market, therefore aggregate supply increases. Directly relating crop expansion and palm oil supply to changes in prices and agricultural rent, as we have done, reiterates this concept, while allowing us to identify where crop expansion is expected at a given price. To our knowledge, studies estimating production and supply based on land rent models are scarce. Other partial equilibrium models built in other studies exploring oil palm agriculture in Indonesia and Malaysia (e.g., Jafari and Othman, 2016; Jafari et al., 2017) focus on other aspects such as shifts in export demands and supply, but do not explicitly draw links to land-use, thereby overlooking this relationship.

4.4.2 Shifts in demand alter our projections of land-use changes

Our study also emphasises the importance of accounting for potential shifts in demand: changes in prices in response to shifts in demand alter our projections of land-use changes (Figure 4.2). Variations in demand elasticities would result in changes in sensitivity of market equilibria to shocks. While we have considered a constant elasticity as a conservative measure, other studies on the Indonesian palm oil market also assumed a constant, lower elasticity (-0.38, Jafari et al., 2017). It is important that studies account for the sensitivity of the market to demand shifts. With future palm oil demands projected to increase (Corley, 2009), shifts in the demand relationship in response to increasing global population and affluence could further shift market equilibria towards higher prices and traded quantities, and therefore result in a greater extent of forest loss with time.

4.4.3 Increasing yields result in increased expansion

By considering how improved crop yields cause shifts in the supply relationship, thereby effecting market feedbacks, our work challenges the notion that agricultural intensification immediately leads to reduced extent of cropland (as argued in Stevenson, Villoria, Byerlee, Kelley, and Maredia, 2013). A slight increase in potential yields nationwide (by 15%) resulted in a notable shift in the supply curve: per unit increase in price, a larger area would be profitable and, therefore, vulnerable to conversion (Figure 4.1). At the same price, yield enhancements could, therefore, favour greater forest loss. Even with the shift in market equilibria favouring lower prices, we found that a greater extent of area was profitable for oil palm expansion due to the increased yields, and as a result, rents. Improving crop yields increases output within existing land and reduces the need for additional cropland. However, the Borlaug hypothesis — that demands can be met on less land via high-intensity farming practices, thus sparing land for nature — is typically based on the assumption that demand is fixed, i.e., inelastic (Hertel, 2012; Villoria et al., 2014). Should elasticities of demand increase, we could potentially witness greater shifts in market equilibria, where a small decrease in prices could increase the amount traded. More attention needs to be paid on the interaction between demand and supply in response to agricultural practices and improved crop yields, particularly with highly commercial and substitutable crops such as palm oil.

4.4.4 Limitations and further directions

It is important to understand the limitations of our study based on the simplifying assumptions made and modelling approach taken. This study has two core limitations. Firstly, the supply curves were primarily constructed across unconverted cells only, and additional to the existing supply and area of oil palm. As the supply curve was based on a crop-expansion model that incorporates the proportion of existing plantations (Chapter 3), distribution of plantations in 2015 was used as a base for the following year. The supply curve was, therefore, not established across cells that were already listed as plantations. This assumption meant that palm oil production on existing plantations remained constant regardless of changes in prices, varying only with yield enhancement, and the the quantity of oil palm fruits when price was USD 0 represents palm oil production across existing plantations. Given equilibrium prices are path-dependent, we also restricted our analyses to market responses over a single period, focusing on impacts of land-use change based on supply and demand scenario changes purely from a 2016 base. Additionally, to examine market shifts, we had to remove all other time-dependent factors, such as the accumulative contagion effect across years and assumptions of time lag between establishing plantations and first harvest of fruits after maturity. Therefore, we were unable to assess the impacts of market feedbacks to agricultural policies on deforestation and biodiversity loss across time. The supply curves do not match prices and quantity produced in 2016, and end-supply levels are an underestimation of actual amounts traded. Nevertheless, this study offers a straightforward analysis that highlights the risks of yield enhancements on the supply relationship.

Secondly, our analyses of equilibrium shifts are constrained by our knowledge of how demand relationships might respond. Demand curves were fitted assuming a constant elasticity of demand (of -1.01) based on a single study, which was in turn determined from a general equilibrium model using information obtained from on a single year (2004, Villoria et al., 2013). Nevertheless, the impact of functional form is likely to be of little importance for relatively small changes in prices. Accounting for how palm oil demands and prices might interact with other substitute markets (i.e., other vegetable oils) could further affect our 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, Chapter 2). Recent studies using general equilibrium models (Taheripour et al., 2017) have suggested that restricting consumption (or demand) of palm oil from Malaysia and Indonesia (who collectively produce $> 80\%$ of the world's palm oil) could potentially restrict expansion locally, but does not reduce the extent of oilseed plantation expansion globally (Taheripour et al., 2019). Considering shifts in overall demands in response to substitute markets would provide us with a fuller picture of market feedbacks, including leakage and displacement of trade internationally and across substitute markets (Carrasco et al., 2014; Santeramo and Searle, 2019; Taheripour et al., 2019).

4.4.5 Conclusion

By integrating spatially explicit land-use models, based on a land rent approach, with a partial-equilibrium model for oil palm market in Indonesia, this study addresses the market dynamics surrounding land-use change. The supply relationship of palm oil is sensitive to changes in prices, and small variations in palm oil prices could affect extents of oil palm expansion. The supply relationship is also influenced by variation in yields and productivity. Therefore, yield enhancement and agricultural intensification do not immediately lead to sparing of land, as increased agricultural rents across remaining forests could instead lead to greater expansion despite the expected drop in equilibrium prices. Changes in demand, and therefore markets, also mean we might expect further land expansion, even with improved yields. By explicitly modelling market feedbacks, and translating shifts in equilibrium prices back to land-use change, this study reiterates the innate relationship between market forces and land-use change, and highlights the importance of considering market feedbacks when assessing the effectiveness of changes in policy in relation to agricultural practices.

Chapter 5

Oil palm intensification generates indirect land-use impacts that drive biodiversity loss in Indonesia

Abstract

Commercial agriculture is the main driver of global forest and biodiversity loss, and conservation research and policies place increasing focus on implementing sustainable agricultural practices to reduce deforestation rates whilst meeting rising global food demands. A key question is how such conservation policies interact with market forces over space and time to impact rates of land-use change, and carbon and biodiversity loss. In this study, we assessed the risk that conservation efforts are being undermined by economic feedbacks that enhance profitability driving indirect land-use change, focusing on oil palm expansion across Indonesia. Using a crop-expansion model based on a land-rent framework, we ran simulations of Indonesian oil palm expansion from 2016–2020 across scenarios depicting different agricultural and land-use policies — varying crop prices, yields and land-use restrictions (i.e. Indonesia's Forest Moratorium, High Carbon Stock [HCS] initiative) — and compared how changes in land-use impact carbon stocks and biodiversity. Increasing crop prices and yields both led to greater extents of oil palm expansion. Although in-situ agricultural intensification increases palm oil production, the extent of deforestation and biodiversity loss also rises due to further expansion from increased profitability. Implementing additional protection of forests, via the Forest Moratorium and HCS initiative, were not effective in reducing deforestation and loss of carbon stocks, suggesting low additionality from these policies. Without stringent and strategic land-use regulations applied spatially, our findings raise concerns that sparing land for nature via high-intensity farming could instead result in unanticipated, indirect impacts on forest clearance.

Keywords

Agricultural intensification, crop expansion, *Elaeis guineensis*, land-use change, market feedbacks, oil palm

5.1 Introduction

The rising demand for food and agricultural commodities from increasing global population and affluence is driving conversion of natural forests into farmland (Gibbs et al., 2010), making agriculture the biggest extinction threat to biodiversity. Responding to this global threat of forest and biodiversity loss from agricultural demands, studies and policies seek to improve sustainable agriculture while reducing forest and biodiversity loss through conservation interventions. Conservation efforts thus far have primarily focused on two broad categories: improving the way we use existing farmland to meet growing demands (Tilman et al., 2011), and introducing policies that prevent expansion into remaining forests (Joppa, Loarie, and Pimm, 2008).

Increasingly, improvements to crop yields and agricultural intensification, i.e., land-sparing farming (Balmford, Green, & Scharlemann, 2005; Green et al., 2005), are promoted as an effective means of meeting global demands while relieving pressures of encroachment into remaining forests. Akin to the Borlaug hypothesis (Hertel, 2012; Villoria et al., 2014), land-sparing has gained traction over the last decade, with many data-based studies emphasising the benefits of adopting high-yielding agricultural practices for protecting forest biodiversity and carbon stocks relative to incorporating them within lower-yielding farmland i.e., land-sharing (e.g., Gilroy et al., 2014; Gutiérrez-Vélez et al., 2011; Phalan, Balmford, Green, and Scharlemann, 2011). Research has identified the potential for increasing agricultural output via closing yield gaps (Licker et al., 2010), and highlighted the role of high-yielding crop varieties and improved management practices to close yield gaps and increase land-use efficiency (Stevenson et al., 2013).

Enforcing land-use regulations is another common approach to conserve forests and biodiversity. While the effectiveness of Protected Areas (PAs) establishment over time is not easy to assess, it can be argued that deforestation and habitat loss are reduced within and around PAs globally (Geldmann et al., 2013), and policies that reduce or restrict land-use change have been relatively successful (e.g., Gaveau et al., 2009; Laurance et al., 2012). Land-use restrictions prioritise protection of areas for different reasons, be it safeguarding biodiversity and ecosystems via protection of High Conservation Value (HCV) areas, or, focusing on mitigating climate change through protecting areas of High Carbon Stocks (HCS) (Rosoman, Sheun, Opal, Anderson, and Trapshah, 2017).

In understanding the impacts of both of these broad policy solutions, research and policy efficacy tends to place emphasis only on direct benefits of reducing deforestation and biodiversity loss. However, the indirect land-use effects that arise from market responses to these conservation interventions, and the resulting impacts on biodiversity and the environment across space and time have received little attention (Larrosa et al., 2016; Lim et al., 2017, Chapter 2). The supply relationship of an agricultural commodity is directly dependent on land use, as land-use change for commercial agriculture is driven by profitability (Angelsen, 2010). Agricultural policies that alter land-use patterns and profitability could, therefore, change land-use patterns, undermining our conservation efforts and altering our projections of land use (Armsworth et al., 2006). Neglecting this complex feedback interaction between land use and markets could lead to gross underestimations of the extent of land-use change, impacts on biodiversity and, ultimately, the efficacy of agricultural intensification efforts.

Sparing land for nature, through improved crop varieties and practices, might seem an effective way to meet demands using less land, but little emphasis is placed on econometric analyses of economic feedbacks (Villoria et al., 2014). Studies comparing the land-sharing versus land-sparing frameworks and highlighting biodiversity outcomes without consideration of the impacts of adopting high-intensity agricultural practices on remaining forests over time, could underestimate the risks of further crop expansion and encroachment into forests. Similarly, the effectiveness of land-use restriction policies could be underestimated, if we do not consider the wider impacts on remaining forests. Establishing PAs and prioritising areas for increased protection could result in leakage of deforestation and forest degradation into surrounding unprotected areas (Ewers and Rodrigues, 2008; Pfeifer et al., 2012; Renwick et al., 2015). Effectiveness of land-use policies against deforestation and land-use change varies greatly (Gaveau et al., 2009), and is dependent on both management, as well as the susceptibility of areas to land use (Hill et al., 2015; Schleicher, Peres, and Leader-Williams, 2019). Without considering the wider implications of our agricultural and land-use policies, via spatially explicit models and accounting for land rent and vulnerability of remaining forests, research remains blind to the risks of indirect land-use changes and the resulting impacts on forests. If we are to make effective conservation decisions, it is important we understand, both spatially and across time, how land-use change for crop expansion could be shaped by conservation interventions, and ultimately how that translates to forest and biodiversity impacts.

In this study, we address this fundamental yet often neglected relationship between land-use change and economic drivers. We do so focusing on oil palm (*Elaeis guineensis* Jacq.) agriculture in Indonesia. As the world's top producer of palm oil (FAO, 2019), Indonesia continues to expand and encroach plantations into dryland and peat swamp forests, driving deforestation (Margono et al., 2014; Sumarga and Hein, 2016) and associated negative impacts on biodiversity (Fitzherbert et al., 2008), carbon emissions (Carlson et al., 2013; Guillaume et al., 2018), and soil and water quality (Dislich et al., 2017). Research and policies aimed at conserving forests and peatlands within Indonesia have continually proposed increasing crop yields and land-use efficiency (Villoria et al., 2013). Land-use regulations aim at reducing further deforestation, via Indonesia's 2011 Forest Moratorium, which protects over 66 Mha of dipterocarp and peat swamp forests for protection against land use (Sloan, 2014), and, within Roundtable for Sustainable Palm Oil (RSPO)-certified concessions, via the High Carbon Stock (HCS) initiative, which protects areas with high carbon biomass, and restricts land use to areas with lower carbon stocks (Rosoman et al., 2017). By incorporating simple market dynamics into land-use models, we explore how expansion of Indonesia oil palm varies under different conservation strategies to understand their impacts on deforestation and biodiversity across space and time.

5.2 Methods

5.2.1 Overview

Using an oil palm expansion model that incorporates a land-rent modelling framework (Chapter 3, Lim et al., 2019)— which focuses on the net profitability from converting land into plantation — we first observed the spatial dimension of the supply relationship between prices and quantity of oil palm fruits produced over the span of five years. We then examined how oil palm expansion over time varied across scenarios representing an array of land management practices, conservation policies and price changes. Based on these shifts in the supply relationship, we assessed how they affected deforestation and biodiversity impacts (the extent of forest loss, carbon losses and the number of species affected), and therefore, the efficacy of these conservation efforts.

5.2.2 Data Collection

We used spatial information of land use and vegetation classes across Indonesia in 2015, mapped as grid cells, each cell representing an area of 250 m by 250 m (Miettinen et al., 2016a). We also derived the potential palm oil yield within each cell, from information on oil palm suitability (Pirker et al., 2016). Spatial information on the areas across Indonesia set aside for conservation from Indonesia's Forest Moratorium (WRI, 2017), other protected areas (Ministry of Forestry, 2010) and oil palm concessions (WRI, 2012) were also collected. We used the most recent land cover classes after 2015 (i.e., 2017, WRI, 2019) and assessments of carbon density across space based on years 2008–2010 (Baccini et al., 2012) — we thus assumed that carbon density values remained constant since 2010, with the exception of land-use change detected in 2015. To assess the impacts of projected land-use changes on biodiversity and carbon, we compiled information describing species richness spatially, based on species ranges and extent of IUCN red-listed amphibians, birds, mammals and reptiles (IUCN, 2019). We focused on species of conservation concern (i.e., classified Near Threatened, Vulnerable, Endangered, Critically Endangered, Extinct, and Data Deficient).

Assessments of costs and returns were based on country-level prices of labour, fuel, fertiliser, as well as of oil palm fruits and timber in 2015 from multiple sources (FAO, 2019; GIZ, 2014; ILO, 2017). We also obtained projected palm oil prices from 2018-2020 via OECD (OECD/FAO, 2018). All prices were deflated to USD2015.

5.2.3 Projecting palm oil supply relationships across time

We used an oil palm expansion model that relates land-use change with economic factors (Lim et al., 2019, Chapter 3). In this model, oil palm expansion across space and time is primarily determined by spatial and temporal variations in agricultural rent, the potential net revenue from agricultural output given the costs of establishing and maintaining the plantation (Angelsen, 2010). This, in turn, is dependent on variation in prices (of palm oil, fertilisers, transport) across years, as well as spatial variation in accessibility and potential palm oil yield across cells . The model also includes a spatial contagion effect that adjusts the rent of a cell according to the proportion of surrounding oil palm plantations: expansion in areas with larger proportions of existing plantations is more likely to occur given reduced setup costs and the ability to withstand initial losses (Garrett et al., 2013; Lim et al., 2019). This model, therefore, allows us to understand the relationship between palm oil supply and prices across Indonesia and across years (Lim et al., 2019, Chapter 3). Where the overall agricultural rent of a cell exceeded the minimum threshold based on prices in a given year, the cell was considered susceptible to conversion into plantation.

Additionally, as the model identifies and converts all areas profitable without accounting for possible constraints in resource capacity for converting plantations in a given time period, we introduced a yearly upper limit of expansion in our projections. This limit acts as a maximum extent of conversion in a single year . We set this yearly limit of 13.13% extent of the existing plantations across Indonesia in the previous year, based on the highest recorded proportional increase in oil palm area (in 2014) since 2010 (FAO, 2019).

This modelling approach forms the basis of our projections of yearly palm oil supply and the extent of oil palm expansion beyond 2015. We evaluated the total agricultural output both from existing and newly converted plantations, with the assumption that maximum potential yields were met. Given an average time lag of four years from establishing a plantation to the first harvest of fruits, model predictions for any given year therefore project hypothetical supply four years later. We repeated this process yearly from 2016 to 2020, updating prices of palm oil and the extent of oil palm plantations accordingly each subsequent year. We commenced conversion each year, starting from the most profitable cell (with the highest agricultural rents), and converted all cells with rents above the minimum threshold until the yearly upper limit was reached.

We restricted our analyses to cells with positive potential palm oil yields, and cells available for conversion to oil palm plantation from 2015: our model only permitted oil palm expansion into cells classified as oil palm concessions or public land, and not cells within protected areas or other plantation crops. Due to computational constraints, we conducted our analyses on a subset of cells stratified randomly sampled across the total dataset (10%, ~2.4 million of 25,111,235 cells), ensuring the same proportion of cells across all provinces, and scaled up the extent of oil palm plantations and quantity of palm oil produced (i.e., values obtained from the 10% sample were extrapolated to represent 100%).

5.2.4 Impacts of agricultural policies on crop expansion, land-use change forest and biodiversity across time

From our model, we evaluated how changes in projected palm oil prices, land-use practices and conservation interventions affected the supply relationship. In particular, we explored the effects of three sets of variables on supply and land-use, summarised in Table 5.1.

Table 5.1: List and descriptions of scenarios. A total of 12 scenarios were explored, considering variations in prices, yields and land-use restrictions.

Scenario Number	Yield	Land-use Restrictions	Changes in Prices across years
1	Current potential yields	No additional restrictions	prices constant from 2015
2	Current potential yields	No additional restrictions	Price fluctuations according to OECD
3	Increased potential yields	No additional restrictions	prices constant from 2015
4	Increased potential yields	No additional restrictions	Decrease in prices from 2015
5	Current potential yields	Moratorium	prices constant from 2015
6	Current potential yields	Moratorium	Price fluctuations according to OECD
7	Increased potential yields	Moratorium	prices constant from 2015
8	Increased potential yields	Moratorium	Decrease in prices from 2015
9	Current potential yields	Moratorium + HCS	prices constant from 2015
10	Current potential yields	Moratorium + HCS	Price fluctuations according to OECD
11	Increased potential yields	Moratorium + HCS	Prices constant from 2015
12	Increased potential yields	Moratorium + HCS	Decrease in prices from 2015

First, we examined how variations in commodity prices across time affect supply, land-use change, deforestation and biodiversity. Serving as a baseline projection, we ran simulations assuming no change in prices across years, i.e., keeping prices of oil palm fruits constant at 2015 values (Table 5.1). As a comparison, we allowed palm oil prices to vary across years, based on recorded prices of oil palm fruits in 2016–2017 (FAO, 2019) and price projections of palm oil from 2018–2020 (OECD/FAO, 2018), translated to prices of oil palm fruits from an average extraction ratio (of ~0.2). To isolate the effect of palm oil prices on land-use change across time, we kept other costs (i.e., fuel, labour and fertiliser prices) constant at 2015 values.

We then examined shocks to the supply from agricultural intensification and improvements in crop yields. Compared with current maximum potential yields, we assumed a nation-wide increase in maximum potential yields by 15% across both existing plantations and cells not already converted to oil palm plantations by 2015. This was set as an arbitrary, conservative assumption of yield increase. With increased crop yields, we assumed scaled decreases in palm oil prices: projected prices determined by OECD were no longer valid since they were based on existing yields. Specifically, we decreased palm oil prices by 5% (based on palm oil price in 2015) when potential yields increased by 15%: the prospect of a fall in production costs not factoring through into prices is not realistic, but accompanying the 15% increased efficiency with a 15% cut in prices would not be neutral, as there would be differential impacts of changes in both prices and costs, depending on spatial heterogeneities. This reduced price was kept constant across years. Other costs were kept at 2015 values, apart from costs directly affected by the change in yields: labour, fertiliser and fuel costs were kept constant per hectare, while total transport costs per hectare varied with increased agricultural yields. We compared these (with decreased prices) with simulations without changes in prices across time.

We also examined the impacts of additional land-use restrictions on oil palm expansion over time, each with a different conservation focus. As a reference, we first assumed no additional restrictions from oil palm expansion other than protected areas (Ministry of Forestry, 2010) and private land. We then compared this with scenarios where we excluded areas that fell within Indonesia's Forest Moratorium (WRI, 2017) (Scenarios 5–8, Table 5.1). We also applied additional restrictions to land use in accordance with guidelines of a HCS initiative, where areas of high carbon stocks are protected from land-use change (Scenarios 9–12, Table 5.1). Cells classified as primary, secondary or logged forests and with aboveground carbon density exceeding 35 $Mgha^{-1}$ were protected from conversion to oil palm plantation (Rosoman et al., 2017).

For each type of land-use restriction, we assessed how oil palm expansion and palm oil production are altered, with and without price variations and changes to potential yields. We therefore had 12 scenarios exploring the extent of market feedbacks to exogenous shocks brought about by different combinations of price variations, yield improvements and land-use restrictions (Table 5.1). For each scenario, we evaluated the amount of oil palm fruits produced, and the extent and distribution of oil palm plantations every year (2016–2020). We also assessed the effectiveness of each conservation intervention in conserving forest aboveground carbon stocks (Baccini et al., 2012) and biodiversity, based on the species richness across areas affected by the expansion, based on species range maps from the IUCN Redlist (IUCN, 2019).

5.3 Results

5.3.1 Impact of changing palm oil prices on crop extent

Even without variations in palm oil prices over time, there was continual yearly oil palm expansion and encroachment into natural forests within our baseline scenario (i.e., assuming current yields, constant prices across time and no additional land-use restrictions). This expansion was solely driven by the spatial contagion effect in the oil palm expansion model: increases in the extent of surrounding plantations increases agricultural rent each year, thereby increasing the extent of oil palm plantations across

Indonesia. By 2020, the total extent of plantations across Indonesia covered 9.31 Mha (Figure 5.1A, Figure 5.2), and the total supply of oil palm fruits reached 129.33 million tonnes by 2024, following the four-year time lag (Figure 5.1B). Newly converted areas stood to lose 121.30 mega tonnes of carbon (Figure 5.1C). Under this baseline scenario, the extent of areas converted into oil palm plantations overlap with 509 species of conservation concern, of which 24 were classified Critically Endangered (Figure 5.1D).

Considering variations in prices from FAO and OECD forecasts (FAO, 2019; OECD/FAO, 2018) while keeping other costs and prices constant across time (Scenario 2), we observed a sharp increase in palm oil production across time, constrained mainly by the yearly expansion limit (13%) imposed within our simulations. Compared to our baseline scenario, we could expect an increase in total oil palm extent to 13.75 Mha by 2020 (Figure 5.3), producing a total of 190.46 million tonnes by 2024. Carbon loss from the expansion rose to 520.55 mega tonnes in 2020, while 531 species of conservation concern would have their ranges reduced (of which 26 were classified Critically Endangered, Figure 5.1D).

5.3.2 Effectiveness of land-use policies on reducing oil palm expansion

Additional land-use restrictions aimed at reducing carbon emissions from deforestation (via the Moratorium and HCS initiative) showed little impact on reducing rates of expansion from 2016 to 2020 (Figure 5.1). Given current yields and keeping prices constant across time, upon implementing the Forest Moratorium, the total extent of oil palm distribution by 2020 reached 9.31 Mha, with a total production of 129.27 million tonnes of oil palm fruits (Figure 5.1, Figure 5.4), similar to the baseline. Loss of carbon stocks from the newly converted areas reached 121.20 Mega tonnes, a reduction of 0.10 Mega tonnes from the baseline scenario (Figure 5.1). Similarly, including protection of forests with high carbon stocks, in accordance with the HCS initiative guidelines, showed little decrease in crop expansion rate across the five years, both with and without variations in crop prices (Appendix B).

5.3.3 Indirect impacts of agricultural intensification on oil palm expansion

In addition to the expected increased baseline output within existing plantations (Figure 5.1A), a 15% increase in yield nationwide resulted in more areas with increased agricultural rent susceptible to conversion to oil palm each year. Under constant prices from 2015, the extent of oil palm reached 13.75 Mha by 2020,

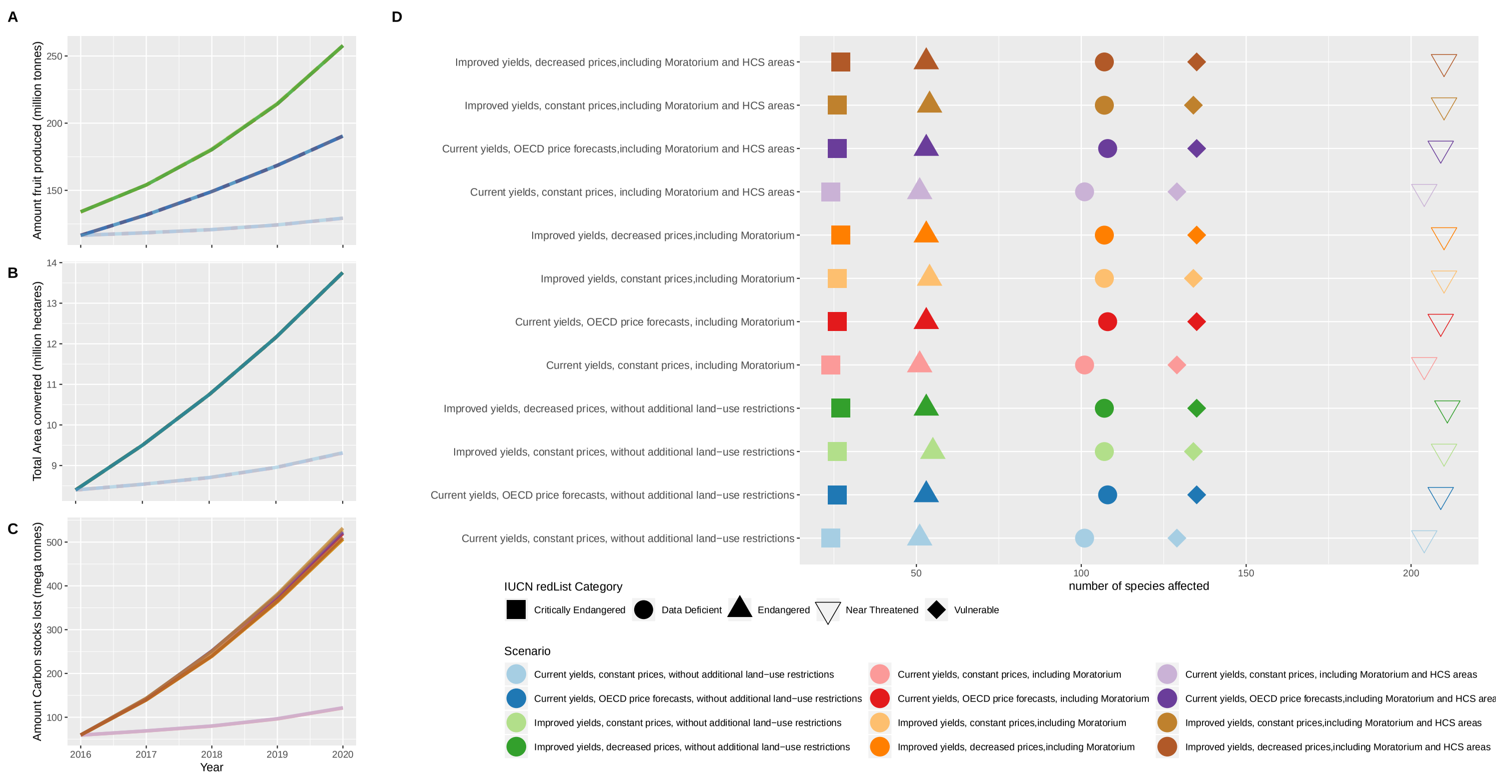

Figure 5.1: Expected projections of (A) agricultural output; (B) total extent of oil palm; (C) loss of aboveground carbon from newly converted oil palm across years, from 2016-2020; and (D) number of species affected. across scenarios (Table 5.1). Simulations Projections were conducted on a sample (10%) 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.

Figure 5.2: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, assuming current potential yields and constant prices across years. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

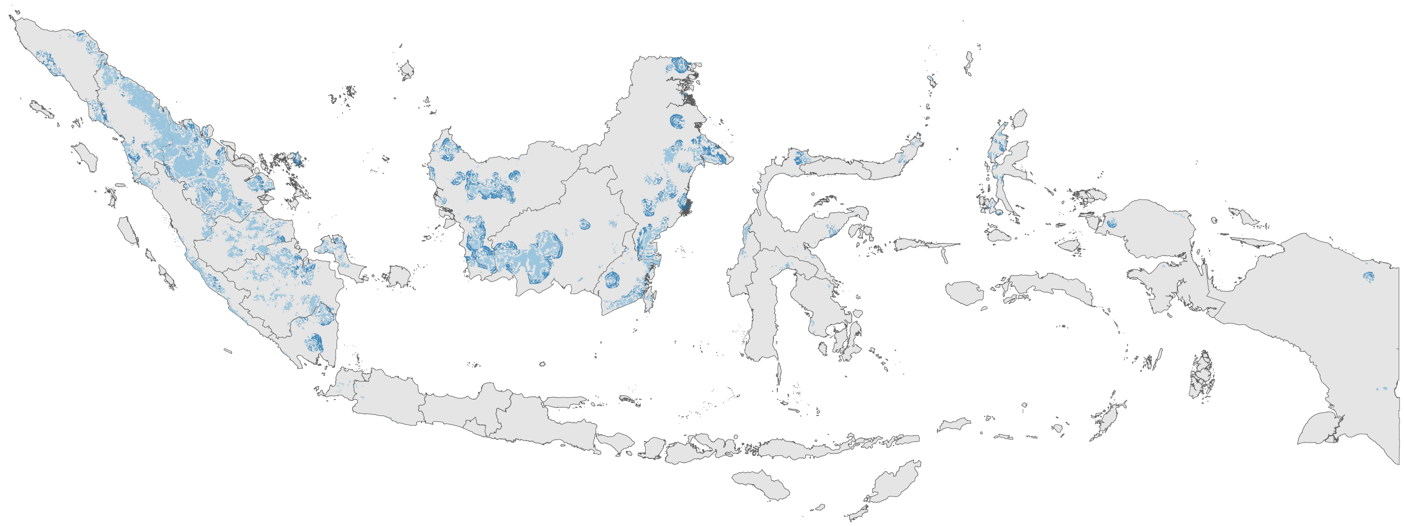

Figure 5.3: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, assuming current potential yields while allowing prices to vary (dark blue) in accordance with FAO and OECD forecasts (OECD/FAO, 2018), compared with assuming constant prices (light blue). Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

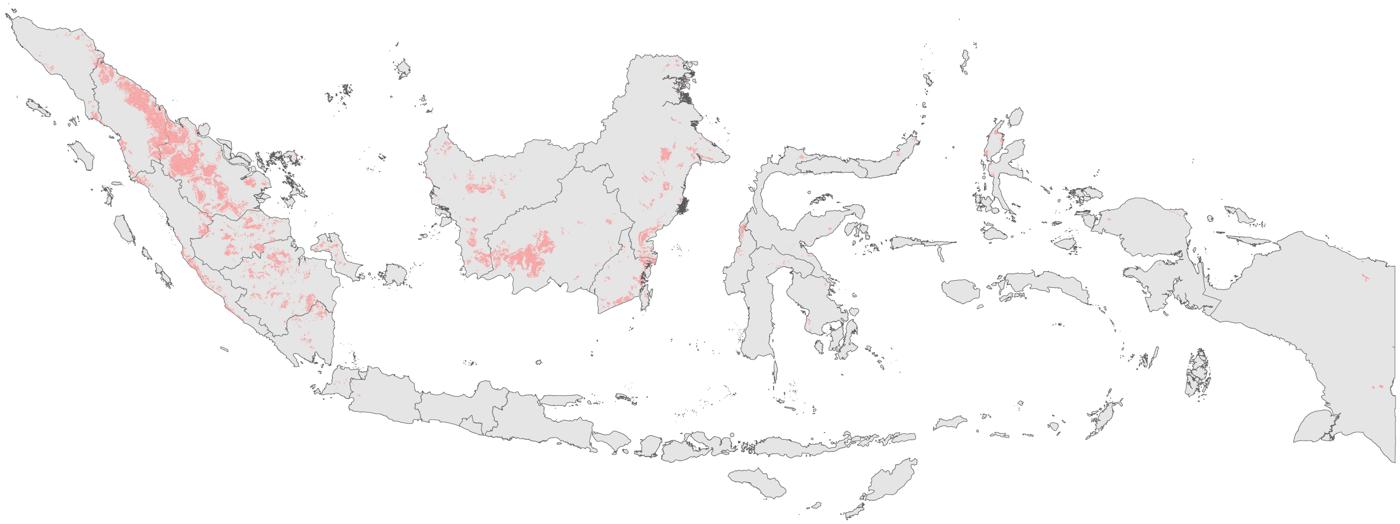

Figure 5.4: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, with Indonesia's Forest Moratorium in place, while assuming current potential yields and constant prices across years. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

constrained by the yearly limits we imposed (Figure 5.1B, Figure 5.5), while amount of fruits produced reached 257.85 million tonnes. From the newly converted areas, 527.27 mega tonnes of carbon stocks would be lost (Figure 5.1C). Even with a 5% decrease in palm oil prices, the increase in yields resulted in a much greater area to have positive rents above the constant threshold each year, limited by constraints of conversion set by the yearly cap in our simulations: by 2020, assuming decreased palm oil prices, we could witness a loss of carbon stocks by 506.70 mega tonnes.

Implementing additional land-use restrictions alongside increased crop yields showed little effectiveness in reducing land-use change (Figure 5.1). From our simulations, with the additional protection from the Forest Moratorium and the HCS initiative, the total extent of oil palm reduced very slightly, but loss of carbon stocks increased (527.80 Mega tonnes C from the Moratorium, and 532.04 mega tonnes from implementing both the Moratorium and the HCS initiative) (See SI for maps of extents of oil palm expansion under different scenarios not presented here).

5.4 Discussion

This study investigates how land-use change and agricultural expansion over time are shaped by conservation interventions, and explores the potential for market feedbacks and unanticipated land-use changes to undermine our conservation efforts. Despite the innate relationship between land use and markets, especially for a highly commercial agricultural commodity such as oil palm, little focus has been placed on linking land-use change and conservation efforts with markets (Armsworth, 2014; Armsworth et al., 2006). The spatial aspect of the supply relationship, in terms of land-use change and crop expansion, although not often emphasised, is instrumental in understanding how land-use changes, and indeed conservation efforts, link with markets and feedbacks. Through a spatially explicit model that links markets to the land-use changes and impacts on biodiversity, this study emphasises this relationship and provides a realistic assessment of the efficacy of agricultural policies meant to reduce land-use and protect forests and biodiversity. We found that increasing both crop prices and yields led to a greater extent of oil palm expansion over time. Increased land-use restrictions from the Forest Moratorium and the HCS initiative were only minimally effective in reducing oil palm expansion.

Land-use change for agricultural expansion is fundamentally driven by economic forces (Lim et al., 2017, Chapter 2); conversion of forests and natural areas into cropland is largely determined by the potential profits from harvest (Lim et al., 2019, Chapter 3).

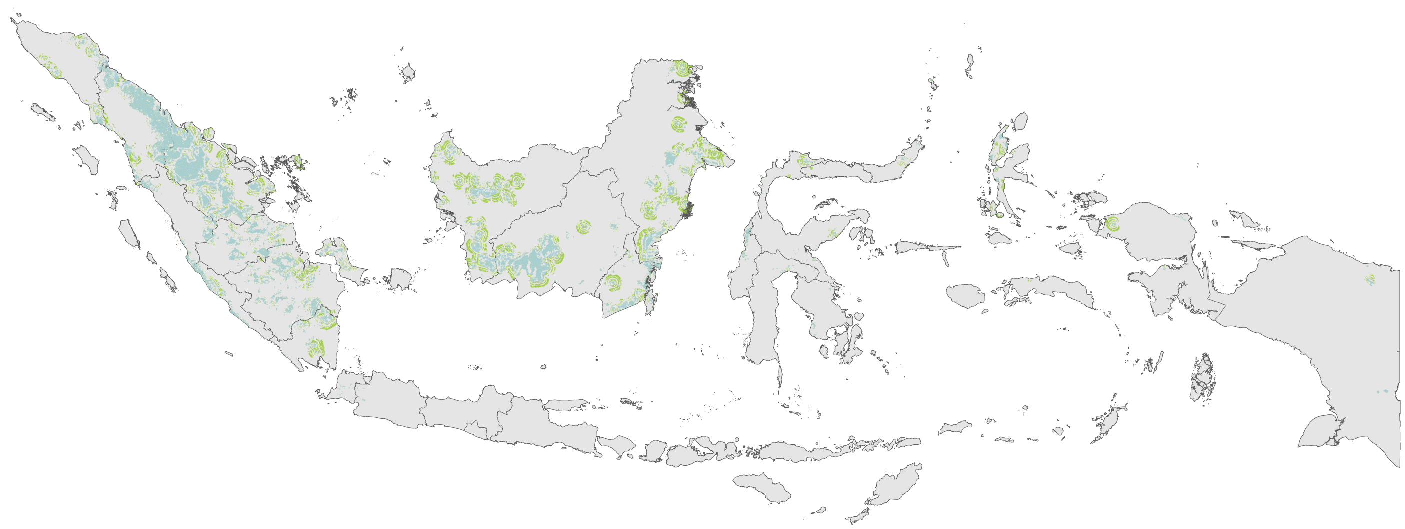

Figure 5.5: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, simulating increased oil palm yields (green) while keeping prices constant across years from 2015, compared to using using current yields (blue). Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

Keeping prices constant across time serves as a baseline scenario for our simulations (Table 5.1). Even without variation in palm oil prices (Scenario 1), we still expect crop expansion to continue, driven by the spatial contagion effect (Lim et al., 2019, Chapter 3). Over time, land rent increases with the proportion of surrounding existing plantations; factors such as an established labour force and infrastructure might reduce costs to establish and maintain plantations (Garrett et al., 2013). With prices forecast to increase in the coming years (OECD/FAO, 2018), production also becomes viable across a wider area (expansion into areas with lower suitability, accessibility and yields) and aggregate supply increases (Scenario 2).

5.4.1 Improving oil palm yields increases crop expansion

Improving crop yields is often lauded as an effective means of reducing pressure on remaining forests (Green et al., 2005; Gutiérrez-Vélez et al., 2011; Phalan, Onial, et al., 2011). Policies to consolidate agriculture on less land (i.e., sparing land for nature) necessitate improved agricultural practices and productivity with implications for cost efficiency and increased agricultural yields (Gutiérrez-Vélez et al., 2011). However, technological improvements offering cost efficiencies also incentivise further expansion, and could result in increased land suitability and profits. The land-sparing framework therefore has larger impacts on the scale and distribution of supply than is usually realised, and it is crucial we consider the potential outcomes of enhancing crop yields, especially on the vulnerability of remaining forests to conversion.

Similar studies based on spatially explicit models that consider impacts on remaining forests and account for crop expansion across space and time (e.g., Phelps et al., 2013), have also raised caution regarding the increased pressures on remaining forests from agricultural intensification. Research must not ignore that remaining forested areas will also increase in rent with adoption of high-intensity farming practices: assessments comparing opposing agricultural strategies (i.e., land-sparing versus land-sharing) cannot only focus on the direct benefits, but need to consider the wider implications on forest vulnerability, both spatially and temporally, and the resulting indirect impacts on forests, carbon stocks and biodiversity. Further land-use restrictions need to be used alongside high-intensity agricultural practices: additional protection is necessary to prevent further loss of key biodiversity areas across the country (Luskin, Lee, Edwards, Gibson, and Potts, 2018; Phalan et al., 2016).

5.4.2 Land-use restrictions offer little protection against immediate oil palm expansion

Both land-use restrictions we explored in our study (the Forest Moratorium and the HCS initiative), however, showed limited effectiveness in limiting oil palm expansion, after five years from 2015, considering constant crop prices and current yields. We observed the same low effectiveness of either land-use policy when prices and crop yields are increased: expansion in the five years was constrained only by the yearly limitations of expansion we imposed within the model simulations. Having focused on land-use policies that place emphasis on retention of carbon stocks within forests for climate change mitigation (Rosoman et al., 2017), it is evident that the areas protected by these policies have little overlap with areas profitable and vulnerable to conversion (Sloan et al., 2012). Protected areas far from the frontier of expansion might be less effective in reducing crop expansion, and there is a need to identify areas that are highly susceptible to crop expansion, and therefore in need of increased protection (Hill et al., 2015). Similarly, other conservation policies with different emphases, as well as future spatial prioritisation studies in the area, need to consider areas most vulnerable to land-use change and agricultural expansion (Hill et al., 2015).

Additionally, our results emphasise the need to consider the repercussions and knock-on effects of imposing land-use restrictions, especially on surrounding unprotected areas. We found that, although marginal, land-use restrictions could be redirecting oil palm expansion to less profitable areas that were not protected by either land-use policy. Having imposed the yearly expansion limit in our simulations, we observed the same total extent of oil palm expansion with and without these land-use restrictions. However, in some cases, unprotected areas with a total higher carbon stocks were converted (Supporting Information Table S1). While leakage is typically difficult to detect empirically, we highlight this risk through spatially explicit simulations and considering socio-economic drivers (Renwick et al., 2015). Nevertheless, displacement of land-use changes from protected areas into surrounding areas has been expressed across previous studies in other areas (Fagan et al., 2013; Meyfroidt et al., 2010). Policies restricting land use therefore need to be wary that this phenomenon could result in conservation efforts being undermined (Renwick et al., 2015).

5.4.3 Limitations and Further Directions

Our model simulations have two key limitations. The crop expansion model (Lim et al., 2019, Chapter 3), while useful in describing the supply relationship across space and time, was fitted on historical data that might have absorbed previous market shocks. It is based on an overall relationship that assumes no exogenous shocks to the market. Additionally, our assessments of forest, carbon and biodiversity losses only account for direct, immediate impacts from oil palm expansion, and do not consider secondary, knock-on effects (e.g., edge effects, loss of ecosystem functioning, increased accessibility for cagebird trappers Symes et al., 2018). Still, our simulations illustrate how future land use reacts to changes in agricultural practices and land-use policies, and how market responses could reduce effectiveness of conservation efforts and increase susceptibility of land to forest and biodiversity loss.

Secondly, our analyses employs a single-crop model which conservatively assumes all land is converted to oil palm depending on agricultural rent, without considering other land uses. To allow for competing land uses, we limited the extent of crop-expansion in our simulations by excluding other plantations and PAs in the expansion model, and restricting our projections to public land and OP concessions. Additionally, we imposed a yearly limit of oil palm expansion across our simulations, constraining conversion to the most profitable areas each year. Our simulations, therefore, while being more realistic and allowing for other land uses to thrive, could also be conservative— a much larger area than shown is susceptible to oil palm expansion. Intensifying oil palm agriculture also increases the likelihood of expansion into existing croplands, displacing less profitable crops like rubber and causing knock-on impacts on overall land-use change (Warren-Thomas et al., 2015). While it is known that oil palm expansion has displaced other crops (Koh and Wilcove, 2008), examining this effect would require comparing land rents of multiple land-use types across time. Nevertheless, the spatially explicit and deterministic nature of this model and the analyses of agricultural rent and the supply relationship allows us to assess the extent of oil palm expansion and the environmental and biodiversity impacts across space and time as palm oil prices vary.

5.4.4 Conclusion

In striving to conserve forests and biodiversity while meeting palm oil demands, it is imperative we account for unintended market feedbacks, and take steps to minimise perverse outcomes of our efforts. Studies that focus only on direct benefits of high-yielding crops and farming practices within existing plantations and neglect their threat to remaining lands, risk overestimation of the efficacy of such policies, both spatially and temporally. Neglect for the wider economic impacts on market and supply could result in overestimation of efficacy of conservation actions. Our study highlights the potential risks involved with current conservation policies and furthers ongoing discussion and research on increased crop yields and improved agricultural practices as a means of conserving forests. From our simulations, both increasing in palm oil prices and improving crop yields result in amplified rates of crop expansion. Additional land-use restrictions such as policies preventing further loss of peatlands have limited effects of reducing rates of forest loss and biodiversity impacts, especially in the near future. Without careful management and protection of remaining land, improving yields to reduce land use could paradoxically result in greater forest and biodiversity loss.

Acknowledgements

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Chapter 6

Thesis discussion

6.1 The role of market forces in managing deforestation from agricultural expansion

This research set out to explore and understand the role of markets in influencing land-use change and conservation efforts. Through developing a conceptual framework to explain the economic underpinnings of these market responses (Lim et al., 2017, Chapter 2), as well as developing a land-use model that incorporates economic factors to explain the drivers of crop expansion (Lim et al., 2019, Chapter 3), this study emphasises the importance of accounting for markets in our assessments of land-use change across space and time. Additionally, this study shows how market feedbacks to conservation interventions could alter the efficacy of our efforts (Chapters 4 & 5). Many conservation projects and policies only focus on the direct outcomes and overlook the potential for unintended feedbacks (Larrosa et al., 2016). However, land-use change for agricultural expansion is fundamentally economic and primarily driven by market incentives, as in the case of oil palm, a highly commercial crop widespread across the tropics. It is crucial our conservation management efforts and policies consider the influence and effect of markets. The importance of linking land-use change with markets cannot be overlooked, and in this project I have highlighted the importance of considering markets in our studies, policies and practices to reduce the impacts of oil palm agriculture and expansion on forests and biodiversity.

In this final chapter, I provide a set of key messages essential for researchers, policy makers and land-managers alike to consider, with evidence generated from the thesis. I explain how indirect and unintended land-use impacts could arise from market feedbacks to our conservation actions. Incorporating the potential market feedbacks in our assessments is a step towards developing integrated policies that could shield or minimise the negative impacts of these perverse outcomes.

6.1.1 Perverse market outcomes could arise from conservation interventions

With the increased reliance on conservation interventions to minimise forest and biodiversity loss, Chapter 2 emphasises the need to consider markets in our policies and decisions. Various interventions have been implemented and proposed to reduce pressure on forests and biodiversity while striving to meet agricultural demands, including designated forest protection, adopting high-intensity farming practices and certification schemes. Studies and policies, however, typically overlook the role of markets governing responses to our policies and conservation interventions. If not considered, policies and practices meant to reduce forest loss and biodiversity impacts could instead backfire. The conceptual framework introduced in Chapter 2 explains how various conservation interventions aimed at regulating land use and resource extraction could instead have unintended consequences through creation of an unregulated market alongside the regulated (but economically inefficient) market. By setting constraints within the regulated market, these policies also allow for leakage and displacement of efforts into an unregulated market (i.e., unregulated/uncertified palm oil production). Implementing sustainable certification schemes like the Roundtable for Sustainable Palm Oil (RSPO) (Ivancic and Koh, 2016) that encourage sustainable practices within certified plantations could instead incentivise inefficient practices within the regulated market, while sustaining an unregulated market (i.e., uncertified palm oil) (Edwards and Laurance, 2012). By framing land use and agricultural expansion in economic terms (i.e., as supply and demand of a commodity), it is clear how conservation measures aimed at regulating land and resource use could instead support the unregulated trading of commodities. If we want to improve the efficacy of our actions, we need to acknowledge that markets might respond unfavourably to our efforts, and incorporate these responses into our policy assessments. Additional steps need to be taken to ensure our conservation efforts are not compromised and potentially made ineffective or even counterproductive in the face of market feedbacks.

6.1.2 Agricultural rent drives oil palm expansion

Reiterating the importance of accounting for markets in land-use change, Chapter 3 identifies the drivers of oil palm expansion across Indonesia, via integrating economic concepts into a land-use model. Understanding what drives oil palm expansion, and therefore where to expect future oil palm expansion, allows for more specific, spatially explicit assessment of the environmental and social impacts, as well as better prioritisation of future conservation efforts. Studies have typically identified areas vulnerable to oil palm expansion based on environmental suitability and accessibility (Austin et al., 2017; Sumarga and Hein, 2016; Vijay et al., 2016), or alluded to the contribution of economic factors in determining crop expansion (Castiblanco et al., 2013; Furumo and Aide, 2017) without fully incorporating market forces. The model described in Chapter 3, by comparison, places greater emphasises on the direct role of economic forces in driving growth and expansion of oil palm across Indonesia (Lim et al., 2019). Crop expansion is driven by profitability. This, in turn, is determined by the costs of establishing and maintaining plantations, as well as commodity prices

(Lim et al., 2019). Variations in crop yields across space also affect production costs and profitability, and therefore land rent. This study also identified a spatial contagion effect of oil palm spread: areas close to existing plantations were more vulnerable to crop expansion (Lim et al., 2019), likely due to reduced establishment and production costs from having plantations in the vicinity (Garrett et al., 2013).

Relating crop expansion to commodity prices and production costs, and therefore farmers' income and profitability, provides a direct, realistic look into drivers of the oil palm expansion across space and time. Prices, both of commodities and of various other factors that affect production costs (eg., fuel, labour and fertilisers), are important in explaining crop expansion and distribution across both space and time. Through this model we can also understand how land-use changes and policies, via altering costs and revenues, impact vulnerability of land to crop expansion both directly and indirectly and at various scales. This includes regulations or subsidies that might affect costs of establishing plantations, as well as changes in accessibility that affect transport costs (e.g., road networks). This is a step towards minimising negative impacts on forests and biodiversity. We can also make spatially explicit projections of future crop expansion, thus identifying areas to focus conservation efforts.

6.1.3 Supply and demand relationships are sensitive to changes in agricultural practices

Having linked spatially explicit patterns of land-use change and crop expansion with market forces in Chapter 3, Chapter 4 further explores the market dynamics of oil palm agriculture. By building supply relationships from the crop expansion model, this chapter also provides proof of concept of the supply relationship across space, and emphasises the innate relationship between land use and the production and supply of an agricultural commodity. The concept of the supply relationship across space, varying with commodity prices, is rarely emphasised in studies, yet is instrumental in understanding land-use impacts and feedbacks. Additionally, through use of partial-equilibrium models, this study answers questions surrounding the influence of market forces on land-use change, and addresses how conservation actions bring about shifts in market equilibria, and ultimately impact on the scale and spatial distribution of forest loss. Supply relationships are sensitive to exogenous market shocks from changes in agricultural practices: a slight increase in crop yields causes a sizeable shift in supply. This suggests that our efforts to reduce land use via improving crop yields could be undermined by shifts in market equilibria, effecting further forest loss that cannot be compensated by drops in prices. Exogenous shocks to the market from changes in agricultural regulations could result in indirect and unanticipated land-use changes. thus challenging our predictions of the extent of land-use change and the efficacy of our efforts and policies. Studies that use general- (e.g., Taheripour et al., 2019; Villoria et al., 2013) or partial-equilibrium models (e.g., Jafari et al., 2017) to characterise oil palm market dynamics have reiterated the importance of accounting for market responses in agricultural and trade policies. This study, by integrating a land-use model with a partial equilibrium model, provides an additional, important spatial component to understanding the interactions between supply and demand.

6.1.4 Increasing yields backfires with further forest loss across time

The indirect impacts of agricultural intensification on land-use change are also amplified across time. Through simulations of a range of commonly implemented measures meant to reduce pressures on forests — i.e., yield enhancement and land-use restrictions — Chapter 5 further explores the cumulative impacts of increasing yields across time, thus providing a realistic assessment of the efficacy of a land-sparing scenario, and its impacts on oil palm expansion, palm oil production and biodiversity and the environment. Similar to increasing prices of palm oil, increased crop yields leads to a much greater extent of oil palm expansion with time. Many studies do not consider the role of market forces when assessing the effectiveness of high-yielding crop varieties, and most choose to ignore the influence of commodity prices and profitability on land-use changes. Especially with global palm oil demands projected to rise further alongside global population and affluence (Corley, 2009), we might expect palm oil prices to rise as well (OECD/FAO, 2018; Sayer, Ghazoul, Nelson, and Klintuni Boedhihartono, 2012). Another interesting, albeit disconcerting, finding from the land-use simulations here is the potential displacement of oil palm expansion brought about by protection of forests (e.g., forests with high carbon stocks). Increased protection of forests via the Forest Moratorium and the HCS initiative resulted in expansion into less profitable areas with potentially higher carbon stocks not protected by either policy, paradoxically increasing loss of carbon stocks.

The key findings in this chapter challenge a number of studies that argue in favour of the land-sparing framework, primarily because this study also considers the impacts of conservation efforts on agricultural rent of remaining forests over space and time. The myopic view that high-intensity farming practices result in less land use neglect, crucially, that remaining forests are at greater risk due to increased profitability. Studies that consider the spatial extent and vulnerability of forests to agricultural expansion, (e.g., Phelps et al., 2013), reiterate that agricultural intensification could result in increased environmental costs. Conversely, studies that ignore the impacts of conservation efforts and land-sparing on remaining forests and biodiversity over time might not realise the full impacts of different strategies on remaining forests over space and time. Importantly, this chapter highlights the potential pitfalls of yield enhancements as a means to reduce land use, and emphasises that increasing crop yields does not immediately equate to land-sparing (Armsworth et al., 2006). The premise of the land-sparing argument comes with its caveats, and it is essential we acknowledge these limitations.

6.2 Caveats

As with any study, simplifying assumptions were made to allow a first look into the complexities surrounding market feedbacks and the potential unintended consequences on land-use changes. It is important to understand the limitations of the thesis based on the assumptions made and modelling approach taken.

Firstly, the crop expansion model (described in Chapter 3) was fitted to distributions of oil palm plantations between 2000 and 2015 (Miettinen, Shi, and Liew, 2016b; Miettinen et al., 2012) and historical yearly prices (Chapter 3), and represents an overall relationship across those years. Market shocks between those years would have been absorbed into the model. The model was also limited by the sensitivity of the data available. Similarly, projections of oil palm expansion from 2015 onwards were based on 2015 oil palm prices and places emphasis on existing plantations in 2015. For simplicity, and to isolate the effect of changing palm oil prices, I kept all other costs (e.g., fertilisers, labour etc.) constant at 2015 values in the projections. Results from the models therefore offer a conservative baseline, that assumes no changes in other factors.

Secondly, this study focused on expansion of a single crop. Accounting for other markets and land uses becomes increasingly complicated in research and policies, but the limitations that come with policies and studies which focus on a single market cannot be ignored. Without spatial information on the distribution of other crops, however, exploring the potential for oil palm expansion to displace other crops becomes challenging. To circumvent this issue, the model did not permit conversion of oil palm from other plantations. This means that the model overlooks the possibility of displacement of other crops by oil palm being more profitable (Koh and Wilcove, 2008; Warren-Thomas et al., 2015), but understanding displacement requires information of distribution of each crop, and evaluating and comparing rents between land uses.

Additionally, model simulations of crop expansion over time (Chapter 5) imposed a yearly expansion limit as a means of accounting for the constraints of oil palm expansion. This conservative approach therefore restricts expansion to the most profitable areas, as opposed to clearing all areas deemed profitable by the model.

Perhaps one of the biggest challenges in modelling and projecting land-use change is disentangling the role of markets, governance and oil palm suitability when assessing crop expansion and economic forces. In this study, I opted for a more generalised approach to allow for the model to be applicable to other systems and crops. Inclusion of fine-scale variation of property rights could account for additional variation in crop-expansion behaviour between companies, and therefore provide clearer explanations of past oil palm expansion. Additionally, incorporating capital assets would certainly improve the realism of the model. However, with the goal being to develop a more general model applicable to other crops and in other systems, incorporating fine-scale niche data on capital assets would not allow us to do that. Incorporating niche data like company-level assets would also mean that future projections of oil palm expansion into public land would not be possible. By excluding areas classified as other plantations, land uses and protected areas, and thus limiting oil palm expansion to concessions or public land, the model is easily repeatable for other regions and crops, absent of specific property rights boundaries that are hard to obtain.

Finally, the results presented across Chapters 4 and 5 were based on a set of assumptions surrounding demand. Given the limitations in data to build demand curves, I assumed constant elasticity of demand in the partial equilibrium model (described in Chapter 4). Other studies have used different values of demand elasticities in their partial equilibrium models (Jafari et al., 2017), but have also kept these values constant. In my assessments of land-use change over time (Chapter 5), I assumed annual prices remained constant over time even with variations in quantity and explored price increases as projected by OECD (OECD/FAO, 2018). The assumptions of constant elasticity and of constant prices with time, nevertheless, offer us a an important baseline from which we can make comparisons in market dynamics.

6.3 Implications for managing oil palm agriculture

The increasing pressure to meet demands for palm oil, among other tropical crops and commodities means the global tropics face continual forest loss, especially within Indonesia and Malaysia. Demand is likely to keep increasing, and global palm oil prices will be influenced by the biofuel market (Sayer et al., 2012). As the world's leader in palm oil production and export (FAO, 2019), Indonesia faces many challenges in terms of forest loss (Margono et al., 2014) biodiversity (Fitzherbert et al., 2008; Dislich et al., 2017), carbon (Carlson et al., 2013), livelihoods, health and well-being both of the local communities and the region (Sayer et al., 2012). With mounting pressure on tropical forests to feed the ever-growing global palm oil demands, and with the world focusing on Indonesia's efforts to reduce deforestation from oil palm agriculture, it is important we identify the key potential pitfalls of our policies, not just in Indonesia, but across other areas, and other crops pan-tropically.

We need to identify areas vulnerable to further crop expansion, as understanding the spread of crops will improve conservation efficacy (Chaplin-Kramer et al., 2015). Policies must consider how land-use changes affect commodity prices, production costs and, ultimately, agricultural rent and profitability: understanding how these economic forces drive oil palm expansion is key to minimising unanticipated land-use changes (Chapter 3, 5). Whether it be development of road networks and infrastructure that improve accessibility to areas previously not profitable, or imposing and introducing taxes or subsidies, an intricate understanding of how agricultural policies translate to land rent is an important step towards making well-informed projections of future expansion, impacts on forests and biodiversity, and ultimately, developing more focused conservation decisions and interventions (Armsworth et al., 2006). Governing bodies responsible for awarding concessions to companies or smallholders also need to be wary of the spatial contagion and agglomeration effect when planning where to issue land-use and oil palm concessions: forests surrounding newly established plantations are more susceptible to further conversion. Active monitoring of the changes in prices and production costs, especially through spatially explicit land rent models (Chapter 3), allows us to anticipate perverse market outcomes arising from our policies (Chapter 5) and take steps to minimise the negative impacts on remaining forests and biodiversity.

Where the focus of policies centres on improving land-use efficiency and productivity via intensification and high-yielding crop varieties to meet demands, we need to be wary of the potential indirect impacts on encroachment into remaining forests and biodiversity (Chapters 4 and 5). While studies have argued that Indonesia can increase production of palm oil without further deforestation (Afriyanti et al., 2016), changes in land-use practices inevitably affect profitability and land use (Chapter 5), and we still need to consider the implications on land-use change at a larger scale. Studies that focus on the role of economic forces in agricultural expansion in other systems and crops have also argued that the costs of conservation efforts could rise with agricultural intensification: following improved yields, opportunity costs of conserving forests increase due to highly profitable land from improved crop yields (Phelps et al., 2013). As such, agricultural intensification needs to be met with extra legislations, land-use restrictions and monitoring (Phalan et al., 2016), particularly in areas of higher susceptibility to expansion (Chapter 3).

Both Chapters 3 and 5), however, raise concerns surrounding the limited effectiveness that current conservation measures have on reducing rates of oil palm expansion in Indonesia. Despite covering a large extent,only a small percentage of area susceptible to conversion would be protected by the Moratorium. Our model projections of future oil palm expansion described in Chapter 3 showed limited effectiveness the Moratorium against immediate future crop expansion (Lim et al., 2019, Chapter 3). Even with simulated increases in oil palm yields (explored in Chapter 5), the Forest Moratorium showed very little effect on reducing rates of expansion. The low additionality of the Moratorium in protecting forests has previously been flagged by other studies (Sloan et al., 2012; Sumarga and Hein, 2016). Similarly, increased protection of primary and secondary forests with high carbon stocks under the HCS initiative (Rosoman et al., 2017), offers little protection against future crop expansion. Further, protecting areas of high carbon stocks might offer protection of old-growth forests, but we also run the risk of displacement of crop expansion efforts into other unprotected areas (Chapter 5).

It is crucial that studies and policies place emphasis on better land-use planning and allocation of land for resources (Law et al., 2015). Consideration of other areas increased protection needs to factor in the potential increases in rent from existing and future land-use and agricultural policies. Areas with high proportions of existing plantations, for instance, are in need of increased legislation and protection (Chapter 3). For conservation efforts like establishing protected areas to be effective against land-use change, they need to be implemented and prioritised not just in areas with high biodiversity, but also at the frontier of deforestation, i.e., within areas and regions most susceptible to future expansion (Hill et al., 2015). Additionally, while difficult to do, we need to monitor the emergence of displacement of land-use changes.

Policies centred on regulating, restricting and redirecting oil palm agriculture cannot only focus on the benefits within existing plantations and protected areas, but must also consider the potential knock-on effects on other competing land uses and crops across Indonesia, such as rice, maize and rubber (Lim et al., 2017). This includes taking steps to ensure displacement or creation of an unregulated market does not emerge, such as monitoring areas susceptible to forest loss, not just by oil palm but other crops that would have been displaced by palm oil as well (Warren-Thomas et al., 2015).

As an internationally traded commodity with high global demand, conservation interventions targeting oil palm agriculture will undoubtedly have wider market implications, and the impacts of agricultural intensification on the palm oil market could also be amplified when we consider the global market. While oil palm agriculture continues to encroach upon forests and threaten biodiversity across Indonesia, it is also rapidly expanding across other countries (FAO, 2019). It is crucial we consider the potential for leakage in the wider market (Wilman, 2019). Policies and interventions are often directed and localised, but market feedbacks can occur across larger temporal and spatial scales, especially between countries in our increasingly tele-coupled world (Carrasco et al., 2017). Conservation actions within one country could translate to displacement of efforts and land-use changes within other countries (Taheripour et al., 2019; Lim et al., 2017, Chapter 2). Market outcomes of agricultural intensification and improved crop yields could be amplified and therefore lead to greater land-use change (Carrasco et al., 2014); given substitutability of vegetable oils, palm oil demand might be affected as prices drop, following shifts in demands from other vegetable oils (Lim et al., 2017, Chapter 2). Although difficult to assess, this is necessary to consider, if we are to ensure our policies have overall benefit.

6.4 Concluding remarks: managing perverse market outcomes while sustainably meeting global agricultural demands

The key issues raised here are not limited to oil palm agriculture, but are shared across many other commercial crops, commodities and land uses. Market feedbacks are inevitable, occur both at local and global scales, and will affect the efficacy of our policies. Through this project, I have shown how market responses to our conservation efforts could paradoxically undermine our intentions. Policies and practices aimed at protecting forests and biodiversity against agricultural expansion cannot be blind to market feedbacks, and need to consider the intricate interactions with different aspects of the market. Unanticipated land-use changes arising from this oversight could be minimised through consideration of agricultural rent of standing forests. A better appreciation of how economic forces shape crop expansion allows conservation efforts to be prioritised in areas of high conservation value (in terms of carbon, biodiversity) and high susceptibility to agricultural expansion due to increased rents. Ultimately, it will also allow us to better anticipate indirect land use changes arising from market responses, and we can mover closer to developing more effective conservation decisions.

Appendices

Appendix A

Supporting information for Chapter 3: Land rents drive oil palm expansion dynamics in Indonesia

A.1 Methods

Data collection

Table A.1: List of variables, maps and datasets used in oil palm expansion model, for years where prices were not available, we used prices from the previous year.

Variable	Units	Description	Notes	References
Oil palm fruit prices	USD per hectare	Annual national prices of oil palm fresh fruit bunches		FAO, 2019
Potential yield	tonnes per hectare	Spatial variation of potential yield of oil palm fruits		Pirker, Mosnier, Kraxner, Havlík, and Obersteiner, 2016
Timber prices	USD per hectare	Annual prices of exported roundwood	timber harvest fixed at 23.1 m^3 per hectare (FAO, 2009)	FAO, 2019
Prices of fuel	USD per hectare	National gasoline prices	not available for 2001, 2003, 2005, 2007, 2009, 2011, 2013, 2015	GIZ, 2014
Price of fertiliser	USD per hectare	National annual fertiliser prices	not available for 2000, 2001, 2015	FAO, 2019
Labour costs	USD per hectare	National annual wages	not available for 2014, 2015	ILO, 2017

Running and comparing models

We fitted our model to land-use maps in 2000 and 2015, therefore simulating crop expansion across Indonesia each year from 2001 to 2014 — we assumed a one-year time lag between price changes and establishing a plantation. Although we incorporated yearly changes in prices, we assumed in our calculations of NPV_i 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 $Rent_i$, NPV_i and EAC of every cell i that had not been converted into oil palm plantation, using deflated prices of oil palm fruits, labour, fertiliser and fuel in that year as well as the potential yield. We then evaluated the total agricultural rent $EACadj_i$ of that cell via equation (3.3). If the agricultural rent of a given cell in that year was positive, or exceeded the minimum threshold K (i.e., $EACadj_i > 0$), the cell was considered economically viable for oil palm agriculture and we simulated conversion to plantation. $EACadj$ was conducted across cells not classified as oil palm plantations (not yet converted): in doing this we evaluated the extent of areas converted in a single year based on agricultural rent. We then updated prices and distribution of existing plantations to re-evaluate agricultural rent across the remaining unconverted cells the following year, and repeated the process for 2002.

We did this every year until the final year (2014). This gives us spatial predictions of oil palm expansion each year from 2001 to 2015, based on annual variations in overall agricultural rent. To account for zoning laws and additional land-use regulations, yearly oil palm expansion was restricted to areas available for conversion, primarily cells within oil palm concessions and cells considered public land. We did not allow oil palm expansion into cells classified as protected areas and as other plantations (considered private areas), except where oil palm concessions were awarded.

We used an optimisation approach to determine parameter values from equation (3.3) that returned an outcome of oil palm expansion by 2015 with closest resemblance to the known distribution of oil palm plantations. This approach selects the combination of parameters that returned the highest average recall, i.e., the highest average proportion of cells correctly predicted across both classes of oil palm plantations and non-plantations. This approach is similar to a maximum likelihood approach (Bolker and R Core Team, 2017), with the exception that we used the average recall to determine the model with the best fit, since it accounts for proportions of both classes (i.e., unconverted or converted to oil palm plantation) correctly predicted by the model. We adapted the mle() function (Bolker and R Core Team, 2017) and ran the model across multiple iterations, varying the parameters values with every iteration via simulated annealing. This approach allows us to generate multiple iterations with a range of combinations of parameter values from a set of starting values. Starting values were, in turn, determined by manually running iterations at regular intervals, before commencing optimisation. All models were run in R (R Core Team, 2018). To determine a suitable model for evaluating oil palm expansion, we ran this optimisation process over series of six models, each with variations of $EACadj_i$ (Table A.2), and selected the model that performed best for future projections of oil palm expansion across Indonesia.

Table A.2: List of models run and compared to explain oil palm expansion, and their descriptions. Agricultural rent $EACadj$ was calculated for every cell i.

Model	Description	Equation
1	Crop expansion only based on agricultural rent (EAC)	$EACadj_i = EAC_i$
2	EAC adjusted by a national minimum threshold K	$EACadj_i = EAC_i - K$
3	EAC adjusted by K and the effect of soil type P	$EACadj_i = EAC_i - P_i - K$
4	EAC adjusted by K, P and a non-linear contagion effect, S	$EACadj_i = EAC_i - P_i - S \times \sqrt{A_{i,t-1}} - K$
5	EAC adjusted by K and a non-linear contagion effect, S	$EACadj_i = EAC_i - S \times \sqrt{A_{i,t-1}} - K$
6	EAC adjusted by K, P and a linear contagion effect of S	$EACadj_i = EAC_i - P_i - S \times A_{i,t-1} - K$

Model 1 was run as a baseline, where oil palm expansion was only explained by spatial variations in net present value (NPV) and equivalent annual costs (EAC), i.e., $K = 0$. Across Models 2 to 6, in contrast, we allow EAC to be adjusted based on different combinations of parameters and functional forms of the spatial contagion effect (Table A.2). Specifically, across these models we included a national minimum threshold rent (K) needed before land is converted to oil palm plantations. This threshold value could include the opportunity cost of capital, recognising the capital could have been invested elsewhere achieving some baseline profit. K is set constant across space and time. P_i (in models 3, 4 and 6), also set constant across space and time, adjusts EAC_i based on soil type, allowing for additional costs incurred from draining peat swamps prior to conversion. S (in models 4 to 6) relates to the proportion of cells devoted to oil palm surrounding each cell, and is meant to account for potential adjustments in rent associated with the location of the cell in relation to existing oil palm plantations. We used the percentage of plantation area within a buffer (set at 0.1 degrees) for cell i in period $t-1$ ($A_{i,t-1}$), i.e., the previous year, 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. Where the contagion effect was non-linear (models 4 and 5), percentages of plantation within the buffer were square-root transformed ($\sqrt{A_{i,t-1}}$) to capture a specifically convex effect, i.e., the impact on costs increases with the percentage of plantations within the buffer but at a diminishing rate (Table A.2). For each of the six sets of models (calculations of $EACadj$), we determined values of the respective combination of parameters selected within each model via the same optimisation process across multiple iterations (154–784), and selected the model with the highest average recall as the final, best performing model. In this optimisation process, we ran multiple iterations for each model we ran, adjusting parameter values slightly for every iteration.

Due to computational limitations, our oil palm expansion models were fitted on a subset of cells evenly distributed across the total dataset (~24,000 out of 25,111,235 cells). Cells were sampled in a stratified-random manner, ensuring the same proportion of cells were sampled across all provinces. Additionally, given this is a single-crop expansion model across a landscape with other crops and land uses, our model was limited in its analyses of the full extent of oil palm plantations. It is well documented that oil palm plantations not only encroach into forests and peatlands, but displace other crops and land uses too (e.g., Warren-Thomas et al., 2015). However, we were not able to model displacement of other crops by oil palm in our analyses, as this would require information of distribution of other plantations, and comparing agricultural rents of multiple crops and land uses across space and time. Additionally, because we lack information of distribution of oil palm plantations abandoned, we did not take this into account; we would have needed to model yearly potential loss across space and time as part of a separate analysis. We also compared models that do not consider the role of agricultural rent, i.e., only focusing on oil palm suitability. Similar to our additional land-use restrictions, this map of oil palm suitability also considers other factors like protected areas and other land uses.

A.2 Results

We selected Model 4 as our final model for validation and projection of oil palm expansion from 2015 to 2025, given it had the highest average recall (0.7580, Table A.3). In this model, considering a discount rate of 10%, there was a minimum threshold (K = USD10,053 per hectare) and a non-linear contagion effect following a square root relationship (S = 987), but there were no additional costs for cells classified as peatlands. Model 5 (average recall = 0.7568, Table A.3) performed almost as well as our Model 4: average recall was 99.98% as well as Model 4. In this model, however, the minimum threshold (K) was lower (USD9,870 per hectare), but with an additional cost of USD1,307 per hectare on peatlands (P). There was a spatial contagion effect (S = USD941 per hectare), following a square-root relationship. Model 6, which adopted a linear relationship of the contagion effect, also did less well, although difference was marginal (average recall = 0.7547; 99.56% as well as Model 4).

As a baseline, a model explaining oil palm expansion with just EAC (Model 1) was not effective (average recall = 0.6113; 80.65% as well as Model 4). Models that excluded the spatial contagion effect (Models 2 and 3) only performed ~89.31% as well as Model 4 (average recall ~0.6775), providing evidence of the need for the contagion to capture oil palm spread dynamics (Table A.3). An oil palm distribution model only focusing on environmental suitability did 91.8% as well as Model 4 (average recall = 0.6962).

Table A.3: Summary of models run to explain oil palm expansion, in addition to yearly evaluation of the net present value and equivalent annual costs. Models were fitted to a subset of the data (~24,000 out of 25,111,235 cells). A maximum of three additional parameters were used, and for each model we presented the combination of parameters that returned the highest average recall. The model with the highest average recall was selected as our best model for subsequent analyses.

Model	Model Description	N iterations	Best performing model					
			Minimum threshold (K)	Cost to convert on peat (P)	Contagion effect (S)	Functional form describing contagion effect	Average Recall	Accuracy
1	EAC only	1	-	-	-	-	0.6113	0.3884
2	EAC adjusted with K	417	7186.06	-	-	-	0.6797	0.6748
3	EAC adjusted with K and P	784	7186.06	2143.00	-	-	0.6761	0.7082
4	EAC adjusted with K and non-linear contagion effect S	251	10053.39	-	986.90	Square root	0.7580	0.9078
5	EAC adjusted with K, P, and non-linear contagion effect S	154	9869.56	1307.46	941.04	Square root	0.7568	0.9098
6	EAC adjusted with K, P, and linear contagion effect S	200	9085.43	3641.01	479.04	Linear	0.7547	0.8724
7	only considering oil palm suitability	-	-	-	-	-	0.6962	0.7544

Table A.4: Summary of model performance across Indonesia and by provinces. Values are represented as proportions. Model was run on 10% of the data (2,242,417 cells).

Area	Number of cells sampled	Number of sampled cells classed oil palm (2000)	Number of sampled cells classed oil palm (2015)	N cells converted by model by 2015	Expansion detected by model	Proportion of expansion into peat detected	Proportion of predicted expansion into other plantations
Indonesia (Total)	2242417	48358	118768	344151	0.701	0.792	0.505
Aceh	50202	1951	2309	13393	0.629	1	0.513
Bali	6831	0	0	0	0	0	0
Banten	11190	0	162	0	0	0	0
Bengkulu	23531	888	2931	8177	0.759	0	0.689
Bangka Belitung Islands	22948	515	1357	6283	0.589	0.167	0.401
Gorontalo	13650	56	8	2004	1	0	0.126
Jambi	67218	3461	7383	23400	0.772	1	0.660
Java (West)	37448	0	131	0	0	0	0
Java (Central)	42578	0	0	0	0	0	0
Java (East)	55082	0	0	0	0	0	0
Kalimantan (Central)	232020	4018	14182	39126	0.889	0.604	0.451
Kalimantan (West)	213109	1993	7345	44242	0.746	0.583	0.629
Kalimantan (South)	56019	2072	4049	12911	0.682	0	0.507
Kalimantan (East)	172964	1278	8070	25383	0.491	1	0.451
Kalimantan (North)	58060	0	516	0	0	0	0
Lampung	43804	632	2127	18968	0.719	0	0.299
Maluku	52871	0	10	0	0	0	0
Maluku (North)	38272	0	1037	0	0	0	0
Nusa Tenggara (West)	23380	0	0	0	0	0	0
Nusa Tenggara (East)	48099	0	0	0	0	0	0
Papua	297979	59	663	0	0	0	0
Papua (West)	113051	26	282	0	0	0	0
Riau	137956	13281	30617	73930	0.842	0.904	0.474
Riau Islands	7684	1	77	24	0	0	0.042
Sulawesi (Southeast)	43259	9	248	0	0	0	0
Sulawesi (West)	15047	831	920	1181	0.239	0	0.486
Sulawesi (South)	43212	114	243	539	0.224	0	0.185
Sulawesi (Central)	53175	871	681	9637	0.132	0	0.315
Sulawesi (North)	15578	0	224	0	0	0	0
Sumatra (West)	40703	1616	3200	8596	0.721	0.775	0.594
Sumatra (South)	123156	3068	9991	26631	0.561	0.533	0.656
Sumatra (North)	77777	11618	20005	29726	0.673	0.922	0.426
Yogyakarta	4564	0	0	0	0	0	0

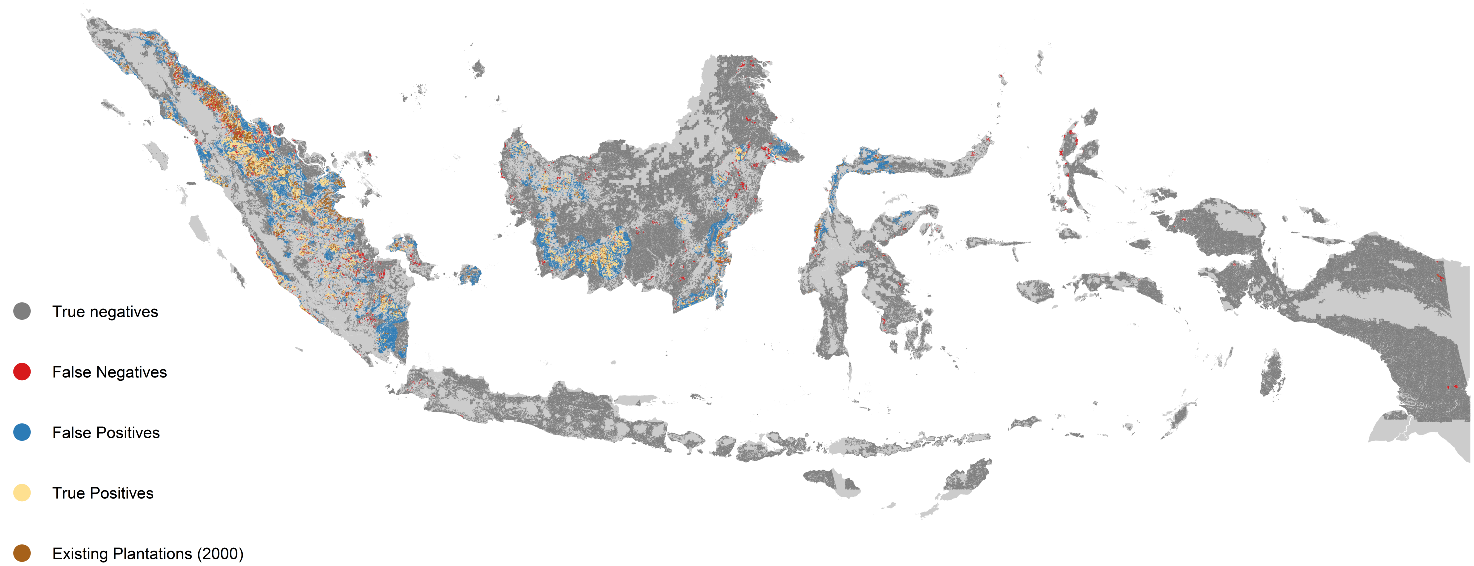

Figure A.1: Performance of oil palm expansion model across Indonesia between 2000 and 2015, validated against a stratified random sample (10%) of cells (250 by 250 m) spanning all provinces (n=2,242,417). Cells classified as other plantations were removed from the figure.

Table A.5: Summary of yearly projections of oil palm expansion from 2015 to 2025, based on model. Projections were made on 10% of the data. Natural areas include areas classified as forests, mosaic vegetation, mangroves and peat swamp forests.

Year	Cells newly converted	Proportion expanded from 2015	Proportion of expansion into natural areas not protected by Moratorium
2016	83533	1.7033	0.9281
2017	179233	2.5091	0.9095
2018	264719	3.2289	0.9064
2019	344216	3.8982	0.9050
2020	413296	4.4799	0.9021
2021	467349	4.9350	0.9001
2022	510179	5.2956	0.8988
2023	541711	5.5611	0.8997
2024	567275	5.7763	0.8983
2025	590089	5.9684	0.8973

Table A.6: Summary of model projections of oil palm expansion in 2025. Projections were made on 10% of the data. Natural areas include areas classified as forests, mosaic vegetation, mangroves and peat swamp forests

Province	Sampled oil palm cells in 2015	Cells newly converted by 2025	Proportion expanded from 2015	Proportion of expansion into natural areas not protected by Moratorium
Bali	0	0	0	0
Banten	162	2722	17.802	0.9982
Yogyakarta	0	0	0	0
Java (West)	131	1467	12.198	0.9959
Java (Central)	0	0	0	0
Java (East)	0	0	0	0
Kalimantan (Central)	14182	106769	8.528	0.9174
Kalimantan (West)	7345	96935	14.197	0.8873
Kalimantan (South)	4049	23318	6.759	0.9854
Kalimantan (East)	8070	80967	11.033	0.9557
Kalimantan (North)	516	28540	56.310	0.9235
Maluku	10	0	1	0
Maluku (North)	1037	12738	13.284	0.9104
Nusa Tenggara (West)	0	0	0	0
Nusa Tenggara (East)	0	0	0	0
Papua	663	13377	21.176	0.7683
Papua (West)	282	22603	81.152	0.7319
Gorontalo	8	4962	621.250	0.8928
Sulawesi (Southeast)	248	2590	11.444	0.9456
Sulawesi (West)	920	3024	4.287	0.9581
Sulawesi (South)	243	2895	12.914	0.9713
Sulawesi (Central)	681	16219	24.816	0.8041
Sulawesi (North)	224	1786	8.973	0.9311
Aceh	2309	12463	6.398	0.9060
Bengkulu	2931	3882	2.324	0.9223
Jambi	7383	14332	2.941	0.8863
Bangka Belitung Islands	1357	5164	4.805	0.8821
Riau Islands	77	1388	19.026	0.7852
Lampung	2127	19819	10.318	0.9808
Riau	30617	57341	2.873	0.7749
Sumatra (West)	3200	8614	3.692	0.9657
Sumatra (South)	9991	27470	3.749	0.9267
Sumatra (North)	20005	18704	1.935	0.9578

Appendix B

Supporting information for Chapter 5: Oil palm intensification generates indirect land-use impacts that drive biodiversity loss in Indonesia

Table B.1: Summary of environmental and biodiversity impacts, based on model projections of oil palm expansion from 2015 – 2020 across different conservation and land-use scenarios. Simulations were conducted on 10% of the total data cells (~2,400,000 cells) and scaled up to calculate the amount of oil palm fruits produced, the total extent of oil palm and the amount of carbon stocks lost from new expansion.

Scenario Number	Yield	Land-use Restrictions	Changes in Prices across years	Total amount produced in 2020 (million tonnes)	Total extent of oil palm by 2020 (million hectares)	Carbon stocks lost from newly converted areas (Mega tonnes)	Number of species with ranges reduced					
							Critically Endangered	Data Deficient	Endangered	Near Threatened	Vulnerable	Total
1	Current potential yields	No additional restrictions	prices constant from 2015	129.33	9.31	121.30	24	101	51	204	129	509
2	Current potential yields	No additional restrictions	Price fluctuations according to OECD	190.46	13.75	520.55	26	108	53	209	135	531
3	Increased potential yields	No additional restrictions	prices constant from 2015	257.85	13.75	527.27	26	107	55	210	134	532
4	Increased potential yields	No additional restrictions	Decrease in prices from 2015	257.73	13.75	506.70	27	107	53	211	135	533
5	Current potential yields	Moratorium	prices constant from 2015	129.27	9.31	121.20	24	101	51	204	129	509
6	Current potential yields	Moratorium	Price fluctuations according to OECD	190.43	13.75	519.29	26	108	53	209	135	531
7	Increased potential yields	Moratorium	prices constant from 2015	257.85	13.75	527.80	26	107	54	210	134	531
8	Increased potential yields	Moratorium	Decrease in prices from 2015	257.68	13.75	506.61	27	107	53	210	135	532
9	Current potential yields	Moratorium + HCS	prices constant from 2015	129.20	9.30	121.80	24	101	51	204	129	509
10	Current potential yields	Moratorium + HCS	Price fluctuations according to OECD	190.44	13.75	523.31	26	108	53	209	135	531
11	Increased potential yields	Moratorium + HCS	Prices constant from 2015	257.86	13.75	532.04	26	107	54	210	134	531
12	Increased potential yields	Moratorium + HCS	Decrease in prices from 2015	257.69	13.75	510.30	27	107	53	210	135	532

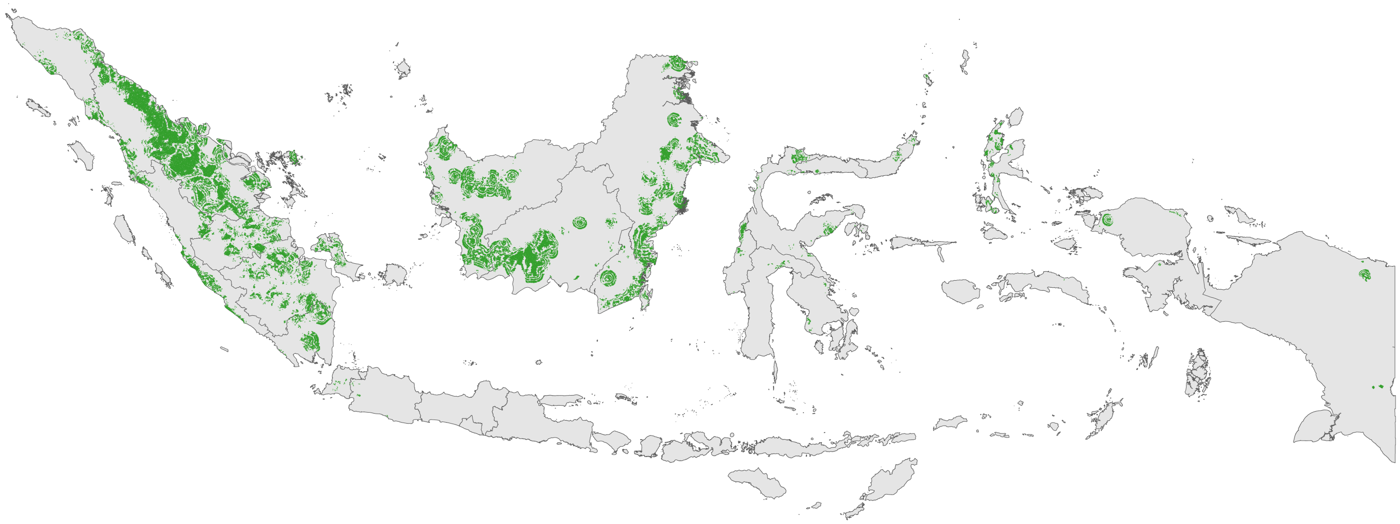

Figure B.1: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, assuming current potential yields and constant prices across years. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

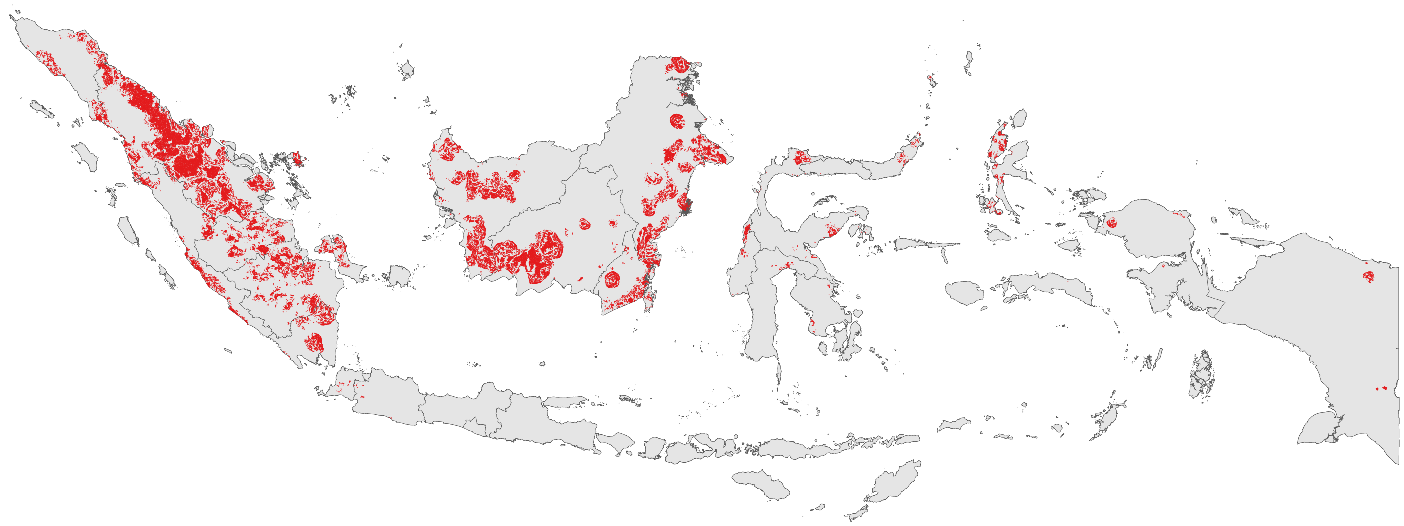

Figure B.2: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, considering additional land-use restrictions from Indonesia's Forest Moratorium, assuming current potential yields, while allowing prices to vary in accordance with FAO and OECD forecasts. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

Figure B.3: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, considering additional land-use restrictions from Indonesia's Forest Moratorium, simulating increased oil palm yields while keeping prices constant across years from 2015. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

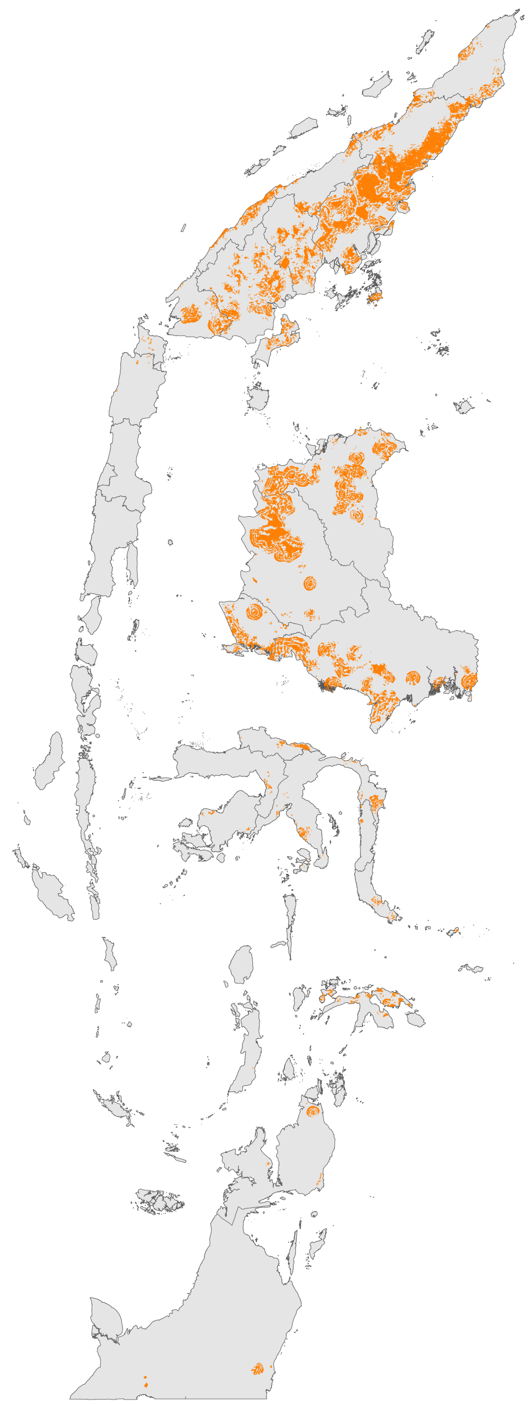

Figure B.4: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, considering additional land-use restrictions from Indonesia's Forest Moratorium, simulating increased oil palm yields and reduced prices of oil palm fruits from 2015. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

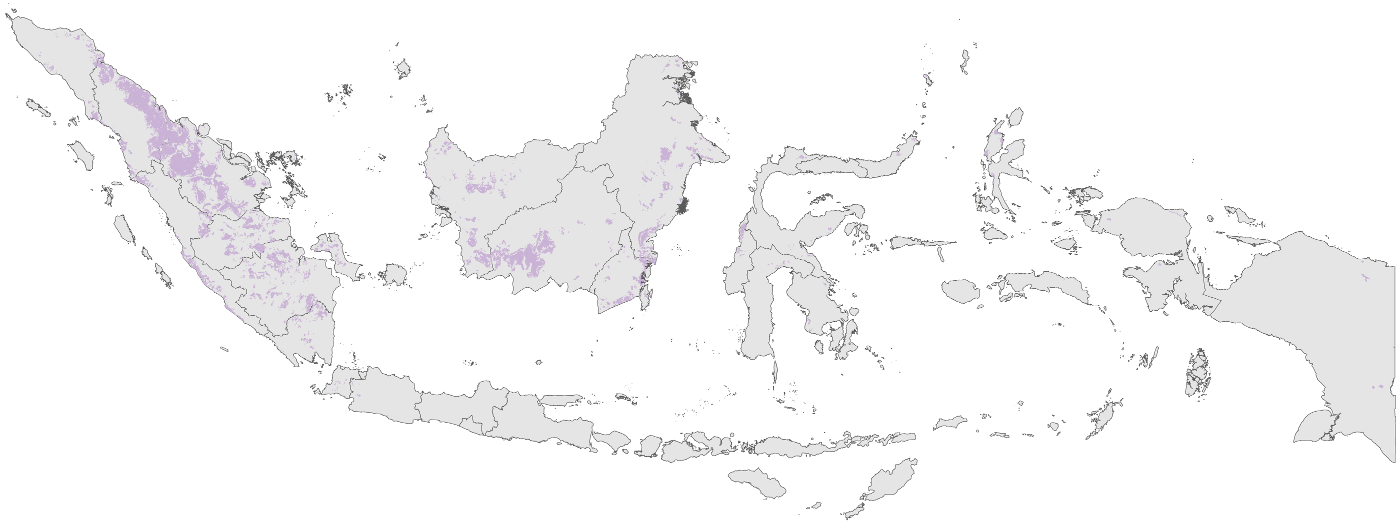

Figure B.5: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, considering additional land-use restrictions from Indonesia's Forest Moratorium and the HCS initiative, assuming current potential yields and constant prices across years. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

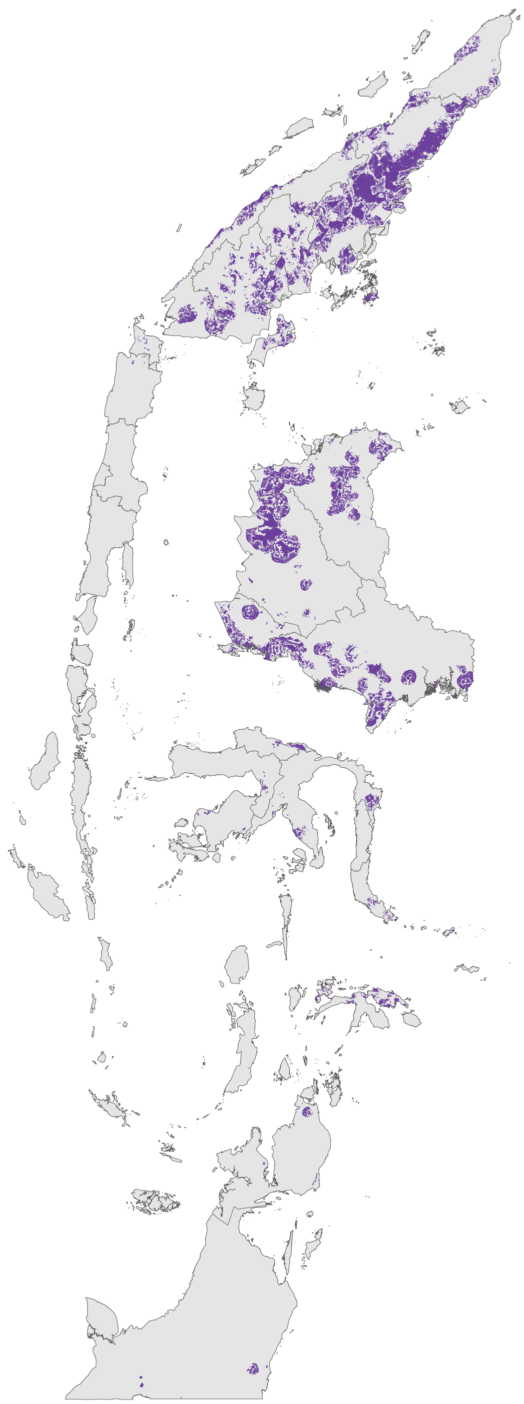

Figure B.6: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, considering additional land-use restrictions from Indonesia's Forest Moratorium and the HCS initiative, assuming current potential yields, while allowing prices to vary in accordance with FAO and OECD forecasts. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

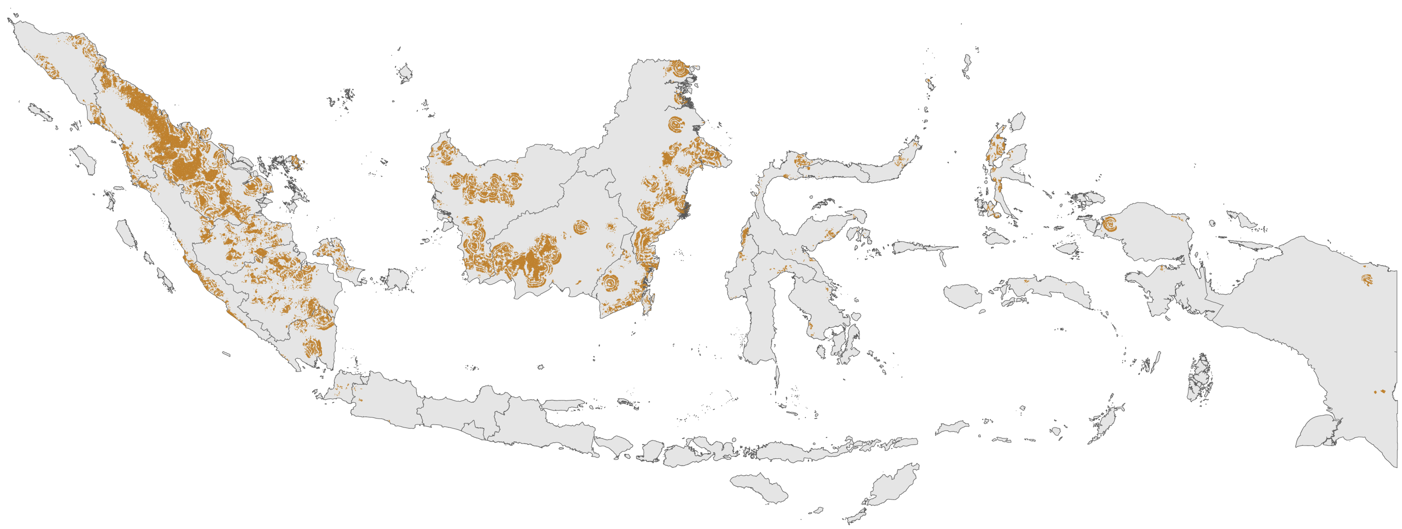

Figure B.7: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, considering additional land-use restrictions from Indonesia's Forest Moratorium and the HCS initiative, simulating increased oil palm yields while keeping prices constant across years from 2015. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

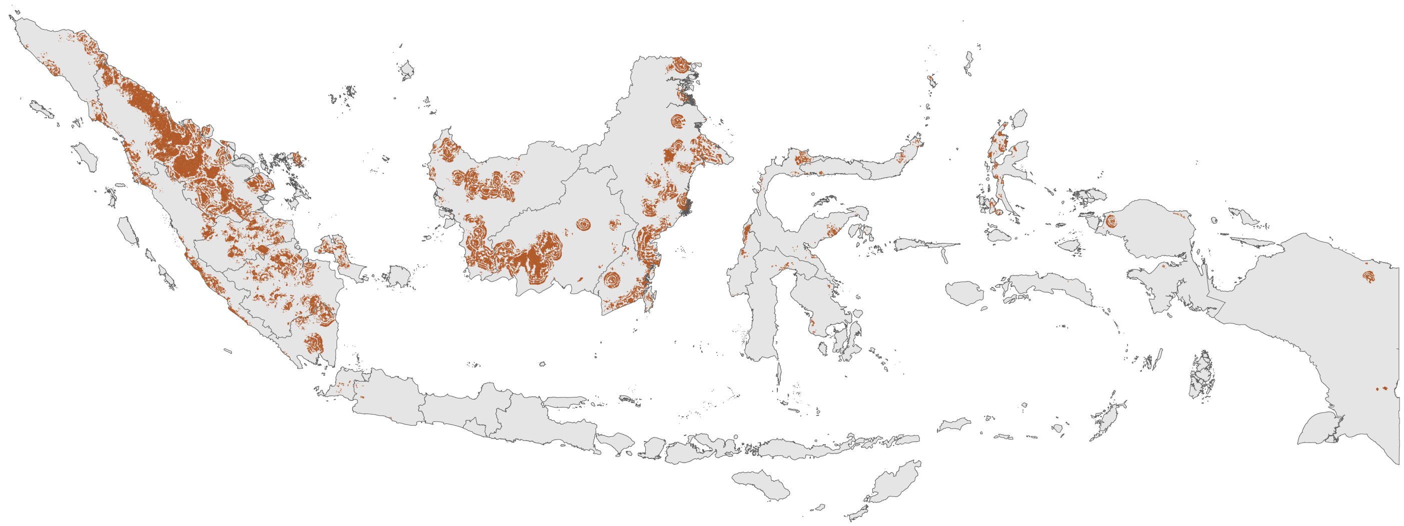

Figure B.8: Model projections of areas susceptible to further oil palm expansion across Indonesia by 2020, considering additional land-use restrictions from Indonesia's Forest Moratorium and the HCS initiative, simulating increased oil palm yields and reduced prices of oil palm fruits from 2015. Projections were conducted on a sample (10%) of cells deemed suitable for crop expansion, including existing plantations and natural areas.

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