ABSTRACT

Title of Dissertation:	FOREST CHANGE AND OIL PALM EXPANSION IN INDONESIA: BIOPHYSICAL AND SOCIOECONOMIC ANALYSIS
	Yu Xin, Doctor of Pilosophy, 2022
Dissertation directed by:	Dr. Laixiang Sun, Professor, Department of Geographical Sciences

Palm oil is the world's most widely used edible oil, and Indonesia has been the largest producer since 2007 and now makes up around 58% of the global market. The oil palm production has benefited the economic growth and lifted the living standards of local people in Indonesia, but this gain is often at the cost of replacing tropical forest, destructing peatland, inducing greenhouse gas (GHG) emissions, and reducing biodiversity. The expansion of oil palm plantation in Indonesia is bound to increase as the global demands continue to grow. The challenge of meeting the increased demand for oil palm products while effectively protecting tropical forest and its ecosystem services is an important tradeoff issue for both scientists and policymakers. However, little is known on the expansion patterns of oil palm in Indonesia, especially the underlying drivers with temporal and spatial details. To effectively address the knowledge gaps and deal with the challenges, this dissertation aims to first characterize the historical patterns driven by the variations in the benefits and costs of oil palm expansion across space and over time. It then projects the possible future spatial patterns and estimates the potential loss of land with high environmental values in order to meet the future global demand for oil palm products.

This dissertation consists of three principle essays. The first essay identifies the major land sources of oil palm expansion in Indonesia with temporal details, and reveals the joint role of biophysical and socioeconomic drivers in shaping the spatial patterns of oil palm expansion by employing spatial panel models at the regency level. The second essay focuses on the temporal dynamics of the biophysical and socioeconomic drivers and the timing of estate crop (mainly oil palm) expansion by using Cox proportional hazard models (CPHMs) and their extensions with time-variant effects at the 1km × 1km grid level. It also explores the role of land use and land cover change (LCLUC) trajectory hopping in estate crop expansion into natural forest by introducing multi-state survival analysis to land-use science. The third essay projects the export demand for oil palm products from Indonesia by 2050 under different global trade scenarios with generalized geo-economic gravity models, and quantifies the possible tradeoffs between oil palm expansion and environmental conservation by allocating the projected demand to 1km × 1km grids across Indonesia applying parametric survival analysis.

This study indicates that oil palm expansion in Indonesia has been strongly stimulated by the export value of oil palm products and prefers land with good biophysical suitability and infrastructure accessibility. As land resources become more limited, the effects of socioeconomic factors decrease following the 'pecking order' sequence, and the plantation expands into remote but fertile areas with high conversion costs or legal barriers. The degraded land surpassed natural forest and became the major direct land source of oil palm expansion in recent years, but degraded land had increasingly served as a land banking mechanism and a clearing-up tactic. This LCLUC trajectory hopping mechanism has made the protected area (PA) designations and sustainable development requirements become less and less effective in protecting tropical natural forest. Lowland secondary forest and peatland are the high-environmental-value (HEV) areas with the highest risks of conversion to oil palm plantation. To cope with the LCLUC trajectory hopping mechanism, Indonesia needs to have well-designed and fully enforced policies which limit/ban expansion into protected areas, peatland conversion, and deforestation of both primary and secondary forest. The country also needs more effective economic compensation mechanisms to promote more environment-friendly oil palm plantation. In this way, it is possible for Indonesia to maintain its leading position in oil palm production and exportation, while enhancing its role in environmental protection, such as climate change mitigation and biodiversity conservation.

This dissertation improves our understanding of oil palm expansion in Indonesia by integrating economic science theory, advanced econometric techniques, and the best available remote-sensing data. It adds to the existing literature on analyzing the impacts of human behaviors on LCLUC at various spatial and temporal scales, especially from a longitudinal perspective.

FOREST CHANGE AND OIL PALM EXPANSION IN INDONESIA: BIOPHYSICAL AND SOCIOECONOMIC ANALYSIS

by

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Dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park, in partial fulfillment of the requirements for the degree of Doctor of Philosophy
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Foreword

Chapters 2-4 contain jointly authored work in which Yu Xin is the primary author. Yu Xin conducted data analysis and led manuscript drafting with advisory input from other authors who are named in the corresponding chapters.

Dedication

To my parents for their unconditional love,

and to the memory of my grandpa who passed away in 2021

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Table of Contents

Contents

List of Tables

List of Figures

List of Abbreviations

AEZ	Agro-Ecological Zones
AIC	Akaike's information criterion
AWC	Available water storage capacity
BACI	Before-after-treatment-intervention
BI	Bird of International
CIESIN	Center for International Earth Science Information Network
CIS	Commonwealth of Independent States
CPHM	Cox proportional hazard model
CPI	Consumer price index
DEM	Digital Elevation Model
DSSAT	Decision Support System for Agrotechnology Transfer
EU	European Union
FAO	United Nations Food and Agriculture Organization
GAEZ	Global Agro-Ecological Zones
GPW	Gridded Population of the World
GDP	Gross domestic product
GHG	Greenhouse gas
GLOBIOM	Global Biosphere Management Model
HEV	High environmental value
HWSD	Harmonized World Soil Database
IIASA	International Institute for Applied Systems Analysis
ILUC	Indirect land use change
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
ISPO	Indonesian Sustainable Palm Oil scheme
ISRIC	International Soil Reference and Information Centre
ISSCAS	Chinese Academy of Sciences
IUCN	International Union for Conservation of Nature
JRC	Joint Research Centre of the European Commission
LAM	Latin America
LCLU	Land cover and land use
LCLUC	Land cover and land use change
MENA	Middle East & North Asia
MoEF	Ministry of Environment and Forestry
MRV	Monitoring, Reporting, and Verification
NAM	North America
NASA	National Aeronautics and Space Administration
OCE	Oceania
PA	Protected area
PADDD	Protected area downgrading, downsizing and degazettement
PE	Partial equilibrium
REDD+	Reducing Emissions from Deforestation and Forest Degradation
RoA	Rest of Asia
RoSEA	Rest of Southeast Asia

RoW	Rest of World
RSPO	Roundtable on Sustainable Palm Oil
RTA	Regional trade agreements
SSA	Sub-Saharan Africa
SSP	Shared Socioeconomic Pathways
SUR	Seemingly unrelated regression
TRAINS	Trade Analysis Information System
UML	Universal Mill List
UN	United Nation
USDA	U.S. Department of Agriculture
VIF	Variance inflation factor
WDI	World Development Indicates
WITS	World Development Trade Solution
WHO	World Health Organization
WTO	World Trade Organization
WWF	World Wildlife Found
WRI	World Resources Institute
WDPA	World Database on Protected Areas
WFDEI	Water and Global Change Program Forcing Data European Reanalysis Interim

1 Introduction

1.1 Background and motivation

Oil palm (*Elaeis guineensis*) is among the world's most important oil crops. It is native to Africa and has been grown and used for local consumption for centuries (Jones & Hughes, 1989). Oil palm plantation has boomed in the last few decades, driven by the increasing global demand for vegetable oil and the globalized supply chains (Henders et al., 2015; Sayer et al., 2012). Palm oil is currently the most consumed edible oil in the world (WWF. 2017). It is used as cooking oil for direct human consumption, as ingredients in many processed foods, pharmaceuticals, detergents, cosmetics, and as biofuel (Qaim et al., 2020). According to USDA (2021a, b), the worldwide production volume of palm oil has increased from 15 million tons to 73 million tons in 2021. The rapid demand for palm oil has led Indonesia to experience the world's largest modern agricultural export expansion (Edwards, 2019). Oil palm was firstly introduced to Indonesia in late nineteenth century (Cramb & Curry, 2012), and started to boom since the mid-1980s (Qaim et al., 2020).

Indonesia has been the largest producer of oil palm products since 2007 and shared approximately 58% of the global market in 2020 (USDA, 2021a, b). Over 66% of palm oil produced in Indonesia is used for export (USDA, 2021b). The oil palm production and export has benefited the economic growth and improved the living standards of local people in Indonesia remarkably in the last two decades, especially in the rural area (Clough et al., 2016; Dib et al, 2018; Edwards, 2019; Euler et al., 2017; Gotta et al., 2017; Purnomo et al., 2020). It is believed to have lifted up to 2.6 million rural residents from poverty during 2000-2016 (Edwards, 2019).

However, the production of palm oil in Indonesia is often criticized for its damage to environment. The increase of oil palm production in Indonesia is mainly contributed by the expansion of the oil palm plantation area rather than the increase of oil palm yields (FAO, 2021). According to the United Nations Food and Agriculture Organization (FAO), the plantation area of oil palm increased from 1.43 million ha to 8.63 million ha in Indonesia from 1996 to 2015 (FAO, 2021). The expansion is even larger when estimated from the recent remote sensing products. Petersen et al. (2016) demonstrates that the plantation of oil palm amounts to 14.1 million ha in Indonesia in 2014, accounting for 62% of the total plantation areas of estate crops in the country. The rapid expansion of oil palm has occurred at the expense of other land covers/uses, such as natural forest, shrub, and other agricultural lands, and has been a major driving force of land cover and land use change (LCLUC) in Indonesia. Oil palm expansion in Indonesia is believed to result in deforestation and destruction of peatland. Indonesia is among the countries with highest rates of deforestation (Achard et al., 2004; Hansen et al., 2009; Margono et al., 2014; Sodhi et al., 2010) and oil palm expansion has been a major driver of the deforestation (Abdullah, 2012; Hansen et al., 2009; Koh & Wilcove, 2008; Miettinen et al., 2011; Vijay et al., 2016; Wicke et al., 2011). Approximately 80-85% of Indonesian deforestation in the 2000s occurred in Kalimantan and Sumatra (Hansen et al., 2009; Miettinen et al., 2011), where also holds over 90% of oil palm expansion during the same period (Abdullah, 2012; Wicke et al, 2011). More than 56% of oil palm expansion in Indonesia occurred at the expense of forests (Koh & Wilcove, 2008; Vijay et al., 2016), 60% of deforestation in Kalimantan and 20%

of forest clearing in Sumatra was owing to oil palm expansion (Carlson et al., 2013; Lee et al., 2014). Around one-tenth of the oil palm plantation in Indonesia were established on peatlands, more than 4% of peatland converted to oil palm plantation by early 2000s (Koh et al., 2011). Such loss of tropical forests and peatlands imposes severe damage to the environment, such as greenhouse gas (GHG) emissions and biodiversity lost (Carnus et al., 2006; Koh et al., 2011; Koh & Wilcove, 2008). Emission from forest conversion and other land-use changes are the main sources of GHG emissions in Indonesia, accounting for around 80% of its total emissions and placing it in the top 10 of global emitters (WRI, 2019). Large quantities of carbon have been released from the clearing and draining of tropical peatlands, since the emission includes not only carbon from the above-ground biomass, but also from the decomposition of wet plant material below ground (Koh et al., 2011). Meanwhile, Indonesia is one of the most biodiversity-rich nations in the world, spanning the Sundaland and Wallacea biodiversity hotspots (Myers et al., 2000), and leads the world in threatened mammals and birds (Sodhi et al., 2009). Approximately 135 species which account for approximately 1/3 of Indonesia's native mammals, as well as 319 species of its native birds are threatened (BI, 2000; Hilton-Taylor, 2000). Oil palm plantation is believed to be the greatest immediate threat to biodiversity in Southeast Asia since monocultures for oil palm production supports significantly less biodiversity than natural land covers and most other plantations (Imron et al., 2010; Wilcove et al., 2013).

In response to the environmental concerns, there are growing movements boycotting palm oil (European Union Parliament news, 2018). As the consumer pressure increased, actions have been taken by the government, international organizations, and palm oil companies, to prevent oil palm expansion into natural forest. The palm oil sectors, together with World Wildlife Found

(WWF), developed its own sustainable certification standards, the Roundtable on Sustainable Palm Oil (RSPO) in 2004 (Von Geibler, 2013). The Indonesian government launched its Indonesian Sustainable Palm Oil scheme (ISPO) (Barthel et al., 2018) and a moratorium on the conversion of peatland and primary forests in 2011 (Indonesian President Instruction no. 10, 2011; Indonesian President Instruction no. 6, 2013). Meanwhile, more companies pledge to eliminate deforestation from their palm oil supply chains (United Nations, 2014), and most of internationally traded palm oil was controlled by companies committed to zero-deforestation palm oil sourcing by 2015 (Bulter, 2015). Indonesian officials and oil palm companies dispute the claims that oil palm plantation is responsible for the loss of natural forest, instead, they demonstrate that the majority of the plantations are established on degraded lands (Armindya et al, 2014; Sheil et al., 2009). Several studies also suggest that low-biomass land, such as shrub and dry agriculture, has become major sources of oil palm expansion in recent years, surpassing natural forest (Agus et al., 2013; Austin et al., 2017; Austin et al., 2019; Gaveau et al., 2016; Gunarso et al., 2013; Vijay et al., 2016).

Oil palm establishment on degraded land or land with low biomass shine lights on the sustainability of oil palm plantation. Since oil palm plantation usually increases carbon stocks than degraded land, like shrub and bare ground (Agus et al., 2009; Germer & Sauerborn, 2008), it is possible that future growth of oil palm plantation could preserve the gains in economic development while providing better environmental supports in terms of climate change mitigation. Austin et al. (2017) demonstrated that around 30.2 million ha of biophysically suitable non-forest land in Indonesia are available for oil palm plantation, and Afriyanti et al. (2017) estimated that with a potential production rate of 27-38 tons fresh fruit bunches/ha, 17-26 million ha in Indonesia is potentially suitable for oil palm while avoiding further cultivation of peatlands and forest. However, why oil palm expansion has shifted to low-biomass land, and the backstories, specifically the sources and timing, of the establishment of the low-biomass lands, remain to be seen. Although the oil palm expansion replacing natural forest peaked in 2008-2009 and followed by a gradual decline, the deforestation rate in Indonesia has experienced a fluctuant increase in 2000-2016, with conversion of forests to shrubland and small-scale agriculture, which are the new major sources of oil palm expansion, increased notably in recent years (Austin et al., 2019; Cisneros et al., 2021). Whether the expansion of oil palm indirectly drives deforestation is an important issue worth investigating, and it may have profound influence on environmental conservation.

The global demand for oil palm products is expected to grow as the world's population continues its march towards nine billion people by 2050 (Nelson et al., 2010), consumer's preference shifts towards vegetable oil containing lower trans-fat due to health consciousness (WHO, 2015), the demand for biofuel blending increases driven by climate change concerns (Castiblanco et al., 2013; Murugesan et al., 2009), and oil palm by far is the oil crop with the highest oil production per unit of land and lowest price to produce (Carter et al., 2007; Sheil et al., 2009). Corley (2009) estimated that the global demand for palm oil is likely to reach 190-256 million tons in 2050 and would require another 25.4-53.0 million ha of oil palm plantation. Oil palm expansion would continue to occur in Indonesia to support the global demand and benefit the well-being of local people, even though there is growing commitment to protect tropical forest, reduce GHG emissions, and conserve biodiversity. In order to more effectively facilitate the projection of future trends and the improvement of land use planning and governance so as to balance the increased demand for oil palm products with the growing commitment to protect tropical forest and its ecosystem services, there is an urgent need to rigorously assess the effects of biophysical and socioeconomic drivers of oil palm expansion in Indonesia both across space and over time.

1.2 Review of previous studies

1.2.1 Oil palm expansion and deforestation in Indonesia

Indonesia is among the countries with the highest deforestation rates, and oil palm has been regarded as one of the major reasons. Koh & Wilcove (2008) employed the FAO data and found that around 56% of oil palm plantation were at the expense of deforestation. In recent years, remote sensing gained its popularity in monitoring humid tropical forest extent and changes, MODIS and Landsat data are widely used due to their public availability and long-lasting continuous record. UMD remote-sensing team first quantified the extent of forest clearing in Indonesia during 1990-2005 based on AVHRR and MODIS data (Hansen et al., 2009), and then successfully disaggregated the total forest cover loss, primary/non-primary status and landforms for Indonesia in 2000-2012 with Landsat data (Margono et al., 2014). It is vital to distinguish between natural forest and planted agro-industrial forest, since high-biomass natural forests supports remarkably higher biodiversity and larger carbon sequestration than the short-cycle plantations. Koh et al. (2011) mapped the extent of oil palm expansion in tropical peatlands in the lower lands of Peninsular Malaysia, Borneo and Sumatra, and Lee et al. (2014) identified the land sources of oil palm plantation in Sumatra based on MODIS data. Due to its longer service time and better spatial resolution, Landsat is used more frequently in such studies (Austin et al., 2017; Austin et al., 2019; Carlson et al., 2013; Gaveau et al., 2016; Gunarso et al., 2013; Vijay et al., 2016). Carlson et al. (2013) quantified the conversion of forest to oil palm plantation during 1990-2010 in Kalimantan, Gunarso et al. (2013), Gaveau et al. (2016), and Austin et al. (2017) examined industrial plantation or oil palm expansion and the land sources of such expansion with more temporal details, Vijay et al. (2016) and Austin et al. (2019) further estimated the impact of oil palm expansion on deforestation. These studies provided reliable information on where the oil palm or industrial plantation expansion occurred and to what extent the expansion is at the expense of natural forest, however, as the temporal resolution changes, the conclusions of these studies differ. Those studies with a time-step longer than 15 years show that more than half of oil palm or industrial plantation expansion in Indonesia occurred at the expense of natural forest (Carlson et al, 2013; Koh & Wilcove, 2008; Lee et al., 2014), meanwhile, the studies with a 5-year time-step show that land with relatively low biomass, such as shrub and dry agriculture, surpassed natural forest and became major sources of the expansion in recent years (Austin et al., 2017; Gaveau et al., 2016; Gunarso et al., 2013; Vijay et al., 2016). There is a knowledge gap on why such differences occurred and on the backstories of the low-biomass lands, which may have profound influence on environmental conservation. Being more specific, the objective information is limited on why oil palm expansion shifted to low-biomass land cover and land use (LCLU) types, where those low-biomass lands came from and when the conversion occurred, and whether the expansion of oil palm from those lands indirectly contributed to deforestation.

1.2.2 Drivers shaping oil palm expansion pattern

Given the history of oil palm plantation in the past few decades in Indonesia, as well as its role in LCLUC and environmental conservation, it is important to assess how the expansion patterns are affected by the biophysical and socioeconomic factors. However, the related studies are inadequate. Piker et al. (2016) and Vijay et al. (2016) assessed the biophysical suitability for oil plantation by identifying suitable ranges of climate, soil, and topography conditions and by using Global Agro-Ecological Zones (GAEZ) model, respectively. Gatto et al. (2015) and Euler et al. (2016) investigated the role of socioeconomic and policy factors in shaping land use dynamic at village level using survey data in Jambi, Sumatra, with seemingly unrelated regression (SUR) and duration model, respectively. There are also several studies considering both biophysical suitability and socio-economic factors. Castiblanco et al. (2013), Austin et al. (2015), Sumarga & Hein (2016) and Shevade & Loboda (2019) each analyzed the land use transitions generated by the oil palm expansion in Colombia over 2002-2008, in Kalimantan during 2000-2010, in Central Kalimantan during 2005-2010, and in Peninsular Malaysia between 1988 and 2012 at the grid-cell level using logistic regression models, with the aim to address biophysical suitability as well as market and infrastructure accessibility. However, as LCLUC for oil palm is fundamentally economic driven (Armsworth et al., 2006; Lim et al., 2019) and the majority of oil palm production in Indonesia is for exporting (Edward, 2019; Indonesia-Investments, 2017; Rulli et al., 2019), the oil palm plantation in Indonesia should be largely influenced by the export markets. Nonetheless, to my best knowledge, Lim et al. (2019), using a novel land rent modelling framework at 250m×250m grids, is the only research addressing the role of potential economic returns from converting other LCLUs to oil palm plantation in explaining and predicting oil palm expansion. In addition, these studies have limited ability in addressing the effects of time-variant variables and/or the complex spatial contagion. Therefore, there is an urgent need for better understanding of the coupled human and natural mechanisms that drive the dynamics and shape the patterns of oil palm plantation with spatial and temporal details.

1.2.3 Projection of future oil palm expansion

The existing literature on projections of oil palm plantation usually extrapolates historical rates of LCLUC (Austin et al., 2015; Carlson et al., 2013; Castiblanco et al., 2013), identifies lands with high biophysical agricultural suitability (Koh & Ghazoul, 2010; Pirker et al., 2016; Vijay et al., 2016), and/or incorporate policy interventions or national goals (Austin et al., 2015; Carlson et al., 2013; Castiblanco et al., 2013; Koh & Ghazoul, 2010; Sumarga & Hein, 2016). Some studies sequentially downscaled and spatially allocated the projection at the national level to finer scale based on the results of logistic regressions which feature the trade-offs between oil palm plantation and environmental protection (Austin et al., 2015; Castiblanco et al., 2013; Sumarga & Hein, 2016). The methods are not without their problems since they make little use of the temporal information nonetheless the demand for oil palm products and the corresponding land use had experienced rapid changes in the last few decades. As the majority of Indonesian oil palm products are for export, and the increasing demand from the global markets has been a major reason of oil palm expansion in Indonesia (Henders et al., 2015), a few studies approached the estimation of future oil palm production from the global demand and/or global trade perspective in recent years. Afriyanti et al. (2016) estimated the global palm oil demand based on the demand for cooking oil and biodiesel as affected by population growth, consumption level, and biodiesel mandates. Mosnier et al. (2017) and Wiebe et al. (2019) projected the demand from Indonesia based on partial equilibrium (PE) models. However, these studies either were not spatially explicit (Afriyanti et al., 2016; Wiebe et al., 2019) or neglected the effects of socioeconomic factors (Mosnier et al., 2017). Therefore, there is a knowledge gap on describing the environmental costs of Indonesian oil palm expansion to meet the growing global market of oil palm products.

1.3 Research questions and objectives

The dissertation is developed in this aforementioned context that there are tough challenges for policymakers and other stakeholders to balance the increased oil palm production in Indonesia with the growing commitment to protect tropical forest as well as its environmental services. To effectively deal with the challenges and attain sustainable production, this dissertation aims to fill in the important knowledge gaps discussed above and develop an in-depth understanding of the oil palm expansion pattern in Indonesia. In order to achieve this goal, this research focuses on characterizing the spatial and temporal patterns of oil palm expansion in Indonesia under the biophysical and socio-economic drivers, and estimating the trade-offs between oil palm production and environmental conservation. The research is divided into three tasks in the flowing chapters.

(1) Question: What are the major land sources of oil palm expansion in Indonesia? Why oil palm expansion distributes with such spatial patterns?
Objective: Identify the major land sources of oil palm expansion from recent remote sensing products, and establish spatial econometric models to quantify the responsiveness of oil palm expansion to the benefits and costs of converting other LCLU types to oil palm plantation at the regency level.

(2) Question: How do the biophysical and socioeconomic factors drive the temporal dynamics of oil palm expansion into natural forest?

Objective: Employ the Cox proportional hazard models (CPHM) and their extensions with time-dependent effects and multi-state analysis to describe the temporal trajectories of oil palm expansion into natural forest and estimate the probabilistic relationships between oil palm expansion and conversion benefits and cost at the grid level, with a special attention to the effectiveness of protected areas over time.

(3) Question: What will be the survival probability of each grid-cell of existing LCLU types to oil palm expansion by 2050?

Objective: Project the oil palm expansion across space by 2050 based on the empirical relationships under different socioeconomic scenarios and quantify trade-offs with environmental conservation.

The research is expected to contribute to the existing literature on analyzing the impacts of human behaviors on LCLUC at various spatial and temporal scales by integrating economic theories, advanced econometric techniques, and best available remote sensing products.

1.4 <u>Structure of the dissertation</u>

To achieve the objectives and answer the questions above, this dissertation consists of five chapters. Chapter 1 provides the general background and motivation of the research, presents a brief overview of the literature on oil palm expansion in Indonesia, and proposes the research questions and objectives, as well as the structure of the dissertation.

Chapter 2 focuses on the land sources of oil palm expansion, and the joint role of biophysical and socioeconomic factors in shaping the spatial patterns of oil palm expansion. This chapter provides a systematic Indonesian-wide quantification of oil palm expansion into different LCLU types with spatial and temporal details and employs a spatial panel modeling approach at regency (second administrative) level to investigate how the benefits and costs of converting other LCLU types to oil palm plantation affects the expansion patterns. It also compares the similarities and differences of the effects of biophysical and socioeconomic driving factors on oil palm expansion into different LCLU types on different islands. Chapter 2 was published in Environmental Research Letters (Xin et al., 2021).

Chapter 3 explores the temporal dynamics of estate crop (mainly oil palm) expansion into natural forests in Indonesia and pays special attention to the expansion into protected areas (PAs). This chapter employs CPHMs and their extensions with time-variant effects at 1km × 1km grid level to characterize the temporal dynamics of estate crop expansion into natural forest in response to the biophysical and socioeconomic drivers. It also depicts the LCLUC trajectories driven by estate crop expansion and reveals the roles played by intermediate status in the conversion from natural forest to estate crop plantation. I introduce multi-state analysis to land-use science to take the intermediate events of LCLUC along temporal trajectory and the complicated relationships among all the LCLUC states into consideration. This chapter is also among the first to demonstrate how the effectiveness of PAs changes over time and explain the trajectories of the changes. This chapter was presented in 2021 Fall AGU conference and is under review for publication in Global Environmental Change – Human and Policy Dimensions.

Chapter 4 projects the export demand for oil palm products from Indonesia by 2050 under different global trade scenarios and estimates the spatially explicit pattern of future oil palm expansion. It employs geo-economic gravity models to predict the export demand for oil palm products from Indonesia up to 2050 under the Shared Socioeconomic Pathways (SSP) 2 with different global trade scenarios, and applies parametric survival analysis to spatially allocate the expected oil palm expansion to 1km × 1km grids across the country based on the empirical effects of the biophysical and socioeconomic factors. It then calculates the trade-offs between oil palm expansion and environmental conservation and provides scientific insights on policies and management strategies to achieve sustainable oil palm production.

Chapter 5 summarizes and concludes the work. I revisit the major results of Chapters 2-4, and discusses their methodological, scientific, and management implications. This chapter then states the limitations of this dissertation and indicates directions for future research.

2 Biophysical and socioeconomic drivers of oil palm expansion in Indonesia[1]

Abstract: Indonesia has been the largest supplier of palm oil since 2007, and now supplies around 56% of the global market. While the existing literature has paid serious attention to the diverse impacts of oil palm plantation on socioeconomic factors and the environment, less is known about the joint role of biophysical and socioeconomic factors in shaping the temporal and spatial dynamics of oil palm expansion. This research investigates how the benefits and costs of converting other land cover and land use (LCLU) types to oil palm plantation affects these expansion patterns. We employ a spatial panel modeling approach to assess the contributions of biophysical and socioeconomic driving factors. Our modeling focuses on Sumatra and Kalimantan, two islands which have accounted for more than 90% of oil palm expansion in Indonesia since 1990, with Sumatra holding the majority of the country's plantations, and Kalimantan having the highest growth rate since 2000. The results show that the expansion in Kalimantan, which has been strongly stimulated by the export value of palm oil products, has occurred in areas with better biophysical suitability and infrastructure accessibility, following the 'pecking order' sequence, whereby more productive areas are already occupied by existing agriculture and plantations, and avoiding areas with high environmental values or socioeconomic costs. As demand for palm oil continues to grow, and land resources become more limited, the expansion in Kalimantan will tend towards the dynamics observed in Sumatra, with plantation expanding into remote and fertile areas with high conversion costs or legal barriers. Bare ground seems to have served as a clearing-up tactic to meet the procedural requirements of oil palm

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plantation for sustainable development. This research facilitates the improved projection of potential areas liable to future expansion, and the development of strategies to manage the leading drivers of land cover and land use change (LCLUC) in Indonesia.

2.1 Introduction

Indonesia is the world's leader in palm oil production. Palm oil is the most widely consumed edible oil in the world (WWF, 2017). According to the U.S. Department of Agriculture (USDA, 2019a, 2019b), the worldwide production of palm oil increased from 15 million tons to 70 million tons from 1995–2017, and Indonesia has been the largest supplier since 2007. Although oil palm cultivation has been questioned in relation to the invasion of villagers' rights to resources (Inoue et al., 2013), intensifying conflicts with local people (Abram et al., 2017), and exacerbating social disparities (Obidzinski et al., 2014) and environmental inequity (Sheil et al., 2009), its positive impacts on economic growth and employment are notable. For example, the oil palm sector of Indonesia in 2017 employed 3.8 million people, and produced about 39 million tons of palm oil from around 14 million ha of plantation areas across different regions of the country (Directorate General of Plantation, 2018; USDA, 2019a, 2019b). The growth in oil palm plantation and production was significantly beneficial to economic development in Indonesia, and is believed to have lifted up to 2.6 million rural residents out of poverty in the period from 2000–2016 (Edwards, 2019). As the global palm oil market is expected to grow in the near future (Carter et al., 2007; Corley, 2009; Research and Markets, 2020), rapid oil palm expansion will continue to be a major feature of land cover and land use change (LCLUC) in Indonesia.

However, the rapid expansion of oil palm has occurred, and will continue to occur, at the expense of other land cover/land use (LCLU), such as natural forests, shrub, and other agricultural land. Oil palm expansion in Indonesia is often criticized for resulting in deforestation and the destruction of peatland (Koh et al., 2011). It has been reported that approximately 80%–85% of Indonesian deforestation in the 2000s occurred in Kalimantan and Sumatra (Hansen et al., 2009; Miettinen et al., 2011), two islands which also underwent oil palm expansion of over 90% during the same period (Abdullah, 2012; Wicke et al., 2011). More than 56% of oil palm expansion in Indonesia occurred at the expense of forests (Kho and Wilcove, 2008; Vijay et al., 2016), placing it among those countries with the highest rates of deforestation (Achard et al., 2004, Hansen et al., 2009, Margono et al., 2014). This level of reduction in tropical and peat forests imposes severe damage on the environment, resulting in increased Greenhouse Gas emissions and biodiversity loss (Carnus et al., 2006; Koh et al., 2011; Koh and Wilcove, 2008).

Out of consideration for environmental protection, there is a growing movement advocating the boycotting of palm oil (European Union Parliament news, 2018). As consumer pressure has increased, actions have been taken by local governments (e.g., the forest moratorium, ISPO) (Barthel et al., 2018; Indonesian President Instruction no. 10, 2011; Indonesian President Instruction no. 6, 2013), international organizations (e.g., REDD+, RSPO) (Koh and Butler, 2009; Von Geibler, 2013), and oil palm companies (Butler, 2015; United Nation, 2014). Several studies suggest that the trend of oil palm expansion has shifted, with low-biomass land areas, such as shrub and dry agriculture, becoming major sources of oil palm expansion in recent years, surpassing natural forest (Austin et al., 2017, 2019; Gaveau et al., 2016; Gunarso et al., 2013; Vijay et al., 2016). Meanwhile, Carlson et al. (2012, 2013, 2018) have demonstrated that there is usually latency between land preparation and oil palm plantation, and a notable percentage of land for oil palm cultivation has been sourced from burned/cleared and bare land in recent years.

Although a number of studies have analyzed LCLUC with respect to oil palm expansion (Austin et al., 2017, 2019; Carlson et al., 2012, 2013; Gaveau et al., 2016; Hansen et al., 2009; Koh et al., 2011; Koh and Wilcove, 2008; Lee et al., 2014; Margono et al., 2014; Vijay et al., 2016), and have provided reliable information regarding the types of LCLUC at different time points, they did not explain why these changes occur in the patterns they observed. Piker et al. (2016) assessed the nature of biophysical suitability for oil palm plantation by identifying suitable ranges of climate, soil, and topographical conditions, and Vijay et al. (2016) used the GAEZ model as the suitability assessment tool. A handful of regional research articles have investigated the biophysical and socioeconomic driving factors associated with specific oil palm plantations (Austin et al., 2015; Castiblanco et al., 2013; Gatto et al., 2015; Ordway et al., 2019; Shevade and Loboda, 2019; Sumarga and Hein, 2016), with the aim of addressing biophysical suitability as well as market and infrastructure accessibility. However, these works were unable to examine the temporal dynamics of oil palm expansion, or to reveal the role of economic benefits and costs in the conversion from other LCLU types to oil palm cultivation, which should be fundamentally economically driven (Armsworth et al., 2006; Lim et al., 2019). The role of economic benefits and costs is particularly important in the context of Indonesia, given the fact that more than 70% of palm oil production in the country is for export (Edwards, 2019; Rulli et al., 2019). The exception in research terms is Lim et al. (2019), who established a novel land rent modelling framework at the grid-cell level to address the role of potential economic returns of LCLU conversion in explaining oil palm expansion in 2000, 2010 and 2015. Nevertheless, their model was unable to identify oil palm expansion in regions without prior plantations in 2000, because the model employed only two simple variables[2] to capture the complex spatial contagion effect, as conceptualized in the von Thünen land rent theory (Angelsen, 2010).

Therefore, there is an urgent need for an effective modeling approach to uncover how biophysical and socioeconomic factors have interactively driven the observed temporal and spatial dynamics of oil palm expansion. To address this knowledge gap would help us to better understand the coupled human and natural mechanisms driving these dynamics and shaping the patterns of oil palm expansion, thereby more effectively facilitating the projection of areas susceptible to future expansion, and the improvement of land use planning and governance, so as to balance the increased demand for palm oil products with the growing concern for protecting tropical forests and their associated ecosystems.

In this research, we have constructed spatial panel econometric models at the regency level (secondary administrative level, roughly equivalent to a US county) to explain the observed LCLU conversions for each 3 (or 4) year time period from 1996–2015, and to demonstrate the major land sources for oil palm expansion. Our modelling approach follows the economic theory that land-use decision makers will choose a rate of conversion from one land-use type to another on the basis of maximizing the present discounted value of a future stream of net benefits of conversion. We estimated the gross economic benefits of land-use conversion to oil palm. This was accomplished with the help of the GAEZ model formulated by the UN-FAO and IIASA (IIASA/FAO, 2021). We proxied for fixed and variable costs of land-use conversion using a constant term and a linear combination of the biophysical variables which characterize the

[2] The first variable relates to the proportion of cells devoted to oil palm surrounding each cell in the sample. The second variable refers to the percentage of plantation area within a buffer of 0.1° for cell i in period $t-1$.

biophysical features of the regency. To the best of our knowledge, this study is among the first to use panel data and spatial econometric modeling to address the expansion patterns of oil palm cultivation in Indonesia.

2.2 Methods

2.2.1 Study area

Indonesia (6°08' N-11°15' S, 94°45' E-141°05' E), is located in Southeast Asia, and with more than 17,500 islands, covering approximately 1,904,569 km^2, is the largest island country in the world. It has 34 provinces, and 282 regencies and municipalities (as of 1996). The five main islands are Sumatra, Java, Kalimantan, Sulawesi and Papua. It has a population of 238 million (as of 2010), 56% of which is rural (FAO, 2011). The land altitude varies from 0 m to 5030 m above sea level. The climate is almost entirely tropical, with temperatures ranging from 21 °C to 33 °C, and the average annual precipitation is around 2700 mm, varying from 1300 mm in East Nusa Tenggara to 4300 mm in parts of Papua (Bappenas, 2004). The wet season lasts from September until March, while the dry season lasts from March until August. Value added in agriculture constitutes around 14% of the gross domestic product (FAO, 2017), with major cultivation areas including food crops, such as rice and secondary crops (maize, cassava, soybean, sweet potatoes, and peanut), and perennial crops, including oil palm, rubber, coconut, coffee, cocoa, tea, etc. Palm oil production is one of the most important industries, employing about 2.4% of the total Indonesian workforce (as of 2017) and contributing fiscal and foreign exchange earnings to the country (Directorate General of Plantation, 2018; Indonesia-Investments, 2017). The Indonesian government has promoted oil palm cultivation as a way to alleviate poverty and advance development in remote areas (Dharmawan et al., 2020).

Sumatra and Kalimantan are the two islands where more than 95% of the oil palm plantations in the country are located (Wicke et al., 2011). Sumatra, located in western Indonesia, is the largest island entirely located in Indonesia, and the sixth-largest island in the world. It has a territory of 473,481 km^2, a population of 51 million (in 2010), and a tropical rainforest climate. Between 1996 and 2015, the annual average temperature measured from 26.6 °C–27.1 °C, and the annual average rainfall was 2500–3000 mm. Kalimantan is the Indonesian portion of Borneo Island, and comprises 73% of the Island's area. It is the largest island in Indonesia, and has a territory of 544,105 km^2, a population of 14 million (in 2010), and a tropical rainforest climate. Generally speaking, Kalimantan is cooler and wetter than Sumatra, with an annual average temperature from 26.1 °C–27.5 °C, and an annual average rainfall of 2700–3500 mm from 1996–2015.

2.2.2 The spatial panel regression model

We firstly constructed a pooled regression model to explain the observed patterns of oil palm expansion. Our model followed the economic theory that the decision makers will convert other land use types to oil palm plantation so as to maximize the discounted value of net benefits (revenue minus cost) of the conversion (Busch and Engelmann, 2018; Busch et al., 2012, 2015). The gross economic benefits were first proxied via a linear combination of the estimated potential yield of oil palm and its export value, and then corrected based on the impact of major climate factors contributing to yearly variations in oil palm yield. These major climate factors include annual average temperature, shortwave radiation, annual precipitation, and precipitation in the driest month. The cost of land conversion and transportation was proxied via a linear combination of slope, elevation, available water storage capacity (AWC) of soil, percentage of protected area (PA), percentage of peatland, access time, population density, and a second-order polynomial on source land cover (Austin et al., 2015; Busch et al., 2012; Mertens and Lambin, 2000; Pirker et al., 2016; Wheeler et al., 2013). Existing publications have demonstrated that previously established plantations had significant effects on conversions to oil palm plantation (Gaveau et al., 2009; Shevade and Loboda, 2019; Sumarga and Hein, 2016), and that fresh fruit bunches of oil palm require to be processed with 48 h of harvesting to ensure oil quality (Furumo and Aide, 2017), taking this into account, we also included the estate crop plantation fraction in 1990 and palm oil mill density as the explanatory variables. Of these explanatory variables, export value, climate factors, PA, population density, and source land ratio are time variant, while others, including potential yield of oil palm, estate crop plantations in 1990, palm oil mill density, access time, slope, elevation, AWC, and peatland percentage, are time invariant.

To summarize, the pooled regression model for estimating the empirical relationships between the observed patterns of oil palm expansion and the variations in benefits and costs of such expansion are specified in the following equation, which shares similarities with the econometric models adopted in Busch et al. (2015) and Busch and Engelmann (2018).

$$d_{it} = exp(\beta_0 + \beta_1 A_i + \beta_2 X_i' + \beta_3 C_{it}' + \beta_4 P_{it} + \beta_5 Pop_{it} + \beta_6 S_{it} + \beta_7 S_{it}^2 + \beta_8 E_{t-1} + \varepsilon_{it}). \quad (2\text{-}1)$$

where d_{it} is the area of oil palm expansion into each source land at regency i over year t – 1 and t. A_i is the potential yield per ha of oil palm plantation at regency i. X_i is a matrix of factors which are largely time-invariant, and which play a significant role in determining the cost of land conversion and transportation, including biophysical and geographical factors such as slope, elevation, AWC, peatland percentage of regency i, as well as factors characterizing accessibility to the market, and infrastructure such as average access time to large cities, density of palm oil mills, and percentage of estate crop plantation in 1990 at regency i. C_{it} is a matrix of climate factors, including annual precipitation, precipitation in the driest month, average annual temperature, and annual average shortwave radiation at regency i in year t. P_{it} is the percentage of regency i within PAs in year t. Pop_{it} is the population density of regency i in year t. S_{it} is the source land ratio at regency i in year t, and the second-order polynomial on S_{it} captures the non-linear trajectory of the expansion (Busch and Engelmann, 2018; Busch et al., 2015; Euler et al., 2017). E_{t-1} is the export value, averaged over the previous time period, because there is usually a time delay of approximately 3 years between the planning and the actual planting of oil palm (Carlson et al., 2012; Gaveau et al., 2016). β_0 captures the unobserved constant determinants of oil palm expansion.

To address the latency between land preparation and oil palm plantation (Carlson et al., 2012, 2018), and to demonstrate the role of bare ground in the oil palm expansion process, we used Kalimantan as an example, and began by running the model using oil palm plus bare ground expansion as the dependent variable[3], then running the model using oil palm as the dependent variable and bare ground as the land source.

The pooled regression model is optimal and unbiased when the errors are independent, homoscedastic, and serially uncorrelated. However, for LCLUC analysis, spatial autocorrelations typically exist among the observations (Elhorst, 2003), and with respect to panel data, there are usually individual (pixel) correlations due to the traits of those individuals not represented by

[3] The choice of this combined dependent variable means that we treat bare ground expansion as a phase of oil palm expansion. We had run the regression using bare ground expansion as the dependent variable. The results are statistically similar to the results we reported hereafter (Table A-8).

explanatory variables (Wooldridge, 2015). We employed spatial panel models to account for individual heterogeneity and spatial autocorrelation between regencies. The neighborhood relationship was defined by the contiguity-based method: two regencies were defined as neighbors if they shared a common border. We ran random effect rather than fixed effect regressions, since time-invariant variables play important roles in oil palm expansion (Pirker et al., 2016). Spatially lagged dependent variables, spatial error autocorrelation, and spatial Durbin models were included in the panel data regressions to account for the spatial dependencies in either dependent variables or unobserved variables (see Appendix A). We used the maximum likelihood approach to estimate the parameters in all the models (Elhorst, 2003). The 'plm' and 'splm' packages in R were used for the estimations of the pooled regression model and spatial panel econometric models (Croissant and Millo, 2008; Millo and Piras, 2012). Section A-1 in the Appendix A provides more technical details regarding the above spatial panel models.

2.2.3 Data

The LCLU data for the period 1990–2015 were acquired from the Ministry of Environment and Forestry (MoEF) of Indonesia. The MoFor has used satellite data, particularly Landsat, for land cover mapping of Indonesia since the 1990s. To date, LCLU maps are available for 1990, 1996, 2000, 2003, 2006, 2009, 2011, 2012, 2013, 2014 and 2015, at a spatial resolution of 30 × 30 m. We used maps from 1990, 1996, 2000, 2003, 2006, 2009, 2012, and 2015 in our analysis, given that it usually takes 2–4 years to allow for sufficient plant growth (Austin et al., 2019) and an equal time interval is preferred in time series data (Brockwell et al., 1991); in addition, the map of 1990 was used to present infrastructure associated with previously established plantations. The land cover maps of Indonesia consist of 23 classes, including 6 classes of natural forest, 1 class of plantation forest, 15 classes of non-forest, and 1 class of no data (Figure 2-1). We removed the class of no data and reclassified the other 22 classes into seven: primary forest, secondary forest, shrub, dry agriculture, estate crop, bare ground, and others. Table A-1 in the supplementary material presents the correspondences between the original 23 classes and the reclassified 7 classes.

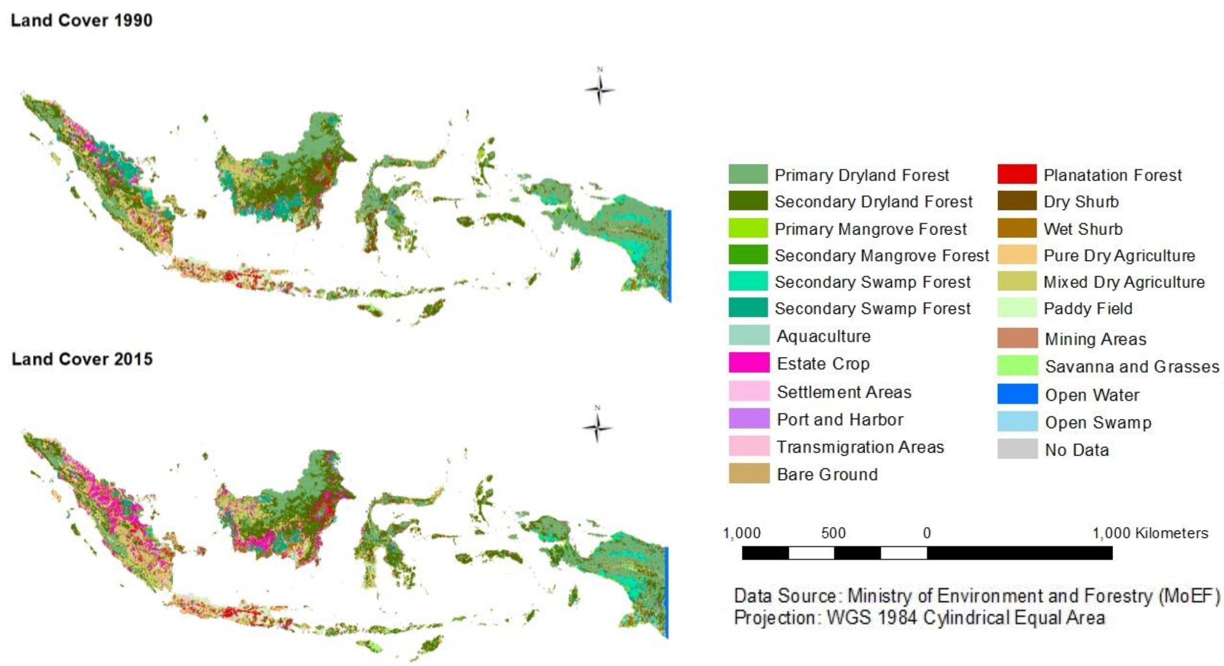


Figure 2-1 Land cover maps of Indonesia (1990 and 2015).

The estate crop plantation class includes oil palm, rubber, coconut, and other plantations. Although oil palm plantation is not an independent class in terms of the available maps, scattered evidence from remote sensing research demonstrates that the plantation of oil palm accounted for about 62% of the total estate crop plantation in the country in 2014 (Petersen et al., 2016). As highlighted in the previous section, the dependent variables in our panel models are the increments in oil palm area. In this regard, data from the Statistical Yearbooks of Indonesia (Statistics Indonesia, 1997–2016) and the Tree Crop Estate Statistics of Indonesia (Directorate

General of Plantation, 2013–2018) show that around 89% of the estate crop plantations in the country were attributed to oil palm from 1996–2015; from 2007–2015, the corresponding percentage was around 95% in Sumatra, while in Kalimantan, the expansion of oil palm accounted for the entirety of estate crop expansion. Therefore, when measuring the dependent variable, i.e., the area of oil palm expansion into each source land at regency *i* in year *t*, we directly use the area of estate crop expansion as the best available proxy for oil palm expansion.

The potential yield of oil palm was collected using GAEZ v4 from IIASA and FAO at a spatial resolution of 10 × 10 km. The GAEZ model provides an integrated agro-ecological assessment methodology, as well as a comprehensive global database for the characterization of climate, soil and terrain conditions relevant to agricultural production (IIASA/FAO, 2021), and can be used to assess the potential productivity of land under different management regimes. GAEZ is widely used in the estimation of agricultural production potentials and yield gaps at the grid-cell level (Gohari et al., 2013; Piker et al., 2016; Tubiello and Fischer, 2007; Zhong et al., 2019). We used the potential yield of palm oil at high input level, with natural rainfall as the input, since it is the commonly used management strategy in oil palm plantation in Indonesia (Pirker et al., 2016). Climatic factors, including annual average temperature, annual precipitation, precipitation of driest month and shortwave radiation, were obtained and calculated from the WFDEI dataset (50 × 50 km) (Weedon et al., 2014). Export values for oil palm in each year were obtained from the FAO, averaged over the 3-4 year observation periods, and deflated to the value of USD in the year 2000.

We calculated the palm oil mill density based on the Universal Mill List (WRI, Rainforest Alliance, Proforest, and Daemeter, 2018). Access time data were organized on the basis of A

Global Map of Accessibility (Nelson, 2008), which describes the travel time to cities with populations larger than 50 000 in 2000 using land- or water-based means of travel and a cost-distance algorithm, and is publicly available as 30 arc-second. The terrain data, including slope and elevation were compiled using elevation data from the Shuttle Radar Topography Mission (NASA, 2009), which is publicly available as 3 arc-second (approximately 90 m resolution at the equator) Digital Elevation Models (DEMs). AWC was extracted from the Harmonized World Soil Database (HWSD) (1 × 1 km) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). Peatland percentages were calculated from the peatland maps collated by the WRI (2012). Population density data were collected from the Gridded Population of the World, which provides estimates of population density every 5 years, based on counts consistent with national censuses and population registers with respect to relative spatial distribution, and adjusted to match United Nations country totals (CIESIN, 2016); here, the spatial resolution is 1 × 1 km for 2000–2015, and 5 × 5 km for 1995. The population data were interpolated to match the study period. PA data were compiled from IUCN Category I–VI, where point features are displayed as circles, representing the reported PA size (WDPA, 2014). Source land ratios were calculated from the LCLU maps, and natural forest ratios were calculated as the sum of primary forest and secondary forest.

Table A-2 lists the variables, the description of the corresponding data, and data sources. Table A-3 reports the measurement units and summary statistics of variables. Tables A-4 – Table A-6 present the pairwise correlations between explanatory variables in the country, Sumatra, and Kalimantan models. Table A-7 reports the variance inflation factors (VIFs). All maps were projected to the same coordinate system, resampled, and calculated at second administrative level, using ArcGIS 10.5.

2.2.4 Limitations of the research

Some of the time-invariant variables we employed, such as palm oil mill density, or access time to large cities, are not actually static over time because the proximity or accessibility would change with the establishment of new processing mills, roads, population clusters, etc. Therefore, the effects of these variables as shown by our models may not be precise, and any of these variables constraining oil palm plantation in the past may not continue to be a constraint in the future. Similarly, new constraints may emerge in the future, such as climate change (Paterson et al., 2017) and soil degradation (Guillaume et al., 2016). In addition, the assessments are limited by the quality of the datasets used for this analysis. The accuracies of LCLU maps and other maps have been constrained by the available techniques and socio-political hurdles with respect to data collection. The resolution and time scale of these maps will possibly influence the estimates of land use conversions and the effects of their driving forces.

2.3 Results and discussion

2.3.1 Land cover and land use change (LCLUC)

As shown in Figure 2-2(a), natural forest decreased significantly between 1990 and 2015 in Indonesia. Primary forest decreased by approximately 24.3%, with the most rapid degradation and deforestation occurring from 1996–2000, then 2003–2006, 2000–2003, 2006–2009, and 2009–2015 in order of decreasing pace. Of the 143,281 km^2 total decrease, 8,763 km^2 occurred in Sumatra, and 31,653 km^2 occurred in Kalimantan, accounting for 16.9% and 24.8% of their primary forest area in 1990, respectively. Although secondary forest experienced over 80%

(125,037 km^2) of primary forest conversions, this decreased by about 15.6% (82,524 km^2) from 1990–2015. Indonesia lost around 20% (227,039 km^2) of its natural forest (primary plus secondary forest) during this period, with the highest deforestation rate (2.11%, 29,746 $km^2\ yr^{-1}$) occurring from 1996–2000, with 2006–2009 a distant second (1.00%, 9,512 $km^2\ yr^{-1}$), followed by 2003–2006 (0.85%, 8,378 $km^2\ yr^{-1}$) and 2012–2015 (0.73%, 6,647 $km^2\ yr^{-1}$). Figures 2-2(b) and (c) illustrate these LCLUC in Sumatra and Kalimantan, respectively. The two islands together represent the majority of areas of deforestation; around 65% (517,629 km^2) of deforestation in Indonesia during 1996–2000 occurred on these two islands, with the corresponding percentage jumping to 97% (408,017 km^2) in the period 2009–2012, and falling back to 85% (392,845 km^2) from 2012–2015. Sumatra lost 44.69% (90,206 km^2) of its natural forest in the period from 1990–2015 (Figure 2-2(b)), accounting for 39.7% of countrywide deforestation, while 24.93% (87,907 km^2) natural forest disappeared in Kalimantan during the same period (Figure 2-2(c)), accounting for 38.7% of the deforestation for the country as a whole. The deforestation rate in Sumatra was consistently higher than the country's average, with the highest annual rates occurring in the periods from 1996–2000 (5.36%, 12,514 $km^2\ yr^{-1}$) and 2006–2009 (3.59%, 4,876 $km^2\ yr^{-1}$), in conjunction with the occurrence of El Nino events (1997 and 2006) (Field et al., 2016). Although the deforestation rate was consistently high, and fluctuated, the total figure decreased as time went by, which is probably due to the long history of agriculture and plantations on the island (National Research Council, 1993; Syuaib, 2016; Wicke et al., 2008), giving rise to the availability of suitable land for productive use which was no longer covered by natural forest (Austin et al., 2017). The deforestation rates in Kalimantan were higher than the country's average after 2000, when industrial oil palm plantation was widely introduced to the island (USDA, 2010).

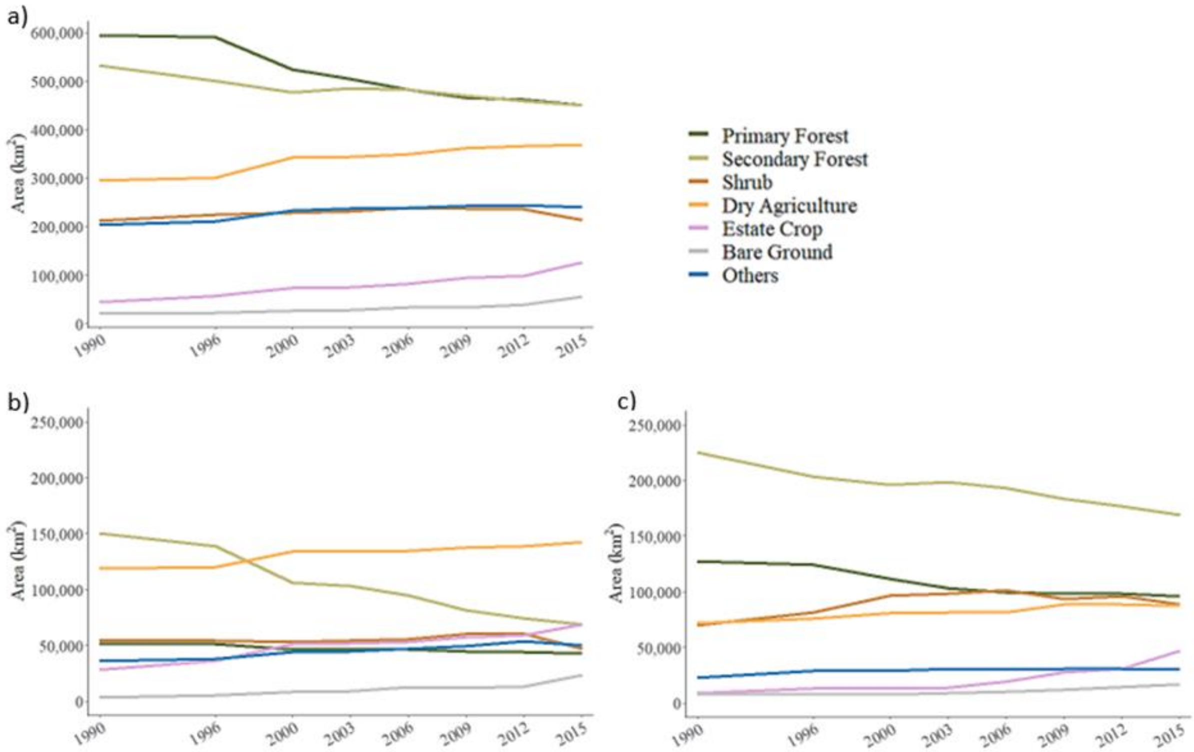


Figure 2-2 LCLUC during 1990-2015. (a) LCLUC for the whole Indonesia; (b) LCLUC in Sumatra; (c) LCLUC in Kalimantan.

Meanwhile, agriculture activity increased significantly (Figure 2-2). The area for dry agriculture increased by the greatest amount, and estate crops experienced the most rapid expansion. Together with those areas degraded to shrub and bare ground, these were the major drivers of deforestation in Indonesia. Estate crop area increased from less than 45,000 km^2 to more than 120,000 km^2 (Figure 2-2(a)), with an average annual speed of 4.24% (annual increase of 3,277 km^2 yr^{-1}). The most rapid estate crop expansion occurred in the period 2012–2015 (with an average annual rate of 8.40%, or 9,089 km^2 yr^{-1}), which was largely a result of the expansion occurring in Kalimantan (with an average annual rate of 15.47%, 5,484 km^2 yr^{-1}), followed by that in 1996–2000 (6.77%, 5,668 $km^2\ yr^{-1}$), mainly driven by the expansion in Sumatra (9.14%, 5,057 $km^2\ yr^{-1}$). Sumatra and Kalimantan together accounted for around 97% of the estate crop expansion in Indonesia in the period from 1990–2015. Sumatra dominated the expansion prior to 2000, constituting 77.1% of the national expansion from 1990–2000 (28,877 km^2, Figure 2-2(b)), while Kalimantan accounted for 63.67% of the national expansion after 2003 (51,645 km^2, Figure 2-2(c)), driven by policy reforms in late 1990s which facilitated direct foreign investment in agriculture (Bissonnette, 2015).

Figure 2-3 Direct conversions related to estate crops for the period 1996-2015. (a) Direct conversions related to estate crops for the whole country; (b) direct conversions related to estate crops in Sumatra; (c) direct conversions related to estate crops in Kalimantan. The area of estate crops for each year are denoted by the bars cross the axis, while the floating stacked bars depict the LCLUC within the six classes. The increments indicate the inflows from other classes to estate crops, and the decrements indicate the outflows from estate crops to other LCLU classes. The inflows are significantly larger than the outflows.

Natural forest, shrub, and dry agriculture are the three major direct LCLU sources of estate crop expansion in Indonesia as a whole, as well as on the two islands specifically (Figure 2-3). Shrub is the largest direct source of estate crop expansion in the country (Figure 2-3(a)), with a contributing share of 32.66% (27,289 km^2), followed by natural forest (27.33%, 22,834 km^2) and dry agriculture (21.45%, 17,924 km^2). Natural forest was the largest direct source of estate crop expansion in Sumatra (Figure 2-3(b)), with a share of 33.59% (13,259 km^2), whereas shrub contributed a higher share as time went by, and was the second largest source, with a share of 23.83% (9,409 km^2). In Kalimantan (Figure 2-3(c)), the trend is somewhat different, as shrub accounted for 42.48% (16,318 km^2) of all direct conversions to estate crop from 1996–2015, and was the largest source in the periods from 2000–2009 and 2012–2015. As time went by, estate crop expansion tended to occur on low-biomass land, such as shrub and dry agriculture, while natural forest became a less important direct source. Dry agriculture became a major source of estate crop expansion for both islands, particularly from 2012–2015 (see Figures 2-3(b) and (c)). These shifting patterns of estate crop expansion are consistent with the findings of Austin et al. (2017), who also reported a steadily declining rate of oil palm plantations displacing natural forest. This shifting pattern may be explained in the context of the following three reasons: (a) Conservation interventions by the government, NGOs and the private sector with respect to the oil palm industry (Barthel et al., 2018; Butler, 2015; Indonesian President Instruction no. 10, 2011; Indonesian President Instruction no. 6, 2013; Koh and Butler, 2009; United Nations, 2014; Von Geibler, 2013) are making some progress towards natural forest protection, although an extension of this protection to cover secondary forest is also needed (Austin et al., 2015; Sumarga and Hein, 2016). (b) As the availability of suitable forestland becomes more limited, estate crop expansion tends to occur via the conversion of existing agricultural land (Meyfroidt et al., 2014). (c) A smallholder requiring access to existing oil palm processing mills will tend to prefer low-biomass land (Walker, 2004, Meyfroidt et al., 2014).

Sizeable conversions are observed in relation to bare ground, particularly in Sumatra and Kalimantan in the period after 2000 (Figure 2-2, 2-3 and A-3). The major sources of bare ground establishment were secondary forest and shrub (Figure A-3). The clearance of natural forest to obtain bare ground made up a higher portion of deforestation as time went by on both islands (see Figure A-3). In the period from 1996–2015, bare ground accounted for 12.03% (4,747 km^2) and 15.30% (4,878 km^2) of the direct sources of oil palm expansion in Sumatra and Kalimantan, respectively (Figure 2-3); oil palm was the only major productive sink of bare ground conversions in Kalimantan and the amount of conversion increased as time went by (Figure A-3). As there is often a latency between land preparation and oil palm plantation (Carlson et al., 2012), bare ground might be regarded as an intermediate phase of oil palm expansion.

2.3.2 Regression results

We first ran pooled regression models of oil palm expansion into the three major land sources in Indonesia during 1996–2015. The regression results, as shown in Table 2-1, indicated that oil palm expansion in Indonesia tended to occur in regencies with longer access times to major cities, lower population density, gentler slope, medium level of source land ratio (owing to the inverted U-shape relationship), lower shortwave radiation, higher peatland percentage, and a more significant presence of estate crop plantation in 1990. Higher export value in the previous period ($t-1$) was positively and significantly associated with a greater prevalence of oil palm expansion, supporting the proposition that oil palm expansion in Indonesia was largely driven by its profitability in terms of export (Armsworth et al., 2006; Lim et al., 2019). Therefore, as the global palm oil demand continues to grow (Research and Markets, 2020), oil palm plantation in Indonesia will continue to expand into both natural forest and low-biomass land. This positive stimulation effect is stronger in relation to expansions into low-biomass LCLU types, such as dry agriculture and shrub, than into natural forest. Numerically speaking, an increase of 1 billion (2000) USD in export value in the previous period promises an increase in oil palm expansion by 7.71%, 15.5%, and 20.2% into natural forest, shrub, and dry agriculture, respectively.

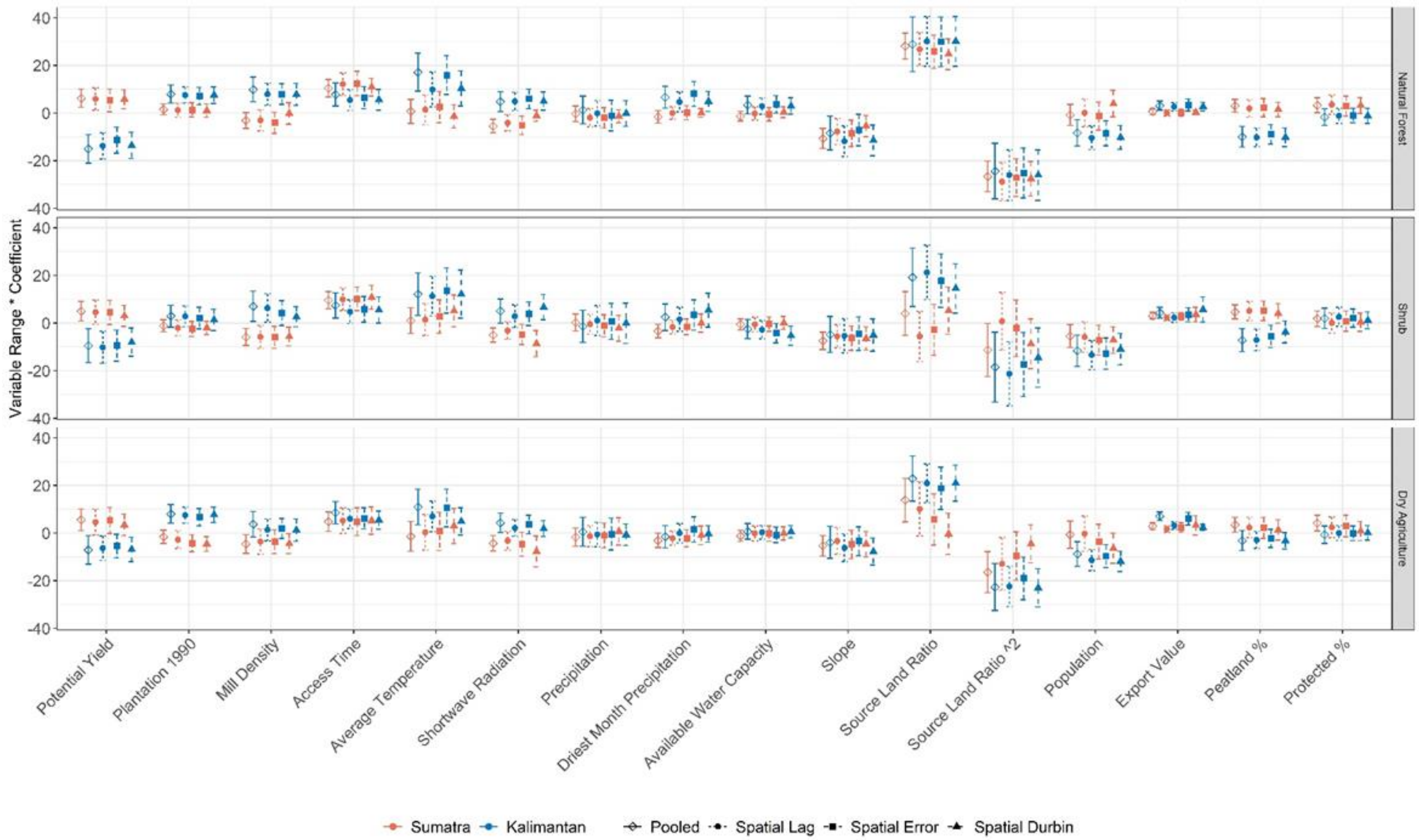
We then ran pooled regression models for each of the two islands, Sumatra and Kalimantan. In order to address the possible individual heterogeneity and spatial autocorrelation issues of the pooled models, we also ran spatial panel random effect models in the forms of spatial lag, spatial error and spatial Durbin. Figure 2-4 visually presents the results of all these regressions for direct comparison. All the spatial panel models showed that there were significant positive spatial autocorrelations on both islands, and that random effects were significantly more important compared to the idiosyncratic errors in Sumatra, but not in Kalimantan (table in Figure 2-4). As shown in Figure 2-4, addressing the spatial autocorrelation did not change the direction, magnitude, and significance inference of the coefficients for individual explanatory variables in the natural forest models, but changed the significance inference of several explanatory variables in the shrub and dry agriculture models. In the shrub models, the effects of oil palm potential yield and driest month precipitation in Sumatra, as well as the effects of mill density in Kalimantan, were largely explained by the positive spatial autocorrelation in the explanatory variables, while the effects of access time in Kalimantan were largely due to the spatial autocorrelation of the oil palm expansions. Meanwhile, the expansion into Kalimantan demonstrated a significant tendency to occur in areas with lower AWC when the spatial autocorrelations of the explanatory variables were addressed. The effects of spatial autocorrelations were larger in the dry agriculture models for both islands, and led to more significant changes in the explanatory variables in the models of Sumatra. When the spatial autocorrelations in Kalimantan were addressed, the coefficients for shortwave radiation became insignificant, while areas with gentler slopes were significantly preferred. For models of Sumatra, the expansion pattern is strongly associated with the significant positive spatial autocorrelation, with the exception that those areas with little estate crop plantation in 1990 were significantly preferred by oil palm expansion to dry agriculture, once the spatial autocorrelations between the explanatory variables were addressed.

Figure 2-4 indicates that oil palm expansion on the two islands also tended to occur in areas relatively remote from major cities, in contrast to the assumptions and results of some other researches (Lim et al., 2019; Pirker et al., 2016, Sumarga and Hein, 2016). This result may be explained by the location choice sequence of plantation developers, which is similar to the pecking order sequence of corporate managers in considering their sources of financing (Myers and Majluf, 1984; Vogt, 1994). This means that suitable areas with better access to major cities were already occupied by existing plantations, so that any new plantations must therefore be located in more remote areas than the existing ones.

Table 2-1 Regression resutls of pooled models for expansion of oil palm into three major land sources in Indonesia.

	Natural Forest			Shrub			Dry Agriculture		
	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.
(Intercept)	-114.400	-2.052	**	-77.669	-1.287		-43.563	-0.727	
Oil palm potential yield	0.015	1.542		0.034	3.246	***	0.039	3.661	****
Plantation in 1990	0.024	1.807	*	0.042	2.976	***	0.032	2.262	**
Mill density	-0.670	-1.495		-1.249	-2.560	**	-1.388	-2.873	***
Access time	2.249	5.174	****	1.864	5.001	****	1.092	2.704	***
Temperature	0.350	1.898	*	0.236	1.181		0.114	0.577	
Shortwave radiation	-0.026	-3.079	***	-0.035	-3.959	****	-0.026	-2.962	***
Precipitation	0.085	0.986		0.043	0.460		-0.093	-1.005	
Driest month precipitation	0.338	2.549	**	-0.282	-1.955	*	-0.114	-0.799	
AWC	-0.898	-0.257		-8.492	-2.177	**	-11.453	-3.053	***
Elevation	0.083	1.113		0.037	0.464		0.062	0.809	
Slope	-0.340	-5.642	****	-0.143	-2.475	**	-0.088	-1.556	
Source land ratio	18.928	13.426	****	15.081	6.888	****	12.282	7.494	****
Source land ratio^2	-18.751	-11.193	****	-22.664	-6.062	****	-14.568	-7.271	****
Population density	-0.109	-2.068	**	-0.142	-2.423	**	-0.093	-1.552	
Export value (t – 1)	0.077	3.720	****	0.155	6.874	****	0.202	9.085	****
Peatland %	0.089	7.913	****	0.089	7.390	****	0.081	6.942	****
Protected %	-0.018	-1.461		0.036	2.903	***	0.039	3.217	***
R^2	0.356			0.257			0.185		
AIC	11184.770			11516.140			11480.520		
Log Likelihood	-5573.384			-5739.071			-5721.262		

Notes: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.



			Sumatra
Spatial lag	NF	φ	0.188***
		λ	0.184***
	Sh	φ	0.200***
		λ	0.221***
	DA	φ	0.240***
		λ	0.319***
Spatial error	NF	φ	0.183***
		ρ	0.193***
	Sh	φ	0.168**
		ρ	0.245***
	DA	φ	0.210***
		ρ	0.344***
Durbin	NF	φ	0.234***
		ρ	-0.553***
		λ	0.590***
	Sh	φ	0.136**
		ρ	0.646***
		λ	-0.513***
	DA	φ	0.202***
		ρ	0.756***
		λ	-0.647***
			Kalimantan
Spatial lag	NF	φ	1.00E-08
		λ	0.340***
	Sh	φ	0.018
		λ	0.343***
	DA	φ	1.00E-08
		λ	0.455***
Spatial error	NF	φ	1.00E-08
		ρ	0.373***
	Sh	φ	0.043
		ρ	0.382***
	DA	φ	1.00E-08
		ρ	0.442****
Durbin	NF	φ	1.00E-08
		ρ	0.032
		λ	0.318*
	Sh	φ	0.039
		ρ	0.690***
		λ	-0.487***
	DA	φ	1.00E-08
		ρ	-0.247***
		λ	0.598***

*Figure 2-4 Spatial panel random effect model results for oil palm expansion in Sumatra and Kalimantan. Vertical pars correspond to 90% confidential intervals. The vertical axis (Variable Range × Coefficient) is the scaled coefficient, which can be used to render the coefficients comparable[4]. The table on the right shows the spatial autocorrelation statistics (λ for spatial lag, ρ for spatial error) and the random effect estimation (φ) of each model; *, **, ***, and **** stand for significant levels of 10%, 5%, 1%, and 0.1%, respectively.*

[4] To make the contributions of variables comparable, explanatory variables are scaled by range method : $Variable_{scaled} = \frac{Variable}{Variable\ Range}$, $Coefficient \times Varialbe = Coefficient_{scaled} \times Variable_{scaled}$, therefore, $Coefficient_{scaled} = Coefficient \times Variable\ Range$.

A comparison of the results between the two islands showed some differences in the patterns of oil palm expansion. The establishment of oil palm plantation occurred earlier, and the expansion was also faster before 2000 in Sumatra than in Kalimantan, while the expansion pace grew more rapidly in Kalimantan after 2003 (Figures 2-2(b) and (c); USDA, 2013). Since Sumatra has a longer oil palm cultivation history and more intense agricultural activity (National Research Council, 1993; Syuaib, 2016; Wicke et al., 2008), the natural forest resources remaining for estate crop plantation has become limited (Figure 2-2(b)). Compared with Sumatra, Kalimantan was a comparative latecomer (Austin et al., 2017; Wicke et al., 2008), and land resources for oil palm expansion on the island were therefore less limited (Figure 2-2(c)). Therefore, the expansion patterns of oil palm in Kalimantan proved to be better characterized by our explanatory models than those of Sumatra.

The direction and significance of the coefficients in terms of individual explanatory variables in Kalimantan were more in line with our expectations, i.e., oil palm expansion would be stimulated by the export value of palm oil products, and would tend to occur in areas with greater biophysical suitability and infrastructure accessibility, as well as with lower conversion cost. The stimulation effects of export value were statistically significant and positive for oil palm expansion into each of the three sources in Kalimantan, but not significant for the case of expansion into natural forest in Sumatra. Oil palm expansion in Kalimantan, particularly into natural forest, was more likely to occur in areas with more suitable climatic conditions, such as high shortwave radiation and higher precipitation in the driest month. In both the countrywide and Kalimantan models, oil palm expansion showed an inverted 'U'-shaped relationship with each of the source land ratios, indicating that oil palm expansion tended to occur in areas within the medium range of the source ratio (Figure A-2). These findings were consistent with those of existing research (Busch and Engelmann, 2018; Busch et al., 2015; Euler et al., 2017). In contrast, on Sumatra Island, such an inverted 'U' shape existed in the expansion into natural forest for all models, and into dry agriculture for the pooled model (Figure A-2). With regard to infrastructure and market factors, the expansion in Kalimantan tended to benefit from existing infrastructure, associated with existing plantations and processing mills, and the beneficial connection was more significant and stronger with expansion into natural forest. By contrast, the plantation in 1990 and mill density did not constrain oil palm expansion into any sources in Sumatra, since oil palm plantation and the associated infrastructure had already dispersed over the island, with the exception of the mountainous area along the west coast. Locations with lower population density were preferred for oil palm expansion into all three land sources in Kalimantan, which could be explained by the following factors: (a) oil palm was less labor intensive than alternative crops (Euler et al., 2017; Feintrenie et al., 2010; Gatto et al., 2017), (b) locations with higher population densities and a longer history of planting traditional crops were less attractive for switching to oil palm (Gatto et al., 2015), and (c) oil palm companies intended to avoid the land tenure conflicts and high transaction costs associated with consolidating land from smallholders (Meyfroidt et al., 2014). Nevertheless, this relationship was significant in Sumatra for the expansion into shrub only. The percentage of peatland showed opposite effects in terms of oil palm expansion in Sumatra versus Kalimantan. The negative relationship in Kalimantan might be ascribed to the fact that oil palm establishments on the island preferred mineral land to peatland, either due to the lower cost of land preparation, or with the intention of reducing GHG emissions (Afriyanti et al., 2016; Meyfroidt et al., 2014; Rulli et al., 2019).

In contrast to our expectations, the potential yield of oil palm showed a negative effect on oil palm expansion in Kalimantan, which could be explained by the location choice sequence of plantation developers, which is similar to the pecking order sequence of corporate managers in considering their sources of financing (Vogt, 1994). Areas with higher potential yield of oil palm also offer greater potential yields for other types of plantations, such as dry agriculture crops and paddy fields; as such, those areas had already been occupied by existing agricultural activity and estate crop plantations. Interestingly, such pecking order effects were not found in Sumatra, which might be explained in terms of the following two reasons: Firstly, compared with Kalimantan, where all source lands are generally suitable for oil palm plantation, with a potential yield (oil) ranging between 4.3 and 7.1 ton ha^{-1}, the potential yield of oil palm in Sumatra ranges between 0.6 and 7.2 ton ha^{-1}, with regencies along the west coast being entirely unsuitable for oil palm plantation. Secondly, owing to its longer history of plantation (National Research Council, 1993; Syuaib, 2016; Wicke et al., 2008), remaining land resources for new plantations in Sumatra have become limited since 1990 (Figure 2-2(b)); as a result, oil palm has to expand into areas with relatively high potential yield, but which are very costly or illegal to convert, such as peatland and logging concessions (Austin et al., 2017; Gaveau et al., 2013; USDA, 2010), and where the high proportion of smallholders (40%) aggravates the situation (Gatto et al., 2015; Meyfroidt et al., 2014; Molenaar et al., 2013). In our analysis at the regency level, PAs showed no significant effect on oil palm expansion. However, we cannot conclude that PAs were not effective in protecting natural forest from plantation expansion, because the spatial resolution at the regency level was quite coarse, and PAs account for only a small portion of the territory of individual regencies. Analysis at the grid level are required to address the effects of PAs.

2.3.3 Bare ground as land banking for oil palm expansion in Kalimantan

Since oil palm is almost the only productive sink of bare ground conversion in Kalimantan, and there is often a latency between forest clearance and oil palm plantation (Carlson et al., 2018), we treated bare ground expansion as a phase of oil palm expansion, and ran the pooled and spatial panel models using oil palm and bare ground expansion together as the dependent variable in the first instance (see Table 2-2). The results show that bare ground developed from natural forest was clustered in areas with large protected sectors, more natural forest cover, and were less significantly stimulated by the export value for the previous period, once spatial autocorrelations within the explanatory variables were addressed. We then ran the pooled and spatial panel models using oil palm expansion as the dependent variable, and bare ground as the land source (Table 2-3). The results indicated that the conversion from bare ground to oil palm plantation was significantly stimulated by the export value for the previous period, and that conversion was clustered in those regencies with a higher proportion of PAs. Considering that bare ground has been developed and converted to oil palm plantation at a rapid pace in recent years (Carlson et al., 2012, 2013), the above results suggest that bare ground had been increasingly used as an indirect clearing-up tactic for oil palm expansion at a later stage, so that the expansion nominally meets the sustainable development requirements. The existence of this land banking mechanism highlights that it is practically important to include bare ground development in any monitoring system, so that the system can more effectively track where and why bare ground is developed, and its eventual utilization. Meanwhile, as the current moratorium and RSPO certification only deals with new licenses and post-certification activities, it is necessary to establish policies to cope with such land banking.

Table 2-2 Results of pooled and spatial panel models for bare ground as land banking for oil palm expansion to natural forest in Kalimantan.

	Pooled			Spatial Lag			Spatial Error			Spatial Durbin		
	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.
(Intercept)	-1014.906	-2.068		-694.287	-1.503		-970.531	-1.949		-915.913	-1.825	
Oil palm potential yield	-0.038	-0.285		-0.051	-0.389		0.020	0.176		0.033	0.304	
Plantation 1990	0.091	0.618		0.115	0.804		0.060	0.447		0.046	0.343	
Mill density	21.254	2.577	**	20.963	2.607	***	20.915	3.274	****	20.210	3.451	****
Access time	2.028	1.364		0.955	0.668		0.894	0.642		0.757	0.560	
Temperature	3.330	2.012	**	2.280	1.464		3.153	1.882	*	2.948	1.747	*
Shortwave radiation	0.046	0.788		0.044	0.787		0.086	1.510		0.110	1.877	*
Precipitation	-0.178	-0.362		-0.195	-0.429		-0.314	-0.575		-0.306	-0.536	
Driest month precipitation	1.285	2.417	**	0.981	2.039	**	1.872	2.984	***	2.104	3.155	***
AWC	28.636	0.997		12.244	0.442		0.964	0.035		-0.852	-0.031	
Slope	-0.331	-0.712		-0.506	-1.133		-0.330	-0.789		-0.337	-0.835	
Source land ratio	14.844	1.928	*	15.691	2.183	**	18.570	2.778	***	17.478	2.752	***
Source land ratio^2	-11.746	-1.398		-11.972	-1.523		-12.665	-1.786	*	-11.134	-1.684	*
Population density	-11.621	-4.368	****	-12.338	-4.888	****	-11.312	-4.541	****	-10.040	-4.024	****
Export value ($t-1$)	0.209	2.299	**	0.144	1.758	*	0.212	1.503		0.303	1.480	
Peatland	-0.091	-2.476	**	-0.103	-2.878	***	-0.096	-2.864	***	-0.085	-2.541	**
Protected %	0.124	1.514		0.149	1.868	*	0.153	2.235	**	0.127	1.963	**
phi				0.033	0.595		1.00E-08	NA		1.00E-08	NA	
rho							0.500	6.857	****	0.688	8.062	****
lambda				0.396	5.167	****				-0.350	-2.218	**
R^2	0.367											
AIC	1442.376			1487.258			1475.436			1473.288		
Log Likelihood	-703.188			-691.629			-685.718			-683.644		

Notes: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

Table 2-3 Results of pooled and spatial panel models of oil palm expansion into bare ground areas of Kalimantan.

	Pooled			Spatial Lag			Spatial Error			Spatial Durbin		
	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.
(Intercept)	-926.470	-1.977	**	-1088.743	-2.526	**	-1266.301	-2.602	***	-1150.240	-2.211	**
Oil palm potential yield	-0.190	-1.347		-0.226	-1.732	*	-0.220	-1.828	*	-0.209	-1.876	*
Plantation 1990	-0.020	-0.126		-0.058	-0.397		-0.096	-0.642		-0.080	-0.529	
Mill density	24.908	2.886	***	26.774	3.350	****	22.057	3.302	****	16.251	2.792	***
Access time	1.440	0.971		0.753	0.550		0.982	0.680		1.035	0.709	
Temperature	3.093	1.969	*	3.683	2.549	**	4.227	2.593	***	3.774	2.167	**
Shortwave radiation	0.054	0.913		0.000	0.005		0.058	0.985		0.141	2.210	**
Precipitation	-0.674	-1.326		-0.397	-0.853		-0.356	-0.636		-0.359	-0.585	
Driest month precipitation	0.815	1.410		0.658	1.255		0.973	1.485		1.126	1.551	
AWC	-36.322	-1.289		-36.259	-1.394		-45.970	-1.671	*	-49.287	-1.788	*
Slope	-0.484	-1.107		-0.436	-1.080		-0.356	-0.920		-0.418	-1.100	
Source land ratio	77.657	1.571		78.387	1.737	*	74.354	1.752	*	55.052	1.427	
Source land ratio2	-722.346	-1.716	*	-729.778	-1.909	*	-642.298	-1.766	*	-452.203	-1.369	
Population density	-9.735	-3.588	****	-10.846	-4.345	****	-10.020	-3.834	****	-9.211	-3.432	****
Export value	0.500	4.866	****	0.258	2.772	***	0.408	2.999	***	0.630	2.924	***
Peatland	-0.145	-3.965	****	-0.146	-4.309	****	-0.143	-4.199	****	-0.129	-3.766	****
Protected %	0.213	2.335	**	0.253	2.996	***	0.236	3.031	***	0.180	2.475	**
phi				8.14E-03	0.245		1.44E-03	0.078		0.011	0.332	
rho							0.399	5.688	****	0.665	7.905	****
lambda				0.340	4.887	****				-0.408	-2.920	***
R2	0.373											
AIC	1478.492			1524.830			1518.596			1515.214		
Log Likelihood	-721.246			-710.415			-707.298			-704.607		

Notes: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

2.4 Conclusion

Oil palm expansion is one of the major drivers of deforestation in Indonesia, especially in Sumatra and Kalimantan. However, as time goes by, these expansions become more likely to occur in low-biomass areas, such as shrub and dry agriculture, than in natural forest. Bare ground often emerges as an intermediate state (i.e., land banking) of conversion from natural forest to oil palm plantation, serving as a clearing-up tactic to meet the procedural sustainable development requirements of oil palm plantation.

Most of the plantation expansion during our study period occurred in Sumatra and Kalimantan, with the two islands hosting the majority of oil palm plantations in Indonesia. Compared with Sumatra, Kalimantan is at an earlier stage of plantation development, with relatively abundant land resources. Consequently, oil palm expansions in Kalimantan are better characterized by our models, meaning that the direction and significance of the coefficients for most of the explanatory variables meet the theoretical expectations underlying the specification of our models. The results of our spatial panel regressions showed that oil palm expansion in Kalimantan was highly stimulated by the export value of oil palm products, took place in areas with better biophysical suitability and infrastructure accessibility, followed the pecking order sequence where more productive areas had already been occupied by existing agricultural activities and estate crop plantations, and avoided areas with high environmental values or socioeconomic costs.

However, as global demand for palm oil products continues to grow at a rapid pace, which in turn drives up its export value, oil palm plantation will continue to expand, subject to the increasing scarcity of land sources. This trend may drive the expansion dynamics in Kalimantan in near future to approach that in Sumatra today, where oil palm plantation has been expanding into remote and fertile areas with high conversion costs or legal barriers, including peatland and logging concessions. Under this highly plausible development scenario, future oil palm expansion in Indonesia would cause more environmental and social issues, such as increasing greenhouse gas (GHG) emissions resulting from LCLU conversion, the failure of land concessions, land right conflicts, etc. Therefore, to balance oil palm expansion and environmental conservation in Indonesia, current regulations, such as forest and peatland moratoriums, RSPO certification, PAs, land use concessions, moratorium of new oil palm license issuance policy, and zero-deforestation commitments, should be continued, and extended to secondary forest and vulnerable ecosystems, as well as fully implemented and enforced. New policies and regulations on land banking are also urgently needed.

3 Land cover and land use change trajectory hopping facilitates estate crop expansion into protected forests in Indonesia[5]

Abstract: It has been a global challenge to balance the world's growing demand for estate crop products with the international commitments to protect natural forest and biodiversity. While the existing literature states that protected area (PA) designations generally reduce deforestation at the national or subnational level, yet little is known regarding how the effectiveness of PA changes over time and what role the intermediate land-cover and land-use change (LCLUC) trajectories have played in the conversion from forest to estate crop. We employ Cox proportional hazard models (CPHMs) and their extensions to characterize the temporal dynamics of estate crop expansion into natural forest in Indonesia during 1996-2015. The results show that the effectiveness of PAs in Sumatra, where the majority of the country's estate crop plantations are located, decreased over time and became insignificant in 2012-2015. A multi-state modeling analysis shows that hopping in LCLUC trajectories with shrub and/or bare ground as intermediates had served as a clearing-up tactic to nominally meet the sustainable development requirements on estate crop expansion and actually facilitate the expansion of estate crops into natural forest, thus decreasing the PA effectiveness. Estate crop expansion via LCLUC trajectory hopping would severely threaten biodiversity because it tends to occur at lowland forest, diminishing natural habitat area and increasing natural forest isolation.

[5] This chapter is under review: Xin, Y., Sun, L. and Hansen, M.C. (in review). Land cover and land use change trajectory hopping facilitates estate crop expansion into protected forests in Indonesia. *Global Environmental Change*.

3.1 *Introduction*

Protected areas (PAs) are widely regarded as a core policy tool for reducing deforestation and conserving biodiversity (Andam et al., 2008; Jones et al., 2018; Laurance et al., 2012; Mascia and Pailler, 2011). However, the effectiveness of PAs is under continuous debate (Geldmann et al., 2019, 2013; Heino et al., 2015; Jones et al., 2018). Although at the national level, PAs have been shown to avoid significantly more tropical deforestation than unprotected areas (Andam et al., 2008; Gaveau et al., 2012, 2009), the establishment of PAs do not guarantee a halt or even remarkable decrease in deforestation (Heino et al., 2015; Laurance et al., 2012; Shah and Baylis, 2015). The effectiveness of PAs is largely influenced by their locations (Andam et al., 2008; Ferraro et al., 2013; Joppa and Pfaff, 2011; Nelson and Chomitz, 2011; Shah and Baylis, 2015), the resources to function them properly (Adams et al., 2019; Geldmann et al., 2013; Linkie et al., 2008; Shah and Baylis, 2015), as well as the anthropogenic pressures on (Jones et al., 2018) and the surrounding of the area (Geldmann et al., 2019; Laurance et al., 2012).

Indonesia is among the countries with highest deforestation rates (Margono et al., 2014). Meanwhile, it is also one of the most biodiversity-rich nations in the world, spanning the Sundaland and Wallacea biodiversity hotspots (Myers et al., 2000), and leading the world in threatened mammals and birds (Sodhi et al., 2009). Estate crop expansion, dominated by palm oil palm, has replaced large areas of natural forest in Indonesia during the last few decades. Although studies show that degraded land with relatively low biomass, such as shrub and dry agriculture, surpassed natural forest and became the major sources of estate crop expansion in the recent years (Austin et al., 2017; Gaveau et al., 2016; Xin et al., 2021), estate crop expansion is believed to be one of the major drivers of deforestation in Indonesia (Austin et al., 2019;

Carlson et al., 2012; Koh and Wilcove, 2008). As the global demand for estate crop commodities, especially oil palm products, are expected to grow (Purnomo et al., 2020), estate crop expansion will continue to be a major driver of forest loss in the country, specifically in Sumatra and Kalimantan (Austin et al., 2019; Taheripour et al., 2019; Xin et al., 2021). Estate crop plantations, especially oil palm oil, are believed to be the greatest immediate threat to biodiversity in Southeast Asia (Wilcove et al., 2013). Therefore, there is an urgent need to evaluate the effectiveness of PAs on estate crop expansion into natural forest.

Recent research on evaluating the effects of PAs focuses on addressing their non-random distribution across the landscape. Matching method is frequently used to reduce the potential selection bias (Andam et al., 2008; Gaveau et al., 2013; Geldmann et al., 2019; Joppa and Pfaff, 2011), Before-After-Treatment-Intervention (BACI) (Shah and Baylis, 2015) and multi-factor regressions (Brun et al., 2015; Haruna et al., 2014) are also used to assess the effects of PAs. There are several studies on the national and/or subnational level of Indonesia, with variant conclusions (Brun et al., 2015; Busch et al., 2012; Curran et al., 2004; Ferraro et al., 2013; Gaveau et al., 2009), which might be explained by the study period. Wade et al. (2020) demonstrated that the temporal trend of forest loss in PAs is similar to that of global forest loss, with notable increase in the tropics. Meanwhile, many researchers believe that the effects of PAs may decrease as the land resources become more limited and human pressure increases (Brun et al., 2015; Jones et al., 2018; Mascia and Pailler, 2011; Pouzols et al., 2014; Watson et al., 2014). However, literature addressing the time-variant effects of PAs is sparse and based on coarse temporal resolution (2 periods, 5-10 years) (Eklund et al., 2016; Haruna et al., 2014; Nolte et al., 2013). Indomalaya had the largest human pressure increase over 1995-2010 across the world and the changes inside PAs were even higher than in the counterfactuals (Geldmann et al., 2019), meanwhile, over 86% of Indonesia's terrestrial national parks experienced human footprint increase during 2012-2017 (Dwiyahreni et al., 2021). However, to our best knowledge, no research addressed the effectiveness of PAs in Indonesia along the temporal trajectories. Therefore, there is an urgent need for an effective modeling approach to fill this important gap.

Survival analysis, specialized for event data modeling and explicitly dealt with the occurrence and timing of events (Wang et al., 2013), gains growing attention in land-cover and land-use change (LCLUC) studies. Cox proportional hazard model (CPHM) is arguably the most popular tool in survival analysis (An et al., 2010; An and Brown, 2008; Cox, 1972; Wang et al., 2013), and is extended in recent years by including covariates interacted with time to address the possible time-dependent effects on hazard under the rapid land change process (Chen et al., 2016). Standard survival analysis concentrates on the timing to a single event of interest, however, there are many examples in which a subject may experience a variety of intermediate events during the study period. This is especially true for LCLUC sciences, since LCLUC is usually a dynamic process with a sequence of changes along temporal trajectory (der Laan et al., 2018; Ekadinata and Vincent, 2011; Lambin et al., 2003). Multi-state model, which jointly considers the occurrences of fatal (final) state and multi non-fatal (intermediate) states, as well as the complicated relationships between all the states, is becoming an increasingly popular tool for biomedical studies (Andersen and Keiding, 2016; Putter et al., 2007; Rueda et al., 2019). Though multi-state models have not been used in land-use sciences yet, together with the long-lasting continuous remote sensing products monitoring LCLUC, they have substantial potential to address the time-related complexities along with the LCLUC trajectories.

In this research, we first describe the temporal trajectories of LCLUC in Indonesia, especially the Sumatra and Kalimantan islands where more than 90% of the country's estate crop expansion occurred (Xin et al., 2021). Addressing the LCLUC trajectories can better describe the role of estate crop expansion in natural forest loss, and provide us with a more comprehensive perspective to evaluate the effectiveness of PAs on, and the environmental cost of, the estate crop expansion. Then we construct standard CPHMs, as well as their extensions with time-dependent effects to explain how PAs affect the estate crop expansion into natural forest from 1996-2015 with temporal details. Multi-state models are employed to show whether the LCLUC trajectories have effects on estate crop expansion into protected natural forest. To the best of our knowledge, this study is among the first to apply multi-state models to land-use sciences and use survival analysis to address the dynamics of PA effectiveness along with temporal details and varying LCLUC trajectories.

3.2 Methods

3.2.1 Land cover and land use change (LCLUC) trajectories

The land cover and land use (LCLU) maps of Indonesia in 1996, 2000, 2003, 2006, 2009, 2012 and 2015 acquired from the Ministry of Environment and Forestry (MoEF), were stacked, subset and analyzed in the ArcGIS environment. The 23 classes of the maps were reclassified to seven classes: primary forest, secondary forest, shrub, dry agriculture, estate crop, bare ground, and others (Table B-1 in the Appendix B). We quantified the LCLUC in each 3 (or 4)-year period. To better present the trajectories of the LCLUC, we visually displayed the conversions among the LCLU classes using a bidirectional Sankey diagram. The seven LCLU classes were used as the nodes in the diagram. Since it usually takes 2-4 years to have sufficient plant growth to be detected by remote sensing (Austin et al., 2019), we define direct conversion as conversions occurred within three years, which is accord with our maps. The direct conversions from one LCLU class to another were used as the links in the Sankey diagram. “NetworkD3” package in R (Allaire et al., 2017) is modified and applied to generate the diagrams. A key advantage of displaying the LCLUC flows by this method is that the position of each LCLU class in the conversion process is determined by the directions and amounts of its inflows and outflows, thus the trajectories of the LCLUC are shown clearly. For example, if the LCLU class expanded during the study period and few of it were converted to other classes (e.g., estate crop), it would be placed at the end of the diagram and considered as a major sink of the LCLUC process. To show how the trajectories varied over time and across space, we generated the diagrams with LCLU data in three periods – 1996-2015, 1996-2006, and 2006-2015, as well as three areas – the whole country of Indonesia, Sumatra, and Kalimantan, respectively.

3.2.2 Cox proportional hazard model (CPHM)

We use survival analysis to emphasize the extent and timing of estate crop expansion. Estate crop plantation in Indonesia in recent years and near future can be considered as irreversible process and thus regarded as the final state of survival analysis due to 1) the increasing demand and the generous economic profits, and 2) the relative long lifecycle of estate crop plantation. Firstly, we define the estate crop plantation in a grid-cell as the single event, with the intermediate status (e.g., the intermediate status bare ground in the natural forest -> bare ground -> estate crop process) being treated as part of survival time. In this way, either the estate crop expansion into natural forest occurred directly or with intermediate status makes no difference and both are included in the analysis. Two related but different metrics are estimated, the hazard rate - the risk of conversion to estate crop plantation at a time of interest, and the survival probability - the likelihood that the land cover/use did not change to estate crop to a given point. Hazard rate can increase or decrease over time with time-varying explanatory variables, whereas survival probability is always constant or decreasing over time (An et al., 2010).

In our research, the calculation of hazard rate is based on the frequently used CPHM, which provides a robust multivariate regression analysis and does not require any assumption about the distribution of survival time as a semi-parametric model (Cox, 1972). The CPHM can be calculated as below:

$$h_i(t) = \lambda_0(t) exp\ (\beta_1 Protect_i + \beta_2 x_{i1} + \cdots + \beta_k x_{ik}) \quad (3\text{-}1)$$

Where we use the occurrence of estate crop plantation as the dependent variable, $h_i(t)$ can be understood as the average risks that a grid i would be subject to over the time period (3 or 4 years). x_{ik} are a set of biophysical and socioeconomic variables selected following the economic theory that estate crop plantation would be established from other LCLU classes to maximize the discounted value of future net benefits (gross benefits minus cost) of the conversion (Busch et al., 2015, 2012; Busch and Engelmann, 2017). The gross economic benefits are proxied by estimated attainable yield of oil palm (IIASA/FAO, 2021), which considers climatic-agricultural potential, soil suitability, as well as terrain suitability (in categories) for the major type of estate crop expanded in the study period, and are corrected with four climate factors (average temperature, shortwave radiation, annual precipitation, and driest month precipitation) that contribute to yearly variation in attainable yield. The costs of land conversion and transportation are proxied via a combination of distance to nearest estate crop plantation in 1990, distance to nearest palm oil processing mills, slope, elevation, peatland percentage, access time to large cities and population density. Some variables are log-transformed prior to analysis to ensure the normality of their distributions. When the model is run across the whole islands, $Protect_i$ represents the ratio of PA in grid i in the starting year of each period (e.g., 1996, 2000, 2003, 2006, 2009, and 2012). When the model is run over the PAs only, we define two binary variables $Protect_{i1}$ and $Protect_{i2}$ with the former representing the establish time (1: after the establishment of PA, 0: before) and the latter representing the location of PA (1: totally within PA, 0: at boundary of PA). Table B-2 lists the variables, the description of the corresponding data, and data resources.

We run the model on 1km × 1km grids. We select grids with more than 90% covered by natural forest in 1996 to run the model. For the models running across the whole islands, we generate a set of samples by systematic sampling in the form of 1×1 km grid, which we place randomly across Indonesia's 1996 LCLU maps. Grids that are placed within two kilometers of a previously chosen grid are rejected. Two kilometers is chosen as a compromise between the wish to address the spatial autocorrelations and the need for an adequate sample (Gaveau et al., 2013). For the models on LCLUC inside PAs, we define the PAs as the area under protection in 2012 - the start year of the last period of our research. All grids within or intersect with the boundaries of the PAs are used in the models to meet the need for an adequate number of events. We assume that a given grid only experience one estate crop expansion event, if two estate crop expansion events were recorded within the study period, the earliest event is used. The Cox models are estimated using "coxph" function in the "survival" package in R (Therneau and Lumley, 2014). Since the coxph functions in R cannot handle left-censored data, only grids where estate crop expansion occurred during our research period or did not occur until the end of the period are included in the model.

The standard CPHM assumes explanatory variables exert constant effects on hazards over time, which might be violated in the process of rapid LCLUC. Therefore, we extend the CPHM with time-dependent effects, following the research of Chen et al. (2016). The extended model is written as:

$$h_i(t) = \lambda_0(t)exp\,(\beta_1 Protect_i + \beta_1' Protect_i \times (t) + \beta_2 x_{i1} + \beta_2' x_{i1} \times (t) + \cdots + \beta_k x_{ik} + \beta_k' x_{ik} \times (t)). \quad (3\text{-}2)$$

Where $Protect_i \times (t)$ and $x_{ik} \times (t)$ represent the time-dependent effects of PAs and each biophysical or socioeconomic factor x_{ik} , respectively (Allison, 2014). Whether to include the time-dependent effects in the model depends on the correlation analysis between the Schoenfeld residuals and the time variable (t) (Zhang et al., 2018). We then use a stepwise process to reduce the possible multicollinearity and the large number of potential independent variables. We perform correlation analysis again on the stepwise selected models to check whether the $x_{ik} \times (t)$ has addressed the time-dependent effects successfully, if not, we apply strata models on these variables to see their effects in each period. Table B-3 and B-4 reports the measurement units and summary statistics of variables across the islands and inside PAs. Table B-5 – Table B-8 present the pairwise correlations between explanatory variables, Table B-9 reports the variance inflation factors (VIFs).

3.2.3 Multi-state regressions

Multi-state regressions intend to reveal the different risks of direct conversions from natural forest to estate crop, conversion with different intermediate status, conditioned on the status of each grid. We use a semi-Markov chain with estate crop plantation as the final (absorbent) states, as shown schematically in Figure 3-1. We consider the grid as a LCLU status when at least half of the grid is covered by this LCLU. Fragmented grids (all LCLU class < 50%) or conversions to LCLU classes other than estate crop or the defined intermediate status are considered as censored. Though there are a small number of conversions from downstream LCLU classes to upstream LCLU classes, we allow only conversions from upstream LCLU to downstream LCLU (Rueda et al., 2019). If the downstream LCLU class only appeared in one period, we exclude it by assuming it as a classification error from the maps, otherwise, we omit the upstream LCLU class as redundant process. The variables used in the multi-state models are similar to those in the standard and extended CPHMs, while a second-order polynomial on the establishment time of the intermediate status (calculated as established year - 1996) is added. We use a 'clock forward' approach, in which the clock keeps moving forward for the grid, also when intermediate events occur. "mstate" package in R (de Wreede et al., 2011) and Cox proportional hazard regressions (Therneau and Lumley, 2014) are used to prepare data and estimate the model. VIFs and pairwise correlations between explanatory variables are calculated to test the multicollinearity, explanatory variables with VIF > 7.5 and pairwise autocorrelation > 0.8 are omitted from the models.

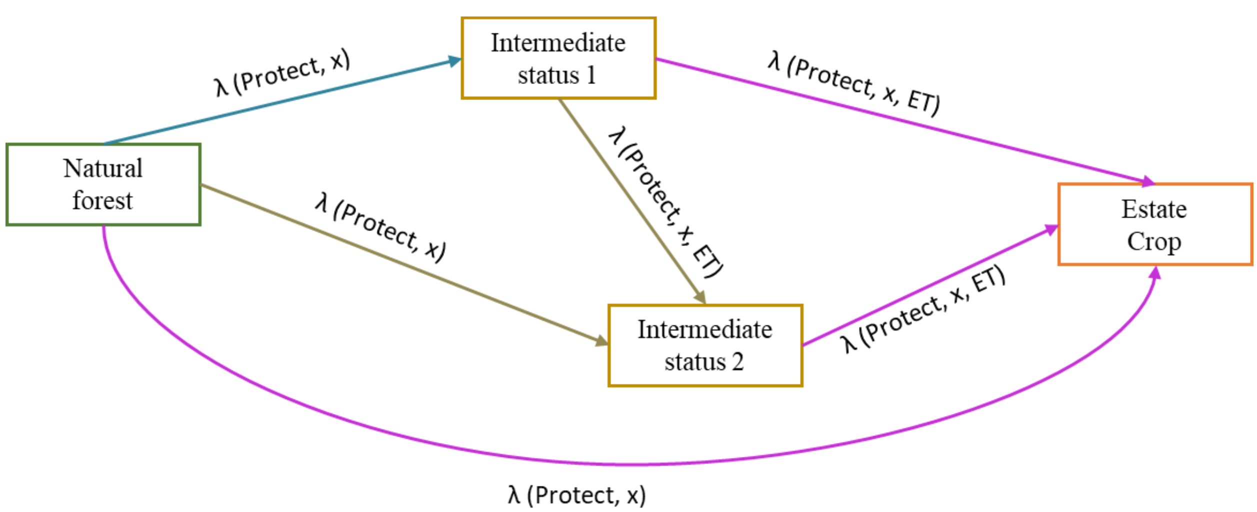


Figure 3-1 Graphical representation of the multi-state model. Nodes represent possible states and links represent possible conversions between states, where parameters that influence the hazard are indicated. Protect, ratio of PA (or two binary variables representing establish time and location of PA in the models on PAs); x, the biophysical and socioeconomic variables; ET, the establishment time of the intermediate status. λ () is the hazard function.

3.3 Results

3.3.1 Land cover and land use change (LCLUC) trajectory in Indonesia

With a 3(or 4)-year time-step, land with relatively low biomass, such as shrub, bare ground, and dry agriculture surpassed natural forest and became major sources of estate crop expansion in recent years. However, when we prolong the time-step to 1996-2015, approximately half of the estate crop expansion in Indonesia during 1996-2015 was at the expense of natural forest in 1996, accounting for 19.80% of the deforestation in this period. 52.11% of estate crop expansion in Sumatra and 46.12% of that in Kalimantan during the same period were at the expense of natural forest in 1996, accounting for 24.43% and 26.12% of the deforestation on the two islands, respectively.

As shown in Figure 3-2, there are multiple LCLUC trajectories in Indonesia, conversions from natural forest to estate crop could either occur directly within one observation period (3-4 years) or take a longer process with degraded land as intermediate status. The LCLUC generally follows a stepwise process, that logging first converts primary forest to secondary forest, which late on degrades to shrubland, then plantations such as dry agriculture and estate crop are largely the consequences of conversions from the degraded land, and bare ground increasingly become an intermediate status before conversions to estate crop. Estate crop plantations are placed at the end of the LCLUC trajectories in all time periods and all study areas because the outflows from estate crop to other LCLU classes are negligible compared with the inflows from other LCLU classes to estate crop. Although the general patterns are similar, the amounts and proportions of

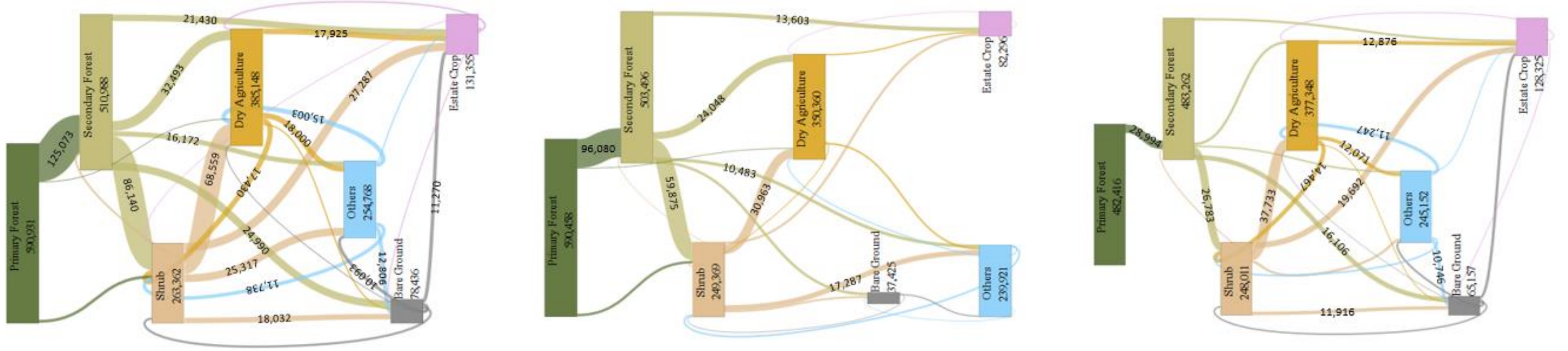
LCLUC varies significantly among different periods, as well as different study areas. In the whole country and Sumatra, the direct conversions from natural forest (mainly secondary forest) were far more than those from low-biomass LCLU classes during 1996-2006, while the conversions from low-biomass LCLU classes surpassed natural forest in 2006-2015 (Figure 3-2 (a)&(b)). In Kalimantan, the conversions from natural land covers to anthropogenic land uses were quite limited in 1996-2006 (less than 20,000 km^2), but expanded remarkably after 2006, and the conversion process became similar to that in Sumatra (Figure 3-2(c)). In 1996-2015, around 44.17% of natural forest conversion to estate crop in Indonesia had at least one intermediate status. The share in Sumatra were around 35.54%, while it is much higher in Kalimantan, at 55.49% (Figure 3-3).

The process of estate crop expansion into natural forest were prolonged in recent years by intermediate status, especially shrub and bare ground (Figure 3-3, Figure B-1 – Figure B-3). Shrub is an important intermediate status, with comparable inflows and outflows at country level. On both islands, more than 1/3 of the shrub converted to estate crop in 1996-2015 were natural forest in 1996 (Figure B-1). Bare ground is another remarkable intermediate status. Around 63% and 68% of bare ground converted to estate crop in 1996-2015 were natural forest in 1996 in Sumatra and Kalimantan, respectively (Figure B-2). In Sumatra, due to the limited area of the remaining natural forest, deforestation to all LCLU classes declined in 2006-2015, except for bare ground (Figure B-4). The major sinks of bare ground conversion were estate crop and plantation forest, though plantation forest also made one of the major sources of bare ground establishment in 2006-2015. In Kalimantan, deforestation to bare ground also increased from 1996-2006 to 2006-2015. Estate crop was the only productive sink of bare ground conversions, making around 56% of the total outflow. Dry agriculture became a major source of estate crop expansion in 2006-2015, however, around 90% of the dry agriculture converted to estate crop in 1996-2015 were established before 1996 (Figure B-3). Therefore, it is more likely that dry agriculture is an alternative agricultural activity than estate crop plantation, rather than an intermediate step in the prolonged process of estate crop expansion into natural forest.

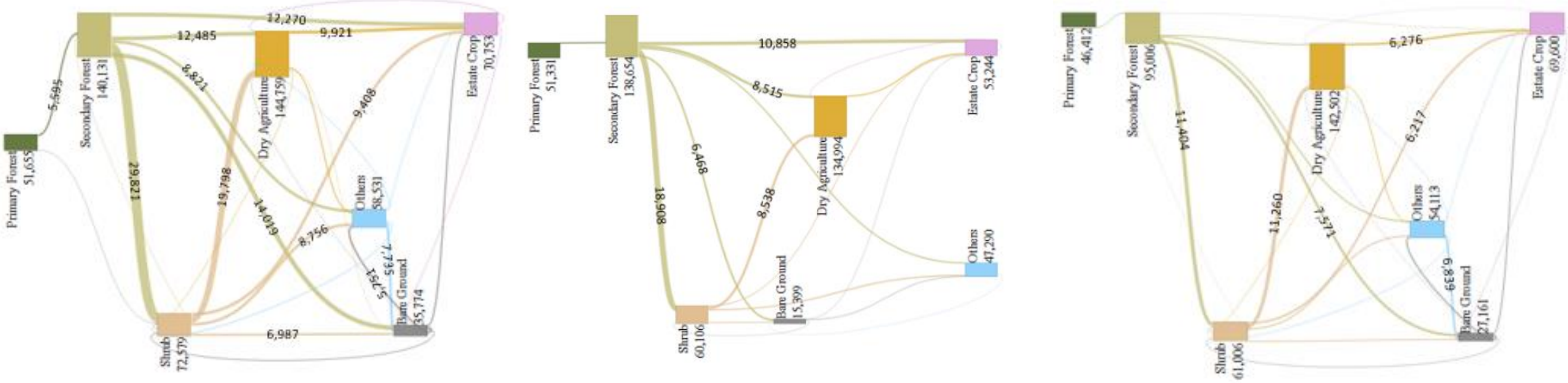
3.3.2 Biophysical and socioeconomic drivers on estate crop expansion into natural forest

Table 3-1 reports the estimation results of CPHMs and their extensions with time-dependent effects, on estate crop expansion into natural forest over 1996-2015 in Sumatra and Kalimantan. Compared with the standard Cox models, the extended models successfully address the time-dependent effects of some variables and reveal their temporal trends. Using the stepwise process to exclude some variables does not change the direction, magnitude, and significance of the remaining variables statistically. Generally speaking, estate crop expansion into natural forest tended to occur in areas with high oil palm attainable yield but low annual average temperature, at gentle slope and low elevation, and close to old plantation and palm oil processing mills, although the effects of accessibility to old plantation and processing mills decreased over time or even changed directions in 2012-2015. The expansion preferred mineral land in early periods but changed to peatland in latter periods. Natural forest with longer access time to large cities had lower risks of converting to estate crop on Sumatra, meanwhile, the effects on Kalimantan were positive. The expansion in Sumatra preferred higher annual precipitation, while the expansion in Kalimantan were more significantly affected by driest month precipitation.

(a)



(b)



(c)

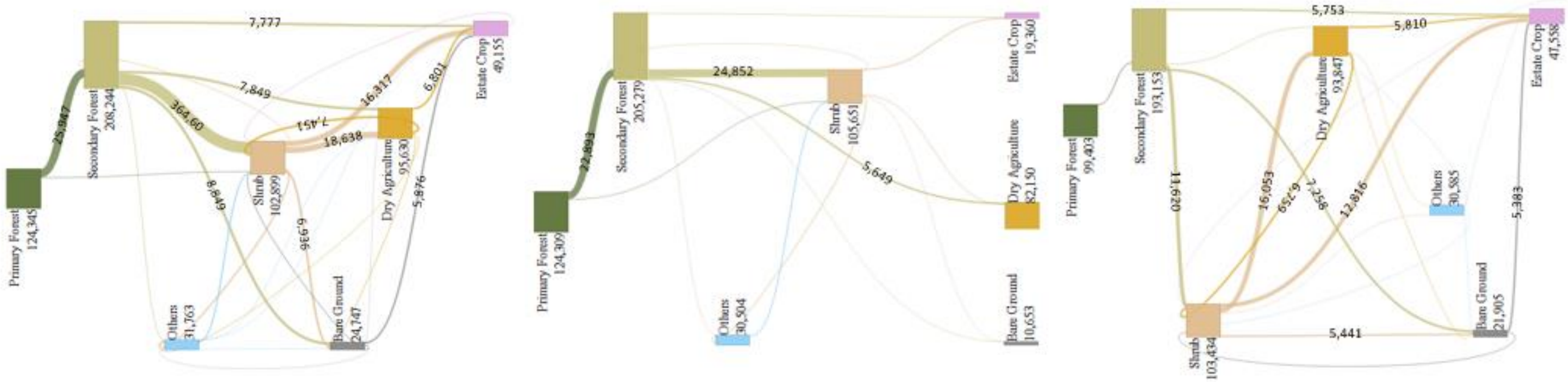


Figure 3-2 Trajectories of LCLUC in Indonesia (a), Sumatra (b), and Kalimantan (c). From left to right, the figures show the LCLUC in 1996-2015, 1996-2006, and 2006-2015. Nodes represent the seven LCLU classes (primary forest, secondary forest, shrub, bare ground, dry agriculture, estate crop and others), and links represent the direct conversions (conversions occurred within 3 or 4 years) among the LCLU classes. The height of each node represents the area which was under such LCLU class in at least one period during the study period. The height of each flow represents the amount of the direct conversion. All nodes and links in all figures are comparable to each other. Node - Links go into the node at left = Area of such LCLU at the start year (1996 or 2006); Node + Links go out of the node at right = Area of such LCLU at the end year (2006 or 2015). The Units are km2. Links smaller than 1000 km^2 for the whole country and 500 km^2 for the Islands were not shown in the figure.

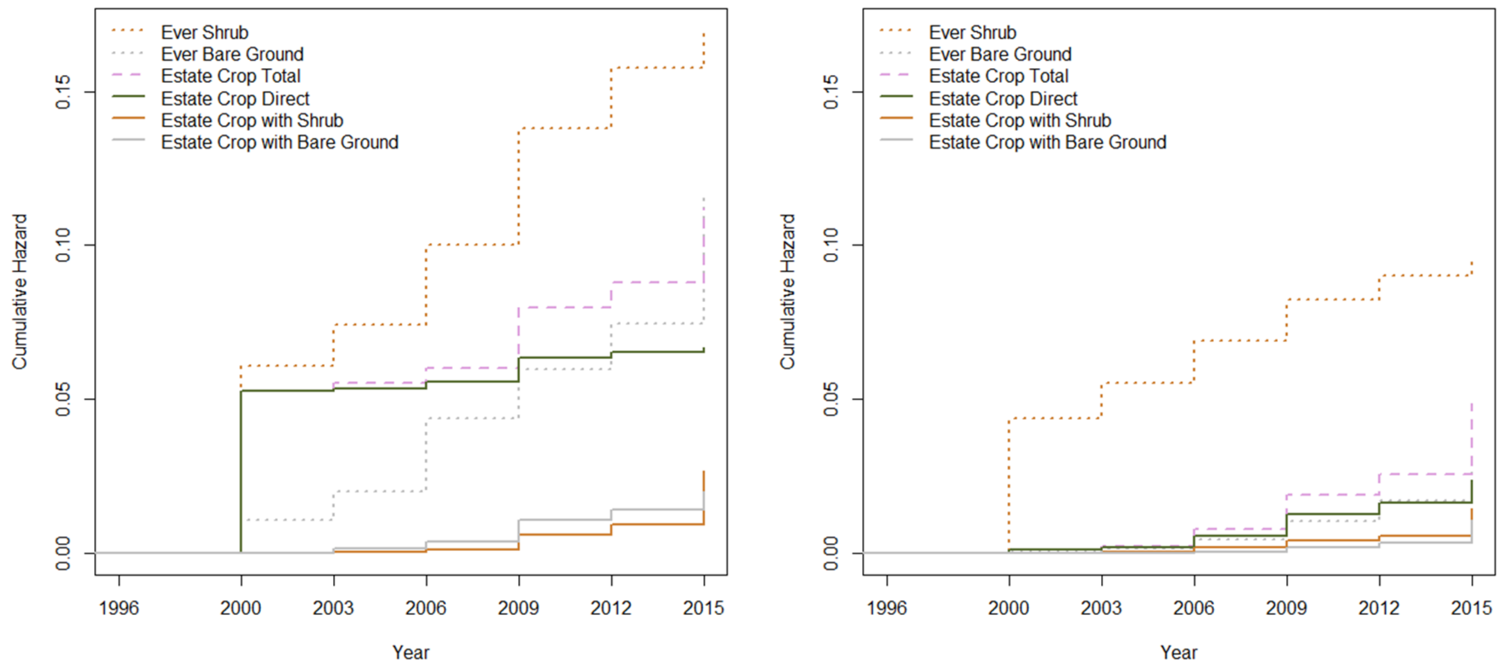


Figure 3-3 Cumulative hazard of deforestation to shrub, bare ground, and estate crop across Sumatra (a) and Kalimantan (b). Ever Shrub and Ever Bare Ground indicate the total deforestation area which were converted to shrub or bare ground for at least one period in 1996-2015.

Table 3-1 Results of standard CPHMs and models extended by time-dependent effects $x_{ik} \times (t)$ on estate crop expansion into natural forest in Sumatra and Kalimantan.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	0.135	1.144	3.647	****	0.146	1.157	3.172	***	0.441	1.555	3.243	***				
Log(Distance to 1990 plantation)	-0.266	0.767	-8.431	****	-0.362	0.696	-8.853	****	-0.168	0.845	-5.076	****	-0.721	0.486	-12.941	****
Log(Distance to oil palm mills)	-0.954	0.385	-27.785	****	-0.935	0.393	-27.343	****	-1.197	0.302	-27.056	****	-1.434	0.238	-12.367	****
Access time	-0.861	0.423	-7.063	****	-0.886	0.412	-7.408	****	0.099	1.104	1.601		0.100	1.105	1.616	
Temperature	-0.093	0.911	-1.627		-0.116	0.890	-2.066	**	-0.193	0.824	-2.358	**	-0.623	0.537	-2.995	***
Shortwave radiation	-0.014	0.986	-3.796	****					0.007	1.007	2.058	**	0.028	1.028	2.111	**
Annual precipitation	0.215	1.240	7.257	****	0.194	1.215	6.890	****	-0.037	0.964	-1.071		0.717	2.049	8.397	****
Driest month precipitation	-0.339	0.712	-8.795	****	-0.748	0.473	-9.280	****	0.146	1.157	5.787	****	0.200	1.222	7.501	****
Slope	-0.291	0.748	-10.027	****	-0.284	0.753	-9.498	****	-0.208	0.812	-6.059	****	-0.195	0.823	-5.962	****
Elevation	-0.053	0.948	-1.176		-0.088	0.916	-1.847	*	-0.565	0.568	-6.436	****	-0.591	0.554	-6.946	****
Population density	0.169	1.185	0.948						-0.571	0.565	-1.665	*				
Protected ratio	-1.121	0.326	-6.345	****	-4.809	0.008	-3.737	****	-2.474	0.084	-6.382	****	-2.602	0.074	-6.629	****
Peatland ratio	0.077	1.080	1.300		-0.549	0.578	-5.912	****	0.073	1.075	0.907		-2.213	0.109	-7.118	****
Log(Oil palm attainable yield) * T													0.086	1.090	3.276	***
Log(Distance to 1990 plantation) * T					0.039	1.040	3.190	***					0.133	1.142	10.153	****
Log(Distance to oil palm mills) * T													0.045	1.046	2.191	**
Access time * T																
Temperature * T													0.096	1.100	2.324	**
Shortwave radiation * T					-0.006	0.994	-6.543	****					-0.004	0.996	-1.822	*
Annual precipitation * T													-0.173	0.841	-9.594	****
Driest month precipitation * T					0.139	1.149	6.857	****								
Slope * T																
Elevation * T																
Population density * T																
Protected ratio * T					0.800	2.226	3.446	****								
Peatland ratio * T					0.226	1.253	8.432	****					0.456	1.577	7.977	****
Concordance	0.914				0.916				0.947				0.950			
AIC	28236.45				28047.43				24322.73				24020.15			
LogLik	-14105.20				-14007.72				-12148.36				-11992.07			
Number of grids	17661								31833							
Number of events	1117								677							

Note: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

Table B-14 – Table B-19 present the results of multi-state regressions, using both CPHMs and their extensions with time-dependent effects, and Figure 3-4 summarizes the effects of PAs on estate crop expansion into natural forest as revealed by these multi-state regressions. Based on the LCLUC trajectories depicted in Figure 3-2 and Figure 3-3, we use shrub and bare ground as the intermediate status of the models, and consequently six direct conversions are modeled: 1) natural forest to shrub, 2) natural forest to bare ground, 3) natural forest to estate crop, 4) shrub to bare ground, 5) shrub to estate crop, and 6) bare ground to estate crop. The results show that deforestation to shrub occurred 8 years earlier had the highest risks of further conversion to estate crop in Sumatra, and deforestation to shrub and bare ground occurred 3 years earlier had highest risks of further conversion to estate crop in Kalimantan. Although conversion with intermediate status made more share in recent years (Figure 3-3), the effects of biophysical and socioeconomic drivers (except PA) did not vary much between the total and the direct estate crop expansion into natural forest, with the exception that the effects of access time to large cities in Sumatra showed no significant temporal trend on the direct expansion, but a decreasing trend on the total expansion. This exception may result from the establishment of and conversion from bare ground in the latent process of LCLUC trajectory hopping. Bare ground establishment preferred natural forest with shorter access time to large cities, the effects decreased significantly as time went by, meanwhile, the further conversion to estate crop tended to occur at bare ground with longer access time to large cities.

3.3.3 Effects of protected areas (PAs) on estate crop expansion into natural forest

The standard CPHM (Table 3-1 Base Model) shows that PAs significantly decreased the risks of estate crop expansion into natural forest in both Sumatra and Kalimantan. However, as shown by the results of the CPHM extended with time-variant effects, (Figure 3-4 the 7th LCLUC type), the effects in Sumatra decreased after 2000 as time went by and became insignificant in 2012-2015. The 3rd LCLUC type in Figure 3-4 indicates that the effects of PAs on preventing direct deforestation to estate crop in Sumatra was high because the hazard level of PAs was only 2%-11% of that in non-PAs at the 90% confidence level and had no significant temporal trend. The decreasing trend of the protection effects was present with shrub as intermediate status (the 5th LCLUC types). After 2000, the effects of PAs on preventing estate crop expansion into established shrub decreased as time went by and the hazard level became significantly higher than that in non-PAs in 2012-2015 (the 5th type). Although PAs had significant effects on preventing deforestation to shrub (49%-63% of the hazard level in non-PAs, the 1st type), the effects were much lower than preventing deforestation to estate crop directly (2%–11% of the hazard level in non-PAs, the 3rd type).

In Kalimantan, although the PAs showed significant effects on preventing the total estate crop expansion into natural forest with no significant temporal trend, the effects on preventing deforestation to shrub and bare ground were remarkably smaller than on preventing direct deforestation to estate crop (Figure 3-4). Especially, the effects of PAs on bare ground establishment directly from natural forest decreased over time and became insignificant in 2012-2015 (85%-101% of the hazard level in non-PAs, the 2nd type), meanwhile, the risks of conversion from established shrub to bare ground inside PAs were even significantly higher than those out of PAs. As PAs showed no significant effects on conversion from bare ground to estate crop ($p > 0.6$ in the base model, not selected in the stepwise-selected extended model), the intensive bare ground establishment inside Kalimantan PAs, especially in 2012-2015 (the 2nd and 4th LCLUC type in Figure 3-4), are noteworthy, and may provide a major source for future estate crop expansion.

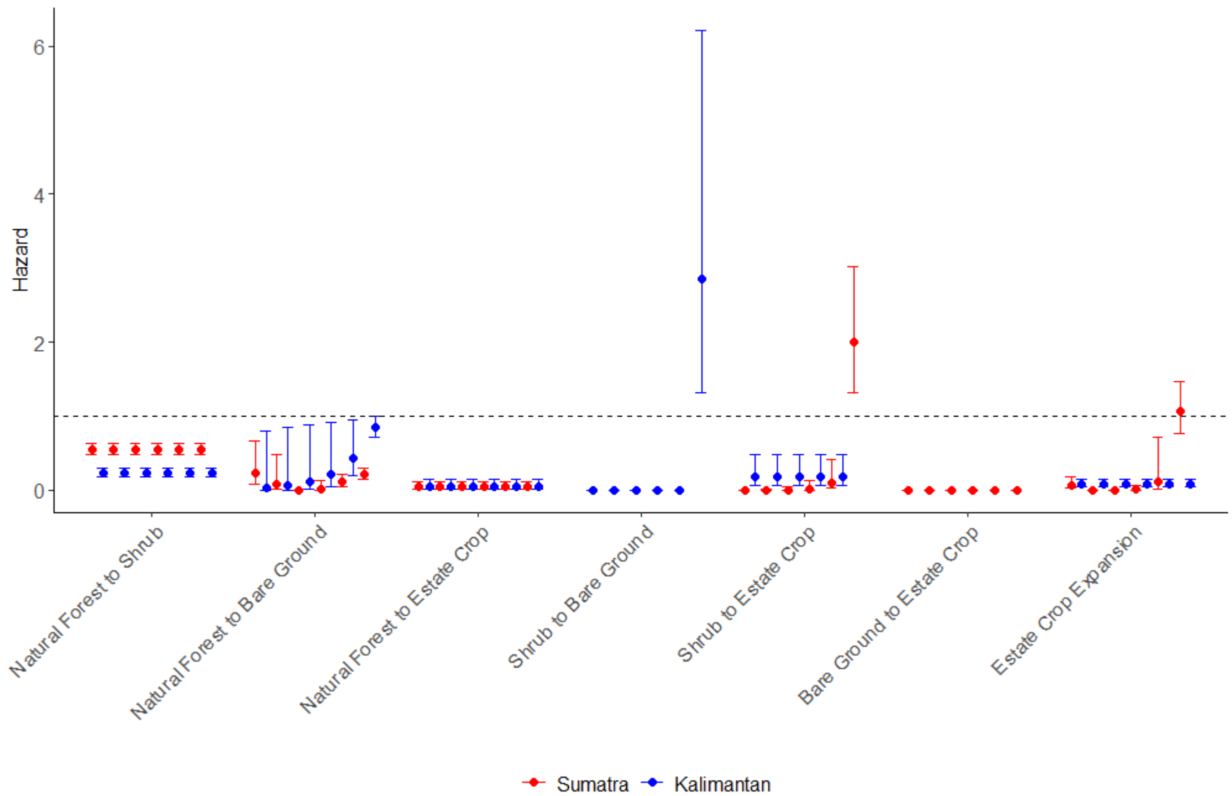


Figure 3-4 Effects of PAs on estate crop expansion into natural forest as revealed by the multi-state regressions. The vertical axis is the exponent of the PA coefficient, $exp(\beta_1)$, indicating the hazard a grid would be subject to because of PAs in each 3(or 4)-year period. The horizontal axis shows different LCLUC types. The first six represent the six direct conversions in the multistate process, and the seventh, Estate Crop Expansion, represents the total estate crop expansion into natural forest. Vertical bars correspond to 90% confidential intervals. For each transition type on each island, the vertical bars from left to right represent time-period 1996-2000, 2000-2003, 2003-2006, 2006-2009, 2009-2012 and 2012-2015, respectively. The dashed horizontal line is Hazard = 1. If the vertical bars fall totally under the dashed horizontal line, the PAs have significant effects in reducing the risks of LCLUC; if the vertical bars fall totally above the dashed horizontal line, the grids inside PAs have higher risks of experiencing the LCLUC than those out of PAs; if the vertical bars intersect with the horizontal line, the effects of PAs are not statistically significant. The effects of PAs on conversion from shrub to bare ground in Sumatra and conversion from bare ground to estate crop in Kalimantan were insignificant during the whole study period ($p > 0.3$ & $p>0.6$), therefore, they are not shown in the figure.

3.3.4 Estate crop expansion into protected natural forest

Figure 3-5 depicts the cumulative hazard of deforestation to shrub, bare ground, and estate crop in PAs. In both Sumatra and Kalimantan, shrub was the largest sink of natural forest loss in

PAs before 2012, while bare ground became the largest sink in 2012-2015. In Sumatra, deforestation to shrub was largest in 1996-2000, followed by 2006-2009, 2009-2012 and 2012-2015. Once deforested to shrub, the risks of further conversion to estate crop increased by about 12 times. Around 94% of further conversion from the established shrub to estate crop occurred in 2012-2015. The establishment of bare ground mainly occurred in 1996-2000 and 2012-2015. Around 95% of further conversion to estate crop in the study period occurred in 2000-2003, over 80% of bare ground developed in 1996-2000 converted to estate crop in this period (Figure B-4). More than 90% of the direct deforestation to estate crop in PAs occurred in 1996-2000. By contrast, estate crop expansion into protected natural forest in Kalimantan were limited, with around 70% of the expansion occurred in 2012-2015 (Figure 3-5). In Kalimantan, deforestation to shrub mainly occurred before 2009, once converted to shrub, the risks of further conversion to estate crop approximately doubled. The further conversion from shrub to estate crop mainly occurred in 2006-2009 and 2012-2015. Over 60% of bare ground established in 1996-2012 further converted to estate crop in 2012-2015 (Figure B-4). Meanwhile, bare ground establishment in 2012-2015 was around 6 times higher than the total amount of 1996-2012 in PAs (Figure 3-5). The newly established bare ground inside and outside PAs in both islands over 2012-2015 may provide a new source for estate crop expansion in near future.

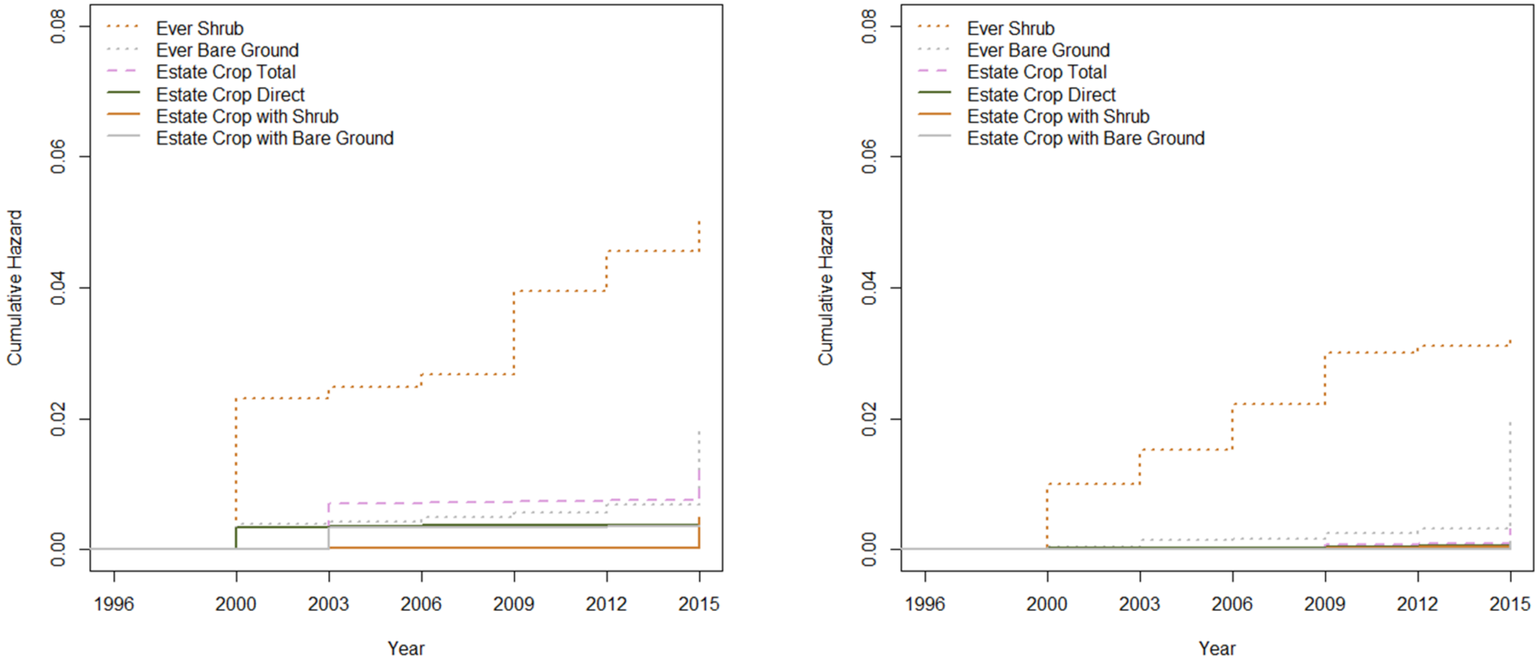


Figure 3-5 Cumulative hazard of deforestation to shrub, bare ground, and estate crop in protected areas. a) Sumatra. b) Kalimantan. Ever Shrub and Ever Bare Ground indicate the total deforestation area which were converted to shrub or bare ground for at least one period in 1996-2015.

Table B-20 and Table B-21 – Table B-25 report the results of the three sets of regressions (as presented in Table 3-1 and Tables B-14 – Table B-19) on PAs only. A technical discussion of the comparison between the regressions on PAs only and on the whole islands is presented in Appendix B (before Table B-20). Figure B-5 highlights the risk levels of natural forest at the boundaries of PAs in comparison with that totally inside PAs, as implied in Table B-20 and Tables B-21 – Table B-25. Figure B-5 shows that the former had significantly higher risks of conversion to estate crop than the latter, although the differences became insignificant in 2012-2015 in Sumatra (the 6th LCLCU type). The decreasing trend in Sumatra was mainly due to the conversions with shrub as intermediate status (the 1st type in Figure B-5). The average risks of deforestation to shrub across grids totally within PAs was about 78% of that across grids at the boundaries of PAs (Table B-23), whereas the corresponding value for the direct deforestation to estate crop was only 6%-8% of those at the boundaries of PAs (Table B-21). Meanwhile, the risks of further conversion to estate crop were not significantly different whether the established shrub was at boundaries of PAs (Table B-22); and the establishment of bare ground in PAs in Sumatra preferred natural forest at boundaries of PAs, though the effects decreased significantly as time went by (Table B-24). In Kalimantan, during the whole study period, natural forest totally within the PAs had around half the risk levels of that at the boundaries of PAs in terms of conversion to shrub or bare ground (Table B23 and Table B24). Meanwhile, the established shrub totally within PAs had around 25% of the risk levels of its counterpart at the boundaries of PAs in terms of further conversion to estate crop (Table B22).

3.4 Discussion

3.4.1 Trajectory hopping as a tactic to facilitate estate crop expansion into natural forest

It has been widely acknowledged that LCLUC varies not only spatially, but also along temporal trajectory, and could be characterized by a sequence of changes (Carlson et al., 2013; der Laan et al., 2018; Ekadinata and Vincent, 2011; Lambin et al., 2003). While our research agrees with the literature that estate crop expansion tends to occur in areas with suitable biophysical conditions, and good accessibility to existing infrastructures (Busch and Engelmann, 2017; Euler et al., 2017; Pirker et al., 2016; Xin et al., 2021), it reveals that the effects of accessibility to existing infrastructures decreased and/or became insignificant as time went by. The decreasing trend could be explained by the location choice sequence of the plantation decision-maker, which is similar to the pecking order sequence of corporate managers when considering sources of financing (Myers and Majluf, 1984). It means that suitable areas with better accessibility to existing infrastructures are occupied in early periods, so that the new plantations must be located in more remote areas. Since accessibility becomes a less constraining factor, estate crop expansion may go further into the remote natural forest and bring new threats to those ecosystems in a stepwise way. Importantly, the evidence discovered by this research include that deforestation to shrub occurred 8 years earlier had the highest risks of further conversion to estate crop in Sumatra, and deforestation to shrub and bare ground occurred 3 years earlier had highest risks of further conversion to estate crop in Kalimantan. The results suggest that trajectory hopping with shrub and/or bare ground as intermediate status has served as a land banking mechanism and a clearing-up tactic to nominally meet the sustainable development requirements on estate crop expansion. Due to the recognition of the value of tropical natural forest in providing ecosystem services (Brandon, 2014; Koh and Wilcove, 2008; Shimamoto et al., 2018) and the increasing consumer pressure (European Parliament, 2017), the local government (Indonesian President Instruction no. 10, 2011; Pouzols et al., 2014), the international organizations (Geibler, 2013), as well as the palm oil companies (Bulter, 2015; Summit, 2014) take actions to restrict the estate crop expansion into natural forest. However, the degraded land has been frequently neglected in the monitoring and evaluation process (Carlson et al., 2012, 2013; Xin et al., 2021). As the LCLUC trajectory hopping with intermediate status make larger portion of estate crop expansion into natural forest, we suggest that it is practically important to effectively track the original sources and eventual utilization of the degraded land, and establish policies to cope with the land banking mechanism.

3.4.2 The effectiveness of protected area (PA) is compromised by the trajectory hopping tactic

Our results show that the risks of estate crop expansion are significantly lower inside than outside PAs when the distribution biases are addressed, which confirms the existing findings that PAs effectively prevented estate crop expansion into natural forest (Gaveau et al., 2012, 2009; Wade et al., 2020). We further show that the risks of estate crop expansion are significantly higher around the boundaries of PAs than inside PAs. This might be attributed to 1) the contestation of the exact boundaries from local communities and local authorities (Gaveau et al., 2012; Kinnaird et al., 2003), 2) the leakage effects that local communities and authorities may intensify extraction activities of natural forest and conversions to productive land uses just outside the PA (Poor et al., 2019), and 3) the ineffective enforcement of border protection (Watson et al., 2014).

With the survival analysis that emphasis the occurrence and timing of estate crop expansion, our research suggests that as time goes by and the land resources outside of PAs become more limited (Dwiyahreni et al., 2021; Geldmann et al., 2019), the effectiveness of PAs decreases, estate crop expansion encroaches more into the PAs and goes deeper into the central area of protected forest. The temporal trend is more significant in Sumatra than Kalimantan because Kalimantan is a comparative latecomer with relatively abundant land resources (Austin et al., 2017; Xin et al., 2021). The multi-state models show that the direct conversion from natural forest to estate crop remained minimal in PAs, the effectiveness of PAs on preventing estate crop expansion into natural forest are significantly reduced by the LCLUC trajectory hopping tactic. The preventing effects of PAs on deforestation to shrub and bare ground are remarkably smaller than on direct deforestation to estate crop plantation, and/or with decreasing trends. Consistent with the finding in Laurance et al. (2012), our results show that deforestation to shrub and bare ground inside PAs strongly mirrors those outside PAs. Natural forest inside PAs suffers from mounting pressures of logging and the effects of PAs become weak, due to the exhaustion of logging concessions and the majority of remaining most valuable timber resources within PAs (Brun et al., 2015; Curran et al., 2004; Wade et al., 2020). Although secondary forest still supports a large portion of biodiversity (Imron et al., 2010; Wilcove et al., 2013), our visualization of LCLUC trajectories show that secondary forest has higher risks of deforestation than primary forest (Linkie et al., 2008), and shrub is the largest sink of deforestation in PAs (Wade et al., 2020), meanwhile, deforestation to bare ground increases remarkably in recent years. Once deforested to shrub and/or bare ground, the risks of future conversion to estate crop become multiplied, especially in recent years (Geldmann et al., 2019). It reinforces our argument that the deforestation to shrub and bare ground in PAs serves the ultimate purpose of estate crop expansion. Therefore, as the global demand for estate crop products grow, estate crop plantation would continue to expand in Indonesia (Purnomo et al., 2020; Taheripour et al., 2019; Xin et al., 2021), not only the estate crop expansion into established shrub and bare ground, but also deforestation to shrub and bare ground in PAs are expected to grow.

The estate crop expansion into protected natural forest may bring more severe threats to biodiversity than natural forest loss, since estate crop plantation, chiefly oil palm, is especially detrimental for biodiversity protection (Wilcove et al., 2013). Biodiversity is not only affected by the size of forest, but also the location of forest, as well as distance to and context among neighboring forest patches (Linkie et al., 2008; Poor et al., 2019). The deforestation related to estate crop expansion largely occurs at lowland forest, which is biophysically suitable for estate crop plantation, but also holds the highest biodiversity richness (Kinnaird et al., 2003). Compared with other LCLU types, monocultures for estate crop production support significantly less biodiversity, either on its own or combined with tropical forest (Imron et al., 2010; Wilcove et al., 2013). Natural forest at the boundaries of protected areas has high risks of conversion to estate crop, which may cut off the networks among the PAs and endanger the long-term survival of threatened and endemic large mammals that roam across large contiguous area of habitat, such as Sumatra tiger (Linkie et al., 2008). As time goes by and land resources become more limited, estate crop expansion goes deeper to the interior PAs, such expansion and associated deforestation results in a landscape with isolated patches of forest on inaccessible steep slopes, thus reduce the distribution of large mammals that preferentially use interior forest area, such as tigers, elephants, orangutan, rhinoceros, tapirs (Kinnaird et al., 2003). Meanwhile, the estate crop expansion is usually associated with roads construction and other human activities, which increases the human footprint around PAs, aggravates the fragmentation of remaining forest, and intensifies the disturbance at forest edges, thus put the biodiversity, especially large-mammal fauna in serious jeopardy (Dwiyahreni et al., 2021; Kinnaird et al., 2003). Therefore, preventing the conversion of natural forest to estate crop plantation is essential to conserving the biodiversity, and should be a top priority of conservationists (Imron et al., 2010; Wilcove et al., 2013).

Compared with the pressures, the resources currently available for effective management of PAs is pale, and the effectiveness of PAs on preventing estate crop expansion into natural forest is decreasing. PA downgrading, downsizing and degazettement (PADDD) has already occurred, and may be accelerated in the face of the increasing global commodity demands and local land pressure, which may further threaten the conservation of natural forest and biodiversity (Mascia and Pailler, 2011; Watson et al., 2014). Given the current situation of PA management in Indonesia, the best strategy may lie in including the establishment of shrub and bare ground in the monitoring system, and incorporating the local communities and nongovernmental organization in the management decisions. Besides the basic management activities such as defining clear protected area boundaries, enforcing regulations, and providing compensation to local communities (Adams et al., 2019; Dwiyahreni et al., 2021), creating buffers for protected area (Gaveau et al., 2013, 2009) and provide alternative income to local communities (Imron et al., 2010; Shah and Baylis, 2015) may be effective measures to maximize biodiversity conservation, since estate crop expansion is especially detrimental for biodiversity protection and occurs more frequently at the boundaries of PAs.

4 Oil palm reconciliation in Indonesia: balancing rising demand and environmental conservation

Abstract: Indonesia is the largest supplier of palm oil, the world's most widely consumed edible oil. The production and exporting of oil palm products have substantially benefitted the economic growth and living standards of local people in the country. However, the expansion of oil palm has imposed significant costs to the environment. Indonesia faces tough challenges to balance the oil palm expansion driven by the increasing global demand for oil palm products with the growing commitment to protect tropical forest and peatland. This research projects the export demand for oil palm products from Indonesia by 2050 under different international trade scenarios using generalized geo-economic gravity models. It further quantifies the possible trade-offs between oil palm expansion and environmental conservation by allocating the projected demand to 1km × 1km grids across Indonesia with the help of parametric survival analysis. The results show that about 313-679 million tons of oil palm products (oil palm fruit equivalent) from Indonesia would be needed by 2050, which would result in an additional expansion of oil palm area by about 18.58-45.59 million hectares in the country. The expansion would continue to occur at the expense of area with high environmental values, such as secondary forest and peatland. About 8% - 22% of secondary forest and 21% - 54% of peatland in Indonesia would lose to oil palm expansion by 2050. It is possible for Indonesia to maintain its leading position in oil palm exportation while enhancing its role in environmental conservation. Shifting from natural forest and peatland to degraded land with relatively low environmental values would reduce the CO_2 emission by about 87-142 Mton per year, but at the expense of increased

transportation and infrastructure accessibility costs. We argue that carefully designed and successfully enforced ecosystem-based policies and plans, together with properly implemented economic compensation mechanisms, can remarkably contribute towards a more sustainable oil palm expansion in Indonesia.

4.1 Introduction

Oil palm is among the world's most important oil crops. It is native to Africa and has been grown and used for local consumption for centuries (Jones & Hughes, 1989). In the last few decades, oil palm plantation has boomed, mainly driven by the increasing global demand for vegetable oil and facilitated by the globalized supply chains (Henders et al., 2015; Sayer et al., 2012). Palm oil is widely used as edible oil for direct human consumption, as ingredient in many processed products, and as biofuel (Qaim et al., 2020). Palm oil has the highest oil production per unit of land, is cheaper to produce, and is priced lower than most alternative vegetable oils (Carter et al. 2007; Sheil et al., 2009). Consumers' preference is shifting towards vegetable oil containing lower trans-fat due to health consciousness (WHO, 2015). Moreover, demand for biofuel blending is bound to increase owing to increasing climate change concerns (Castiblanco et al., 2013; Murugesan et al., 2009). The world's population continues its march towards nine billion people by 2050. As a result, global demand for palm oil is expected to grow in the coming decades (Nelson et al., 2010).

The worldwide production of palm oil increased from 15 million tons to over 72 million from 1995 to 2020 (USDA, 2021a, b). Indonesia played an important role and to some degree epitomized the sweeping changes in palm oil production and the globalization of the supply chain (Edwards, 2019). Oil palm was firstly introduced to Indonesia in late nineteenth century

(Cramb & Curry, 2012), and started to boom since the mid-1980s (Qaim et al., 2020). Indonesia has been the largest supplier of palm oil since 2007 (USDA, 2021a) and shared approximately 58% of the global market in 2020 (USDA, 2021b). Over 66% of palm oil produced in Indonesia were used for export (USDA, 2021b). The palm oil production and exporting have remarkably benefitted the economic growth and living standards of local people in Indonesia, especially in rural area (Clough et al., 2016; Dib et al, 2018; Edwards, 2019; Euler et al., 2017; Gotta et al., 2017; Purnomo et al., 2020). Palm oil has been the largest agricultural export of Indonesia in the last two decades (Edwards, 2019), the export value of palm oil reached USD 22.97 billion in 2020 and contributed around 16% of Indonesia's agricultural gross domestic product (GDP) (Afifa, 2021; WTO, 2021). It is believed that the sector has lifted around 2.6 million rural Indonesians out of poverty in 2000–2016 (Edward, 2019) by either providing income through farming and employment channels (Dib et al., 2018) or indirect benefits from local infrastructure development (Mosnier et al., 2017). However, after three decades of rapid expansion, global trade and international cooperation are now at a crossroad as backlashes against globalization have emerged worldwide (Dur et al., 2020; Razzaque et al., 2019) and the COVID-19 pandemic has brought opposing forces on international relations (Kerr et al., 2020). As the production for export markets comprises a sustainable share of the oil palm production in Indonesia, the global trade turmoil may rise considerable uncertainties to the oil palm sector of the country.

Meanwhile, palm oil plantation is often criticized for its damages to environment, by replacing tropical rainforest (Abdullah, 2012; Hansen et al., 2009; Koh & Wilcove, 2008; Miettinen et al., 2011; Vijay et al., 2016; Wicke et al., 2011), driving land cover and land use (LCLU) changes (Wicke et al., 2011; Xin et al., not published yet), inducing CO_2 emissions

(Carlson et al., 2012; Guillaume et al., 2015; Koh et al., 2011; Kotowska et al., 2015), threatening biodiversity (Barnes et al., 2014; Fitzherbert et al, 2008; Koh & Wilcove, 2008), and harming other ecosystem services (Comte et al., 2012; Ganser et al., 2017; Johnston et al., 2012). Recent remote-sensing estimations on subnational level in Indonesia showed that during 2000-2010, 60% of deforestation in Kalimantan (Carlson et al. 2013) and 20% of forest clearing in Sumatra (Lee et al. 2014) was owing to oil palm expansion. Although degraded land surpassed natural forest and became the largest direct source of oil palm plantation in recent years (Austin et al., 2017; Gaveau et al., 2016; Xin et al., 2021), evidence shows that the degraded land is possibly used as a land banking mechanism for nominally meeting the sustainable development requirements and actually facilitating estate crop expansion into natural forest (Xin et al., 2021; Xin et al., not published yet). Emissions from forestry, LCLU change, and peatland loss are Indonesia's main sources of CO_2 emissions, accounting for almost 60% of the country's total emissions and placing it in the top ten of global emitters (WRI, 2014). Such reduction in tropical forest and peatland has imposed severe biodiversity loss since oil palm plantations support much fewer species than natural forests and other plantations (Fitzherbert et al., 2008; Wilcove et al., 2013).

The above discussion indicates that oil palm expansion in Indonesia is likely to continue to grow due to its contribution to global vegetable oil consumption and economic benefits to local people. On the other hand, the commitments to protect tropical forest, reduce CO_2 emissions and conserve biodiversity is growing as well. This tension brings an urgent need to quantify the expected and plausible future patterns of oil palm expansion and the associated trade-off with environmental conservation. The existing literature on projections of oil palm plantation usually extrapolates historical rates of LCLU change (Austin et al., 2015; Carlson et al., 2013; Castiblanco et al., 2013), identifies lands with high biophysical suitability (Koh & Ghazoul, 2010; Pirker et al., 2016; Vijay et al., 2016), and/or incorporates policy interventions or national goals (Austin et al., 2015; Carlson et al., 2013; Castiblanco et al., 2013; Koh & Ghazoul, 2010; Sumarga & Hein, 2016). In order to quantify the trade-offs between oil palm plantation and environmental protection, some studies sequentially downscaled and spatially allocated the projection at the national level to finer scales with the assistance of logistic regressions to identify the most probable areas of future oil palm plantation (Austin et al., 2015; Castiblanco et al., 2013; Sumarga & Hein, 2016). However, the methods make little use of the important temporal information. In recognition of that the growing worldwide demand for oil palm products and the increasing global trade volumes are the major drivers of oil palm expansion in Indonesia (Henders et al., 2015; Xin et al., 2021), a few studies approached the estimation of future oil palm production in the country from the perspective of global demand and/or global trade (Afriyanti et al., 2016; Purnomo et al., 2020; Mosnier et al., 2017; Wiebe et al., 2019). However, none of the research addressed the uncertainties along with the emergent global trade turmoil, and they either were not spatially explicit (Wiebe et al., 2019; Afriyanti et al., 2016; Purnomo et al., 2020) or neglected the effects of socio-economic factors in the spatial allocation (Mosnier et al., 2017). Therefore, there is an important knowledge gap on spatially explicit characterization of the trade-offs between meeting the growing global demand for oil palm products under different international trade scenarios and minimizing the environmental costs of oil palm expansion in Indonesia.

To fill this knowledge gap and add new evidence to the literature on the local environmental impacts of global market, this study 1) runs trade flow analysis to identify the major importers of oil palm products from Indonesia; 2) Employs generalized geo-economic gravity models with panel data to link global market to oil palm production in Indonesia, and projects the demands for oil palm products exported from Indonesia up to 2050 in response to different scenarios of future global market; 3) Uses survival analysis to characterize the spatial patterns of oil palm expansion in Indonesia based on biophysical and socio-economic factors, and allocates the projected export quantities to 1km × 1km grids across the country; 4) Quantifys the spatially explicit potential trade-offs between oil palm expansion and environmental conservation. This paper aims to help the policymakers and other stakeholders to base their considerations on historical patterns and come up with properly planned and spatially explicit strategies for future development.

4.2 Materials and methods

4.2.1 Trade flow analysis

Our trade flow analysis focused on yearly physical trade flows of the primary commodities in the oil palm sector, including oil palm fruit, palm kernel cake, palm oil, palm kernel oil, between Indonesia and the countries/regions of apparent consumption. Following the analysis of Henders et al. (2015) which traced the flows of several agricultural products through international supply chains based on production data and physical bilateral trade flows between countries/regions, we extended their work and established the annual physical trade flow matrices for oil palm products over period of 1996-2015. Quantities of palm kernel cake, palm oil, and palm kernel oil were converted into oil palm fruit with conversion factors of 3, 3.3, and 3.3, respectively, and the oil palm fruit equivalent quantities were then arranged into a matrix where each cell represented a trade flow from country/region A to country/region B (Henders et al., 2015). By tracing the flows of products through international supply chains using the matrix, we excluded the transit countries in the supply chains. In combination with the information on country-level production and consumption of the primary commodities, we described the quantities of the consumptions in importer countries/regions that could be attributed to the oil palm production of Indonesia. We selected the top 30 importers of Indonesian oil palm products to run the further analysis.

4.2.2 Generalized geo-economic gravity model with panel data

Since the majority of Indonesian oil palm products are for export (Edwards, 2019; Indonesia-Investments, 2017), the geo-economic gravity model, which is widely used as an econometric approach to estimate the relationships between the bilateral trade flows and trade detriments (Egger & Pfaffermayr, 2003; Kepaptsoglou et al., 2010; Lee & Lim, 2014) and exhibits considerable empirical robustness and explanatory power (Kepaptsoglou et al., 2010), is a good fit to characterize the trade patterns and project the future demand for oil palm products from Indonesia. The trade detriments in geo-economic gravity models mainly include the GDP and population of the countries, the geographical distances between the countries (De Benedictis & Taglioni, 2011; Tinbergen, 1962), and some economic and political variables (Irshad et al., 2018; Lee & Lim, 2014; Lee & Park, 2007; Lewer & Van den Berg, 2007; Westerlund & Wihelmsson, 2011; Zidi & Dhifallah, 2013). Compared with the classical gravity models which usually use cross-section data and relationships for a specific time period, generalized gravity models with panel data are especially good at capturing the relationships among variables over time and observing the trading partners' individual effects (Egger & Pfaffermayr, 2003; Lee & Lim, 2014). In this study, we employed generalized geo-economic gravity models, and focused on the unilateral trade of oil palm products between Indonesia and other countries/regions.

We started from a pooled regression model. The equation is expressed as below:

$$\ln(Export_{it}) = \beta_0 + \beta_1 \ln(GDPP_{it}) + \beta_2 \ln(Pop_{it}) + \beta_3 Ex_{it} + \beta_4 Tff_{it} + \beta_5 RTA_{it} + \beta_6 RTAIDN_{it} + \beta_7 WTO_{it} + \beta_8 \ln(Dist_i) + \beta_9 Colony_i + +\beta_{10} Rel_i + \varepsilon_{it} \quad (4\text{-}1)$$

Where $Export_{it}$ is the quantity of equivalent oil palm fruits exported from Indonesia to each country/region in year t, which is calculated from the trade flow analysis. $GDPP_{it}$ is the GDP per capita of importer country/region in year t, and is converted into constant 2010 USD; Pop_{it} is the population of the importer country/region in year t. Ex_{it} is the real exchange rate of the importer country/region. Tff_{it} represents the impacts of tariff rates on trade flows. RTA_{it} is the number of regional trade agreements (RTAs) of the importer country/region in year t, $RTAIDN_{it}$ is the number of RTAs between the importer country/region and Indonesia in year t. WTO_{it} is a dummy variable representing whether the country/region is a member of World Trade Organization (WTO) in year t. $Dist_i$ is the population weighted distance between the importer country/region and Indonesia. $Colony_i$ represents whether Indonesia has ever been colony of the Importer country/region. Rel_i represents how the importer country/region shares the same religion with Indonesia. β_0 captures the unobserved constant determinants of the export quantity.

The pooled regression is unbiased and optimal when the errors are independent, homoscedastic, and serially uncorrelated. However, for panel data, there are usually individual correlations due to the traits of the individuals not represented by explanatory variables (Wooldridge, 2015). Fixed-effect models are commonly used to estimate the gravity equations (Egger & Pfaffermayr, 2003; Lee & Lim, 2014; Westerlund & Wilhelmsson, 2011) since they address the country/region effects and individual heterogeneity well, are robust in gravity model, and fit nicely with the gravity theory (Lee & Lim, 2014). However, random-effect models can avoid eliminating the time-invariant variables, such as the distance, as well as the cultural and historical variables in the model, and may perform statistically better than the fixed-effect models when the estimations are unbiased (Zidi & Dhifallah, 2013). The equation (4-2) shows the fixed-effect model, and the equation (4-3) shows the random-effect model.

$$\ln(Export_{it}) = \beta_1 \ln(GDPP_{it}) + \beta_2 \ln(Pop_{it}) + \beta_3 Ex_{it} + \beta_4 Tff_{it} + \beta_5 RTA_{it} + \beta_6 RTAIDN_{it} + \beta_7 WTO_{it} + \alpha_i + \varepsilon_{it} \tag{4-2}$$

$$\ln(Export_{it}) = \beta_0 + \beta_1 \ln(GDPP_{it}) + \beta_2 \ln(Pop_{it}) + \beta_3 Ex_{it} + \beta_4 Tff_{it} + \beta_5 RTA_{it} + \beta_6 RTAIDN_{it} + \beta_7 WTO_{it} + \beta_8 \ln(Dist_i) + \beta_9 Colony_i + \beta_{10} Rel_i + \alpha_i + \varepsilon_{it} \tag{4-3}$$

Where α_i captures all types of unobserved country/region-specific heterogeneity that is time-invariant. We run the F-test and Hausman test to check whether the estimation of the pooled models and the random-effect models are consistent, respectively.

Besides the growing population, the global demand for oil palm products is also expected to grow due to the change of consumers' preference to vegetable oil containing lower trans-fat (WHO, 2015) and the increasing demand for biofuel blending driven by climatic concerns (Castiblanco et al., 2013; Murugesan et al., 2019), therefore, we also considered models with time effect, and added $\ln(Time)$ as another explanatory variable[6]. Equations (4-4) – (4-6) show the pooled model, the fixed-effect model, and the random-effect model, respectively.

$$\ln(Export_{it}) = \beta_0 + \beta_1 \ln(GDPP_{it}) + \beta_2 \ln(Pop_{it}) + \beta_3 Ex_{it} + \beta_4 Tff_{it} + \beta_5 RTA_{it} + \beta_6 RTAIDN_{it} + \beta_7 WTO_{it} + \beta_8 \ln(Dist_i) + \beta_9 Colony_i + \beta_{10} Rel_i + \beta_{11} \ln(Time) + \varepsilon_{it} \tag{4-4}$$

[6] $Time$ is calculated as $Time = Year - 1995$.

$$\ln(Export_{it}) = \beta_1 \ln(GDPP_{it}) + \beta_2 \ln(Pop_{it}) + \beta_3 Ex_{it} + \beta_4 Tff_{it} + \beta_5 RTA_{it} + \beta_6 RTAIDN_{it} + \beta_7 WTO_{it} + \beta_8 \ln(Time) + \alpha_i + \varepsilon_{it} \tag{4-5}$$

$$\ln(Export_{it}) = \beta_0 + \beta_1 \ln(GDPP_{it}) + \beta_2 \ln(Pop_{it}) + \beta_3 Ex_{it} + \beta_4 Tff_{it} + \beta_5 RTA_{it} + \beta_6 RTAIDN_{it} + \beta_7 WTO_{it} + \beta_8 \ln(Dist_i) + \beta_9 Colony_i + \beta_{10} Rel_i + \beta_{11} \ln(Time) + \alpha_i + \varepsilon_{it} \tag{4-6}$$

We used the yearly data from 1996 to 2012 to run the models and extrapolated them to 2013-2015 to test their accuracy for prediction. We then selected models with best statistical performance to project the future export demands for oil palm products (oil palm fruit equivalent) from Indonesia under three international trade scenarios, with the Shared Socioeconomic Pathways (SSP) 2, which presents a middle-of-the-road projection and reflects an extension of the historical experience (Riahi et al., 2017).

4.2.3 International trade scenarios

Production for export markets makes a sustainable share of oil palm sector in Indonesia (USDA, 2021b), therefore, the uncertainties in global trade and international cooperation are expected to have considerable impacts on future oil palm production of the country. We projected the future export demands for oil palm products in Indonesia under three alternative international trade scenarios.

a. Business as usual: the WTO membership, number of RTAs, and number of RTAs with Indonesia of each importer keep the same as in year 2015.

b. More open world: all the 30 top importers join WTO by 2035, numbers of RTAs and numbers of RTAs with Indonesia increase proportionally and double by 2050.

c. Less open world: WTO membership of each importer keeps the same as year 2015, numbers of RTAs and numbers of RTAs with Indonesia decrease proportionally and halve by 2050.

We selected WTO memberships, numbers of RTAs, and numbers of RTAs with Indonesia of the importer countries/regions to characterize the international trade, because 1) WTO is believed to have large positive effects on international trade by creating a predictable environment and enhancing transparency of its members' trade policies (Larch et al., 2019); 2) RTAs simulate international trade by lowering prices of the tradable goods and increasing market access of the trading partners (Korinek et al., 2009); and 3) RTAs may affect the trade flows not only between members, but also from non-member countries/regions (Korinek et al., 2009; Sun & Reed, 2010).

4.2.4 Parametric survival analysis

We employed the parametric survival analysis to describe the historical spatial pattern of oil palm expansion in Indonesia and project the spatial allocation of oil palm expansion up to 2050. Survival analysis has gained its attention in land use sciences in recent years (An & Brown, 2008; An et al., 2011; Wang et al., 2013; Chen et al., 2016; Xin et al., not published yet). Compared with the logistic regression which uses cross-sectional procedures, survival analysis explicitly deals with the occurrence and timing of events with longitudinal data, and offers more temporal details than whether the events occur (Wang et al., 2013). Cox proportional hazard model, the most popular tool in the survival analysis (An and Brown 2008, An et al. 2011; Chen et al., 2016; Xin et al., not published yet), cannot – on its own, be used for extrapolation and prediction, because it is a semi-parametric model and its baseline hazard function is unspecified

(Chen et al, 2016; Davies et al., 2013). Therefore, we use parametric survival analysis, which has a range of potential standard distributions, characterizes the observed patterns of changes in the risks of the events, and allows for extrapolation of survival probability and hazard varying over time (Crowther & Lambert, 2014; Ishak et al., 2013) in this research. Commonly used assumed survival distributions include exponential, Weibull, Gompertz, Gamma, log-normal, log-logistic, and generalized gamma distributions (Cox et al., 2007; Davies et al., 2013; Ishak et al, 2013; Jackson 2016). We fitted these seven alternative distributions to our data and compared the goodness of fit using the AIC (Akaike's information criterion) to evaluate model performance and determine the appropriate distribution (Davies et al., 2013; Ishak et al, 2013; George et al. 2014).

The occurrence of oil palm expansion was used as the dependent variable of the parametric survival models. We selected a set of biophysical and socioeconomic variables charactering the economic benefits of oil palm plantation as well as land conversion and transportation costs as the independent variables, flowing the economic theory that oil palm planation would be established from other LCLU classes to maximize the discounted value of future net benefits of the conversion (Busch et al., 2012; Busch and Engelmann, 2017; Xin et al., 2021). The economic benefits of oil palm plantation is approximated by attainable yield of palm oil, meanwhile, the land conversion and transportation costs are proxied by a combination of distance to nearest existing estate crop plantation, distance to nearest palm oil processing mills, slope, elevation, peatland ratio, access time to large cities, population density, protected area ratio, and oil palm concession ratio (Austin et al., 2015; Busch et al., 2012; Busch et al., 2015; Furumo & Aide, 2017; Geveau et al., 2013; Pirker et al., 2016; Sumarga & Hein, 2016; Xin et al., not published yet). To address the possible differences of the hazards among different LCLU types, we also included LCLU type in 1996 as an independent variable (Austin et al., 2017; Gaveau et al., 2016; Xin et al., not published yet).

We ran the models on 1km × 1km grids. We generated a set of samples by systematic sampling across Indonesia's 1996 LCLU map in the form of 1km × 1km grid. Grids placed within two kilometers of a previously chose grid were rejected as a compromise between the wish to address the spatial autocorrelations and the need for an adequate sample (Gaveau et al., 2013; Xin et al., not published yet). We then randomly selected around 1/3 of the grids to train the models and used the rest of the grids to test the out-of-sample accuracy. We reclassified the LCLU maps to six LCLU classes, they are natural forest, shrub, bare ground, dry agriculture, estate crop, and others. A LCLU type was assigned to each grid based the majority of the grid area. Occurrence of an event was defined as the time when the land firstly converted to estate crop. Dry agriculture developed after 1996 was considered as a competing risk of estate crop expansion and treated as interval-censored, since more than 90% of the dry agriculture converted to estate crop in the study period were established before 1996, and dry agriculture was another major sink of LCLU changes in Indonesia (Xin et al., 2021; Xin et al., not published yet). The R package "flexsurv" were used for the estimation of the parametric hazard models (Jackson, 2016).

We downscaled the projected export demand for Indonesian oil palm products (oil palm fruit equivalent) by 2050 to oil palm expansion at 1km × 1km grids, with the risk of expansion at a given grid determined by the prediction of the empirical parametric model established using 1996-2015 data. Since the actual yield of Indonesian oil palm fruit showed no remarkable trend (FAO,

2021) and the attainable yield was estimated in terms of oil equivalent (IIASA/FAO, 2021), we defined a conversion factor as

$\frac{\text{average actual yield (fruit) of 1996-2015}}{\text{attainable yield (oil, 1981-2010 climatology) of existing plantation}}$, and calculated the predicted actual yield of oil palm fruit in each grid based on its attainable yield (oil, 2041-2070 climatology). Then we selected the grids with highest risks that would meet the amount of projected demand for Indonesian oil palm products (oil palm fruit equivalent) at national level by 2050 under each international trade scenario.

4.2.5 Tradeoffs between oil palm expansion and environmental conservation

To quantify the tradeoffs between oil palm expansion and environmental conservation, we identified land biophysically suitable for oil palm plantation but with relatively low environmental values (low-environmental-scenario), and quantified the amount of oil palm products that could be produced by the land. The tradeoffs were quantified by comparing the amounts of CO_2 emissions from oil palm expansion in 2015-2050, as well as the costs of transportation and infrastructure accessibility of oil palm production, estimated under the low-environmental-value scenario and the international trade scenarios with comparable amounts of oil palm production.

To estimate the CO_2 emissions from oil palm expansion, we employed a stock-difference method which accounted for CO_2 emissions from changes in above ground biomass (AGB), below ground biomass (BGB) and peat soil carbon (IPCC, 2006). We did not include changes of mineral soil carbon in the calculation as they typically have relatively low amounts of organic matter (IPCC, 2006) and are usually associated with large uncertainties (Carlson et al., 2013). The non-CO_2 emissions, such as methane (CH_4) and nitrous oxide (N_2O), were also not included in the calculation, since non-CO_2 emissions usually occur at land conversions from paddy field and managed soils (IPCC, 2006), while the amount of conversion from paddy filed to oil palm plantation in Indonesia is limited (Xin et al., 2021) and the soil non-CO_2 flux changes are negligible compared to the CO_2 emissions (Murdiyarso et al., 2010). Changes of net CO_2 emissions (ΔE) per year between t_1 and t_2 from oil palm expansion was calculated as follows.

$$\Delta E = (E_{Peat} + E_{AGB} + E_{BGB})/(t_2 - t_1) \tag{4-7}$$

Where E_{Peat} is the emission from peatland, including dead organic matter and soil organic matter. E_{AGB} and E_{BGB} are emissions from AGB and BGB due to LCLU changes, respectively. They are calculated as equations (4-8) – (4-10).

$$E_{peat} = \sum_t (A_t * R_{peat} * T_t) \tag{4-8}$$

$$E_{AGB} = \frac{44}{12} * (C_{AGB,t1} - C_{AGB,t2}) \tag{4-9}$$

$$E_{BGB} = \frac{44}{12} * (C_{BGB,t1} - C_{BGB,t2}) \tag{4-10}$$

Where A_t is the area of oil palm expansion on peatland in year t. R_{peat} is CO_2 emission rate for oil palm expansion, representing the average CO_2 emissions from peat per unit area per year. T_t represents the time (in years) that CO_2 emissions would last in the study period, for example, as we estimate the CO_2 emission in 2015-2050, the T for oil palm planted in 2030 would be 20 years. C_{AGB} and C_{BGB} are the carbon stocks of AGB and BGB, respectively, with positive values representing net carbon loss and negative values representing net carbon sequestrations. The coefficient 44/12 is the conversion factor from carbon to CO_2.

The costs of transportation and infrastructure accessibility of oil palm production are represented by the access time to large cities, distance to existing oil plantation, and distance to oil palm processing mills. We ran t tests on each variable between the low-environmental-value scenario and the comparable international trade scenarios.

4.2.6 Data

The panel data on historical oil palm production and biliteral trade flows of oil palm products for the trade analysis were obtained from FAOSTAT (FAO, 2021). We gave priority to the reported export flows for the bilateral trade flows since we are interested in the export quantities from Indonesia. We compared our results to Henders et al. (2015) which prioritized import flows and ran trade analysis on several commodities (including oil palm) in 2000-2011, and we found no major differences in the results. Since fresh oil palm fruit bunches require to be processed within 48 hours of harvesting (Furumo & Aide, 2017), only palm kernel cake, palm oil, and palm kernel oil were traded internationally.

We compiled a vector of time-variant independent variables at the country/region level for the generalized geo-economic gravity models. The GDP per capital and the population of the importer countries were acquired from the WDI database (World Bank, 2021) for historical models, and from SSP2 (IIASA, 2018) for projection models. Real exchange rate was calculated by transferring the nominal exchange rate into real exchange rate using the consumer price index (CPI), with the equation real = $nominal \times \frac{CPI_{Importer}}{CPI_{Indonesia}}$, the nominal exchange rate and CPI were collected from the WDI database (World Bank, 2021). We calculated the tariff as the weighted average of the applied tariff rates on the internationally tradable oil palm products, including palm kernel cake, palm oil, and palm kernel oil, based on their share in the oil palm fruit equivalent trade flows. Tariff rates on the internationally tradable oil palm products were obtained from the UNCAD TRAINS at the HS 6-digit level (WITS, 2021). The numbers of RTAs and RTAs with Indonesia were organized from the Regional Trade Agreements database (WTO, 2021). WTO is a dummy variable determined by the status and date of the importer's

WTO membership (WTO, 2021). We also applied a vector of time-invariant independent variables in the pooled and random effect models. The population weighted distance is extracted from GeoDist database (CEPII, 2021). The cultural proximity, such as historical colonial relationships and similarities in religion, were collected from the Gravity database (CEPII, 2021). Table C-1 lists the variables used in the generalized geo-economic gravity models, along with the data sources and the descriptions of the corresponding data. Table C-2 reports the measurement units and summary statistics of variables, Table C-3 presents the pairwise correlations between explanatory variables, and Table C-4 reports the variance inflation factors (VIFs).

The LULC maps, at a spatial resolution of 30 × 30 m, covering 1990-2015 with 3(or 4)-year interval, were acquired from the Ministry of Environment and Forestry (MoEF) of Indonesia. The maps consist of 23 LCLU classes, we reclassified them to six classes, including natural forest, shrub, bare ground, dry agriculture, estate crop, and others (Table C-5). The maps in 1996, 2000, 2003, 2006, 2009, 2012, and 2015 were stacked and analyzed in the ArcGIS environment at 1km × 1 km grid level to determine the occurrence of the oil palm expansion. Although oil palm is not an independent class of the available maps, the Statistical Yearbooks of Indonesia (Statistics Indonesia, 1997–2016) showed that around 89% of the estate crop expansion in the country were attributed to oil palm in 1996–2015. Therefore, the occurrence of oil palm expansion was proxied as the first time when estate crop was observed in the study period. Only expansion occurred during our research period (1996-2015) or did not occur until the end of the period were included in the model. The map of 1996 was applied to determine the land sources of oil palm expansion, which was used as an independent variable of the survival analysis to address the potential differences of the hazards among different LCLU types. The 1990 map and the 2015 map were used to estimate the distance to existing plantation in historical models and the projection model, respectively.

The distance to existing plantation, together with a vector of other variables at the grid cell level combining different sources of georeferenced data were compiled to represent the conversion and transportation costs of oil palm expansion. Those variables include distance to nearest palm oil processing mills (World Resources Institute, Rainforest Alliance, Proforest, and Daemeter, 2018), access time to large cities (Nelson, 2008), elevation and slope (NASA, 2009), peatland ratio (World Resources Institute, 2012), population density (CIESIN, 2016), protected area ratio (WDPA, 2014), and oil palm concession ratio (Indonesia Ministry of Forestry). The population density data were interpolated to match the study period. The protected area data were extracted from IUCN Category I-VI. The attainable yield of palm oil, which was used to approximate the gross economic benefits, were obtained from Global Agro-Ecological Zones (GAEZ) model (IIASA/FAO, 2021). It considers climatic-agricultural potential, soil suitability, and terrain suitability for oil palm plantation, and is reported as oil equivalent. The baseline yield in 1981-2010 climatology were used in historical models, and future yield in the 2041-2070 climatology were used in the projection model. Table C-6 lists the variables used in the survival analysis, along with the data sources and the descriptions of the data. Table C-7 reports the measurement units and summary statistics of variables, table C-8 presents the pairwise correlations between explanatory variables, and Table C-9 reports the VIFs.

The estimation of CO_2 emissions from oil palm expansion followed the IPCC (2006) framework. We applied the carbon emission rate developed by Murdiyarso et al., (2010) to estimate the CO_2 emissions from peat soil, which is 36.59 Mg of CO_2 per hectare per year during the first 25 years after LCLU change, and in line with Tier 2 in the IPCC (2006) guidelines for national GHG inventories. We assume the oil palm expansion into peatland would occur proportionally over the study period. The CO_2 emission rates from oil palm on peat are highly variable due to the different methodology, levels of details, and results validation (Valin et al., 2014). The CO_2 emissions from peat soil might be underestimated in this research since the emission rate we used (Murdiyarso et al., 2010) is close to the lower bound of the range in literature (Page et al., 2011; Valin et al., 2014). Losses of AGB and BGB were estimated in a spatially explicit manner, combining the projected spatial distribution of oil palm expansion with a dataset of biomass carbon stocks. The biomass carbon stocks (AGB and BGB) dataset was centered on the year 2010 (Spawn & Gibbs, 2020), we adjusted it to the year 2015 based on the LCLU maps (MoEF, 2020), the emission factors for the AGB which is generally in line with our 23 classes LCLU maps (Agus et al., 2013), and the root: shoot ratios (Mokany et al., 2006, Wolf et al., 2015). The AGB of oil palm plantation was estimated as 36MgC/ha (Agus et al., 2013), and the BGB equaled to 15% of AGB (Wolf et al., 2015), basically in line with Tiers 2 and 3 in the IPCC (2006) guidelines for national GHG inventories.

4.3 Results

4.3.1 Major importers of Indonesian oil palm products

As shown by Figure 4-1, European Union (EU) and India were the two largest markets for Indonesian oil palm products, accounting for around 1/3 to 2/3 of the Indonesian exports. From 1996-2015, oil palm products exported to EU decreased from over 57% to around 18%, though the absolute amount increased gradually. Meanwhile, China, as well as other emerging economies in Rest of Asia (e.g. Pakistan, Bangladeshi), Sub-Saharan Africa (e.g. South Africa) and Middle east & North Africa (e.g. Egypt), became new major markets for oil palm exports from Indonesia. We identified the top 30 importers of Indonesian oil palm products, including India, China, Netherlands, Germany, Italy, Span, Belgium-Luxembourg[7], France, United Kingdom, Pakistan, Bangladesh, Republic Korea, Sri Lanka, Singapore, Malaysia, Viet Nam, Myanmar, Egypt, Iran, Saudi Arabia, Jordan, United Arab Emirates, New Zealand, Russian, Ukraine, Turkey, United States of America, Brazil, South Africa, and Tanzania. They together made more than 85% of the total export quantity of oil palm products from Indonesia each year. These 30 top importers were used to run the geo-economic gravity models and project the quantity of oil palm products (oil palm fruit equivalent) that would be needed from Indonesian exports up to 2050.

[7] The trade flows of Belgium and Luxembourg were recorded as a whole before 2000 (FAO, 2021).

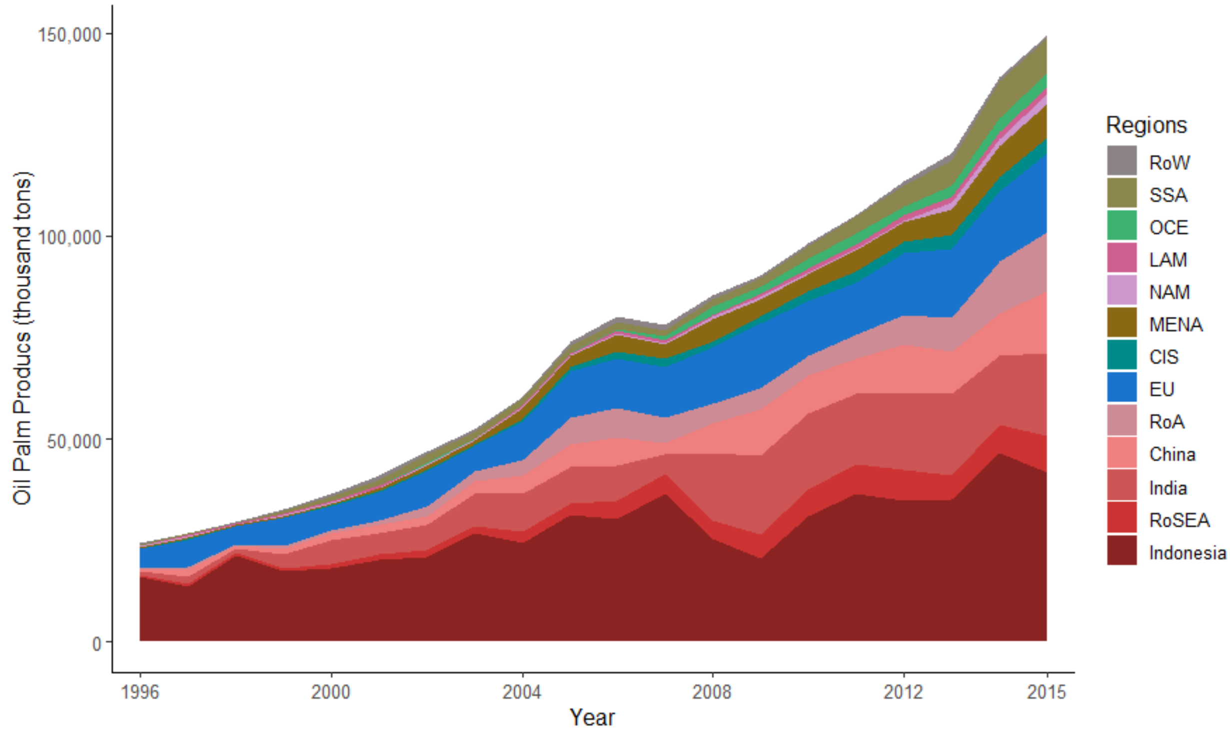


Figure 4-1 Exports of oil palm products (oil palm fruit equivalent) from Indonesia, 1996-2015. RoSEA = Rest of Southeast Asia (expect for Indonesia), RoA = Rest of Asia (except for Southeast Asia), EU = European Union, CIS = Commonwealth of Independent States, MENA = Middle East & North Asia, NAM = North America, LAM = Latin America, OCE = Oceania, SSA = Sub-Saharan Africa, RoW = Rest of the world (see Table C-10 for full region classification list).

4.3.2 Historical trade patterns of Indonesian oil palm products

We first ran geo-economic gravity models on Indonesian exports of oil palm products with the pooled panel data. The direction, magnitude, and significance level of the coefficients on independent variables didn't differ substantially with or without the time effect, although including the time effect increased the performance of the model substantially in terms of both R^2 and AIC (Table 4-1). The results, as shown in Table 4-1, demonstrated that the drivers of oil palm products exported from Indonesia were generally in line with our expectations. The trade flows were positively affected by the GDP per capita and the population of the importers, and were higher with shorter geographical distances to Indonesia. International trade, including numbers of RTAs and WTO memberships, as well as historical colonial relationships and common religion also increased the trade flows. The time effect was significantly positive, indicating that the export demand for oil palm products increased as time went by, even when the changes in the selected socio-economic variables were addressed. However, in contrast to our expectations, the trade flows increased as the tariff rate increased, which might be explained by the individual heterogeneity of the importers. India, the largest importer of Indonesian oil palm products since 2000, had high tariff rates up to 100% in the study period (WITS, 2021).

Table 4-1 Regression results of geo-economic gravity models on Indonesian exports of oil palm products with pooled data.

	Basic Model			With Time Effect		
	estimate	t-value	sig.	estimate	t-value	sig.
Intercept	8.821	5.484	****	7.610	5.483	****
Ln(GDP per capita)	0.153	2.639	***	0.085	1.691	*
Ln(Population)	0.572	10.753	****	0.566	12.370	****
Exchange Rate	1.56E-05	0.694		-1.23E-05	-0.632	
Tariff Rate	0.010	2.330	**	0.010	2.786	***
FTA	0.040	5.792	****	0.038	6.403	****
FTA with IDN	-0.088	-0.583		-0.140	-1.081	
WTO	1.029	4.864	****	0.774	4.225	****
Ln(Distance)	-1.029	-6.857	****	-0.970	-7.504	****
colony	2.632	8.497	***	2.780	10.416	****
Religion	1.370	3.302	***	0.924	2.573	**
Ln (Time)				0.845	12.152	****
R2	0.433			0.581		
AIC	1363.750			1235.653		

Note: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

To address the possible individual heterogeneity issues of the pooled models, we then ran fixed-effect models and random-effect models, and tested the consistency of the pooled and random-effect models. The F-tests (basic models: $F = 6.2852$, p-value < 0.001; models with time effect: $F = 11.401$, p-value < 0.001) showed that there were significant individual effects, thus the pooled models were inconsistent. Meanwhile, the basic random-effect model was inconsistent (χ^2= 112.78, p-value < 0.001) according to the Hausman tests, however, the model became consistent when the time effect was addressed (χ^2= 11.923, p-value = 0.155). The time effect was significantly positive in all the models addressing it. In all the fixed-effect and random-effect models (Table 4-2), the effects of tariff rate became insignificant, indicating that the un-expected negative effects can be partially explained by the individual heterogeneity. Similar to the pooled model, all the panel models showed that population and GDP per capita, as well as the international trade involvement (number of RTAs and WTO membership) of the importer countries had positive effects on the trade flow of Indonesian oil palm products, while the exchange rate and the number of RTAs with Indonesia did not have significant effects on the trade flows.

4.3.3 Projection of future export demand for Indonesian oil palm products

We chose to use fixed-effect and random-effect models with time effects to project the future demand for oil palm exports from Indonesia, because the two models had the best statistical performance. By comparing the models and extrapolating the models to 2013-2015, we found that the fixed-effect and random-effect models with time effect were 1) efficient with relatively high correlation between the actual and fitted values (Figure C-1) and low AICs (Table 4-2); 2) consistent according to the results of the Hausman test (χ^2= 11.923, p-value = 0.155); 3) had good prediction accuracy since the means of the predicted amounts from the two models for 2013-2015 were in $\pm$ 10% (average ~2%) of the actual amounts (Table C-11). We used the population and GDP under the SSP2 scenario to do the projections under the three international trade scenarios, and kept the other independent variables as the average values of 1996-2015.

Table 4-2 Results of fixed-effect and random-effect geo-economic gravity models on Indonesian exports of oil palm products.

	Fixed Effect						Random Effect					
	Basic Model			With Time Effect			Basic Model			With Time Effect		
	estimate	t-value	sig.	estimate	t-value	sig.	estimate	t-value	sig.	estimate	t-value	sig.
Intercept							0.864	0.262		5.643	1.970	**
Ln(GDP per capita)	2.055	6.521	****	0.722	1.929	*	0.494	4.126	****	0.148	1.383	
Ln(Population)	4.202	5.406	****	1.542	1.783	*	0.845	7.055	****	0.615	5.871	****
Exchange Rate	-3.49E-05	-0.502		5.77E-06	0.086		2.03E-05	0.504		-3.24E-06	-0.093	
Tariff Rate	0.001	0.187		-0.001	-0.260		-1.21E-04	-0.021		8.89E-04	0.176	
FTA	0.022	1.157		0.022	1.203		0.051	3.899	****	0.034	3.026	***
FTA with IDN	-0.212	-0.639		0.031	0.096		0.338	1.375		0.004	0.017	
WTO	0.747	2.810	***	0.751	2.950	***	1.194	4.850	****	0.815	3.792	****
Ln(Distance)							-1.091	-3.439	****	-0.898	-3.285	***
colony							2.449	3.070	***	2.790	4.067	****
Religion							2.818	3.085	***	1.132	1.419	
Ln(Time)				0.635	6.038	****				0.796	11.998	****
R2	0.372			0.425			0.378			0.536		
AIC	1174.062			1137.817			1237.075			1112.220		
							var	std.dev	share	var	std.dev	share
idiosyncratic							0.823	0.907	0.674	0.755	0.869	0.676
individual							0.399	0.632	0.326	0.362	0.601	0.324

Note: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

As shown by Figure 4-2, we estimate the export demand for oil palm products (oil palm fruit equivalent) from Indonesia will be around 396 million tons (219 – 573 million tons) under the business-as-usual scenario, 679 million tons (476 – 882 million tons) under the more-open-world scenario, and 313 million tons (158 – 468 million tons) under the less-open-world scenario.

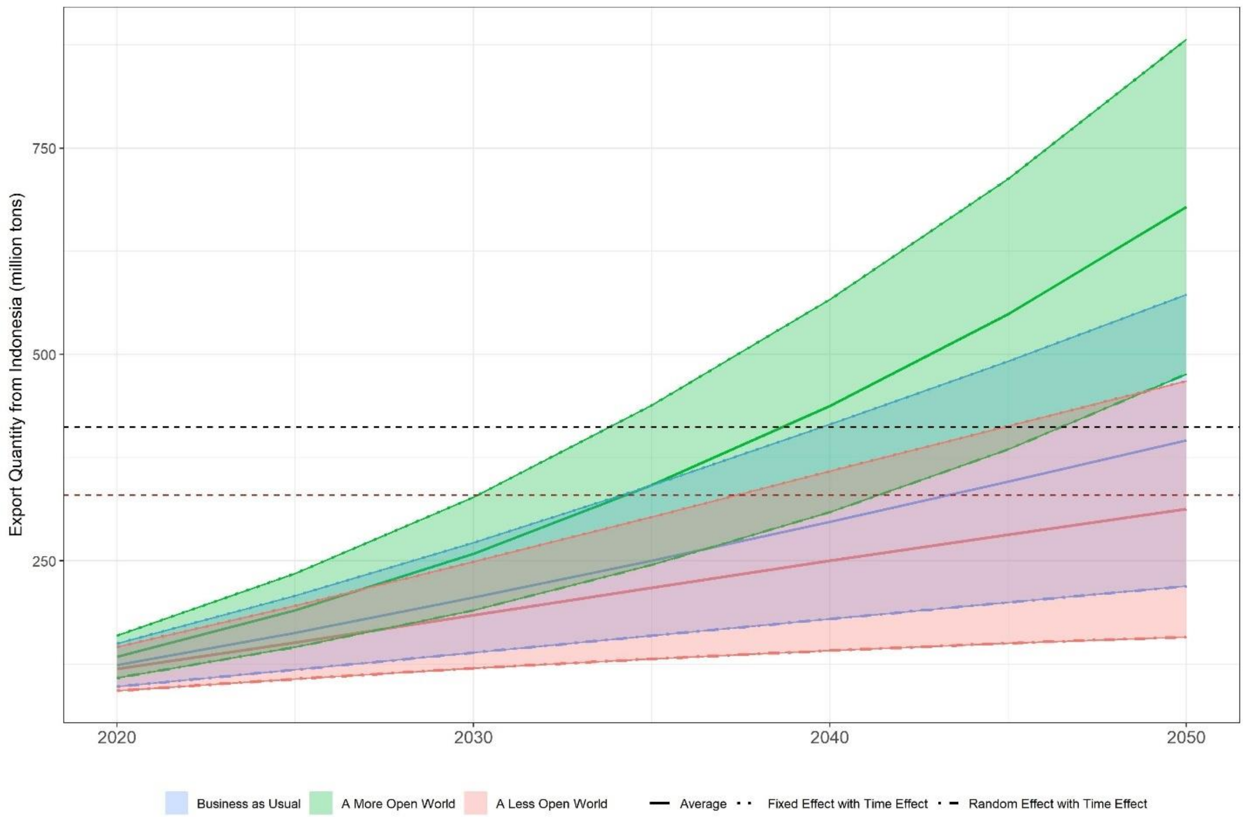


Figure 4-2 Projected export demand for oil palm products (oil palm fruit equivalent) from Indonesia, 2020-2050. The results of fixed-effect and random-effect models made the upper and lower bound of the projection, respectively. The dashed horizontal lines, from bottom to top, respectively represent the oil palm fruit could be produced by the current oil palm plantation (2015 map) + shrub and bare ground (2015 map) out of protected area on mineral land with moderate or high attainable yield (> 3 tons/ha (oil), GAEZ 2041-2070 climatology) + unplanted oil palm concessions (2015 map) with moderate or high attainable yield with 1) the same actual/potential yield ratio as 1996-2015 average, 2) actual/potential yield ratio increased by 25%.

4.3.4 Spatial pattern of projected oil palm expansion by 2050

We used the parametric model with Gompertz distribution to characterize the historical pattern of oil palm expansion in Indonesia and allocate the projected expansion by 2050 to 1km

× 1km grids across the country, since it had the lowest AIC among the seven survival distributions we tested (Table C-12). Table 4-3 reports the results of the Gompertz parametric hazard model on oil palm expansion over 1996-2015. Oil palm expansion tended to occur at land at gentle slope and low elevation, close to old plantation and palm oil processing mills, and with shorter access time to large cities. The insignificance of attainable yield could be explained by its high correlation with elevation (correlation = -0.74, Table C-8), it became significantly positive (coefficient = 0.039, p-value = 0.019; Table C-13) when elevation was excluded from the model. Population density had significantly negative effects on oil palm expansion, since oil palm is less labor intensive than alternative crops (Clough et al., 2016; Euler et al., 2017; Gatto et al., 2017; Xin et al., 2021). The expansion preferred peatland, the risks of conversion to oil palm plantation on peatland was around 1.22 (95% confidence interval: 1.10 – 1.35) times of that on mineral land. The hazard level of oil palm expansion inside protected areas was 17.7% (11.7% - 26.9%) of that out of protected areas, while the hazard level inside oil palm concessions was 2.53 (2.35 – 2.73) times of that out of the oil palm concessions, indicating that the established policies had significant effects on directing the oil palm expansion. For the land sources of oil palm expansion, natural forest, shrub and bare ground had higher risks of converting to oil palm plantation than dry agriculture and other land use/cover types.

Table 4-3 Results of Gompertz parametric hazard model on oil palm expansion in Indonesia over 1996-2015.

	coef	Hazard	z	sig.
Log(Oil Palm attainable yield)	-0.00274	0.997265	-0.12745	
Log(Distance to old plantation)	-0.0863	0.917321	-11.9522	****
Log(Distance to oil palm mills)	-0.85294	0.426161	-49.0927	****
Access time	-0.42254	0.65538	-9.82004	****
Slope	-0.24812	0.780266	-13.0719	****
Elevation	-0.11066	0.895242	-3.07915	***
Population density	-0.88173	0.414068	-3.90779	****
Protected ratio	-1.73185	0.176957	-8.12399	****
Peatland ratio	0.199992	1.221393	3.853457	****
Oil palm concession ratio	0.928686	2.531182	24.06413	****
Natural forest	1.063385	2.896157	11.86213	****
Shrub	0.898994	2.457129	9.772996	****
Dry agriculture	0.121085	1.128721	1.313067	
Bare ground	0.957471	2.605099	7.062339	****
shape	0.152749		39.39382	****
rate	-4.78761		-41.2108	****
LogLik		-15293.21		
AIC		30618.42		
Number of grids		65282		
Number of events		2935		

Note: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

Under the current conversion rate from attainable yield of palm oil to actual yield of oil palm products, Indonesia would need to harvest an additional 18.65 – 45.57 million hectares of oil palm by 2050 to meet the demand for exports. As presented by Figure 4-3, the majority of the oil palm expansion would continue to occur in Sumatra and Kalimantan, where more than 90% of the historical expansion occurred (Wicke et al., 2011; Xin et al., 2021). In addition, Papua, which is now heavily forested, would be a new frontier and contribute a remarkable portion of the expansion in the future, due to the limited remaining land availability on the two islands, especially Sumatra.

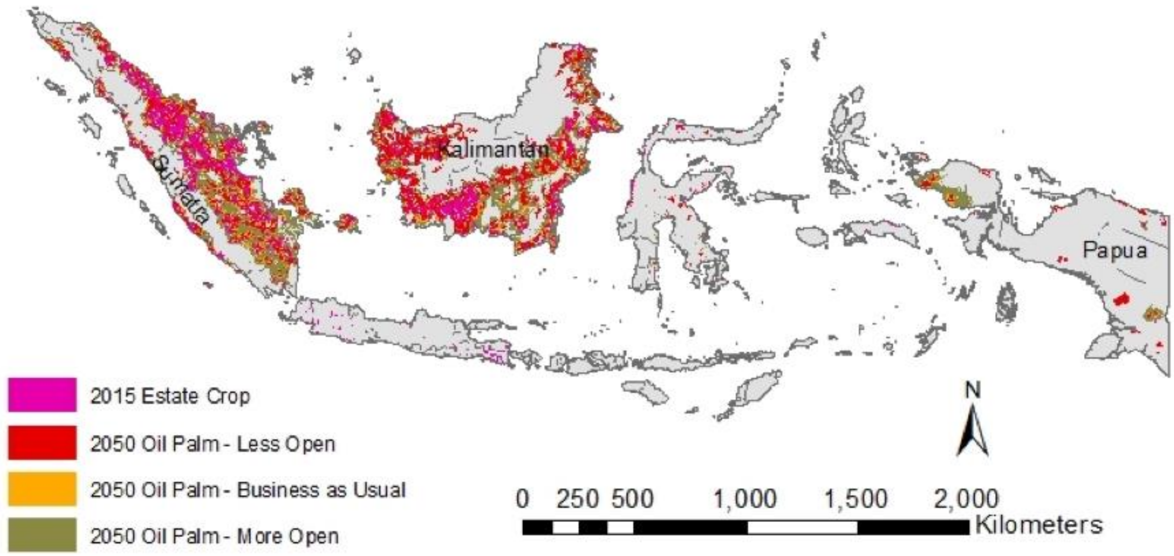


Figure 4-3 Spatial allocation of projected oil palm expansion under different international trade scenarios, 2050.

4.3.5 Tradeoffs between oil palm expansion and environmental conservation

Although the protected areas and oil palm concessions had significant effects on directing oil palm plantation, the oil palm expansion had occurred and would continue to occur at the expense of land with high environmental values (Table C-14). Around 16%-18% of projected oil palm expansion would occur at peatland, which would lead to a severe loss of tropical peatland in Indonesia. At least 21% of peatland in Indonesia would be drained and used by oil palm plantation by 2050, the share would increase to 29% under the business-as-usual scenario, and over 54% under the more-open -world scenario. Less than 4% of the oil palm expansion would occur at the expense of primary forest (2015 map), since most of the remaining primary forest locates at remote area which is not socioeconomically and/or biophysically suitable for oil palm plantation. However, around 20% of the of the projected oil palm expansion would replace the secondary forest (2015 map), resulting in 8% - 21% of secondary forest loss. In total, 5%-13% of natural forest (primary forest and secondary forest) in Indonesia would be converted to oil palm plantation by 2050. Similar to the expansion into primary forest, the projected expansion into protected area is generally limited due to the location bias.

Land biophysically suitable for oil palm expansion (attainable yield of palm oil > 3 ton/ha, GAEZ 2041-2070 climatology) and has relatively low environmental values, including the unplanted oil palm concessions to 2015 and the shrub and bare ground on mineral land out of protected areas, is about 18.45 Mha across Indonesia (Figure C-2). Together with the existing oil palm plantation, the land could produce approximately 330 million tons of oil palm products (oil palm fruit equivalent) under the current yield achievement ratio and oil extraction rate, which can at least support the export demand by 2030 under all three international trade scenarios, and largely support the export demand till 2050 under the less-open-world scenario. If the actual yield of oil palm products could improve by 25%, either through better management of oil palm plantation (Woittiez et al., 2017; Purnomo et al.,2020) or improvement of palm oil processing (Carter et al. 2007; Purnomo et al., 2020), the land could produce approximately 412 million tons of oil palm products (oil palm fruit equivalent), and largely support the export demand by 2050 under the business-as-usual scenarios (Figure 4-2).

Prioritizing environmental conservation and shifting oil palm expansion to land with relatively low environmental values would reduce the CO_2 emission at the expense of increasing the costs of transportation and infrastructure accessibility. Compared with the business-as-usual scenario, the low-environmental-value scenario would reduce the emission by 141.6 Mton CO_2 per year, while the access time to large cities, the distance to existing plantation (2015), and the distance to oil palm processing mills would increase by 32.2% (95% CI: 31.6% - 32.9%), 132.6% (131.1% - 134.1%), and 148.6% (146.8 - 150.5%), respectively. Similarly, compared with the less-open-world scenario, the CO_2 emission under the low-environmental-value scenario would be reduced by 87.1 Mton per year, well the factors of transportation and infrastructure accessibility would increase by 24.4% (23.7% - 25.0%), 115.2% (113.7% - 116.6%), and 142.2% (141.9% - 145.6%), respectively (Table C-15).

4.4 Discussion

4.4.1 Rising demand for oil palm products from Indonesia

Oil palm plantation in Indonesia has been growing as the global market becomes larger (Henders et al., 2015; Sayer et al., 2012). European Union was the largest market of Indonesian oil palm products, while the emerging economies, such as India, China, and other countries in Asia and Africa, is and would be the new forces driving the rapid growth of demand for oil palm products from Indonesia, due to their growing population, rising income, and increasingly important role in global trade.

This study employed generalized geo-economic gravity models and explored possible future trends of oil palm production in Indonesia under international trade scenarios, considering the historical trade patterns, the projected population and income of the importer countries, and the time effect. The export demand for oil palm products from Indonesia grows as time goes by, even when the increases in the selected socio-economic factors, such as population, income, number of RTAs, and WTO memberships of the importer countries are addressed. The positive time effect might be contributed by the shifts of consumer's preference towards vegetable oil with lower trans-fat due to health consciousness (WHO, 2015) and the increasing demand for biofuel blending due to climatic change concerns (Castiblanco et al., 2013; Murugesan et al., 2019). Our model reveals that tariff rates and real exchange rates have no significant effects on the trade flows of oil palm products from Indonesia, verifying that demands for oil palm products are relatively inelastic to price (Abdulla, 2012; Rifin, 2010), which might be explained by that 1) palm oil is much cheaper than any other vegetable oil (Carter et al. 2007; Sheil et al., 2009) and 2) Indonesia produces approximately 58% of the global demand (USDA, 2021b) for palm oil and the oil palm products from two major producers (Indonesia and Malaysia) are generally complementary rather than competing (Rifin, 2010). The inelasticity of price, as well as the insignificant effects of RTAs numbers between each importer country and Indonesia indicate that the impacts on oil palm expansion in Indonesia would be limited when some key importers (e.g. EU) push for sustainability oil palm production through economic tools (Jafari et al., 2017; Rifin et al., 2020). Therefore, the trend of rising demand for oil palm products from Indonesia is expected to continue even if there are growing movements boycotting Indonesian oil palm products due to the concerns on their threats to environmental conservation.

We estimate that about 313-679 million tons of oil palm products (oil palm fruit equivalent) from Indonesia would be needed by the top 30 importers by 2050 under different international trade scenarios (less-open-world scenario, business-as-usual scenario, and more-open-world scenario), resulting in an additional expansion by 18.58 – 45.59 million hectares. Our results are in accord with the research of Afriyanti et al. (2016) which projected the global demand for crude palm oil based on population growth, consumption levels, and renewable energy demand. The advantage of our generalized geo-economic gravity models is that they allowed us to directly address the influence of global market on Indonesia oil palm production and provided the opportunities to spatial-explicitly allocate the projected oil palm expansion at 1km × 1km grid level, rather than estimating the total global demand and the portions potentially supported by Indonesian suitable area. Generalized geo-economic gravity models outperform partial equilibrium models, such as IMPACT (Wiebe et al., 2019) and GLOBIOM (Mosnier et al., 2017), on projecting oil palm production, because the partial equilibrium models tend to underestimate the global demand for oil palm products by assuming simple exponential demand curves with constant price and income elasticities (Robinson et al., 2013) and commonly overestimate the price (Von Lampe et al., 2013), while the demands for oil palm products are relatively inelastic to price (Abdulla, 2012; Rifin, 2010).

4.4.2 Tradeoffs between oil palm expansion and environmental conservation

The increasing export demand for oil palm products would require oil palm expansion in Indonesia (Xin et al., 2021). The majority of the oil palm expansion would continue to occur at Sumatra and Kalimantan, while Papua would become a new frontier as the remaining land suitable for oil palm plantation becomes limited on the two islands. Our survival analysis reveals that although current policies have shown some positive effects on directing oil palm expansion, with the absence of broader and/or more effectively enforced policies, the future expansion would continue to occur at the expense of high-environmental-value (HEV) areas, especially secondary forest and peatland. Around 20% of projected oil palm expansion would occur at the cost of secondary forest, resulting in a loss of 8% - 21% of current secondary forest (5%-13% of natural forest) in Indonesia by 2050. The tropical peatland would be severely threatened, potentially 21% - 54% of peatland in Indonesia would be drained and used by oil palm plantation. These trends are in line with previous research demonstrating that secondary forest and peatland face high risks of loss to oil palm plantation in Indonesia (Austin et al., 2015;

Harrison et al., 2019; Sumarga & Hein, 2016; Wilcove et al., 2013; Xin et al., 2021). Secondary forest supports a large portion of biodiversity (Imron et al., 2010; Wilcove et al., 2013) and peatland conservation is essential for the reduction of CO_2 emission and climate change mitigation (WRI, 2014; Austin et al., 2015). Therefore, current policies and regulations on avoiding deforestation and conserving peatland, such as the primary forest and peatland moratoriums (Indonesian President Instruction no. 10, 2011), Roundtable on Sustainable Palm Oil (RSPO, Von Geibler, 2013), Indonesian Sustainable Palm Oil scheme (ISPO, Barthel et al., 2018), and zero-deforestation commitments (Bulter, 2015), should be extended to secondary forest and effectively enforced, and new strategies on peatland protection are urgently needed.

We also explored a scenario of oil palm production without further expansion into HEV land (low-environmental-value scenario). The biophysically suitable land with relatively low environmental values is around 18.45 Mha across Indonesia. It would largely support the export demand for oil palm products up to 2050 under the less-open-world scenario with current actual/potential yield ratio, and that under the business-as-usual scenario with a 25% increase of actual/potential yield ratio driven by better management practice on oil palm plantation and/or improvement on palm oil processing. Dry agriculture land out of concessions were not considered as possible land sources for oil palm expansion in this scenario, trying to avoid the possible effects of land use displacement (Lapola et al., 2010; Richards et al., 2014). Therefore, diverting oil palm expansion away from HEV land could allow Indonesia to continue to benefit its economic growth through oil palm exportation, meanwhile, enhance its role in tropical forest protection, climate change mitigation, and biodiversity conservation.

Shifting the oil palm expansion to low-environmental-value land would reduce the CO_2 emission by 87.1 – 141.6 Mton per year in the study period. However, the reduction in CO_2 emission would be generated at the expense of significantly increased land conversion costs and decrease the profitability of the oil palm plantation. Consistent with the previous findings, our parametric survival analysis demonstrates that the historical pattern of oil palm expansion in Indonesia generally followed the economic theory that the land would be converted to oil palm plantation to maximize the discounted value of net benefits of the conversion (Busch et al., 2012; Busch & Engelmann, 2017; Xin et al., 2021). Shifting the oil palm expansion from historical pattern to biophysically suitable area with low environmental values would significantly increase the transportation and infrastructure accessibility costs. Compared with the less-open-world and business-as-usual and scenarios, the low-environmental-value scenario would increase the access time to large cities, the distance to existing plantation (2015), and the distance to oil palm processing mills by 24.4% - 32.2%, 115.2% - 132.6%, and 142.2% -148.6%, respectively. It is believed to be possible for future oil palm expansion to shift to the remote degraded land, regardless of the increasing costs, as the effects of accessibility to existing infrastructures showed decreasing trend in the historical pattern of oil palm expansion (Xin et al., not published yet). The fact that oil palm expansion in Indonesia is generally innovated by large industrial companies and followed by smallholders (Weibe et al, 2019; Qaim et al., 2020) may facilitate the shift, since industrial companies have the ability to build necessary infrastructures (Lee et al., 2014) and are easier to be regulated (Pacheco et al., 2020). Properly implemented economic compensation mechanisms, such as the REDD+ programs (Irawan et al., 2013) and government-driven payments for environmental services programs (Van Noordwijk et al., 2010), may provide economic incentives towards more sustainable oil palm expansion (Clough et al., 2016).

4.5 Conclusion

Oil palm expansion in Indonesia is expected to grow as being driven by the increasing global demand for oil palm products, even though there are growing commitments on environmental conservation. This research projects the export demand for oil palm products from Indonesia by 2050, spatially allocates the demand-driven oil palm expansion to 1km × 1km grids across the country, and quantifies the possible trade-offs between oil palm expansion and environmental conservation. Around 313-679 million tons of oil palm products (oil palm fruit equivalent) would be need from Indonesia by 2050, resulting in an additional amount of 18.59-45.59 million hectares of oil palm expansion in the country. With current implementation and enforcement of existing policies and regulations, the expansion would continue to occur at the expense of land with high environmental values, especially secondary forest and peatland. The biophysically suitable area with relatively low environmental values could largely support the export demand up to 2050 under the less-open-world and business-as-usual scenarios. Shifting oil palm expansion to the low-environmental-value land would potentially reduce CO_2 emissions by 87.1-141.6 Mton per year, but at the expense of significantly increased costs of transportation and infrastructure accessibility.

To balance oil palm expansion and environmental conservation in Indonesia, current policies and regulations, such as protected areas, land use concessions, RSPO, ISPO, primary forest moratoriums, and zero-deforestation commitments, need to be continued, fully implemented and effectively enforced. Simultaneously, much more attention should be paid to the conservation of secondary forest and peatland, which hold high environmental values but face high risks of loss. Effective economic compensation mechanisms are also needed to provide economic incentives to promote more environment-friendly oil palm plantation.

5 Conclusion

5.1 Major findings

Indonesia is the largest producer and exporter of oil palm products in the world, oil palm plantation has expanded substantially over the last few decades and would continue to increase in the near further owing to the increasing global demand. While most previous studies focused on the land sources of oil palm expansion at different time point, the coupled human and natural mechanisms that drive the expansion pattern are seldom addressed, especially with spatial and temporal details at different scales. This dissertation is a pioneering and systematic study in quantifying the historical patterns driven by the variations across space and over time in the benefits and costs of oil palm expansion, and projecting the possible future spatial patterns and loss of areas with high environmental values to meet the future global demand for oil palm products. It is among the first to depict the spatial and temporal patterns of LCLUC in Indonesia driven by oil palm expansion and to reveal how the patterns evolve over time. Chapters 2 and 3 addresses the historical relationships between biophysical and socioeconomic factors and oil palm expansion at different spatial scales, by employing spatial panel models at the regency level and survival analysis at the 1km ×1km grid level, respectively. The two different types of models are largely complementary in serving the emphases of this dissertation on 1) spatial relationships versus timing of events; 2) direct conversion versus LCLUC trajectories with intermediate status. Chapter 3 also introduces multi-state survival analysis to land-use science for the first time, and reveals the effects of LCLUC trajectory hopping in oil palm expansion. Chapter 4 estimates the demand for Indonesian oil palm products from the global market up to 2050 using generalized geo-economic gravity models, and downscales it to 1km ×1km grids using parametric survival analysis to project the geographical distribution of future oil palm expansion in Indonesia and quantify the tradeoffs between oil palm production and protecting areas of high environmental values. This dissertation contributes to the existing research on impacts of human behaviors on LCLUC at various spatial and temporal scales, introduces new methodology to land-use sciences to character the LCLUC trajectories with temporal details, and provides scientific insights to support the sustainable development decisions to balance the increasing demand for agricultural products with the growing commitment to protect tropical environment.

Chapter 2 finds that oil palm expansion has become more likely to occur in low-biomass areas, such as shrub and dry agriculture, than in natural forest as time goes by, and bare ground often emerges as an intermediate status of conversion from natural forest to oil palm plantation, serving as land banking and a clearing-up tactic to meet the procedural sustainable development requirements of oil palm plantation. Sumatra and Kalimantan accounted for more than 90% of oil palm expansion in Indonesia in 1990-2015, with Sumatra holding the majority of the country's plantation, and Kalimantan as a comparative latecomer having the highest growth rate since 2000. The expansion in Kalimantan, which has been highly simulated by the export value of palm oil products, has preferred areas with better biophysical suitability and infrastructure accessibility, following the 'pecking order' sequence, and avoiding areas with high environmental values or socioeconomic costs. As the land resources are more limited in Sumatra, the plantation in Sumatra has been expanding more into remote and fertile areas with high conversion costs or legal barriers. Therefore, current regulations should be better implemented and enforced, and new policies and management regulations on land banking are urgently needed.

Chapter 3 focuses on the timing of oil palm expansion in Sumatra and Kalimantan, and finds that although the estate crop (mainly oil palm) expansion tends to occur in areas with suitable biophysical conditions and good accessibility to existing infrastructures, the effects of accessibility to existing infrastructures has decreased and/or became insignificant as times goes by. The effectiveness of PAs in Sumatra has decreased over time and became insignificant in 2012-2015. Shrub and bare ground are identified as intermediate status in LCLUC trajectories of estate crop expansion. A multi-state survival analysis reveals that the trajectory hopping has served as a clearing-up tactic to nominally meet the sustainable development requirements on estate crop expansion but actually facilitate the expansion into natural forest, and has compromised the effectiveness of PAs. The continuing estate crop expansion into protected natural forest via the trajectory hopping mechanism would severely threaten the biodiversity by diminishing its habitat area and increasing natural forest isolation, since it tends to occur at lowland forest which also holds the highest biodiversity richness. It is important to effectively track the original sources and eventual utilization of degraded lands, since the diffusion of the trajectory hopping mechanism would make the PA designations and sustainable development requirements become less and less effective in protecting natural vegetation.

Chapter 4 estimates that 313-679 million tons of oil palm products (oil palm fruit equivalent) from Indonesia would be needed by 2050 under different international trade scenarios, which would result in an additional 18.58-45.59 million ha of oil palm expansion in Indonesia. The oil palm expansion would continue to occur at expense of areas with high environmental values, especially secondary forest and peatland. About 8%-22% of secondary forest and 21%-54% of peatland in Indonesia would lose to oil palm expansion by 2050. If environmental conservation is prioritized, together with better plantation management and higher oil extraction rate, it is possible for Indonesia to support the export demand for oil palm products with minimum environmental cost. The shift from natural forest and peatland to degraded land with lower environmental values would reduce the CO_2 emission but increase the economic cost of oil palm expansion through transportation and infrastructure accessibility. Therefore, more effective economic compensation mechanisms may be needed to provide economic incentives towards more environment-friendly oil palm expansion.

5.2 Policy implications

This work provides scientific insights and several critical implications for policies and management strategies to achieve sustainable oil palm production in Indonesia. Chapter 4 reveals that international restrictions on the trade of oil palm produced in Indonesia, such as the increased tariff rate and the reduced number of RTAs with Indonesia, have no significant effects on export demand for oil palm productions from Indonesia. Therefore, domestic initiatives, including governmental and nongovernmental regulatory actions, as well as economic incentives, would be essential to promote more environment-friendly oil palm production. A number of actions have been taken by local governments (e.g., the forest moratorium, ISPO) (Barthel et al., 2018; Indonesian President Instruction no. 10, 2011; Indonesian President Instruction no. 6, 2013), international organizations (e.g., REDD+, RSPO) (Koh and Butler, 2009; Von Geibler, 2013), and oil palm companies (e.g., zero-deforestation palm oil sourcing) (Butler, 2015; United Nation, 2014), however, their gains are believed to have been diminished by limited coverage of the policies, weak institutional capacity, corruption, and the lack of monitoring (Enrici & Hubacek, 2018; Groom et al., 2022; Meehan & Tacconi, 2017; Taheripour et al., 2019; Tacconi et al., 2019).

The results of this research shine light on the fact that existing policies have some positive effects on directing oil palm expansion and protecting natural forest. Chapter 2 indicates that degraded land with low biomass has surpassed natural forest and become the largest land source of oil palm expansion in Indonesia, while Chapters 3 and 4 show that the legal barriers, such as the PAs and land use concessions, have been effective to prevent oil palm expansion into natural forest.

However, the policies have fallen short of their stated goals. This research identifies two potential reasons. Firstly, as demonstrated by Chapter 2 and Chapter 3, the land banking mechanism is found at both the regency level and the grid level to nominally meet the sustainable development requirements on oil palm production but actually facilitate the expansion into natural forest. The land banking mechanism potentially serves as a clear-up tactic, for example, to get sustainability certifications from certification systems (Carlson et al., 2018), and limit the power of policies to yield conservation and climate benefits. Chapter 3 future specifies that degraded land, such as shrub and bare ground, has increasingly served as the intermediate status of the LCLUC trajectory hopping mechanism as time goes by and the land resources become more limited, to comprise the effectiveness of PAs on oil palm-driven deforestation and facilitate the oil palm expansion into land with legal barriers. Due to the growing contribution of the land banking and/or trajectory hopping mechanisms, there is an urgent need to trace the LCLUC trajectories through the monitoring system, and shift from targeting only oil palm expansion into natural forest to introducing initiatives that directly limit deforestation (Taheripour et al., 2019). Secondly, the research findings suggest that secondary forest and peatland are among the high-environmental-value lands with the highest risks of converting to oil palm plantation. However, current policies, such as the moratorium, sustainability certification, and REDD+, generally emphasize the protection of primary forest and show limited effects on peatland conservation (Cattau et al., 2016; Carlson et al., 2018; Groom et al., 2022). As secondary forest supports a large portion of biodiversity (Imron et al., 2010; Wilcove et al., 2013) and peatland conservation is essential for emission reduction (IPCC, 2006; Murdiyarso et al., 2010; Page et al., 2011; Taheripour et al., 2019), extending the adoption of the policies to secondary forest and enforcing stricter restrictions on peatland would be necessary to achieve biodiversity conservation and climate change mitigation.

Since weak governance and corruption are major challenges in the execution of the policies (Enrici & Hubacek, 2018; Meehan & Tacconi, 2017), monitoring is necessary to ensure that the policies are fully implemented and effectively enforced, which echoes the importance of taking advantage of remote sensing technology and have a monitoring system in place (Goetz et al., 2015; Tacconi et al., 2019). The monitoring, reporting, and verification (MRV) system required by REDD+ (Herold & Skutsch, 2011) should be fully applied to oil palm expansion in Indonesia, to help the stakeholders understand the actual effects of the policies and make adjustments accordingly. As the MRV system building requires tremendous investments and efforts (Goetz et al., 2015) while Indonesia's institutional capacity is restricted by budgets and personnel (Meehan & Tacconi, 2017; Tacconi et al., 2019), it would be helpful to identify the hotspot area with the highest risks of oil palm-driven deforestation. Chapter 3 demonstrates that natural forests with high oil palm attainable yield but low annual average temperature, at gentle slope and low elevation, and close to old plantation and palm oil processing mills are at high risk of further oil palm expansion, either with or without intermediate status. The high-risk natural forests, especially those on peatland, should be prioritized for monitoring and conservation.

The results of this research suggest that oil palm expansion tends to occur in areas with good accessibility to existing infrastructures. Therefore, developing new oil palm processing mills and associated road networks in low-environmental-value land (e.g., degraded land on mineral land outside of PAs) with good biophysical suitability for oil palm plantation could effectively direct the oil palm expansion to areas with minimum environmental costs. The governments could either design and establish the infrastructures by themselves or encourage the industrial companies to do so with effective economic compensation mechanisms. As economic profits of preserving forests for carbon credits cannot compete with converting to oil palm plantation (Butler et al., 2009), facilitating infrastructure development could be a potentially cost-effective and efficient incentive for future economic compensation mechanisms, such as REDD+ and government-driven payments, to better contribute to the conservation of tropical natural forest and its environmental services.

The recent boom of oil palm production in Indonesia has mainly relied on the expansion of cultivated area (Euler et al., 2016), whereas land intensification is an alternative way to increase oil palm production and potentially reduce the environmental costs (Phalan et al., 2011). Yield gaps in oil palm plantation are large, as the average attainable yield of current oil palm plantation in Indonesia is approximately 5.5 ton oil per ha per year (IIASA/FAO, 2021), while the average actual yield is around 3.5 ton oil per ha per year (USDA-FAS, 2021). There is tremendous potential for improving oil palm yield, especially that of smallholder plantations, because smallholders now own around 40% of the plantation area in Indonesia (Woittiez, 2019) with an expected growing share (Pirker et al., 2016), while they obtain only around 50% of the attainable yield on average (Euler et al., 2016). Smallholders face a set of agronomic constraints to achieve the full potential of oil palm plantation, including insufficient and/or imbalanced nutrition, low-quality planting materials, sub-optimal planting density, low harvesting frequency, poor water management, and inappropriate pruning and weeding activities (De Vos et al., 2021; Soliman et al., 2016; Woittiez, 2019). Such constraints are tied closely with the limited knowledge about best management practices and imperfect access to input markets, including materials, labor, and capital (Euler et al., 2016; Soliman et al., 2016). Beyond the agronomic limitations, limited access to markets and oil palm processing mills decreases the oil extraction rates and the output prices (Euler et al., 2016), and drawbacks the yield and profits of smallholder plantations.

Ideally, these limitations could be addressed via the collaboration of local governments, certification systems (e.g., RSPO, ISPO), farmer groups, and companies (De Vos et al., 2021; Soliman et al., 2016; Woittiez, 2019). Providing technical support and training on oil palm cultivation (e.g., balanced mineral nutrients and empty fruit bunch application, 7-10 days harvesting interval, high-quality planting material, timely pruning and weeding of the circle around the trunk) (De Vos et al., 2021; Lee et al., 2014; Donough et al., 2010), improving access to finance and input markets (Woittiez, 2019), investing in infrastructures (e.g., waterworks and roads) (Euler et al., 2016; Hoffmann et al., 2017; Woittiez, 2019), and promoting marketing cooperatives and linkages between processing mills and farmers (Euler et al., 2016; Woittiez, 2019) are among the potential initiatives to close the yield gap of smallholder plantations. The gross margins of the smallholders are expected to grow due to higher yields and better output prices, although the expenses would increase due to external inputs and hired labor (Euler et al., 2016; De Vos et al., 2021). The imbalanced minimal fertilizer application and the infrequent harvesting are the main reasons for yield gaps in industrial plantation (Feintrenie et al., 2010; Donough et al., 2010). Besides minimizing the cultivated area to meet oil palm demand, the implementation of these policies may also contribute to environmental conservation by reducing negative impacts on freshwater quality via improved nutrient and herbicides management (Soliman et al., 2016; Woittiez et al., 2019) and protecting against erosion and biodiversity loss with good practice of weeding (De Vos et al., 2021).

Targeting the oil palm expansion only to the degraded land and filling the yield gaps between actual and attainable yields appear to be the most sustainable ways to produce sufficient oil palm products to meet future demand while protecting tropical environment. As indicated by Chapter 4, with an increase of 25% of actual yield, the biophysically suitable and low-environmental-value land in Indonesia additionally to the existing oil palm plantation would produce approximately 412 million tons of oil palm products (oil palm fruit equivalent), which would support the export demand by 2050 under the business-as-usual scenario. If the country could push the actual yield to the attainable yield, an additional 112 million tons of oil palm products (oil palm fruit equivalent) would be produced, which is as much as the expansion of 8.1 – 9.5 million ha of new plantations.

5.3 <u>Limitations of the research</u>

This dissertation acknowledges several limitations. Some of the time-invariant variables we used, such as palm oil mills, access time to large cities, oil palm concessions, are not actually static. For example, the proximity or accessibility to infrastructures would change with new establishments of processing mills, roads, population clusters, etc. Therefore, the effects of these variables as shown by our models may not be precise, and any of these variables constraining oil palm plantation in the past may not continue to be constraints in the future. Similarly, new constraints may emerge in the future, such as climate change (Paterson et al., 2017) and soil degradation (Guillaume et al., 2016). We used the attainable yields of oil palm from the GAEZ model, which has the baseline data in 1981-2010 climatology and the estimated data in climatology of a few future periods, and shows a yield decrease by approximately 25% from 1981-2010 climatology to 2041-2070 (2050s) climatology, however, the response details of the single crop (e.g. oil palm) to the climate change and soil degradation could not be fully investigated due to GAEZ's comparatively simple modeling procedures.

The assessments are limited by the quality of the datasets used for this analysis. The accuracies of LULC maps and other maps have been constrained by the available techniques and socio-political hurdles with respect to data collection. The resolution and time scale of these maps will possibly influence the estimates of land use conversions and the effects of the driving forces. Due to the availability of the LCLU maps, we used estate crop as the target land use category in our research, assuming that the estate crop other than oil palm do not have significant effects on the results and ignoring the conversions among different estate crop types. Although the statistics from the government (Statistics Indonesia, 1997-2016) shows that around 89% of estate crop expansion in the country were attributed to oil palm from 1996-2015 and the percentage are even higher in Sumatra and Kalimantan, there are some other crops, such as coconut, cocoa, coffee, which might have some influence. It would be better to rerun the analysis when detailed and continuous maps of oil palm are available.

This dissertation didn't address the effects of moratorium and its restrictions on primary forest and peatland (Indonesian President Instruction no.10, 2011; Indonesian President Instruction no.6, 2013; Government Regulation no.57, 2016), since it focuses on the study period 1996-2015 and there is often a 3-year time lag between the planning and the actual planting of oil palm.

In this dissertation, I treated dry agriculture as a competing risk of oil palm expansion, since more than 90% of the dry agriculture converted to oil palm in 1996-2015 were established before 1996. However, as the pressure on sustainable palm oil production increases and the oil palm plantation profits more than dry agricultural activities, the oil palm expansion may replace the newly established dry agriculture, making dry agriculture an intermediate status of the LCLUC trajectory.

5.4 Future research

Oil palm plantation has been boomed in Indonesia in the last few decades, lots of actions have been taken to address its negative effects on environmental conservation in recent years. However, the effects of the recent policies and management regulations are still understudied. Future research can explore the effects of moratorium and its restrictions on primary forest and peatland. The moratorium on the granting of new logging, oil palm, and timber concession licenses on primary forest and peatland took effect in May 2011 (Indonesian President Instruction no.10, 2011), was successively extended for three times on two-year terms (Alisjahbana et al., 2017) and finally made permanent in August 2019 (Reuters, 2019) with the same objectives and provisions. Additional restrictions on the conversion of peatlands were implanted in 2016, prohibiting the conversion of peatland across the country regardless of license status (Alisjahbana et al., 2017; Groom et al., 2022). With the moratorium in force for 10 years, it is possible to estimate its impacts on oil palm expansion, as well as the associated deforestation and LCLUC, when the most recent LCLU maps are available. It will provide scientific insights on whether the policy is enforced successfully and whether the objectives and provisions need to be extended, such as to secondary forest, to effectively reduce the GHG emissions and conserve the tropical environment. It would also be possible to analysis the impacts of the moratorium restrictions on peatland in another few years. As we estimated in Chapter 4, Indonesia would lose 21%-54% of its peatland to oil palm plantation by 2050 under the empirical oil palm expansion pattern, therefore, it’s essential to know whether the moratorium and its restrictions on peatland would be effective in preventing oil palm expansion on peatland.

Another topic that calls for further exploration is the possible effects of land use displacement. The moratorium focuses on logging, oil palm, and timber concessions, but not dry agriculture activities and estate crop plantations other than oil palm. The global concerns of the negative environmental impacts from agricultural activities other than oil palm is also relatively minimal. Such imbalance between oil palm and other agricultural activities may lead to indirect effects of oil palm expansion on environmental conservation via displacement of other agricultural activities to areas with high environmental values (Barona et al., 2010; Lapola et al., 2010; Meyfroidt, et al., 2014; Richards et al., 2014). For example, oil palm companies would buy lands from local framers with higher price due to the legal barriers on oil palm expansion into natural forest, and the local farmers may proceed to invest their capital and skills and establish new agricultural activities at the frontier of natural forest. If the land use displacement occurs, the effects of policies and regulation standards on reducing environmental impacts of oil palm expansion will be offset by the indirect land use change (ILUC). Identifying the possible land use displacement can be useful to address the broader policy implications on oil palm expansion and the associated ILUC, thus more effectively balance the oil palm expansion demand with the environmental conservation urge.

In addition to socioeconomic and the policy factors that can shape future oil palm plantation, climate change should also be considered in projecting future trajectories. Global and regional climates are changing due to rising GHG emissions, and the changing temperature and precipitation patterns would impact the suitability of crop production, thus alter the economic benefits and costs of LCLUC. Future research can try to improve the performance of Agro-Ecological Zones (AEZ) model with the help of process-based crop growth simulation models, such as the Decision Support System for Agrotechnology Transfer (DSSAT) model (Jones et al., 2003), to assess the impacts of climate change on oil palm plantation. Such improvement would help us to better project the future spatial pattern of oil palm expansion, estimate the tradeoffs between oil palm plantation and environmental protection, as well as design and implement policies and management regulations.

Appendix A: Supplement information for Chapter 2

Section A1. Spatial panel models

Our objective is to estimate the following model efficiently and consistently:

$$d_{it} = exp(\alpha + \beta X_{it} + \varepsilon_{it}) \tag{A-1}$$

where d_{it} is the area of oil palm expansion into each source land at regency *i* over year t – 1 and *t*. X is a panel of explanatory variables (time-variant and time-invariant; same as those list in the pooled model) and ε_{it} is an error term.

$$log\ (d_{it}) = \alpha + \beta X_{it} + \varepsilon_{it} \tag{A-2}$$

For oil palm expansion models, the standard pooled estimation may be insufficient due to the individual heterogeneity and the spatial autocorrelation among regencies. Therefore, spatial panel models, including spatially lagged dependent variable, spatial error autocorrelation, and spatial Durbin models, were implemented. We ran random effect rather than fixed effect regressions, because we are also interested in the time-invariant variables.

Random effect spatial lag models

$$log\ (d_{it}) = \lambda \sum_{j=1}^{N} w_{ij}\ log\ (d_{jt}) + X_{it}\boldsymbol{\beta} + \varepsilon_{it} \tag{A-3}$$

$$\varepsilon_{it} = a_i + u_{it} \tag{A-4}$$

$$E(u_t)=0;\ E(u_t u_t) = \sigma^2 I_N \tag{A-5}$$

Random effect spatial error models

$$log\ (d_{it}) = X_{it}\boldsymbol{\beta} + \varphi_{it} \tag{A-6}$$

$$\varphi_{it} = \rho \sum_{j=1}^{N} w_{ij}\ \varphi_{jt} + \alpha_i + u_{it} \tag{A-7}$$

$$\varepsilon_{it} = a_i + u_{it} \tag{A-8}$$

$E(u_t)=0;\ E(u_t u_t) = \sigma^2 I_N$ (A-9)

Random effect spatial Durbin models

$$log\ (d_{it}) = \lambda \sum_{j=1}^{N} w_{ij}\, log\ (d_{jt}) + \alpha_i + X_{it}\boldsymbol{\beta_1} + \rho \sum_{j=1}^{N} w_{ij}\, X_{it} + \varepsilon_{it} \quad \text{(A-10)}$$

$$\varepsilon_{it} = a_i + u_{it} \quad \text{(A-11)}$$

$E(u_t)=0;\ E(u_t u_t) = \sigma^2 I_N$ (A-12)

In Eq. (A-3), (A-6), (A-15),

- d_{it} represents the aggregate indicator of water quality in year t.
- X_{it} includes 1) the time-variant variable: climatic factors in year t, such as annual precipitation, precipitation in the driest month, average annual temperature, shortwave radiation; the percentage of regency within PAs in year t; population density in year t; source land ratio (second-order polynomial) in year t, and export value averaged over the previous period; and 2) Time-invariant variables: biophysical and geographical factors, such as potential yield of oil palm plantation, slope, elevation, AWC, peatland percentage; and factors characterizing accessibility to market and infrastructure, such as average access time large cities, density of palm oil mills, and percentage of estate crop plantation in 1990.
- w_{ij} is the spatial weight.

Table A-1 LCLU classification.

Class	Description	Re-Class
Primary Dryland Forest	Natural forest, dry habitat	Primary Forest
Secondary Dryland Forest	Logging signs, dry habitat	Secondary Forest
Primary Mangrove Forest	No or low human activity, wetland forest in coastal areas	Primary Forest
Secondary Mangrove Forest	Logging signs, wetland forest in coastal areas	Secondary Forest
Primary Swamp Forest	Natural forest, wet habitat	Primary Forest
Secondary Swamp Forest	Logging signs, wet habitat	Secondary Forest
Plantation Forest	Dominated by homogeneous tree species for specific purposes, structural composition. Reforestation, industrial plantation forest, community plantation forest	Others
Dry Shrub	Highly degraded logged-over area, non-wet habitat, ongoing process of succession	Shrub
Wet Shrub	Highly degraded logged-over area, wet habitat, ongoing process of succession	Shrub
Savanna and Grasses	Grasses and scattered natural trees and shrubs	Others
Pure Dry Agriculture	Agricultural activities on dry/ non-wet land, e.g. moor, mixed garden, agriculture fields	Dry Agriculture
Mixed Dry Agriculture	Agricultural activities on dry/ non-wet land mixed with shrubs, thickets, and logged-over forest	Dry Agriculture
Paddy Field	Agriculture areas on wet habitat, especially for paddy	Others
Estate Crop	Planted estate areas, mostly with perennials crops or other agricultural trees commodities	Estate Crop
Settlement Areas	Rural, urban, industrial and other built-up areas	Others
Transmigration Areas	Unique settlement areas associated with houses and agroforestry and/or garden	Others
Port and Harbor	Big enough to be delineated as independent object	Others
Bare Ground	No vegetation cover	Bare Ground
Mining Areas	Open mining activities	Others
Open Swamp	Wetland with few vegetation	Others
Fish Pond/Aquaculture	Aquaculture activities	Others
Open Water	Ocean, rivers, lakes, and ponds	Others
Cloud and No-Data	Clouds, cloud shadows or data gaps with a size of more than 4 cm^2 at 100,000 scale display	No Data (Removed)

Table A-2 Variable, data description and data sources.

Variable	Data Description	Data Source
Land cover and land use	Land use and land cover maps of Indonesia, 1990-2015	Indonesian Ministry of the Environment and Forestry. 2020. Indonesian Land Cover Closure. Available at: http://webgis.menlhk.go.id:8080/pl/pl.htm.
Potential yield of oil palm	IIASA/FAO. Global Agro-ecological Zones (GAEZ v3.0, v4)	http://webarchive.iiasa.ac.at/Research/LUC/GAEZv3.0/ https://iiasa.ac.at/web/home/research/researchPrograms/water/GAEZ_v.4_Data_Portal.html
Precipitation (Rainfall)	Weedon, G.P., G. Balsamo, N. Bellouin, S. Gomes, MJ Best, and P. Viterbo, 2014: The WFDEI meteorological forcing data set. WATCH Forcing Data methodology applied to ERA-Interim reanalysis data. Water Resource Research, 50: 7505-14.	https://doi.org/10.5065/486N-8109.
Precipitation of driest month		
Temperature		
Radiation (shortwave)		
Export quantity and value	Export quantity and value of palm oil and products, UN-FAO	http://www.fao.org/faostat/en/#data/TP.
Palm oil mill density	Universal Mill List (UML) (WRI/ Rainforest Alliance /Proforest/Daemeter, 2018)	www.globalforestwatch.org
Access time	Travel time to major cities: A global map of Accessibility (Nelson, A., 2008)	https://forobs.jrc.ec.europa.eu/products/gam/index.php
Elevation	Shuttle Radar Topography Mission (NASA, 2009)	https://earthexplorer.usgs.gov/
Slope		
Available Water Capacity (AWC)	Harmonized world soil database (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012)	http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/
Peatland percentage	Peat lands (World Resources Institute, 2012. Accessed through Global Forest Watch)	www.globalforestwatch.org
Population density	Gridded Population of the World (GPW) (CIESIN)	http://sedac.ciesin.columbia.edu/gpw/index.jsp http://dx.doi.org/10.7927/H4NP22DQ
Protected area	World Database on Protected Areas (WDPA). IUCN and UNEP. Cambridge (UK). c2014.	www.protectedplanet.net
Sub-national administrative boundary	GeoNetwork – Sub-national Administrative Units of Indonesia. (FAO, 2002)	http://www.fao.org/geonetwork/srv/en/main.home?uuid=c8ee1300-88fd-11da-a88f-000d939bc5d8

Table A-3 Measurement units and summary statistics of variables.

Variable	Unit	Indonesia			Sumatra			Kalimantan		
		mean	min	max	mean	min	max	mean	min	max
Expansion into forest	‰	1.17	0	185.94	3.33	0	146.90	2.78	0	185.94
Expansion into shrub	‰	1.12	0	257.86	2.81	0	257.86	3.40	0	57.50
Expansion into dry agriculture	‰	0.77	0	152.63	1.91	0	152.63	2.16	0	129.13
Potential yield of oil palm	ton/ha in terms of oil	4.90	0	7.59	5.75	0.56	7.21	6.57	4.33	7.12
Plantation in 1990	%	3.20	0	71.76	9.35	0	71.76	1.77	0	16.23
Precipitation	mm/day	6.96	2.80	13.41	7.67	4.21	12.42	7.87	5.30	12.75
Precipitation of driest month	mm/day	0.72	0	6.68	1.32	0	5.58	1.09	0	5.38
Temperature	K	299.53	296.51	301.45	299.76	296.76	301.29	299.81	298.12	301.14
Radiation	W/m^2	206.06	154.02	248.85	187.06	165.31	205.94	189.39	167.93	212.72
Export value	Billion 2000 USD	4.55	0.66	13.66	4.55	0.66	13.66	4.55	0.66	13.66
Palm oil mill density	$/100\ km^2$	0.041	0	3.35	0.16	0	3.35	0.028	0	0.39
Access time	day	0.28	1.48E-3	2.50	0.28	6.62E-3	0.97	0.67	0.035	2.067
Elevation	100m	3.02	0.026	14.66	3.66	0.050	14.66	1.52	0.065	5.55
Slope	degree	4.91	0.20	16.91	5.40	0.29	16.91	3.49	0.20	9.69
AWC	m/m	0.12	0.015	0.15	0.12	0.050	0.15	0.12	0.069	0.15
Peatland	%	3.00	0	73.22	6.50	0	62.98	10.84	0	73.22
Population density	k persons $/km^2$	0.85	1.74E-3	16.13	0.23	0.020	6.59	0.11	2.70E-3	2.07
Protected area	%	6.00	0	78.27	10.53	0	78.27	5.58	0	26.33
Forest ratio	1	0.24	0	0.98	0.29	0	0.81	0.41	0	0.93
Shrub ratio	1	0.090	0	0.97	0.10	0	0.73	0.18	1.16E-4	0.69
Dry agriculture ratio	1	0.28	0	0.97	0.36	0	0.94	0.27	8.88E-3	0.82

Table A-4 Pairwise correlations between explanatory variables in country models.

	Shortwave radiation	Precipitation	Driest month precipitation	Temp	Protected %	Elevation	Slope	Mill density	AWC	Access time	Population	Natural forest ratio	Shrub ratio	Dry agriculture	Oil palm potential	Export value (t-1)	Peatland %	Plantation in 1990
Shortwave radiation	1	-0.525	-0.55	-0.052	-0.243	-0.066	-0.033	-0.195	-0.19	-0.419	0.084	-0.374	-0.101	-0.043	-0.58	-0.047	-0.278	-0.219
Precipitation	-0.525	1	0.61	-0.041	0.251	0.117	0.002	0.044	0.189	0.291	-0.04	0.141	-0.039	0.089	0.454	0.06	0.156	0.089
Driest month precipitation	-0.55	0.61	1	-0.086	0.334	0.137	0.123	0.11	0.113	0.447	-0.073	0.354	0.002	0.007	0.273	0.075	0.179	0.197
Temp	-0.052	-0.041	-0.086	1	-0.318	-0.766	-0.763	0.175	0.026	-0.304	0.24	-0.458	-0.014	0.007	0.491	0.025	0.244	0.119
Protected %	-0.243	0.251	0.334	-0.318	1	0.397	0.392	-0.039	0.02	0.416	-0.192	0.547	0.023	-0.096	-0.115	0.002	0.074	-0.034
Elevation	-0.066	0.117	0.137	-0.766	0.397	1	0.787	-0.123	-0.089	0.215	-0.209	0.367	-0.077	-0.006	-0.488	0	-0.222	-0.077
Slope	-0.033	0.002	0.123	-0.763	0.392	0.787	1	-0.144	-0.159	0.29	-0.323	0.575	0.076	0.036	-0.407	0	-0.249	-0.118
Mill density	-0.195	0.044	0.11	0.175	-0.039	-0.123	-0.144	1	0.064	-0.041	-0.06	-0.07	-0.054	0.105	0.173	0	0.206	0.484
AWC	-0.19	0.189	0.113	0.026	0.02	-0.089	-0.159	0.064	1	0.008	0.149	-0.059	-0.167	0.003	0.27	0	0.122	0.105
Access time	-0.419	0.291	0.447	-0.304	0.416	0.215	0.29	-0.041	0.008	1	-0.257	0.743	0.17	-0.276	0.022	0	0.226	-0.094
Population	0.084	-0.04	-0.073	0.24	-0.192	-0.209	-0.323	-0.06	0.149	-0.257	1	-0.321	-0.136	-0.208	0.054	0.018	-0.116	-0.078
Natural forest ratio	-0.374	0.141	0.354	-0.458	0.547	0.367	0.575	-0.07	-0.059	0.743	-0.321	1	0.172	-0.304	-0.095	-0.05	0.136	-0.115
Shrub ratio	-0.101	-0.039	0.002	-0.014	0.023	-0.077	0.076	-0.054	-0.167	0.17	-0.136	0.172	1	-0.138	0.06	-0.069	0.173	-0.055
Dry agriculture ratio	-0.043	0.089	0.007	0.007	-0.096	-0.006	0.036	0.105	0.003	-0.276	-0.208	-0.304	-0.138	1	0.167	0.054	-0.072	0.073
Oil palm potential yield	-0.58	0.454	0.273	0.491	-0.115	-0.488	-0.407	0.173	0.27	0.022	0.054	-0.095	0.06	0.167	1	0.001	0.28	0.219
Export value (t-1)	-0.047	0.06	0.075	0.025	0.002	0	0	0	0	0	0.018	-0.05	-0.069	0.054	0.001	1	0	0
Peatland %	-0.278	0.156	0.179	0.244	0.074	-0.222	-0.249	0.206	0.122	0.226	-0.116	0.136	0.173	-0.072	0.28	0	1	0.133
Plantation in 1990	-0.219	0.089	0.197	0.119	-0.034	-0.077	-0.118	0.484	0.105	-0.094	-0.078	-0.115	-0.055	0.073	0.219	0	0.133	1

Table A-5 Pairwise correlations between explanatory variables in Sumatra models.

	Shortwave radiation	Precipitation	Driest month precipitation	Temp	Protected %	Elevation	Slope	Mill density	AWC	Access time	Population	Natural forest ratio	Shrub ratio	Dry agriculture	Oil palm potential	Export value (t-1)	Peatland %	Plantation in 1990
Shortwave radiation	1	-0.214	-0.314	-0.078	0.196	0.023	0.061	-0.242	0.221	0.001	0.093	0.049	-0.017	0.199	-0.101	-0.219	-0.182	-0.207
Precipitation	-0.214	1	0.603	-0.152	0.276	0.114	0.145	-0.082	0	0.092	-0.114	0.094	-0.049	0.058	-0.083	0.016	-0.166	-0.032
Driest month precipitation	-0.314	0.603	1	-0.096	0.203	0.09	0.111	0.028	-0.08	0.204	0.015	0.12	-0.117	-0.163	-0.077	0.135	-0.03	0.168
Temp	-0.078	-0.152	-0.096	1	-0.399	-0.903	-0.779	0.291	0.284	-0.364	0.141	-0.535	0.13	0.062	0.832	0.117	0.458	0.279
Protected %	0.196	0.276	0.203	-0.399	1	0.5	0.435	-0.148	0.016	0.516	-0.13	0.614	-0.155	-0.249	-0.527	0.004	-0.099	-0.226
Elevation	0.023	0.114	0.09	-0.903	0.5	1	0.837	-0.253	-0.334	0.408	-0.138	0.624	-0.117	-0.17	-0.893	0	-0.398	-0.327
Slope	0.061	0.145	0.111	-0.779	0.435	0.837	1	-0.288	-0.522	0.463	-0.179	0.731	-0.012	-0.246	-0.661	0	-0.436	-0.377
Mill density	-0.242	-0.082	0.028	0.291	-0.148	-0.253	-0.288	1	0.107	-0.191	-0.048	-0.259	-0.182	0.105	0.228	0	0.169	0.464
AWC	0.221	0	-0.08	0.284	0.016	-0.334	-0.522	0.107	1	-0.247	0.067	-0.27	-0.194	0.191	0.165	0	0.241	0.241
Access time	0.001	0.092	0.204	-0.364	0.516	0.408	0.463	-0.191	-0.247	1	-0.281	0.711	0.242	-0.524	-0.512	0	0.205	-0.335
Population	0.093	-0.114	0.015	0.141	-0.13	-0.138	-0.179	-0.048	0.067	-0.281	1	-0.245	-0.183	-0.11	0.152	0.014	-0.114	0.104
Natural forest ratio	0.049	0.094	0.12	-0.535	0.614	0.624	0.731	-0.259	-0.27	0.711	-0.245	1	-0.052	-0.551	-0.596	-0.104	-0.068	-0.403
Shrub ratio	-0.017	-0.049	-0.117	0.13	-0.155	-0.117	-0.012	-0.182	-0.194	0.242	-0.183	-0.052	1	-0.253	0.052	-0.065	0.198	-0.264
Dry agriculture ratio	0.199	0.058	-0.163	0.062	-0.249	-0.17	-0.246	0.105	0.191	-0.524	-0.11	-0.551	-0.253	1	0.228	0.046	-0.285	-0.041
Oil palm potential yield	-0.101	-0.083	-0.077	0.832	-0.527	-0.893	-0.661	0.228	0.165	-0.512	0.152	-0.596	0.052	0.228	1	0.007	0.299	0.309
Export value (t-1)	-0.219	0.016	0.135	0.117	0.004	0	0	0	0	0	0.014	-0.104	-0.065	0.046	0.007	1	0	0
Peatland %	-0.182	-0.166	-0.03	0.458	-0.099	-0.398	-0.436	0.169	0.241	0.205	-0.114	-0.068	0.198	-0.285	0.299	0	1	0.132
Plantation in 1990	-0.207	-0.032	0.168	0.279	-0.226	-0.327	-0.377	0.464	0.241	-0.335	0.104	-0.403	-0.264	-0.041	0.309	0	0.132	1

Table A-6 Pairwise correlations between explanatory variables in Kalimantan models.

	Shortwave radiation	Precipitation	Driest month precipitation	Temp	Protected %	Elevation	Slope	Mill density	AWC	Access time	Population	Natural forest ratio	Shrub ratio	Dry agriculture ratio	Oil palm potential yield	Export value (t-1)	Peatland %	Plantation in 1990
Shortwave radiation	1	-0.231	-0.315	0.485	-0.042	-0.445	-0.381	0.387	-0.269	-0.495	0.116	-0.557	-0.204	0.524	0.127	-0.156	0.287	0.039
Precipitation	-0.231	1	0.729	-0.287	0.257	0.107	0.079	0.118	0.333	0.518	-0.244	0.335	-0.174	-0.121	-0.16	0.127	0.177	-0.146
Driest month precipitation	-0.315	0.729	1	-0.36	0.154	0.31	0.241	0.073	0.435	0.528	-0.095	0.382	-0.198	-0.158	-0.363	0.206	0.028	-0.145
Temp	0.485	-0.287	-0.36	1	-0.274	-0.877	-0.818	0.319	-0.112	-0.631	0.472	-0.708	0.414	0.256	0.703	0.096	0.356	0.222
Protected %	-0.042	0.257	0.154	-0.274	1	0.18	0.164	-0.081	-0.021	0.555	-0.298	0.384	0.004	-0.42	-0.372	0	0.152	0.082
Elevation	-0.445	0.107	0.31	-0.877	0.18	1	0.964	-0.261	0.014	0.522	-0.312	0.698	-0.363	-0.294	-0.818	0	-0.384	-0.202
Slope	-0.381	0.079	0.241	-0.818	0.164	0.964	1	-0.269	-0.156	0.454	-0.298	0.633	-0.387	-0.224	-0.752	0	-0.47	-0.143
Mill density	0.387	0.118	0.073	0.319	-0.081	-0.261	-0.269	1	0.159	-0.166	0.09	-0.247	-0.226	0.292	0.101	0	0.607	0.106
AWC	-0.269	0.333	0.435	-0.112	-0.021	0.014	-0.156	0.159	1	0.289	0.142	0.174	0.012	-0.121	-0.11	0	0.231	-0.148
Access time	-0.495	0.518	0.528	-0.631	0.555	0.522	0.454	-0.166	0.289	1	-0.456	0.782	-0.154	-0.539	-0.466	0	-0.05	-0.172
Population	0.116	-0.244	-0.095	0.472	-0.298	-0.312	-0.298	0.09	0.142	-0.456	1	-0.47	0.303	0.217	0.214	0.075	-0.009	-0.173
Natural forest ratio	-0.557	0.335	0.382	-0.708	0.384	0.698	0.633	-0.247	0.174	0.782	-0.47	1	-0.181	-0.716	-0.479	-0.143	-0.12	-0.104
Shrub ratio	-0.204	-0.174	-0.198	0.414	0.004	-0.363	-0.387	-0.226	0.012	-0.154	0.303	-0.181	1	-0.482	0.366	-0.016	0.082	0.098
Dry agriculture ratio	0.524	-0.121	-0.158	0.256	-0.42	-0.294	-0.224	0.292	-0.121	-0.539	0.217	-0.716	-0.482	1	0.132	0.048	0.007	-0.087
Oil palm potential yield	0.127	-0.16	-0.363	0.703	-0.372	-0.818	-0.752	0.101	-0.11	-0.466	0.214	-0.479	0.366	0.132	1	0	0.143	0.267
Export value (t-1)	-0.156	0.127	0.206	0.096	0	0	0	0	0	0	0.075	-0.143	-0.016	0.048	0	1	0	0
Peatland %	0.287	0.177	0.028	0.356	0.152	-0.384	-0.47	0.607	0.231	-0.05	-0.009	-0.12	0.082	0.007	0.143	0	1	-0.145
Plantation in 1990	0.039	-0.146	-0.145	0.222	0.082	-0.202	-0.143	0.106	-0.148	-0.172	-0.173	-0.104	0.098	-0.087	0.267	0	-0.145	1

Table A-7 VIFs of models.

	Indonesia	Sumatra	Kalimantan
Shortwave radiation	3.23	1.945	3.764
Precipitation	2.338	2.085	3.581
Driest month precipitation	2.145	2.03	3.316
Temp	3.614	8.219	12.06
Protected %	1.672	2.481	3.489
Elevation	5.215	17.987	75.805
Slope	5.434	10.281	38.412
Mill density	1.392	1.55	2.962
AWC	1.233	2.082	2.649
Access time	2.865	3.934	5.598
Population	1.413	1.768	2.561
Natural forest ratio	5.283	9.281	28.235
Shrub ratio	1.226	2.339	10.016
Dry agriculture ratio	1.607	4.218	19.743
Oil palm potential yield	3.621	9.572	8.671
Export value (t-1)	1.034	1.395	1.95
Peatland %	1.388	2.256	3.784
Plantation in 1990	1.491	2.519	2.001

* Synthesizing the pairwise correlations and VIFs, we eliminated elevation from the Sumatra and Kalimantan models.

Table A-8 Results of pooled and spatial panel models for bare ground expansion to natural forest in Kalimantan.

	Pooled			Spatial Lag			Spatial Error			Spatial Durbin		
	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.
(Intercept)	-780.084	-1.622		-584.550	-1.233		-813.448	-1.575		-706.839	-1.326	
Oil palm potential yield	0.027	0.203		0.014	0.104		0.061	0.480		0.071	0.598	
Plantation 1990	0.145	1.009		0.195	1.291		0.131	0.904		0.088	0.625	
Mill density	7.088	0.877		6.175	0.725		6.635	0.921		6.998	1.070	
Access time	1.879	1.290		1.374	0.917		1.235	0.825		1.000	0.680	
Temperature	2.542	1.567		1.908	1.195		2.633	1.515		2.252	1.257	
Shortwave radiation	0.041	0.719		0.036	0.620		0.067	1.119		0.089	1.438	
Precipitation	-0.125	-0.260		-0.136	-0.295		-0.082	-0.151		0.069	0.119	
Driest month precipitation	1.430	2.744	***	1.100	2.300	*	1.661	2.703	***	1.726	2.583	***
AWC	12.269	0.436		0.804	0.028		-7.747	-0.263		-10.109	-0.349	
Slope	-0.280	-0.615		-0.311	-0.666		-0.242	-0.537		-0.323	-0.742	
Source land ratio	9.009	1.194		7.841	1.072		10.535	1.498		9.638	1.468	
Source land ratio2	-6.907	-0.838		-6.065	-0.757		-6.116	-0.808		-4.311	-0.619	
Population density	-11.846	-4.543	****	-12.420	-4.764	****	-11.365	-4.365	****	-9.780	-3.771	
Export value	0.222	2.482	**	0.138	1.701	*	0.220	1.728	*	0.361	1.729	****
Peatland	-0.069	-1.908	*	-0.072	-1.915	*	-0.073	-2.027	**	-0.066	-1.861	*
Protected %	0.143	1.785	*	0.161	1.894	*	0.164	2.169	**	0.132	1.874	*
phi				6.71E-02	0.930		3.19E-02	0.672		3.55E-02	0.738	*
rho							0.441	5.997	****	0.707	8.610	****
lambda				0.368	4.852	****				-0.474	-2.940	***
R2	0.411											
AIC	1433.057			1480.652			1472.891			1468.827		
Log likelihood	-698.529			-688.326			-684.446			-681.414		

Notes: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

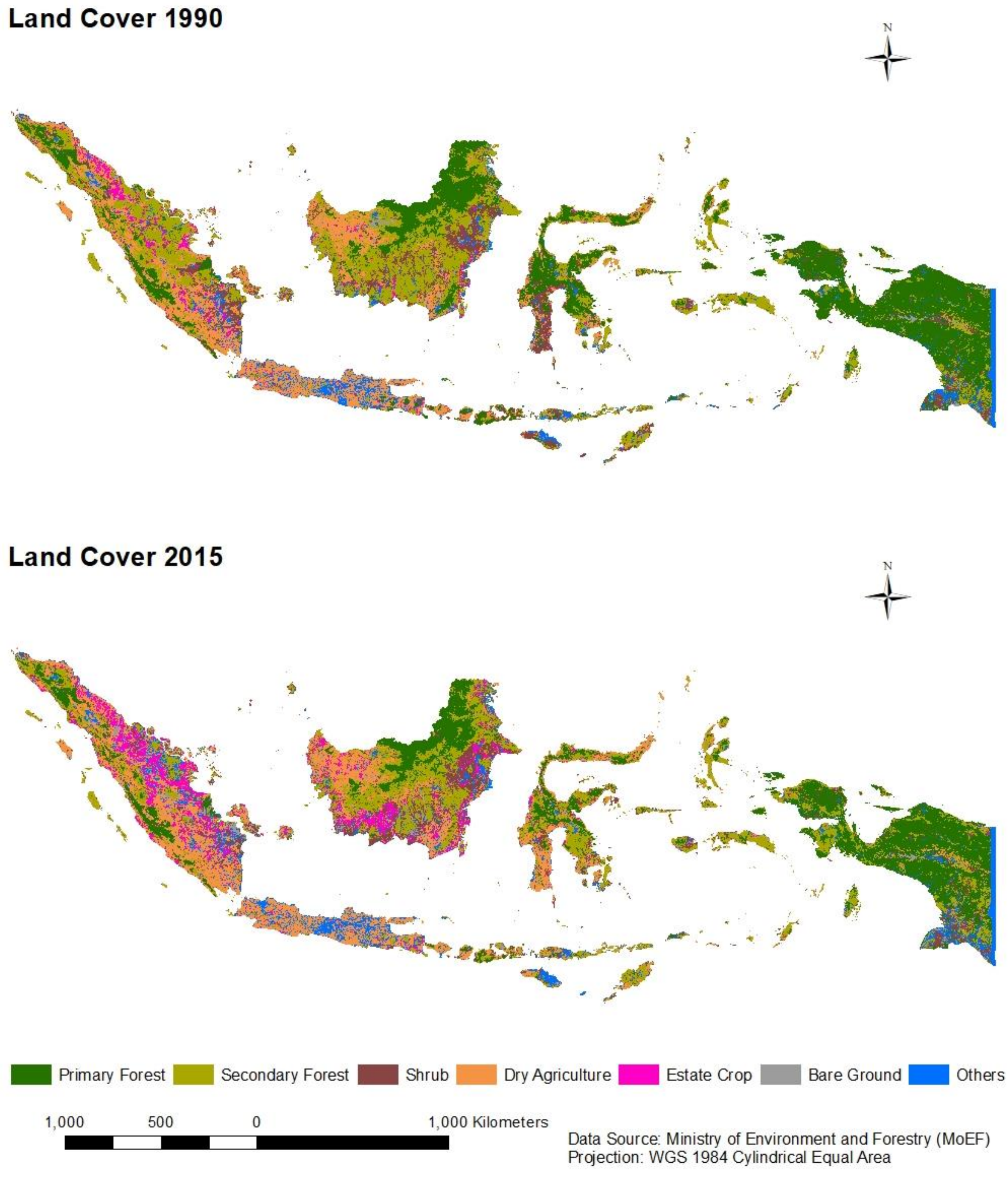


Figure A-1 Land cover maps of Indonesia (1990 and 2015) with 7 grouped classes.

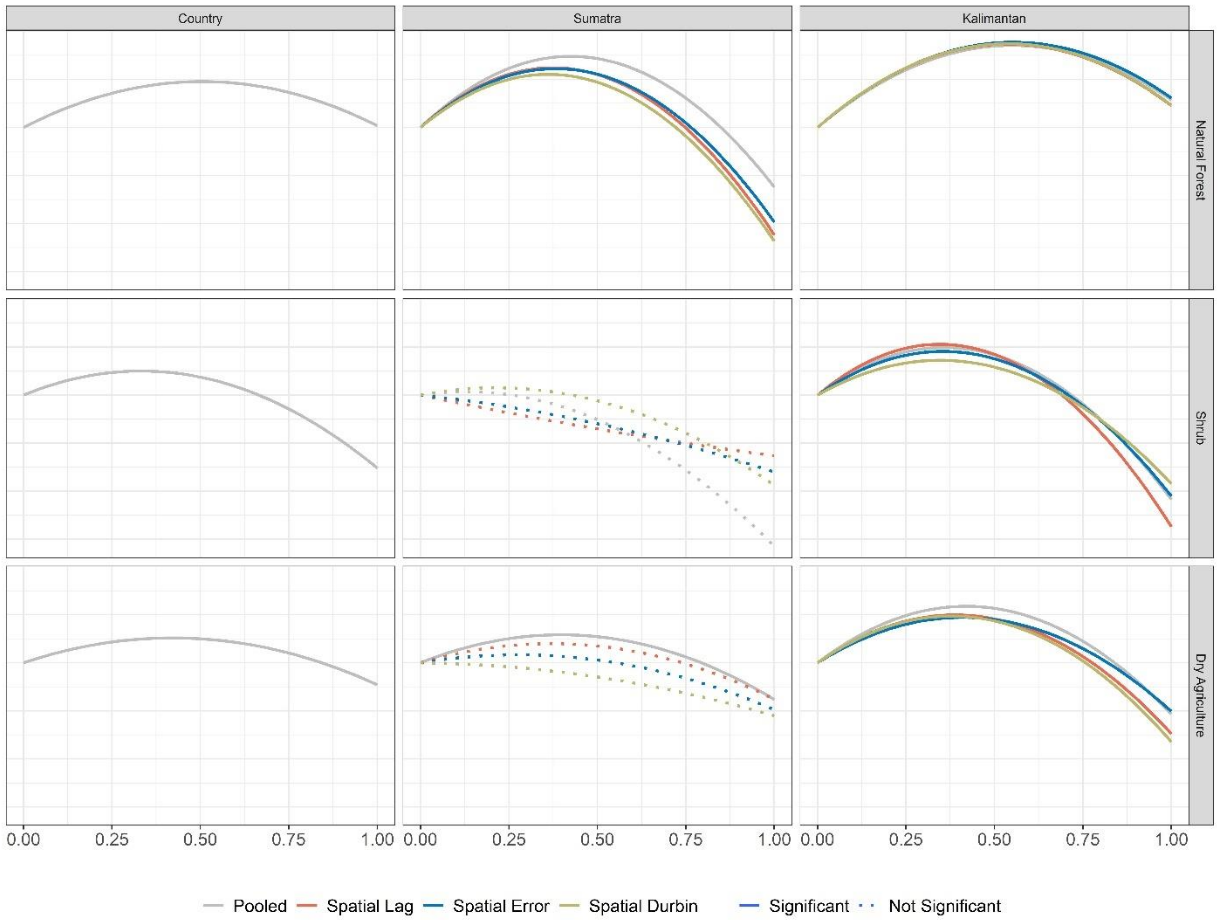


Figure A-2 The polynomial relationship between oil palm expansion and source land ratio.

In Sumatra, the inverted "U" shape existed only in the expansion into natural forest for all models (inflection points at 0.361-0.424) and into dry agriculture for the pooled model (inflection points at 0.397). In Kalimantan, the inverted "U" shape existed in all models, the inflection points are around 0.538-0.553 for natural forest, 0.346-0.359 for shrub, and 0.379-0.420 for dry agriculture.

Appendix B: Supplement information for Chapter 3

Table B-1 LCLU classification.

Class	Description	Re-Class
Primary Dryland Forest	Natural forest, dry habitat	Primary Forest
Secondary Dryland Forest	Logging signs, dry habitat	Secondary Forest
Primary Mangrove Forest	No or low human activity, wetland forest in coastal areas	Primary Forest
Secondary Mangrove Forest	Logging signs, wetland forest in coastal areas	Secondary Forest
Primary Swamp Forest	Natural forest, wet habitat	Primary Forest
Secondary Swamp Forest	Logging signs, wet habitat	Secondary Forest
Plantation Forest	Dominated by homogeneous tree species for specific purposes, structural composition. Reforestation, industrial plantation forest, community plantation forest	Others
Dry Shrub	Highly degraded logged-over area, non-wet habitat, ongoing process of succession	Shrub
Wet Shrub	Highly degraded logged-over area, wet habitat, ongoing process of succession	Shrub
Savanna and Grasses	Grasses and scattered natural trees and shrubs	Others
Pure Dry Agriculture	Agricultural activities on dry/ non-wet land, e.g. moor, mixed garden, agriculture fields	Dry Agriculture
Mixed Dry Agriculture	Agricultural activities on dry/ non-wet land mixed with shrubs, thickets, and logged-over forest	Dry Agriculture
Paddy Field	Agriculture areas on wet habitat, especially for paddy	Others
Estate Crop	Planted estate areas, mostly with perennials crops or other agricultural trees commodities	Estate Crop
Settlement Areas	Rural, urban, industrial and other built-up areas	Others
Transmigration Areas	Unique settlement areas associated with houses and agroforestry and/or garden	Others
Port and Harbor	Big enough to be delineated as independent object	Others
Bare Ground	No vegetation cover	Bare Ground
Mining Areas	Open mining activities	Others
Open Swamp	Wetland with few vegetation	Others
Fish Pond/ Aquaculture	Aquaculture activities	Others
Open Water	Ocean, rivers, lakes, and ponds	Others
Cloud and No-Data	Clouds, cloud shadows or data gaps with a size of more than 4 cm^2 at 100,000 scale display	No Data

Table B-2 Variable, data description and data sources

Variable	Unit	Data Description	Data Source
Occurrence of LCLUC	0 or 1	Collected from land use and land cover maps of Indonesia, 1996-2015	Indonesian Ministry of the Environment and Forestry. 2020. Indonesian Land Cover Closure. Available at: http://webgis.menlhk.go.id:8080/pl/pl.htm.
Attainable yield of oil palm	ton/ha oil	IIASA/FAO. Global Agro-ecological Zones (GAEZ v4)	https://gaez.fao.org/
Distance to old oil palm plantation (1990)	km	land use and land cover maps of Indonesia, 1990	Indonesian Ministry of the Environment Life and Forestry. 2020. Indonesian Land Cover Closure. Available at: http://webgis.menlhk.go.id:8080/pl/pl.htm.
Distance to oil palm processing mills	km	Universal Mill List (UML) (WRI/Rainforest Alliance/Proforest/Daemeter, 2018)	https://www.globalforestwatch.org/
Access time	day	Travel time to major cities: A global map of Accessibility (Nelson, A., 2008)	https://forobs.jrc.ec.europa.eu/products/gam/index.php
Precipitation (Rainfall)	mm/day	The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data (Weedon et al., 2014)	https://rda.ucar.edu/datasets/ds314.2/
Precipitation of driest month	mm/day		
Temperature	K		
Radiation (shortwave)	W/m2		
Elevation	100 m	Shuttle Radar Topography Mission (NASA, 2009)	https://earthexplorer.usgs.gov/
Slope	degree		
Population density	K persons per km^2	Gridded Population of the World (CIESIN)	https://beta.sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density
Protected area	1	World Database on Protected Areas (WDPA)	http://www.protectedplanet.net/
Peatland percentage	1	Peat lands (World Resources Institute, 2012. Accessed through Global Forest Watch)	https://www.globalforestwatch.org/

Table B-3 Units and summary statistics of explanatory variables across natural forest (1996 map) in Sumatra and Kalimantan.

Variable	Unit	Sumatra			Kalimantan		
		Mean	Max	Min	Mean	Max	Min
Attainable yield of oil palm	ton/ha oil	3.144	7.076	0	2.826	7.094	0
Distance to oil palm processing mills	km	33.361	186.079	0.303	70.594	337.664	0.128
Distance to old oil palm plantation	km	29.014	184.922	0.124	76.210	254.056	0
Access time	day	0.572	2.563	0.006	1.445	4.650	0.006
Temperature	K	299.673	301.861	295.158	298.928	301.164	295.364
Shortwave radiation	W/m^2	186.001	209.362	161.512	183.301	217.461	165.797
Annual precipitation	mm/day	7.773	13.600	4.080	8.631	13.500	3.81
Driest month precipitation	mm/day	1.567	6.170	0	2.026	7.650	0
Elevation	100 m	5.085	32.125	0	3.739	20.312	0
Slope	degree	7.534	40.553	0	6.756	34.606	0
Population density	K persons per km^2	0.057	6.093	0.003	0.014	5.773	0
Protected area	1	0.268	1	0	0.129	1	0
Peatland	1	0.229	1	0	0.100	1	0

Table B-4 Units and summary statistics of explanatory variables in PAs of Sumatra and Kalimantan.

Variable	Unit	Sumatra			Kalimantan		
		Mean	Max	Min	Mean	Max	Min
Attainable yield of oil palm	ton/ha oil	2.299	7.024	0	1.835	7.094	0
Distance to oil palm processing mills	km	41.149	186.079	0	102.996	253.735	1.028
Distance to old oil palm plantation	km	32.212	185.183	0.287	120.267	255.274	0.323
Access time	day	0.659	2.599	0.010	1.874	4.268	0.013
Temperature	K	299.260	301.564	295.158	298.100	301.056	295.364
Shortwave radiation	W/m^2	188.216	209.362	162.546	184.038	217.461	165.797
Annual precipitation	mm/day	8.065	13.593	4.265	8.536	13.528	4.238
Driest month precipitation	mm/day	1.875	6.175	0	1.873	6.768	0
Elevation	100 m	7.207	33.011	0.013	5.941	21.277	0
Slope	degree	9.856	36.559	0.062	8.604	34.273	0
Population density	K persons per km^2	0.060	3.395	0.003	0.011	0.667	0
Protected area 1	1	0.838	1	0	0.933	1	0
Protected area 2	1	0.667	1	0	0.809	1	0
Peatland	1	0.188	1	0	0.180	1	0

Table B-5 Pairwise correlations between explanatory variables in models across Sumatra.

	Log(Attainable yield of oil palm)	Log(Distance to old oil palm plantation)	Log(Distance to oil palm processing mills)	Access time	Temperature	Shortwave radiation	Annual precipitation	Driest month precipitation	Slope	Elevation	Population density	Protected area	Peatland
Log(Attainable yield of oil palm)	1	-0.241	-0.352	-0.306	0.689	-0.148	-0.170	-0.135	-0.640	-0.854	-0.082	-0.237	0.364
Log(Distance to old oil palm plantation)	-0.241	1	0.567	0.284	-0.257	0.322	0.115	0.055	0.258	0.266	-0.058	0.150	-0.203
Log(Distance to oil palm processing mills)	-0.352	0.567	1	0.217	-0.349	0.383	0.213	0.135	0.350	0.390	-0.019	0.262	-0.161
Access time	-0.306	0.284	0.217	1	-0.354	0.061	0.064	0.175	0.313	0.332	-0.106	0.142	0.035
Temperature	0.689	-0.257	-0.349	-0.354	1	-0.178	-0.224	-0.193	-0.702	-0.791	-0.071	-0.239	0.466
Shortwave radiation	-0.148	0.322	0.383	0.061	-0.178	1	-0.037	-0.148	0.158	0.167	0.007	0.165	-0.121
Annual precipitation	-0.170	0.115	0.213	0.064	-0.224	-0.037	1	0.612	0.236	0.191	0.062	0.196	-0.255
Driest month precipitation	-0.135	0.055	0.135	0.175	-0.193	-0.148	0.612	1	0.179	0.155	0.041	0.203	-0.110
Slope	-0.640	0.258	0.350	0.313	-0.702	0.158	0.236	0.179	1	0.756	0.136	0.245	-0.525
Elevation	-0.854	0.266	0.390	0.332	-0.791	0.167	0.191	0.155	0.756	1	0.104	0.272	-0.449
Population density	-0.082	-0.058	-0.019	-0.106	-0.071	0.007	0.062	0.041	0.136	0.104	1	0.060	-0.114
Protected area	-0.237	0.150	0.262	0.142	-0.239	0.165	0.196	0.203	0.245	0.272	0.060	1	-0.161
Peatland	0.364	-0.203	-0.161	0.035	0.466	-0.121	-0.255	-0.110	-0.525	-0.449	-0.114	-0.161	1

Table B-6 Pairwise correlation between explanatory variables in models across Kalimantan.

	Log(Attainable yield of oil palm)	Log(Distance to old oil palm plantation)	Log(Distance to oil palm processing mills)	Access time	Temperature	Shortwave radiation	Annual precipitation	Driest month precipitation	Slope	Elevation	Population density	Protected area	Peatland
Log(Attainable yield of oil palm)	1	-0.478	-0.512	-0.445	0.664	0.247	-0.150	-0.278	-0.527	-0.797	0.092	-0.305	0.203
Log(Distance to old oil palm plantation)	-0.478	1	0.769	0.533	-0.700	-0.504	0.365	0.372	0.430	0.551	-0.169	0.228	-0.233
Log(Distance to oil palm processing mills)	-0.512	0.769	1	0.475	-0.732	-0.448	0.424	0.352	0.498	0.609	-0.135	0.223	-0.221
Access time	-0.445	0.533	0.475	1	-0.594	-0.343	0.284	0.319	0.425	0.499	-0.168	0.213	-0.204
Temperature	0.664	-0.700	-0.732	-0.594	1	0.511	-0.298	-0.418	-0.594	-0.760	0.162	-0.276	0.352
Shortwave radiation	0.247	-0.504	-0.448	-0.343	0.511	1	-0.347	-0.389	-0.268	-0.333	0.175	0.000	0.373
Annual precipitation	-0.150	0.365	0.424	0.284	-0.298	-0.347	1	0.541	0.191	0.168	-0.068	0.001	-0.059
Driest month precipitation	-0.278	0.372	0.352	0.319	-0.418	-0.389	0.541	1	0.283	0.339	-0.110	-0.007	-0.193
Slope	-0.527	0.430	0.498	0.425	-0.594	-0.268	0.191	0.283	1	0.723	-0.094	0.165	-0.369
Elevation	-0.797	0.551	0.609	0.499	-0.760	-0.333	0.168	0.339	0.723	1	-0.118	0.274	-0.321
Population density	0.092	-0.169	-0.135	-0.168	0.162	0.175	-0.068	-0.110	-0.094	-0.118	1	-0.027	0.073
Protected area	-0.305	0.228	0.223	0.213	-0.276	0.000	0.001	-0.007	0.165	0.274	-0.027	1	0.043
Peatland	0.203	-0.233	-0.221	-0.204	0.352	0.373	-0.059	-0.193	-0.369	-0.321	0.073	0.043	1

Table B-7 Pairwise correlations between explanatory variables in models on Sumatra PAs.

	Log(Attainable yield of oil palm)	Log(Distance to old oil palm plantation)	Log(Distance to oil palm processing mills)	Access time	Temperature	Shortwave radiation	Annual precipitation	Driest month precipitation	Slope	Elevation	Population density	Protected area 1	Protected area 2	Peatland
Log(Attainable yield of oil palm)	1	-0.043	-0.202	-0.310	0.643	-0.029	-0.244	-0.212	-0.584	-0.822	-0.068	0.046	0.013	0.332
Log(Distance to old oil palm plantation)	-0.043	1	0.658	0.130	-0.051	0.384	0.140	0.017	0.007	0.024	-0.288	-0.030	0.085	-0.083
Log(Distance to oil palm processing mills)	-0.202	0.658	1	0.158	-0.244	0.366	0.298	0.143	0.124	0.219	-0.239	0.031	0.132	-0.120
Access time	-0.310	0.130	0.158	1	-0.425	-0.048	0.220	0.339	0.333	0.376	-0.130	0.008	0.089	0.020
Temperature	0.643	-0.051	-0.244	-0.425	1	-0.076	-0.284	-0.317	-0.655	-0.757	-0.008	0.024	0.001	0.399
Shortwave radiation	-0.029	0.384	0.366	-0.048	-0.076	1	-0.101	-0.272	0.007	0.032	-0.055	-0.136	0.038	-0.151
Annual precipitation	-0.244	0.140	0.298	0.220	-0.284	-0.101	1	0.711	0.343	0.265	0.002	0.175	0.104	-0.245
Driest month precipitation	-0.212	0.017	0.143	0.339	-0.317	-0.272	0.711	1	0.274	0.234	-0.026	0.231	0.137	-0.110
Slope	-0.584	0.007	0.124	0.333	-0.655	0.007	0.343	0.274	1	0.692	0.158	-0.041	-0.037	-0.484
Elevation	-0.822	0.024	0.219	0.376	-0.757	0.032	0.265	0.234	0.692	1	0.078	-0.053	-0.013	-0.401
Population density	-0.068	-0.288	-0.239	-0.130	-0.008	-0.055	0.002	-0.026	0.158	0.078	1	0.269	0.076	-0.088
Protected aea 1	0.046	-0.030	0.031	0.008	0.024	-0.136	0.175	0.231	-0.041	-0.053	0.269	1	0.486	0.082
Protected area 2	0.013	0.085	0.132	0.089	0.001	0.038	0.104	0.137	-0.037	-0.013	0.076	0.486	1	0.047
Peatland	0.332	-0.083	-0.120	0.020	0.399	-0.151	-0.245	-0.110	-0.484	-0.401	-0.088	0.082	0.047	1

Table B-8 Pairwise correlations between explanatory variables in models on Kalimantan PAs.

	Log(Attainable yield of oil palm)	Log(Distance to old oil palm plantation)	Log(Distance to oil palm processing mills)	Access time	Temperature	Shortwave radiation	Annual precipitation	Driest month precipitation	Slope	Elevation	Population density	Protected area 1	Protected area 2	Peatland
Log(Attainable yield of oil palm)	1	-0.608	-0.607	-0.528	0.736	0.409	-0.044	-0.402	-0.581	-0.808	0.475	-0.270	-0.226	0.482
Log(Distance to old oil palm plantation)	-0.608	1	0.899	0.745	-0.812	-0.726	0.198	0.513	0.575	0.656	-0.644	0.205	0.204	-0.419
Log(Distance to oil palm processing mills)	-0.607	0.899	1	0.674	-0.807	-0.688	0.286	0.537	0.602	0.665	-0.599	0.239	0.213	-0.452
Access time	-0.528	0.745	0.674	1	-0.697	-0.520	0.138	0.445	0.522	0.564	-0.602	0.199	0.230	-0.405
Temperature	0.736	-0.812	-0.807	-0.697	1	0.625	-0.073	-0.491	-0.655	-0.824	0.623	-0.332	-0.239	0.611
Shortwave radiation	0.409	-0.726	-0.688	-0.520	0.625	1	-0.351	-0.458	-0.417	-0.433	0.378	-0.239	-0.180	0.377
Annual precipitation	-0.044	0.198	0.286	0.138	-0.073	-0.351	1	0.454	0.305	-0.003	0.129	0.209	0.103	-0.204
Driest month precipitation	-0.402	0.513	0.537	0.445	-0.491	-0.458	0.454	1	0.456	0.463	-0.350	0.267	0.192	-0.442
Slope	-0.581	0.575	0.602	0.522	-0.655	-0.417	0.305	0.456	1	0.669	-0.319	0.348	0.235	-0.615
Elevation	-0.808	0.656	0.665	0.564	-0.824	-0.433	-0.003	0.463	0.669	1	-0.543	0.318	0.236	-0.563
Population density	0.475	-0.644	-0.599	-0.602	0.623	0.378	0.129	-0.350	-0.319	-0.543	1	-0.063	-0.129	0.271
Protected aea 1	-0.270	0.205	0.239	0.199	-0.332	-0.239	0.209	0.267	0.348	0.318	-0.063	1	0.551	-0.480
Protected area 2	-0.226	0.204	0.213	0.230	-0.239	-0.180	0.103	0.192	0.235	0.236	-0.129	0.551	1	0.261
Peatland	0.482	-0.419	-0.452	-0.405	0.611	0.377	-0.204	-0.442	-0.615	-0.563	0.271	-0.480	-0.261	1

Table B-9 VIFs across Sumatra and Kalimantan.

	Sumatra			Kalimantan		
	Whole Island	Protected Area	Protected Area Reduced	Whole Island	Protected Area	Protected Area Reduced
Log(Attainable yield of oil palm)	2.134	23.862	2.837	1.871	4.860	6.379
Log(Distance to old oil palm plantation)	1.334	6.528	6.074	1.522	5.643	5.628
Log(Distance to oil palm processing mills)	1.206	4.717	4.541	1.585	2.761	3.241
Access time	1.428	2.002	2.001	1.514	3.956	5.669
Temperature	1.719	4.578	5.251	2.267	8.854	
Shortwave radiation	1.197	4.146	3.674	1.989	7.441	4.263
Annual precipitation	1.473	5.465	5.273	2.017	5.401	4.846
Driest month precipitation	1.270	7.430	7.123	1.953	8.572	3.481
Slope	2.825	10.659	6.087	2.803	14.604	4.682
Elevation	3.492	37.554		3.114	19.663	
Population density	1.020	6.763	6.117	1.059	5.640	3.969
Protected area	1.067	3.746	3.711	1.025	1.979	1.560
		2.909	2.870		1.930	1.724
Peatland	1.363	5.831	5.824	1.707	2.944	3.025

* Synthesizing the pairwise correlations and VIFs, we eliminated elevation from all the protected area models, and temperature from the Kalimantan protected area models.

Tests of the proportionality

Table B-10 – Table B-13 show the variables failing to meet the proportionality assumptions with extended models. The first columns of Table B-10 – Table B-13 show the total estate crop expansion into natural forest. The second to seventh columns show the direct transitions in the multi-state models. EC represents estate crop, NF represents natural forest, BG represents bare ground. The heighted factors indicate that the directions and trends of effects of the strata models are similar to the extended model, though the proportionality assumptions are not met. Strata models were not used on the LCLUC inside protected areas (PAs) due to the limited number and temporal clustering of estate crop expansion.

Table B-10 Variables falling to meet the proportionality assumption with extended model in Sumatra.

	EC expansion	NF to EC	Shrub to EC	BG to EC	NF to Shrub	NF to BG	Shrub to BG
Log(Attainable yield of oil palm)					✓		
Log(Distance to old oil palm plantation)	✓	✓	✓		✓	✓	
Log(Distance to oil palm processing mills)		✓			✓		✓
Access time					✓	✓	✓
Temperature							
Shortwave radiation					✓		✓
Annual precipitation			✓		✓		
Driest month precipitation	✓	✓			✓		
Slope					✓		
Elevation					✓		
Population density			✓		✓		
Protected area	✓					✓	
Peatland	✓				✓	✓	

* EC expansion: the effect of Log (Distance to old oil palm plantation) became significantly positive in 2012-2015. Shrub to EC: the effects of population density were significantly positive in 2006-2009, but negative in other periods. NF to BG: Access time: decreasing trend, not significant in 2012-2015. Shrub to BG: Access time: time-variant, no significant temporal trend. The effects of unhighlighted climatic factors were time-variant and showed no significant temporal trend.

Table B-11 Variables falling to meet the proportionality assumption with extended model in Kalimantan.

	EC expansion	NF to EC	Shrub to EC	BG to EC	NF to Shrub	NF to BG	Shrub to BG
Log(Attainable yield of oil palm)	✓				✓		
Log(Distance to old oil palm plantation)	✓	✓	✓				
Log(Distance to oil palm processing mills)		✓		✓		✓	✓
Access time							
Temperature				✓	✓		
Shortwave radiation	✓	✓	✓		✓		✓
Annual precipitation	✓	✓	✓				
Driest month precipitation					✓		
Slope						✓	
Elevation			✓		✓	✓	
Population density					✓		
Protected area						✓	✓
Peatland	✓	✓	✓		✓	✓	✓

* EC expansion: Log(Attainable yield of oil palm): significant negative in 2006-2009, positive in other periods. NF to Shrub: Log(Attainable yield of oil palm): significantly negative, decreasing trend. Peat: significantly positive in 1996-20000, significantly negative in 2012-2015. NF to BG: Log(Distance to oil palm processing mills): negative, inverted U shape, largest in 2003-2009. Elevation: no significant.

Table B-12 Variables falling to meet the proportionality assumption with extended model in Sumatra PAs.

	EC expansion	NF to EC	Shrub to EC	BG to EC	NF to Shrub	NF to BG	Shrub to BG
Log(Attainable yield of oil palm)							
Log(Distance to old oil palm plantation)	✓				✓	✓	
Log(Distance to oil palm processing mills)					✓		
Access time					✓	✓	
Temperature		✓			✓	✓	✓
Shortwave radiation	✓				✓	✓	
Annual precipitation	✓				✓	✓	
Driest month precipitation					✓	✓	✓
Slope					✓	✓	
Population density					✓	✓	✓
Protected area 1	✓	✓			✓	✓	
Protected area 2	✓				✓		
Peatland	✓	✓				✓	

Table B-13 Variables falling to meet the proportionality assumption with extended model in Kalimantan PAs.

	EC expansion	NF to EC	Shrub to EC	BG to EC	NF to Shrub	NF to BG	Shrub to BG
Log(Attainable yield of oil palm)					✓	✓	
Log(Distance to old oil palm plantation)		✓			✓	✓	
Log(Distance to oil palm processing mills)					✓		
Access time					✓	✓	
Temperature					✓		
Shortwave radiation	✓					✓	
Annual precipitation			✓		✓		
Driest month precipitation	✓	✓			✓	✓	
Slope					✓		
Population density		✓			✓		
Protected area 1							
Protected area 2							
Peatland							

Table B-14 Multi-state analysis results on Sumatra and Kalimantan - transition from natural forest to estate crop.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	0.197	1.217	2.879	***	0.246	1.280	3.286	***	0.009	1.009	0.107					
Log(Distance to 1990 plantation)	-0.332	0.718	-10.063	****	-0.238	0.789	-4.756	****	-0.301	0.740	-7.060	****	-0.627	0.534	-13.778	****
Log(Distance to oil palm mills)	-0.928	0.395	-24.117	****	-0.765	0.465	-13.789	****	-1.282	0.277	-28.618	****	-1.514	0.220	-14.247	****
Access time	-0.922	0.398	-5.800	****	-0.897	0.408	-5.726	****	-0.096	0.909	-1.067					
Temperature	-0.037	0.964	-0.583						-0.372	0.689	-3.749	****	-0.910	0.402	-4.021	****
Shortwave radiation	-0.002	0.998	-0.370						0.024	1.024	4.855	****	0.021	1.021	4.426	****
Annual precipitation	0.223	1.250	6.334	****	0.233	1.262	7.507	****	-0.016	0.984	-0.359		0.626	1.869	6.167	****
Driest month precipitation	-0.510	0.600	-8.903	****	-0.750	0.473	-8.088	****	0.259	1.295	7.682	****				
Slope	-0.268	0.765	-7.726	****	-0.283	0.753	-9.535	****	-0.276	0.759	-6.406	****	-0.252	0.777	-6.026	****
Elevation	-0.079	0.924	-1.538						-0.494	0.610	-4.185	****	-0.537	0.584	-4.658	****
Population density	0.071	1.073	0.344						-1.090	0.336	-0.950					
Protected ratio	-3.203	0.041	-5.883	****	-3.121	0.044	-5.764	****	-3.041	0.048	-4.228	****	-3.133	0.044	-4.403	****
Peatland ratio	-0.291	0.747	-3.984	****	-0.578	0.561	-5.368	****	0.081	1.084	0.738		-2.106	0.122	-5.824	****
Log(Oil palm attainable yield) * T																
Log(Distance to 1990 plantation) * T					-0.068	0.935	-2.594	***					0.092	1.097	6.258	****
Log(Distance to oil palm mills)* T					-0.121	0.886	-3.887	****					0.049	1.050	1.903	*
Access time * T																
Temperature * T													0.139	1.149	2.487	**
Shortwave radiation * T																
Annual precipitation * T													-0.160	0.852	-6.282	****
Driest month precipitation * T					0.106	1.112	3.247	***					0.063	1.065	8.044	****
Slope * T																
Elevation * T																
Population density * T																
Protected ratio * T																
Peatland ratio * T					0.191	1.210	3.543	****					0.494	1.638	6.705	****
Concordance	0.927				0.926				0.96				0.962			
Likelihood ratio test	3352				3400				2929				3030			
Wald test	1862				1964				2289				2497			
Score (logrank) test	3385				3406				4172				4465			
AIC	18365.06				18317.69				10989.91				10892.49			
LogLik	-9169.53				-9145.85				-5481.96				-5431.24			
Number of grids	17661								31833							
Number of events	1117								677							

Table B-15 Multi-state analysis results on Sumatra and Kalimantan - transition from shrub to estate crop.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	0.681	1.975	1.728	*	0.604	1.830	1.563		0.021	1.021	0.082					
Log(Distance to 1990 plantation)	-0.032	0.968	-0.369		-1.780	0.169	-5.680	****	-0.182	0.834	-3.561	****	-1.678	0.187	-10.053	****
Log(Distance to oil palm mills)	-0.743	0.476	-9.102	****	-0.720	0.487	-9.032	****	-0.987	0.373	-13.439	****	-1.036	0.355	-15.688	****
Access time	-0.121	0.886	-0.453						0.041	1.042	0.305					
Temperature	-0.289	0.749	-1.797	*	-0.247	0.782	-1.515		-0.317	0.729	-2.435	**				
Shortwave radiation	-0.007	0.993	-0.946						0.004	1.004	0.673		0.038	1.038	2.234	**
Annual precipitation	0.148	1.160	2.152	**	-1.030	0.357	-2.879	***	-0.062	0.940	-0.701		1.855	6.394	10.253	****
Driest month precipitation	-0.230	0.795	-2.691	***					0.073	1.075	1.236					
Slope	-0.395	0.674	-3.905	****	-0.430	0.650	-4.694	****	-0.260	0.771	-2.798	***	-0.264	0.768	-3.151	***
Elevation	-0.005	0.995	-0.035						-0.760	0.468	-3.095	***	-0.717	0.488	-3.399	****
Population density	-5.335	0.005	-1.027		35.319	2.18E+15	3.532	****	-3.521	0.030	-1.374		-1.670	0.188	-2.194	**
Protected ratio	0.379	1.460	1.667	*	-17.030	4.02E-08	-2.715	***	-1.698	0.183	-2.907	***	-1.726	0.178	-2.865	***
Peatland ratio	0.010	1.010	0.073						-0.252	0.777	-1.472		-2.816	0.060	-2.984	***
Establish Time	0.271	1.312	3.499	****	-0.568	0.567	-3.256	***	0.116	1.123	1.490		-1.082	0.339	-1.589	
Establish Time ^2	-0.013	0.987	-3.341	****					-0.003	0.997	-0.689		0.092	1.097	1.959	*
Log(Oil palm attainable yield) * T																
Log(Distance to 1990 plantation) * T					0.348	1.416	5.524	****					0.310	1.363	9.036	****
Log(Distance to oil palm mills)* T																
Access time * T																
Temperature * T																
Shortwave radiation * T					-0.002	0.998	-1.759	*					-0.008	0.992	-2.460	**
Annual precipitation * T					0.238	1.269	3.549	****					-0.413	0.662	-10.907	****
Driest month precipitation * T					-0.034	0.966	-2.021	**					0.037	1.038	3.384	****
Slope * T																
Elevation * T																
Population density * T					-8.375	2.31E-04	-3.357	****								
Protected ratio * T					2.953	19.170	2.810	***								
Peatland ratio * T													0.484	1.623	2.909	***
Establish Time * T					0.183	1.200	4.946	****					0.196	1.216	1.673	*
Establish Time ^2 * T					-0.004	0.996	-5.786	****					-0.015	0.985	-1.938	*
Concordance		0.752				0.795				0.824				0.843		
AIC		4488.04				4376.13				5636.46				5427.06		
LogLik		-2229.02				2171.06				-2803.23				-2695.53		
Number of grids					2389								2744			
Number of events					319								408			

Table B-16 Multi-state analysis results on Sumatra and Kalimantan - transition from bare ground to estate crop.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	-0.027	0.973	-0.599						0.791	2.206	2.320	**	-2.328	0.098	-3.052	***
Log(Distance to 1990 plantation)	-0.038	0.962	-0.479		0.473	1.605	1.758	*	-0.113	0.893	-1.952	*	-0.765	0.465	-2.460	**
Log(Distance to oil palm mills)	-0.957	0.384	-10.456	****	-0.958	0.384	-10.920	****	-0.445	0.641	-7.521	****	-0.453	0.636	-8.096	****
Access time	0.488	1.630	1.878	*	0.535	1.708	2.069	**	0.524	1.689	3.620	****	0.476	1.609	3.701	****
Temperature	-0.345	0.708	-1.696	*	-0.391	0.676	-2.104	**	-0.271	0.763	-1.718	*	-2.543	0.079	-2.218	**
Shortwave radiation	0.008	1.008	0.799						-0.025	0.976	-3.222	***	-0.024	0.977	-3.255	***
Annual precipitation	0.122	1.130	1.756	*					-0.060	0.942	-0.820					
Driest month precipitation	-0.075	0.928	-0.966						-0.051	0.950	-0.796		-0.115	0.891	-2.408	**
Slope	-0.269	0.764	-2.217	**	-0.286	0.751	-2.313	**	0.014	1.014	0.174					
Elevation									-0.590	0.554	-2.740	***				
Population density	6.609	741.953	3.126	***	8.001	2984.619	3.639	****	-0.480	0.619	-0.292					
Protected ratio	-163.588	9.01E-72	-4.525	****	-341.182	6.71E-149	-9.550	****	-0.510	0.601	-0.679					
Peatland ratio	0.718	2.050	4.064	****	0.665	1.945	3.791	****	0.273	1.314	1.561		-8.565	0.000	-3.129	***
Establish Time	0.048	1.049	0.439						0.616	1.852	2.943	***	0.566	1.761	2.894	***
Establish Time ^2	-0.003	0.997	-0.484						-0.019	0.981	-2.379	**	-0.017	0.983	-2.182	**
Log(Oil palm attainable yield) * T													0.583	1.791	3.109	***
Log(Distance to 1990 plantation) * T					-0.114	0.892	-1.941	*					0.133	1.142	2.384	**
Log(Distance to oil palm mills)* T																
Access time * T																
Temperature * T													0.404	1.497	1.988	**
Shortwave radiation * T																
Annual precipitation * T																
Driest month precipitation * T																
Slope * T																
Elevation * T													-0.090	0.914	-2.731	***
Population density * T																
Protected ratio * T																
Peatland ratio * T													1.505	4.506	3.270	***
Establish Time * T																
Establish Time ^2 * T																
Concordance	0.783				0.781				0.795				0.820			
AIC	2845.32				2835.31				3090.57				3042.35			
LogLik	-1408.66				-1408.65				-1530.29				-1506.17			
Number of grids	1066								494							
Number of events	254								302							

Table B-17 Multi-state analysis results on Sumatra and Kalimantan - transition from natural forest to shrub.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	-0.053	0.948	-3.695	****	-0.150	0.860	-6.440	****	-0.107	0.899	-7.079	****				
Log(Distance to 1990 plantation)	-0.108	0.897	-4.766	****	0.121	1.129	2.906	***	0.081	1.085	3.410	****	0.088	1.092	3.671	****
Log(Distance to oil palm mills)	-0.280	0.756	-9.202	****	0.153	1.165	2.968	***	-0.436	0.647	-18.036	****	-0.430	0.651	-17.627	****
Access time	-1.086	0.338	-12.465	****	-1.073	0.342	-11.936	****	-0.504	0.604	-12.537	****	-0.493	0.611	-12.469	****
Temperature	-0.097	0.908	-2.575	**	-0.141	0.869	-3.668	****	-0.212	0.809	-4.965	****	-0.628	0.533	-9.740	****
Shortwave radiation	-0.010	0.990	-3.415	****	0.056	1.057	10.193	****	0.003	1.003	1.217		-0.012	0.988	-2.847	***
Annual precipitation	0.158	1.172	8.787	****	0.276	1.318	8.120	****	-0.325	0.722	-20.862	****	-0.451	0.637	-18.297	****
Driest month precipitation	-0.159	0.853	-6.783	****	-0.720	0.487	-12.190	****	-0.159	0.853	-6.245	****	-0.534	0.587	-8.058	****
Slope	-0.150	0.861	-13.153	****	-0.166	0.847	-13.513	****	0.006	1.006	0.448					
Elevation	-0.176	0.839	-6.766	****	-0.281	0.755	-6.019	****	-0.773	0.462	-14.017	****	-0.761	0.467	-19.486	****
Population density	-3.740	0.024	-3.080	***	-3.372	0.034	-2.777	***	0.734	2.083	3.251	***	0.757	2.132	3.326	****
Protected ratio	-0.612	0.542	-7.853	****	-0.593	0.553	-7.772	****	-1.447	0.235	-10.502	****	-1.456	0.233	-10.609	****
Peatland ratio	0.479	1.615	9.158	****	0.769	2.157	7.677	****	-0.270	0.763	-4.781	****	-0.306	0.736	-5.353	****
Log(Oil palm attainable yield) * T					0.037	1.037	4.245	****					-0.038	0.963	-11.747	****
Log(Distance to 1990 plantation) * T					-0.092	0.912	-6.913	****								
Log(Distance to oil palm mills)* T					-0.199	0.819	-10.705	****								
Access time * T																
Temperature * T													0.156	1.169	6.076	****
Shortwave radiation * T					-0.026	0.974	-13.169	****					0.005	1.005	3.843	****
Annual precipitation * T					-0.073	0.930	-6.104	****					0.068	1.071	7.143	****
Driest month precipitation * T					0.195	1.216	11.957	****					0.096	1.101	6.013	****
Slope * T																
Elevation * T					0.037	1.037	2.819	***								
Population density * T																
Protected ratio * T																
Peatland ratio * T					-0.119	0.888	-3.881	****								
Concordance	0.825				0.853				0.873				0.877			
AIC	44655.85				43918.76				53313.29				53090.32			
LogLik	-22364.92				-21938.38				-26643.65				-26529.16			
Number of grids	17661								31833							
Number of events	2527								2870							

Table B-18 Multi-state analysis results on Sumatra and Kalimantan - transition from natural forest to bare ground.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	0.038	1.039	1.186		0.053	1.055	2.284	**	0.107	1.113	0.366					
Log(Distance to 1990 plantation)	0.050	1.051	1.310		-0.184	0.832	-2.561	**	0.042	1.043	0.814					
Log(Distance to oil palm mills)	-0.580	0.560	-13.710	****	-0.567	0.567	-13.267	****	-0.976	0.377	-16.792	****	-1.584	0.205	-9.993	****
Access time	-0.836	0.433	-7.053	****	-0.769	0.464	-6.543	****	-0.020	0.980	-0.243		0.495	1.640	1.748	*
Temperature	0.076	1.079	1.066		0.099	1.104	1.488		0.015	1.015	0.155		-0.733	0.480	-2.768	***
Shortwave radiation	-0.039	0.961	-8.698	****	-0.045	0.956	-9.594	****	-0.016	0.985	-3.250	***	0.035	1.035	1.984	**
Annual precipitation	-0.150	0.860	-4.434	****	-0.153	0.858	-4.580	****	0.035	1.035	0.851		-0.246	0.782	-2.157	**
Driest month precipitation	0.215	1.240	5.125	****					0.043	1.044	1.273					
Slope	-0.304	0.738	-13.364	****	-0.323	0.724	-14.837	****	-0.064	0.938	-1.622		-0.274	0.761	-3.573	****
Elevation	-0.023	0.977	-0.512						-0.744	0.475	-7.457	****				
Population density	-2.324	0.098	-1.439		-2.330	0.097	-1.447		0.953	2.594	2.371	**				
Protected ratio	-2.068	0.126	-11.496	****	-3.540	0.029	-3.215	****	-0.359	0.698	-2.181	**	-4.210	0.015	-1.752	*
Peatland ratio	-0.051	0.950	-0.651		0.689	1.992	4.644	****	0.498	1.645	4.609	****	-2.835	0.059	-4.065	****
Log(Oil palm attainable yield) * T																
Log(Distance to 1990 plantation) * T					0.060	1.061	3.417	****								
Log(Distance to oil palm mills)* T													0.144	1.155	4.117	****
Access time * T													-0.118	0.888	-2.031	**
Temperature * T													0.157	1.171	2.723	***
Shortwave radiation * T													-0.010	0.990	-2.778	***
Annual precipitation * T													0.065	1.067	2.920	***
Driest month precipitation * T					0.043	1.043	4.450	****								
Slope * T													0.045	1.046	2.944	***
Elevation * T													-0.163	0.849	-7.244	****
Population density * T																
Protected ratio * T					0.292	1.339	1.417						0.675	1.963	1.597	
Peatland ratio * T					-0.198	0.820	-5.369	****					0.649	1.913	4.885	****
Concordance		0.892				0.895				0.900				0.907		
AIC		19910.39				19858.41				11731.18				11605.76		
LogLik		-9942.20				-9914.21				-5852.59				-5785.88		
Number of grids				17661									31833			
Number of events				1201									653			

Table B-19 Multi-state analysis results on Sumatra and Kalimantan - transition from shrub to bare ground.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	0.519	1.680	0.897						0.798	2.220	1.774	*	1.062	2.893	2.377	**
Log(Distance to 1990 plantation)	-0.118	0.888	-1.534		0.837	2.310	3.177	***	0.299	1.349	3.441	****	0.284	1.328	3.630	****
Log(Distance to oil palm mills)	-0.060	0.942	-0.685		-1.001	0.367	-5.550	****	-0.415	0.661	-4.049	****	-1.640	0.194	-6.912	****
Access time	0.787	2.197	3.181	***	0.831	2.296	3.407	****	0.276	1.318	1.307		-2.764	0.063	-3.425	****
Temperature	-0.097	0.907	-0.638						0.183	1.201	1.069					
Shortwave radiation	0.026	1.027	2.676	***	0.028	1.029	2.874	***	0.018	1.018	2.083	**	0.020	1.020	2.874	***
Annual precipitation	-0.252	0.777	-2.852	***	-0.179	0.836	-2.540	**	-0.150	0.861	-1.583					
Driest month precipitation	0.111	1.117	1.286						0.209	1.233	3.005	***				
Slope	-0.534	0.586	-3.408	****	-0.498	0.608	-4.338	****	-0.099	0.906	-1.146		-0.170	0.844	-2.912	***
Elevation	0.107	1.113	0.858						-0.400	0.670	-1.335					
Population density	-32.273	0.000	-6.781	****	-60.491	5.36E-27	-4.661	****	0.261	1.299	0.538		17.130	2.75E+07	3.885	****
Protected ratio	-0.622	0.537	-2.848	***	-68.547	1.70E-30	-0.954		1.107	3.024	4.142	****	-1678.549	0.000	-2.226	**
Peatland ratio	-0.041	0.960	-0.240						0.281	1.324	1.556		-6.814	0.001	-4.293	****
Establish Time	-0.458	0.633	-3.956	****	-0.711	0.491	-5.069	****	-0.732	0.481	-5.332	****	-1.430	0.239	-3.498	****
Establish Time ^2	0.024	1.024	3.898	****	0.091	1.095	4.845	****	0.034	1.035	4.639	****	0.025	1.025	2.703	***
Log(Oil palm attainable yield) * T																
Log(Distance to 1990 plantation) * T					-0.208	0.812	-4.170	****								
Log(Distance to oil palm mills)* T					0.211	1.235	5.058	****					0.263	1.301	5.237	****
Access time * T													0.578	1.783	3.650	****
Temperature * T																
Shortwave radiation * T																
Annual precipitation * T																
Driest month precipitation * T																
Slope * T																
Elevation * T																
Population density * T					5.979	394.852	2.272	**					-4.454	0.012	-3.182	***
Protected ratio * T					11.423	9.14E+04	0.954						279.933	3.74E+121	2.227	**
Peatland ratio * T													1.323	3.755	4.752	****
Establish Time * T													0.150	1.162	2.003	**
Establish Time ^2 * T					-0.009	0.991	-4.016	****								
Concordance		0.747				0.772				0.750				0.804		
AIC		4657.32				4587.75				3293.34				3151.26		
LogLik		-2313.66				-2278.87				-1631.67				-1558.63		
Number of grids	2389								2744							
Number of events	336								226							

Technical comparison between the regressions on PAs only and on the whole islands

The standard CPHMs and the models extended with time-dependent effects running on the PAs show that compared with these models running on whole islands, oil palm attainable yield, terrain factors, as well as the accessibility to existing infrastructures and local markets had similar effects on estate crop expansion into natural forest (Table B-20). Different from the models on the whole islands, where estate crop expansion preferred mineral land in early periods but changed to peatland in later periods (Table 3-1), estate crop expansion into natural forest in PAs kept preferring mineral land in the whole study period on both islands, though the effects decreased as time went by on Kalimantan.

The multi-state models (Table B-23 and Table B-24) reveal that the patterns of shrub and bare ground establishment in PAs on both islands generally mirrored those across the whole islands. Nearly all biophysical and socio-economic drivers had the same directions and magnitudes inside the PAs as across the whole islands, except that 1) the establishment of shrub inside PAs had more significant preference for area with higher oil palm attainable yield on both islands, 2) the establishment of shrub in PAs preferred mineral land on both islands but changed to peatland in recent years in Kalimantan, 3) the establishment of shrub in Kalimantan PAs preferred area with lower population density and were not limited by driest month precipitation, 4) the establishment of bare ground in Sumatra PAs preferred area close to 1990 plantation and was not limited by oil palm attainable yield or driest month precipitation, 5) the establishment of bare ground in Kalimantan PAs preferred area with high oil palm attainable yield and high population density. In Sumatra, compared with the direct conversions from natural forest to estate crop, accessibility to existing infrastructures and local markets became not restricting on conversion with shrub as intermediate status, while oil palm attainable yield had more significant effects. Shrub established in 2003-2009 in PAs had highest risks of further conversion to estate crop. In Kalimantan, direct estate crop expansion in PAs was very limited. The estate crop expansion through the prolonged LCLUC trajectories with either shrub or bare ground as an intermediate status started to prefer peatland in recent year.

In Sumatra, the risks of estate crop expansion were significantly higher before the establishment of PAs than after, however, the effects in Kalimantan were opposite. Conversions with bare ground as an intermediate status in Sumatra PAs were mainly affected by the establishment time of the PAs. Over 80% of deforestation to bare ground in 1996-2000 occurred before the establishment of PAs, and all the bare ground further converted to estate crop plantation. In Kalimantan, natural forest had higher risks of deforestation to shrub and bare ground before the establishment of PAs, however, few of these shrub or bare ground further converted to estate crop, which might because the area was used for logging and a failed mega rice project before the establishment of PA.

Table B-20 . Results of standard CPHMs and the models extended by time-dependent effects $x_{ik} \times (t)$ on estate crop expansion into protected natural forest.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	0.042	1.043	0.976		0.075	1.078	1.931	*	0.344	1.411	1.203		0.386	1.471	1.123	
Log(Distance to 1990 plantation)	-0.250	0.778	-2.310	**	-0.596	0.551	-2.476	**	0.348	1.416	2.779	***	-1.149	0.317	-6.992	****
Log(Distance to oil palm mills)	-1.199	0.302	-12.499	****	-1.411	0.244	-5.143	****	-2.003	0.135	-17.936	****	-1.981	0.138	-17.350	****
Access time	-0.961	0.382	-5.670	****	-1.691	0.184	-3.677	****	0.557	1.746	2.089	**	0.454	1.574	1.631	
Temperature	0.096	1.101	0.572													
Shortwave radiation	0.073	1.076	10.561	****	0.348	1.417	19.197	****	-0.036	0.964	-2.561	**	-0.401	0.669	-7.836	****
Annual precipitation	0.528	1.695	10.456	****	-0.689	0.502	-3.393	****	0.083	1.086	0.600		0.435	1.544	2.310	**
Driest month precipitation	-0.684	0.505	-7.367	****					-0.133	0.876	-0.857		-0.394	0.674	-1.813	*
Slope	-0.525	0.592	-12.280	****	-0.648	0.523	-12.978	****	-0.115	0.891	-2.990	***	-0.143	0.866	-3.002	***
Population density	-1.189	0.305	-7.269	****	0.527	1.694	2.159	**	0.602	1.826	3.440	****	0.612	1.843	3.427	****
Protected 1	-2.556	0.078	-12.782	****	4.213	67.589	4.743	****	11.1398	6.89E+04	16.676	****				
Protected 2	-0.668	0.513	-5.137	****	-4.023	0.018	-6.197	****	-1.582	0.206	-7.825	****				
Peatland ratio	0.026	1.026	0.191		-0.523	0.593	-2.841	***	-0.763	0.466	-2.609	***	-8.357	2.35E-04	-3.268	***
Log(Oil palm attainable yield) * T																
Log(Distance to 1990 plantation) * T					0.218	1.244	2.134	**					0.308	1.361	7.121	****
Log(Distance to oil palm mills)* T					0.084	1.087	1.380									
Access time * T					0.192	1.212	1.768	*								
Temperature * T																
Shortwave radiation * T					-0.088	0.915	-13.005	****					0.070	1.072	7.431	****
Annual precipitation * T					0.121	1.129	2.180	**								
Driest month precipitation * T																
Slope * T																
Population density * T					-0.617	0.540	-5.463	****								
Protected 1 * T					-5.032	0.007	-6.555	****								
Protected 2 * T					0.657	1.929	5.778	****					-0.304	0.737	-7.670	****
Peatland ratio * T													1.305	3.687	3.009	***
Concordance	0.956				0.979				0.976				0.981			
Likelihood ratio test	3045				4160				800.4				904.5			
Wald test	3162				2008				1825				1088			
Number of grids	44288								38889							
Number of events	565								125							

Table B-21 Multi-state analysis results on protected natural forest - transition from natural forest to estate crop.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	0.010	1.010	0.231		0.248	1.281	2.948	***	0.142	1.153	1.748	*				
Log(Distance to 1990 plantation)	-0.444	0.641	-3.087	***	-1.781	0.169	-4.499	****					-0.249	0.780	-1.719	*
Log(Distance to oil palm mills)	-1.453	0.234	-5.739	****	-1.652	0.192	-7.198	****	-2.192	0.112	-7.477	****	-2.264	0.104	-6.448	****
Access time	-2.623	0.073	-5.559	****	-2.868	0.057	-5.177	****	-0.509	0.601	-1.092					
Temperature	-0.181	0.834	-1.437		-0.269	0.764	-2.180	**								
Shortwave radiation	0.129	1.138	9.006	****	0.155	1.168	11.237	****	-0.226	0.798	-3.685	****	-0.627	0.534	-8.231	****
Annual precipitation	0.200	1.222	1.058						0.141	1.151	0.552					
Driest month precipitation	-0.060	0.941	-0.372						-0.949	0.387	-2.100	**	-0.621	0.537	-1.526	
Slope	-0.560	0.571	-8.696	****	-0.531	0.588	-8.543	****	0.061	1.063	1.081					
Population density	-0.156	0.855	-1.105						0.810	2.249	2.921	***	0.559	1.750	2.482	**
Protected 1	-1.165	0.312	-4.400	****	18.265	8.56E+07	30.565	****	15.427	5.01E+06	19.656	****				
Protected 2	-2.854	0.058	-7.390	****					-1.064	0.345	2.607	***				
Peatland ratio	0.802	2.230	3.349	****	-1.553	0.212	-1.312		-1.081	0.339	-1.541					
Log(Oil palm attainable yield) * T					-0.135	0.874	-2.567	**								
Log(Distance to 1990 plantation) * T					1.183	3.265	3.375	****								
Log(Distance to oil palm mills)* T																
Access time * T																
Temperature * T																
Shortwave radiation * T													0.091	1.096	6.588	****
Annual precipitation * T																
Driest month precipitation * T																
Slope * T																
Population density * T					-0.327	0.721	-2.291	**								
Protected 1 * T					-18.987	5.68E-09	-45.339	****								
Protected 2 * T					-2.493	0.083	-6.554	****					-0.379	0.685	-3.412	****
Peatland ratio * T					2.056	7.816	2.035	**								
Concordance	0.98				0.986				0.972				0.987			
AIC	2580.39				2454.78				395.08				364.40			
LogLik	1277.20				-1212.39				-186.54				-175.20			
Number of grids	44288								38889							
Number of events	172								28							

Table B-22 Multi-state analysis results on protected natural forest - transition from shrub to estate crop.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	5.556	258.854	3.882	****					-0.156	0.856	-1.642					
Log(Distance to 1990 plantation)	-0.680	0.507	-1.020						0.408	1.503	1.757	*	0.702	2.018	2.194	**
Log(Distance to oil palm mills)	0.832	2.297	1.796	*					-1.690	0.184	-10.903	****	-1.553	0.212	-9.232	****
Access time	4.870	130.381	8.942	****					-1.420	0.242	-1.655	*	-1.195	3.03E-01	-1.369	
Temperature	0.753	2.123	1.260													
Shortwave radiation	-0.099	0.906	-2.472	**					-0.022	0.978	-1.015		-0.078	0.925	-5.154	****
Annual precipitation	1.354	3.874	4.646	****					0.721	2.057	3.355	****	5.306	201.465	4.273	****
Driest month precipitation	-1.026	0.358	-2.082	**					-0.643	0.526	-2.469	**	-0.668	0.513	-1.924	*
Slope	-0.154	0.857	-1.022						-0.035	0.965	-0.478					
Population density	-3.056	0.047	-7.037	****					-0.402	0.669	-0.801					
Protected 1	-9.094	1.12E-04	-7.557	****					No occurred before the establishement of protected area							
Protected 2	-0.160	0.852	-0.845						-1.322	0.267	-4.313	****	-1.359	0.257	-4.264	****
Peatland ratio	-3.995	0.018	-6.466	****					-0.867	0.420	-1.772	*	-654.164	0.000	-2.423	**
Establish Time	1.591	4.907	5.430	****					0.646	1.908	2.488	**	49.762	4.09E+21	10.289	****
Establish Time ^2	-0.069	0.934	-5.856	****					-0.033	0.967	-1.892	*	-2.910	0.054	-9.478	****
Log(Oil palm attainable yield)																
Log(Distance to 1990 plantation)																
Log(Distance to oil palm mills)																
Access time * T																
Temperature * T																
Shortwave radiation * T																
Annual precipitation * T													-0.953	0.386	-3.643	****
Driest month precipitation * T																
Slope * T																
Population density * T																
Protected 1 * T																
Protected 2 * T																
Peatland ratio * T													108.992	2.16E+47	2.423	**
Establish Time * T													-8.224	2.68E-04	-10.023	****
Establish Time ^2 * T													0.481	1.617	9.185	****
Concordance	0.981								0.937				0.939			
AIC	2246.94								510.35				479.63			
LogLik	-1108.47								-242.18				-225.82			
Number of grids	2011								1183							
Number of events	214								48							

Table B-23 Multi-state analysis results on protected natural forest - transition from natural forest to shrub.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effect				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	0.014	1.014	1.717	**					0.050	1.051	2.463	**				
Log(Distance to 1990 plantation)	-0.401	0.669	-10.694	****	-0.811	0.445	-13.036	****	0.046	1.047	0.872		-0.302	0.739	-2.941	***
Log(Distance to oil palm mills)	-0.312	0.732	-5.737	****	0.470	1.600	4.785	****	-0.743	0.476	-13.948	****	-1.144	0.318	-12.000	****
Access time	-0.281	0.755	-2.994	**	1.342	3.826	9.015	****	-0.776	0.460	-10.047	****	-1.681	0.186	-11.349	****
Temperature	0.232	1.261	5.754	****	0.179	1.196	4.169	****	-0.208	0.812	-2.101	**	-0.216	0.806	-2.410	**
Shortwave radiation	0.003	1.003	0.749		0.087	1.090	13.686	****	0.042	1.043	6.360	****	0.056	1.058	8.432	****
Annual precipitation	0.095	1.100	4.011	****					-0.567	0.567	-12.124	****	-0.510	0.601	-4.994	****
Driest month precipitation	-0.102	0.903	-3.625	****	-0.626	0.534	-10.808	****	-0.137	0.872	-2.250	**	-0.584	0.558	-2.261	**
Slope	-0.208	0.812	-21.208	****	-0.274	0.761	-13.974	****	-0.119	0.888	-6.307	****	-0.059	0.943	-2.482	**
Population density	-0.208	0.812	-5.778	***	0.453	1.573	7.836	****	-0.073	0.930	-1.718	*				
Protected 1	0.816	2.262	7.434	****	1.798	6.037	7.730	****	-0.617	0.540	-5.335	****	-1.821	0.162	-6.586	****
Protected 2	-0.243	0.784	-4.363	****	-0.255	0.775	-4.478	****	-0.757	0.469	-8.382	****	-0.781	0.458	-8.462	****
Peatland ratio	-0.770	0.463	-10.684	****	-0.675	0.509	-9.826	****	0.209	1.233	2.481	**	-1.414	0.243	-8.173	****
Log(Oil palm attainable yield) * T					0.007	1.007	2.511	**					0.016	1.017	3.679	****
Log(Distance to 1990 plantation) * T					0.151	1.164	7.626	****					0.160	1.173	3.483	****
Log(Distance to oil palm mills)* T					-0.334	0.716	-11.761	****					0.173	1.189	4.210	****
Access time * T					-0.537	0.584	-11.755	****					0.290	1.336	6.044	****
Temperature * T																
Shortwave radiation * T					-0.029	0.972	-13.316	****								
Annual precipitation * T					0.038	1.038	4.614	****					-0.067	0.936	-1.595	
Driest month precipitation * T					0.151	1.163	9.857	****					0.132	1.142	1.782	*
Slope * T					0.025	1.026	5.292	****					-0.015	0.985	-1.977	**
Population density * T					-0.289	0.749	-12.088	****					-0.033	0.968	-1.753	*
Protected 1 * T					-0.858	0.424	-6.228	****					0.175	1.192	1.653	*
Protected 2 * T																
Peatland ratio * T													0.549	1.731	7.835	****
Concordance	0.86				0.881				0.912				0.921			
AIC	44095.76				42813.73				22848.64				22378.87			
LogLik	-22034.88				-21385.86				-11411.32				-11168.44			
Number of grids	44288								38889							
Number of events	2205								1221							

Table B-24 Multi-state analysis results on protected natural forest - transition from natural forest to bare ground.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	-0.092	0.912	-6.523	****	-0.064	0.938	-4.151	****	3.426	30.766	9.962	****	10.541	3.78E+04	5.584	****
Log(Distance to 1990 plantation)	-0.275	0.759	-2.845	***	-0.217	0.805	-2.091	**	0.304	1.356	3.054	***	-0.767	0.465	-6.489	****
Log(Distance to oil palm mills)	-1.017	0.362	-11.149	****	-2.205	0.110	-8.423	****	-0.726	0.484	-7.764	****	-0.751	0.472	-8.232	****
Access time	-0.806	0.447	-3.669	****	-1.858	0.156	-3.479	****	0.682	1.978	5.195	****	0.529	1.697	4.296	****
Temperature	0.365	1.441	3.018	***	0.613	1.847	2.845	***	0.571	1.769	2.791	**				
Shortwave radiation	0.035	1.035	5.589	****	-0.071	0.932	-2.908	***	-0.004	0.996	-0.376		-0.066	0.936	-1.592	
Annual precipitation	-0.074	0.929	-1.342						0.673	1.960	10.580	****	0.638	1.893	9.006	****
Driest month precipitation	-0.228	0.796	-3.235	***	-0.488	0.614	-6.086	****	-0.326	0.721	-4.215	****	-1.037	0.355	-1.871	*
Slope	-0.234	0.791	-11.395	****	-0.096	0.908	-2.321	**	-0.141	0.868	-1.961	**	0.252	1.287	2.980	***
Population density	-1.125	0.325	-7.174	****	0.771	2.162	5.705	****	0.439	1.551	4.450	****	0.479	1.614	5.044	****
Protected 1	-1.814	0.163	-10.374	****	-4.960	0.007	-11.122	****	-0.925	0.397	-3.0097	***	-2.382	0.092	-7.335	****
Protected 2	-0.491	0.612	-3.753	****	-1.440	0.237	-3.004	***	-0.616	0.540	-4.834	****	-0.634	0.531	-4.878	****
Peatland ratio	0.425	1.529	2.938	***	5.540	254.641	11.942	****	0.672	1.958	4.190	****	-1.808	0.164	-4.493	****
Log(Oil palm attainable yield) * T													-1.280	0.278	-3.915	****
Log(Distance to 1990 plantation) * T													0.246	1.279	8.234	****
Log(Distance to oil palm mills)* T					0.325	1.384	5.915	****								
Access time * T					0.400	1.492	3.693	****								
Temperature * T					-0.077	0.926	-2.243	**								
Shortwave radiation * T					0.007	1.007	1.350						0.016	1.016	2.223	**
Annual precipitation * T					-0.019	0.981	-1.733	*								
Driest month precipitation * T													0.158	1.171	1.666	*
Slope * T					-0.026	0.974	-3.689	****					-0.088	0.916	-4.841	****
Population density * T					-0.378	0.685	-9.813	****								
Protected 1 * T					1.134	3.110	-4.558	****								
Protected 2 * T					0.173	1.189	-1.962	**								
Peatland ratio * T					-1.246	0.288	-13.107	****					0.460	1.584	5.895	****
Concordance		0.895				0.903				0.936				0.941		
AIC		9583.05				9033.69				8926.29				8804.34		
LogLik		-4778.52				-4494.85				-4450.15				-4384.17		
Number of grids					44288								38889			
Number of events					532								495			

Table B-25 Multi-state analysis results on protected natural forest - transition from shrub to bare ground.

	Sumatra								Kalimantan							
	Base Model				Model with Time-Variant Effects				Base Model				Model with Time-Variant Effects			
	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.	coef	Hazard	z	sig.
Log(Oil palm attainable yield)	0.051	1.052	1.077						0.071	1.074	0.649					
Log(Distance to 1990 plantation)	-0.689	0.502	-7.643	****	-0.515	0.597	-5.946	****	1.218	3.381	6.502	****				
Log(Distance to oil palm mills)	1.942	6.973	7.074	****					0.163	1.177	1.604					
Access time	0.673	1.960	1.672	*					0.646	1.907	3.523	****				
Temperature	0.790	2.203	3.261	***	1.076	2.934	6.502	****								
Shortwave radiation	-0.116	0.890	-6.446	****	-0.212	0.809	-6.457	****	0.002	1.002	0.144					
Annual precipitation	-1.255	0.285	-7.276	****	8.293	3996.313	7.536	****	-0.031	0.969	-0.228					
Driest month precipitation	1.305	3.689	9.134	****	-7.040	0.001	-4.720	****	0.129	1.138	0.572					
Slope	-0.114	0.892	-0.956		-0.197	0.822	-1.516		-0.395	0.674	-2.974	***				
Population density	0.561	1.753	4.316	****	-1.630	0.196	-1.808	*	0.478	1.613	2.991	***				
Protected 1	12.014	1.65E+05	Inf	****					16.745	1.87E+07	Inf	****				
Protected 2	-0.167	0.846	-0.734						-0.211	0.810	-1.121					
Peatland ratio	0.989	2.688	6.216	****	7.338	1538.130	3.027	***	1.346	3.843	4.754	****				
Establish Time	-0.546	0.579	-2.119	**					-0.661	0.516	-6.939	****				
Establish Time ^2	0.022	1.023	1.559						0.031	1.031	5.853	****				
Log(Oil palm attainable yield) * T																
Log(Distance to 1990 plantation) * T																
Log(Distance to oil palm mills)* T					0.405	1.500	7.813	****								
Access time * T																
Temperature * T																
Shortwave radiation * T																
Annual precipitation * T					-1.762	0.172	-8.316	****								
Driest month precipitation * T					1.595	4.931	5.319	****								
Slope * T																
Population density * T					0.447	1.563	2.742	***								
Protected 1 * T																
Protected 2 * T																
Peatland ratio * T					-1.086	0.337	-2.660	***								
Establish Time * T					-0.135	0.873	-3.517	****								
Establish Time ^2 * T					0.006	1.006	3.036	***								
Concordance		0.905				0.934				0.819						
AIC		3689.10				3562.30				3319.33						
LogLik		-1129.55				-1766.15				-1645.66						
Number of grids				2011								1183				
Number of events				282								256				

* Around 95% of deforestation to bare ground with shrub as an intermediate status in Kalimantan PAs occurred in 2012-2015, so the extended model was not used.

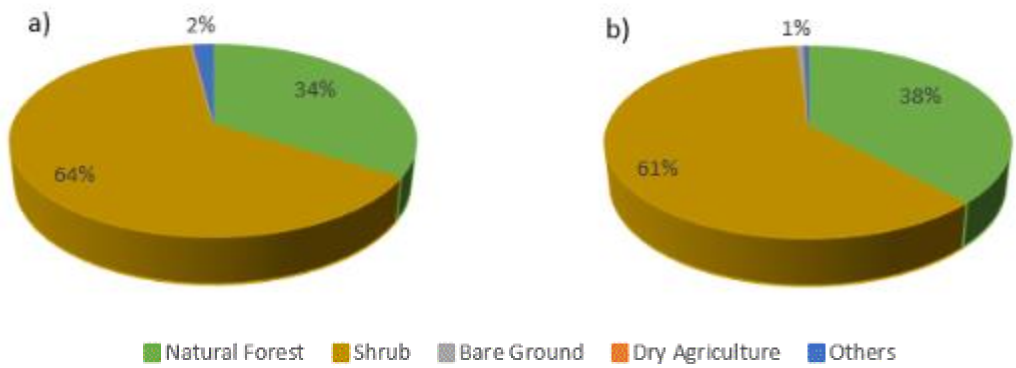


Figure B-1 Land sources (1996) of shrub converted to estate crop during 1996-2015. a) Sumatra; b) Kalimantan.

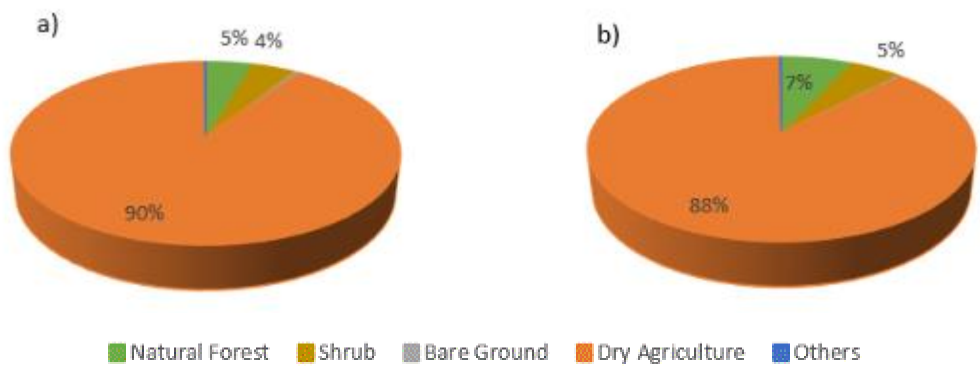


Figure B-2 Land sources (1996) of dry agriculture converted to estate crop during 1996-2015. a) Sumatra; b) Kalimantan.

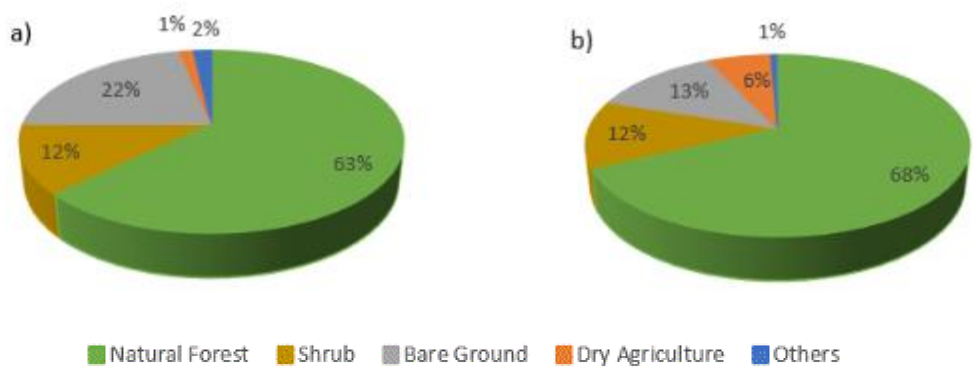


Figure B-3 Land sources (1996) of bare ground converted to estate crop during 1996-2015. a) Sumatra; b) Kalimantan.

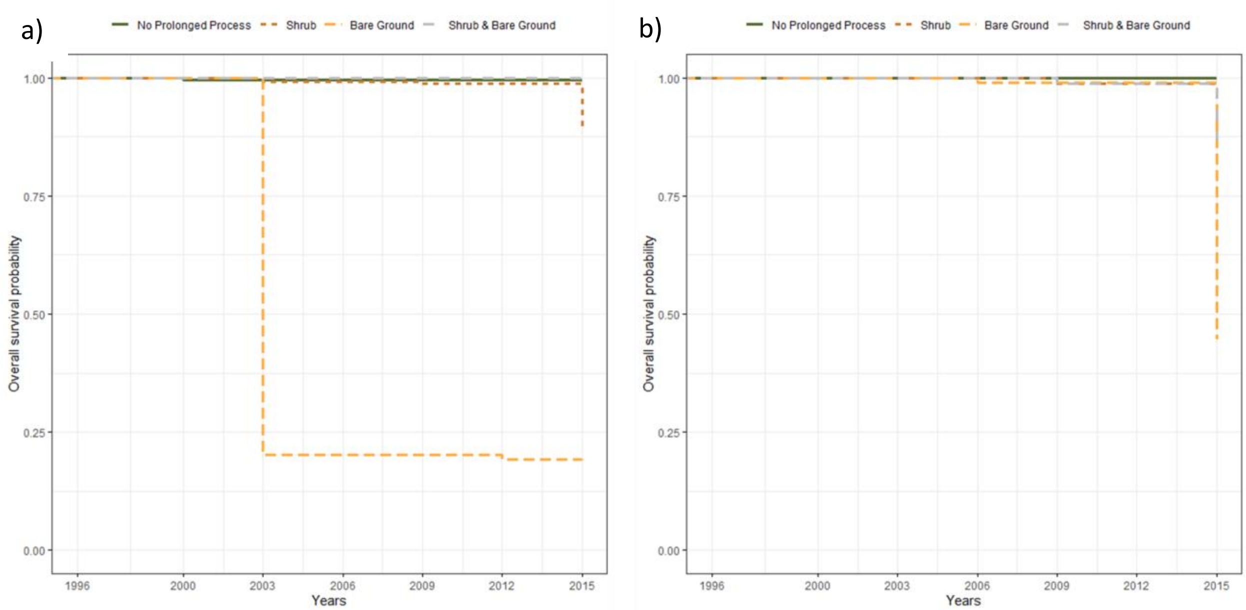


Figure B-4 Overall survival probability of natural forest loss to estate crop in protected area. a) Sumatra. b) Kalimantan. "No Prolonged Process" represents the direction conversion from natural forest to estate crop, "Shrub" represents the prolonged LCLUC trajectories with shrub as an intermediate status, "Bare Ground" represents the prolonged trajectories with bare ground as intermediate status, and "Shrub & Bare Ground" represent the prolonged trajectories with both shrub and bare ground as intermediate status.

Appendix C: Supplement information for Chapter 4

Table C-1 Variable, data description and data sources of geo-economic gravity models.

Variable	Data Description	Data Source
Export Quantity	Detailed trade matrix. (FAO)	FAO. 2021. Available at: http://www.fao.org/faostat/en/#data/TM
GDP per capita Population	Historical: World Development Indicators (WDI) database (World Bank) Projection: Shared Socioeconomic Pathway 2 (SSP2) (IIASA, 2018)	World Bank. 2021. Available at: https://databank.worldbank.org/reports.aspx?source=world-development-indicators IIASA. 2018. Available at: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10
Real exchange rate	Official exchange rate and CPI from World Development Indicators (WDI) database	World Bank. 2021. Available at: https://databank.worldbank.org/reports.aspx?source=world-development-indicators
Tariff	Data from UNCTAD TRAINS by country on products at the HS 6-digit level (WITS)	World Integrated Trade Solution. 2021. Available at: https://wits.worldbank.org/tariff/trains/country-byhs6product.aspx?lang=en.
RTA RTA with Indonesia	Regional Trade Agreements database (WTO)	WTO. 2021. Available at: http://rtais.wto.org/UI/PublicMaintainRTAHome.aspx
WTO	Status and dates of WTO membership (WTO)	WTO. 2021. Available at: https://www.wto.org/english/thewto_e/whatis_e/tif_e/org6_e.htm
Distance	Population weighted distance from GeoDist database (CEPII)	CEPII. 2021. Available at: http://www.cepii.fr/CEPII/en/bdd_modele/presentation.asp?id=6
Colony Religion	Gravity database - Proxies for cultural proximity (CEPII)	CEPII. 2021. Available at: http://www.cepii.fr/CEPII/en/bdd_modele/presentation.asp?id=8

Table C-2 Units and summary statistics of variables used in geo-economic gravity models.

Variable	Unit	Mean	Max	Min
Export Quantity	tons	1308327	19238596	941.84
GDP per capita	constant 2010 US$	18097.14	52719.29	254.76
Population	person	159648898	1350695000	3835100
Real exchange rate	LCU per 2010 US$	639.19	24544.94	0.0091
Tariff	%	9.47	100	0
RTA	1	12.32	37	0
RTA with Indonesia	1	0.577	2	0
WTO	0 or 1	0.905	1	0
Distance	km	8151.40	16024.37	1012.92
Colony	0 or 1	0.04	1	0
Religion	0-1	0.12	0.43	0

Table C-3 Pairwise correlations between explanatory variables in geo-economic gravity models.

	Ln (GDP per capita)	Ln (Population)	Exchange Rate	Tariff Rate	RTA	RTA with IDN	WTO	Ln (Distance)	colony	Religion	Ln (Time)
Ln (GDP per capita)	1	-0.326	-0.224	-0.388	0.624	-0.546	0.130	0.445	0.237	-0.260	0.076
Ln (Population)	-0.326	1	0.047	0.447	-0.124	0.058	-0.129	0.102	-0.189	-0.167	-0.075
Exchange Rate	-0.224	0.047	1	-0.029	-0.157	0.353	-0.243	-0.278	-0.046	-0.085	0.090
Tariff Rate	-0.388	0.447	-0.029	1	-0.170	0.123	-0.023	-0.113	-0.056	0.039	-0.059
RTA	0.624	-0.124	-0.157	-0.170	1	-0.460	0.148	0.440	0.318	-0.331	0.031
RTA with IDN	-0.546	0.058	0.353	0.123	-0.460	1	0.083	-0.796	-0.160	0.008	0.069
WTO	0.130	-0.129	-0.243	-0.023	0.148	0.083	1	0.030	0.066	-0.025	0.116
Ln (Distance)	0.445	0.102	-0.278	-0.113	0.440	-0.796	0.030	1	0.153	-0.087	-0.070
colony	0.237	-0.189	-0.046	-0.056	0.318	-0.160	0.066	0.153	1	-0.112	-0.028
Religion	-0.260	-0.167	-0.085	0.039	-0.331	0.008	-0.025	-0.087	-0.112	1	0.053
Ln (Time)	0.076	-0.075	0.090	-0.059	0.031	0.069	0.116	-0.070	-0.028	0.053	1

Table C-4 VIFs in geo-economic gravity models.

	VIF
Ln (GDP per capita)	2.53
Ln (Population)	1.64
Exchange Rate	1.30
Tariff Rate	1.44
FTA	1.97
FTA with IDN	3.82
WTO	1.24
Ln (Dist)	3.18
colony	1.16
Religion	1.34
Ln (Time)	1.06

Table C-5 LCLU classification

Class	Description	Re-Class
Primary Dryland Forest	Natural forest, dry habitat	Natural Forest
Secondary Dryland Forest	Logging signs, dry habitat	Natural Forest
Primary Mangrove Forest	No or low human activity, wetland forest in coastal areas	Natural Forest
Secondary Mangrove Forest	Logging signs, wetland forest in coastal areas	Natural Forest
Primary Swamp Forest	Natural forest, wet habitat	Natural Forest
Secondary Swamp Forest	Logging signs, wet habitat	Natural Forest
Plantation Forest	Dominated by homogeneous tree species for specific purposes, structural composition. Reforestation, industrial plantation forest, community plantation forest	Others
Dry Shrub	Highly degraded logged-over area, non-wet habitat, ongoing process of succession	Shrub
Wet Shrub	Highly degraded logged-over area, wet habitat, ongoing process of succession	Shrub
Savanna and Grasses	Grasses and scattered natural trees and shrubs	Others
Pure Dry Agriculture	Agricultural activities on dry/ non-wet land, e.g. moor, mixed garden, agriculture fields	Dry Agriculture
Mixed Dry Agriculture	Agricultural activities on dry/ non-wet land mixed with shrubs, thickets, and logged-over forest	Dry Agriculture
Paddy Field	Agriculture areas on wet habitat, especially for paddy	Others
Estate Crop	Planted estate areas, mostly with perennials crops or other agricultural trees commodities	Estate Crop
Settlement Areas	Rural, urban, industrial and other built-up areas	Others
Transmigration Areas	Unique settlement areas associated with houses and agroforestry and/or garden	Others
Port and Harbor	Big enough to be delineated as independent object	Others
Bare Ground	No vegetation cover	Bare Ground
Mining Areas	Open mining activities	Others
Open Swamp	Wetland with few vegetation	Others
Fish Pond/ Aquaculture	Aquaculture activities	Others
Open Water	Ocean, rivers, lakes, and ponds	Others
Cloud and No-Data	Clouds, cloud shadows or data gaps with a size of more than 4 cm^2 at 100,000 scale display	No Data

Table C-6 Variable, data description and data sources of parametric hazard models.

Variable	Data Description	Data Source
Occurrence of oil palm expansion	Collected from land use and land cover maps of Indonesia, 1996-2015	Indonesian Ministry of the Environment Life and Forestry. 2020. Indonesian Land Cover Closure. Available at: http://webgis.menlhk.go.id:8080/pl/pl.htm.
Attainable yield of oil palm	IIASA/FAO. Global Agro-ecological Zones (GAEZ v4)	https://gaez.fao.org/
Distance to old oil palm plantation (1990 & 2015)	land use and land cover maps of Indonesia, 1990 & 2015	Indonesian Ministry of the Environment Life and Forestry. 2020. Indonesian Land Cover Closure. Available at: http://webgis.menlhk.go.id:8080/pl/pl.htm.
Distance to oil palm processing mills	Universal Mill List (UML) (WRI/Rainforest Alliance/Proforest/Daemeter, 2018)	https://www.globalforestwatch.org/
Access time	Travel time to major cities: A global map of Accessibility (Nelson, A., 2008)	https://forobs.jrc.ec.europa.eu/products/gam/index.php
Elevation	Shuttle Radar Topography Mission (NASA, 2009)	https://earthexplorer.usgs.gov/
Slope		
Population density	Gridded Population of the World (CIESIN)	https://beta.sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density
Protected area	World Database on Protected Areas (WDPA)	http://www.protectedplanet.net/
Peatland ratio	Peat lands (World Resources Institute, 2012. Accessed through Global Forest Watch)	https://data.globalforestwatch.org/datasets/gfw::indonesia-peat-lands/about
Oil palm concession ratio	Indonesia oil palm Concessions, 2015. (Indonesia Ministry of Forestry. Accessed through Global Forest Watch)	https://data.globalforestwatch.org/datasets/gfw::indonesia-oil-palm-concessions/about

Table C-7 Units and summary statistics of explanatory variables used in parametric hazard models.

Variable	Unit	Mean	Max	Min
Attainable yield of oil palm (historical, 1981-2010 climatology)	ton/ha oil	3.224	7.442	0
Attainable yield of oil palm (2041-2070 climatology)	ton/ha oil	2.559	6.046	0
Distance to old oil palm plantation (1990)	km	67.535	557.648	0
Distance to old oil palm plantation (2015)	km	49.409	557.386	0
Distance to oil palm processing mills	km	135.681	832.484	0.037
Access time	day	0.91	5.88	0
Elevation	100 m	3.700	43.097	-3.04
Slope	degree	5.865	50.004	0
Population density	K persons per km^2	0.116	22.474	0.000
Protected area ratio	1	0.127	1	0
Peatland ratio	1	0.081	1	0
Oil palm concession ratio	1	0.070	1	0

Table C-8 Pairwise correlations between explanatory variables in parametric hazard models.

	Ln (Oil Palm attainable yield)	Ln (Distance to old plantation)	Ln (Distance to oil palm mills)	Access time	Slope	Elevation	Population density	Protected ratio	Peatland ratio	Oil palm concession ratio	LCLU
Ln (Oil Palm attainable yield)	1	-0.221	-0.298	-0.193	-0.597	-0.737	0.04	-0.235	0.175	0.148	0.115
Ln (Distance to old plantation)	-0.221	1	0.52	0.438	0.208	0.199	-0.133	0.156	-0.059	-0.138	-0.251
Ln (Distance to oil palm mills)	-0.298	0.52	1	0.212	0.271	0.242	0.091	0.109	-0.139	-0.299	-0.252
Access time	-0.193	0.438	0.212	1	0.195	0.233	-0.193	0.155	-0.011	-0.053	-0.277
Slope	-0.597	0.208	0.271	0.195	1	0.699	-0.069	0.21	-0.252	-0.176	-0.179
Elevation	-0.737	0.199	0.242	0.233	0.699	1	-0.035	0.262	-0.192	-0.157	-0.123
Population density	0.04	-0.133	0.091	-0.193	-0.069	-0.035	1	-0.054	-0.054	-0.051	0.026
Protected ratio	-0.235	0.156	0.109	0.155	0.21	0.262	-0.054	1	0.022	-0.102	-0.137
Peatland ratio	0.175	-0.059	-0.139	-0.011	-0.252	-0.192	-0.054	0.022	1	0.086	-0.078
Oil palm concession ratio	0.148	-0.138	-0.299	-0.053	-0.176	-0.157	-0.051	-0.102	0.086	1	0.11
LCLU	0.115	-0.251	-0.252	-0.277	-0.179	-0.123	0.026	-0.137	-0.078	0.11	1

Table C-9 VIFs in parametric hazard models.

	VIF
Ln (Oil Palm attainable yield)	1.54
Ln (Distance to old plantation)	1.10
Ln (Distance to oil palm mills)	1.22
Access time	1.21
Slope	1.67
Elevation	2.21
Population density	1.17
Protected ratio	1.01
Peatland ratio	1.27
Oil palm concession ratio	1.11
LCLU	1.39

Table C-10 Region classification.

Region	Countries and regions
China	China (mainland), China (Hong Kong SAR), China (Macao SAR), China (Taiwan Province of)
India	India
Indonesia	Indonesia
Rest of Southeast Asia	Brunei Darussalam, Cambodia, Lao People's Democratic Republic, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Thailand, Timor-Leste, Viet Nam
Rest of Asia	Afghanistan, Armenia, Azerbaijan, Bangladesh, Bhutan, Democratic People's Republic of Korea, Georgia, Japan, Kazakhstan, Kyrgyzstan, Mongolia, Nepal, Pakistan, Republic of Korea, Sri Lanka, Tajikistan, Uzbekistan
Commonwealth of Independent States	Belarus, Russian Federation, Ukraine
European Union	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom
Latin America	Argentina, Bolivia, Brazil, Paraguay, Belize, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Mexico, Nicaragua, Panama, Peru, Puerto Rico, Suriname, Uruguay, Venezuela (Bolivarian Republic of)
Middle East & North Africa	Algeria, Bahrain, Egypt, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Occupied Palestinian Territory, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates, Yemen
North America	Canada, United States of America
Oceania	Australia, Fiji, New Caledonia, New Zealand, Vanuatu
Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Togo, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
Rest of the World	Albania, Bahamas, Bosnia and Herzegovina, Chad, Falkland Islands (Malvinas), French Guiana, Iceland, Jamaica, Montenegro, Norway, Republic of Moldova, Serbia, Solomon Islands, Switzerland, The former Yugoslav Republic of Macedonia, Trinidad and Tobago, Turkey, Turkmenistan, Western Sahara

Table C-11 Comparison between the fitted and actual amounts of total export quantity (oil palm fruit equivalent) from Indonesia, 2013-2015.

		2013	2014	2015	Total
Value	Actual	70491156	72812484	93826813	2.37E+08
	Fixed Base	87932061.3	1.03E+08	1.2E+08	3.12E+08
	Fixed with Log(Time)	77779715.7	85561944	94825856	2.58E+08
	Random Base	48734923	53568706	57979112	1.6E+08
	Random with Log(Time)	62087562.9	69126137	74829132	2.06E+08
	Pooled Base	28414048.7	31335153	31985502	91734704
	Pooled with Log(Time)	54263680.9	62659823	66176380	1.83E+08
	Average of Fixed with Log(Time) and Random with Log(Time)	69933639.3	77344040	84827494	2.32E+08
Comparison	Fixed Base	-24.74%	-42.01%	-28.28%	-31.44%
	Fixed with Log(Time)	-10.34%	-17.51%	-1.06%	-8.87%
	Random Base	30.86%	26.43%	38.21%	32.41%
	Random with Log(Time)	11.92%	5.06%	20.25%	13.11%
	Pooled Base	59.69%	56.96%	65.91%	61.31%
	Pooled with Log(Time)	23.02%	13.94%	29.47%	22.79%
	Average of Fixed with Log(Time) and Random with Log(Time)	0.79%	-6.22%	9.59%	2.12%

Note: Comparison is calculated as (actual – model fitted)/actual *100%

Table C-12 AICs of parametric hazard models.

	AIC
Log-logistic	31064.02
Generalized gamma	31050.33
Exponential	32419.18
Weibull (AFT)	31053.45
Gompertz	30618.62
Gamma	31608.99
Lognormal	31345.26
# Events	2935
# Grids	65282

Table C-13 Results of Gompertz parametric hazard model on oil palm expansion in Indonesia over 1996-2015, elevation excluded.

	coef	Hazard	t-value	sig.
Log(Oil Palm attainable yield)	0.03938	1.040165	2.119557	**
Log(Distance to old plantation)	-0.08708	0.916606	-12.0603	****
Log(Distance to oil palm mills)	-0.85598	0.424868	-49.2933	****
Access time	-0.42641	0.652852	-9.91454	****
Slope	-0.27847	0.75694	-16.7757	****
Population density	-0.92523	0.39644	-4.0375	****
Protected ratio	-1.73952	0.175605	-8.1295	****
Peatland ratio	0.211752	1.235841	4.089313	****
Oil palm concession ratio	0.938233	2.555461	24.37513	****
Natural forest	1.048006	2.851959	11.70486	****
Shrub	0.899477	2.458317	9.778057	****
Dry agriculture	0.113435	1.120119	1.230968	
Bare ground	0.948194	2.581044	6.991118	****
shape	0.152684		39.38191	****
rate	-4.86213		-42.4269	****
LogLik		-15298.36		
AIC		30636.72		
Number of grids		65282		
Number of events		2935		

Note: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively

Table C-14 Projected oil palm expansion into area with high environmental values.

	Expansion into Protected Areas	Expansion into Peatlands	Expansion into Primary Forest	Expansion into Secondary Forest	Expansion into Natural Forest
Less open world	0.79%	16.94%	2.94%	19.82%	22.76%
Business as usual	0.68%	18.40%	2.84%	19.74%	22.59%
More open world	1.16&	17.82%	3.97%	21.42%	25.38%
	Loss of Protected Areas	Loss of Peatlands	Loss of Primary Forest	Loss of Secondary Forest	Loss of Natural Forest
Less open world	0.64%	21.02%	1.21%	8.19%	4.70%
Business as usual	0.73%	29.91%	1.54%	10.69%	6.11%
More open world	2.33%	54.22%	4.01%	21.70%	12.85%

Table C-15 Results of t-tests on low-environmental-value scenario vs. comparable international trade scenarios

			t-tests			
Variable	Scenarios	Mean	Difference of means	95% confidence interval		t-value
Distance to oil palm processing mills	Business as usual	19.60	25.99	25.69	26.28	171.98
	Less open world	21.19	24.40	24.08	24.71	151.38
	More open world	45.58				
	Low environmental values	22.85				
Distance to 2015 estate crop plantation	Business as usual	6.40	9.51	9.39	9.63	155.44
	Less open world	6.47	9.44	9.32	9.57	151.21
	More open world	8.80				
	Low environmental values	15.91				
Access time to large cities	Business as usual	0.53	0.17	0.17	0.18	92.97
	Less open world	0.57	0.14	0.13	0.14	69.92
	More open world	0.53				
	Low environmental values	0.71				

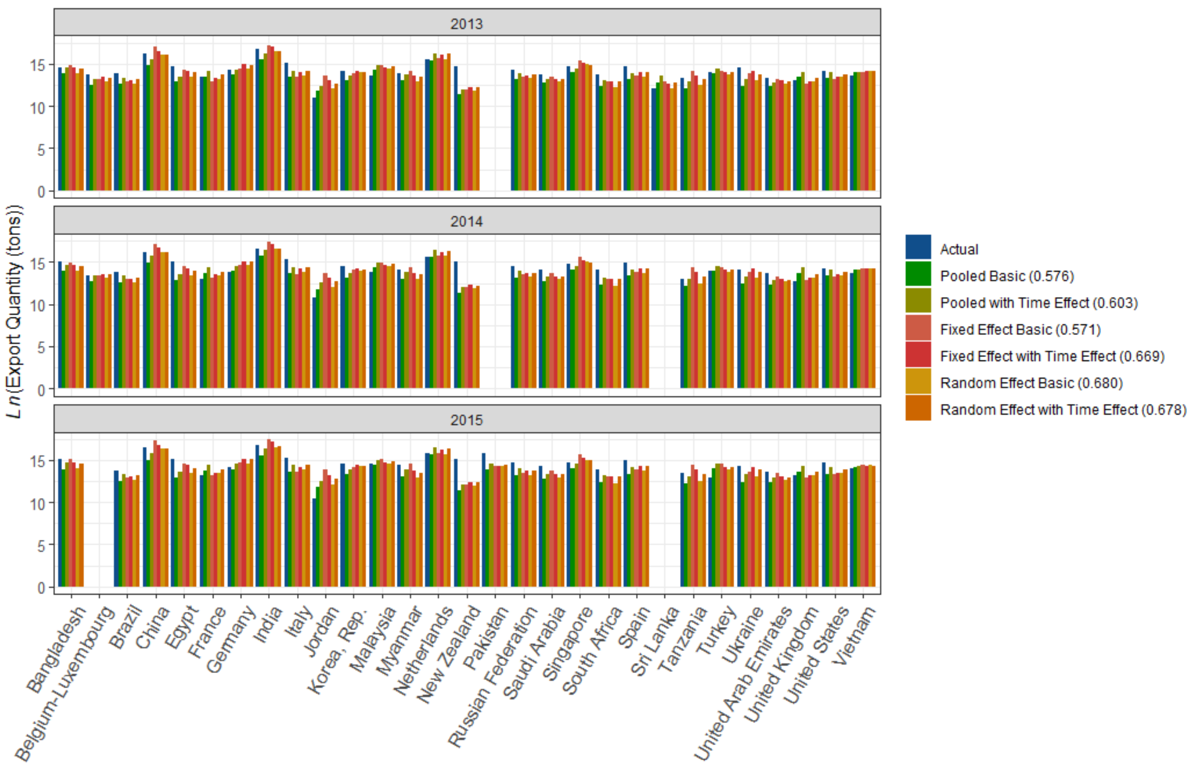


Figure C-1 Comparison between the fitted and actual amounts of trade flows (oil palm fruit equivalent) between Indonesia and the top 30 importers, 2013-2015. The values in the legend labels show the correlations between the model fitted values and the actual value.

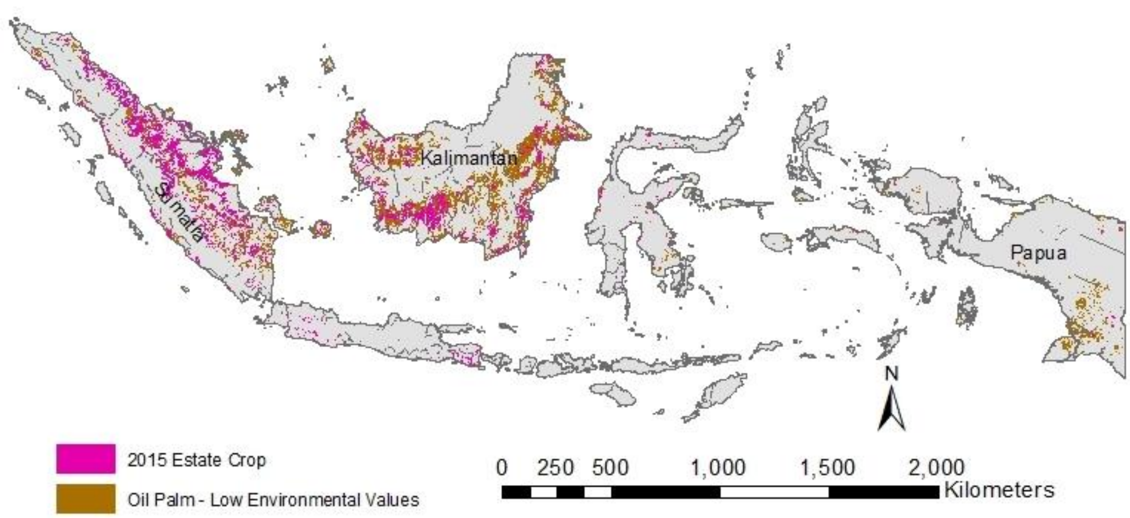


Figure C-2 Distribution of land biophysically suitable for oil palm plantation and with low environmental values. Those land include the unplanted oil palm concessions to 2015, and the shrub and bare ground on mineral land out of protected areas with attainable palm oil yield > 3 ton/ha.

Bibliography

Abdullah, A., 2012. *The economic and environmental analysis of palm oil expansion in Indonesia: export demand approach and EIRSAM model*. Graduate School of International Development, Nagoya University, Japan.

Abram, N.K., Meijaard, E., Wilson, K.A., Davis, J.T., Wells, J.A., Ancrenaz, M., Budiharta, S., Durrant, A., Fakhruzzi, A., Runting, R.K. and Gaveau, D., 2017. Oil palm–community conflict mapping in Indonesia: A case for better community liaison in planning for development initiatives. *Applied Geography*, *78*, pp.33-44. https://doi.org/10.1016/j.apgeog.2016.10.005

Achard, F., Eva, H.D., Mayaux, P., Stibig, H.J. and Belward, A., 2004. Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. *Global Biogeochemical Cycles*, *18*(2). https://doi.org/10.1029/2003GB002142

Adams, V.M., Iacona, G.D. and Possingham, H.P., 2019. Weighing the benefits of expanding protected areas versus managing existing ones. *Nature Sustainability*, *2*(5), pp.404-411. https://doi.org/10.1038/s41893-019-0275-5

Afifa, 2021. Indonesian palm oil goods exports up 13.6% to US$22.97bn in 2020. *TEMPO.CO*. Available from https://en.tempo.co/read/1431724/indonesian-palm-oil-goods-exports-up-13-6-to-us22-97bn-in-2020

Afriyanti, D., Kroeze, C. and Saad, A., 2016. Indonesia palm oil production without deforestation and peat conversion by 2050. *Science of the Total Environment*, *557*, pp.562-570. https://doi.org/10.1016/j.scitotenv.2016.03.032

Agus, F., Gunarso, P., Sahardjo, B.H., Harris, N., van Noordwijk, M. and Killeen, T.J., 2013. Historical CO2 emissions from land use and land use change from the oil palm industry in Indonesia, Malaysia and Papua New Guinea. *Roundtable on Sustainable Palm Oil, Kuala Lumpur*.

Agus, F., Runtunuwu, E., June, T., Susanti, E., Komara, H., Syahbuddin, H., Las, I. and van Noordwijk, M., 2009. Carbon dioxide emission in land use transitions to plantation. *Jurnal Litbang Pertanian*, *28*(4), pp.119-126.

Alisjahbana, A.S. and Busch, J.M., 2017. Forestry, forest fires, and climate change in Indonesia. *Bulletin of Indonesian Economic Studies*, *53*(2), pp.111-136. https://doi.org/10.1080/00074918.2017.1365404

Allaire, J.J., Ellis, P., Gandrud, C., Kuo, K., Lewis, B.W., Owen, J., Russell, K., Rogers, J., Sese, C., Yetman, C.J., Gandrud, M.C., 2017. Package “networkD3”. *D3 JavaScript Network Graphs from R.*

Allison, P.D., 2014. *Event history and survival analysis: Regression for longitudinal event data*. SAGE publications.

An, L. and Brown, D.G., 2008. Survival analysis in land change science: Integrating with GIScience to address temporal complexities. *Annals of the Association of American Geographers*, *98*(2), pp.323-344. https://doi.org/10.1080/00045600701879045

An, L., Brown, D.G., Nassauer, J.I. and Low, B., 2011. Variations in development of exurban residential landscapes: timing, location, and driving forces. *Journal of Land Use Science*, *6*(1), pp.13-32. https://doi.org/10.1080/1747423X.2010.500686

Andam, K.S., Ferraro, P.J., Pfaff, A., Sanchez-Azofeifa, G.A. and Robalino, J.A., 2008. Measuring the effectiveness of protected area networks in reducing deforestation. *Proceedings of the national academy of sciences*, *105*(42), pp.16089-16094. https://doi.org/10.1073/pnas.0800437105

Andersen, P.K. and Keiding, N., 2002. Multi-state models for event history analysis. *Statistical methods in medical research*, *11*(2), pp.91-115. https://doi.org/10.1191/0962280202SM276RA

Angelsen, A., 2010. Policies for reduced deforestation and their impact on agricultural production. *Proceedings of the national Academy of Sciences*, *107*(46), pp.19639-19644. https://doi.org/10.1073/pnas.0912014107

Armindya Y.R. and Kristanto, P.H., 2014. Govt Denies Report of Illegal Land Clearing for Palm Oil Use. *Tempo*. Available from https://en.tempo.co/read/607377/govt-denies-report-of-illegal-land-clearing-for-palm-oil-use

Armsworth, P.R., Daily, G.C., Kareiva, P. and Sanchirico, J.N., 2006. Land market feedbacks can undermine biodiversity conservation. *Proceedings of the National Academy of Sciences*, *103*(14), pp.5403-5408. https://doi.org/10.1073/pnas.0505278103

Austin, K.G., Kasibhatla, P.S., Urban, D.L., Stolle, F. and Vincent, J., 2015. Reconciling oil palm expansion and climate change mitigation in Kalimantan, Indonesia. *PLoS One*, *10*(5), p.e0127963. https://doi.org/10.1371/journal.pone.0127963

Austin, K.G., Mosnier, A., Pirker, J., McCallum, I., Fritz, S. and Kasibhatla, P.S., 2017. Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments. *Land use policy*, *69*, pp.41-48. https://doi.org/10.1016/j.landusepol.2017.08.036

Austin, K.G., Schwantes, A., Gu, Y. and Kasibhatla, P.S., 2019. What causes deforestation in Indonesia?. *Environmental Research Letters*, *14*(2), p.024007. https://doi.org/10.1088/1748-9326/AAF6DB

Bappenas, 2004. Sumberdaya alam dan lingkungan hidup indonesia: antara krisis dan peluang (Natural resources and environments of Indonesia: between crisis and poverty) *Bappenas*

Barnes, A.D., Jochum, M., Mumme, S., Haneda, N.F., Farajallah, A., Widarto, T.H. and Brose, U., 2014. Consequences of tropical land use for multitrophic biodiversity and ecosystem functioning. *Nature communications*, *5*(1), pp.1-7. https://doi.org/10.1038/ncomms6351

Barona, E., Ramankutty, N., Hyman, G. and Coomes, O.T., 2010. The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environmental Research Letters*, *5*(2), p.024002. https://doi.org/10.1088/1748-9326/5/2/024002

Barthel, M., Jennings, S., Schreiber, W., Sheane, R., Royston, S., Fry, J., Khor, Y.L. and McGill, J., 2018. *Study on the Environmental Impact of Palm Oil Consumption and on Existing Sustainability Standards: Final Report and Appendices*. Publications Office of the European Union.

BirdLife International, 2000. *Threatened Birds of the World.* Lynx Edicions, Barcelona, Spain; Cambridge, UK.

Brandon, K., 2014. Ecosystem services from tropical forests: review of current science. *Center for Global Development Working Paper*, (380). https://doi.org/10.2139/SSRN.2622749

Brockwell, P.J. and Davis, R.A., 2009. *Time series: theory and methods*. Springer Science & Business Media.

Brun, C., Cook, A.R., Lee, J.S.H., Wich, S.A., Koh, L.P. and Carrasco, L.R., 2015. Analysis of deforestation and protected area effectiveness in Indonesia: A comparison of Bayesian spatial models. *Global environmental change*, *31*, pp.285-295. https://doi.org/10.1016/j.gloenvcha.2015.02.004

Bulter, R., 2015. Palm oil major makes deforestation-free commitment. *Mongabay Environmental News*, Available from https://news.mongabay.com/2015/02/palm-oil-major-makes-deforestation-free-commitment/

Busch, J. and Engelmann, J., 2017. Cost-effectiveness of reducing emissions from tropical deforestation, 2016–2050. *Environmental Research Letters*, *13*(1), p.015001. https://doi.org/10.1088/1748-9326/aa907c

Busch, J., Ferretti-Gallon, K., Engelmann, J., Wright, M., Austin, K.G., Stolle, F., Turubanova, S., Potapov, P.V., Margono, B., Hansen, M.C. and Baccini, A., 2015. Reductions in emissions from deforestation from Indonesia's moratorium on new oil palm, timber, and logging concessions. *Proceedings of the National Academy of Sciences*, *112*(5), pp.1328-1333. https://doi.org/10.1073/pnas.1412514112

Busch, J., Lubowski, R.N., Godoy, F., Steininger, M., Yusuf, A.A., Austin, K., Hewson, J., Juhn, D., Farid, M. and Boltz, F., 2012. Structuring economic incentives to reduce emissions from deforestation within Indonesia. Proceedings of the National Academy of Sciences, 109(4), pp.1062-1067. https://doi.org/10.1073/pnas.1109034109

Butler, R., 2015. Palm oil major makes deforestation-free commitment. *Mongabay. com*, *3*.

Butler, R.A., Koh, L.P. and Ghazoul, J., 2009. REDD in the red: palm oil could undermine carbon payment schemes. *Conservation letters*, *2*(2), pp.67-73. https://doi.org/10.1111/j.1755-263X.2009.00047.x

Carlson, K.M., Curran, L.M., Asner, G.P., Pittman, A.M., Trigg, S.N. and Adeney, J.M., 2013. Carbon emissions from forest conversion by Kalimantan oil palm plantations. Nature Climate Change, 3(3), pp.283-287. https://doi.org/10.1038/nclimate1702

Carlson, K.M., Curran, L.M., Ratnasari, D., Pittman, A.M., Soares-Filho, B.S., Asner, G.P., Trigg, S.N., Gaveau, D.A., Lawrence, D. and Rodrigues, H.O., 2012. Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia. *Proceedings of the National Academy of Sciences*, *109*(19), pp.7559-7564. https://doi.org/10.1073/pnas.1200452109

Carlson, K.M., Heilmayr, R., Gibbs, H.K., Noojipady, P., Burns, D.N., Morton, D.C., Walker, N.F., Paoli, G.D. and Kremen, C., 2018. Effect of oil palm sustainability certification on deforestation and fire in Indonesia. *Proceedings of the National Academy of Sciences*, *115*(1), pp.121-126. https://doi.org/10.1073/pnas.1704728114

Carnus, J.M., Parrotta, J., Brockerhoff, E., Arbez, M., Jactel, H., Kremer, A., Lamb, D., O'Hara, K. and Walters, B., 2006. Planted forests and biodiversity. *Journal of forestry*, *104*(2), pp.65-77. https://doi.org/10.1093/jof/104.2.65

Carter, C., Finley, W., Fry, J., Jackson, D. and Willis, L., 2007. Palm oil markets and future supply. *European Journal of Lipid Science and Technology*, *109*(4), pp.307-314. https://doi.org/10.1002/ejlt.200600256

Castiblanco, C., Etter, A. and Aide, T.M., 2013. Oil palm plantations in Colombia: a model of future expansion. *Environmental science & policy*, *27*, pp.172-183. https://doi.org/10.1016/j.envsci.2013.01.003

Cattau, M.E., Marlier, M.E. and DeFries, R., 2016. Effectiveness of Roundtable on Sustainable Palm Oil (RSPO) for reducing fires on oil palm concessions in Indonesia from 2012 to 2015. *Environmental Research Letters*, *11*(10), p.105007. https://doi.org/10.1088/1748-9326/11/10/105007

Chen, Y., Li, X., Liu, X., Ai, B. and Li, S., 2016. Capturing the varying effects of driving forces over time for the simulation of urban growth by using survival analysis and cellular automata. *Landscape and Urban Planning*, *152*, pp.59-71. https://doi.org/10.1016/j.landurbplan.2016.03.011

Cisneros, E., Kis-Katos, K. and Nuryartono, N., 2021. Palm oil and the politics of deforestation in Indonesia. *Journal of Environmental Economics and Management*, *108*, p.102453. https://doi.org/10.1016/j.jeem.2021.102453

Clough, Y., Krishna, V.V., Corre, M.D., Darras, K., Denmead, L.H., Meijide, A., Moser, S., Musshoff, O., Steinebach, S., Veldkamp, E. and Allen, K., 2016. Land-use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes. *Nature communications*, *7*(1), pp.1-12. https://doi.org/10.1038/ncomms13137

Comte, I., Colin, F., Whalen, J.K., Grünberger, O. and Caliman, J.P., 2012. Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia: a review. *Advances in Agronomy*, *116*, pp.71-124. https://doi.org/10.1016/B978-0-12-394277-7.00003-8

Corley, R.H.V., 2009. How much palm oil do we need?. *Environmental Science & Policy*, *12*(2), pp.134-139. https://doi.org/10.1016/j.envsci.2008.10.011

Cox, C., Chu, H., Schneider, M.F. and Munoz, A., 2007. Parametric survival analysis and taxonomy of hazard functions for the generalized gamma distribution. *Statistics in medicine*, *26*(23), pp.4352-4374. https://doi.org/10.1002/sim.2836

Cox, D.R., 1972. Regression models and life-tables. *Journal of the Royal Statistical Society: Series B (Methodological)*, *34*(2), pp.187-202. https://doi.org/10.1111/J.2517-6161.1972.TB00899.X

Cramb, R. and Curry, G.N., 2012. Oil palm and rural livelihoods in the Asia–Pacific region: An overview. *Asia Pacific Viewpoint*, *53*(3), pp.223-239. https://doi.org/10.1111/j.1467-8373.2012.01495.x

Croissant, Y. and Millo, G., 2008. Panel data econometrics in R: The plm package. *Journal of statistical software*, *27*(2). https://doi.org/10.18637/jss.v027.i02

Crowther, M.J. and Lambert, P.C., 2014. A general framework for parametric survival analysis. *Statistics in Medicine*, *33*(30), pp.5280-5297. https://doi.org/10.1002/sim.6300

Curran, L.M., Trigg, S.N., McDonald, A.K., Astiani, D., Hardiono, Y.M., Siregar, P., Caniago, I. and Kasischke, E., 2004. Lowland forest loss in protected areas of Indonesian Borneo. *Science*, *303*(5660), pp.1000-1003. https://doi.org/10.1126/SCIENCE.1091714

Davies, C., Briggs, A., Lorgelly, P., Garellick, G. and Malchau, H., 2013. The “hazards” of extrapolating survival curves. *Medical Decision Making*, *33*(3), pp.369-380. https://doi.org/10.1177/0272989X12475091

De Benedictis, L. and Taglioni, D., 2011. The gravity model in international trade. In *The trade impact of European Union preferential policies* (pp. 55-89). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-16564-1_4

De Vos, R.E., Suwarno, A., Slingerland, M., Van Der Meer, P.J. and Lucey, J.M., 2021. Independent oil palm smallholder management practices and yields: can RSPO certification make a difference?. *Environmental Research Letters*, *16*(6), p.065015. https://doi.org/10.1088/1748-9326/ac018d

de Wreede, L.C., Fiocco, M. and Putter, H., 2011. mstate: an R package for the analysis of competing risks and multi-state models. *Journal of statistical software*, *38*(1), pp.1-30. https://doi.org/10.18637/JSS.V038.I07

Dharmawan, A.H., Mardiyaningsih, D.I., Komarudin, H., Ghazoul, J., Pacheco, P. and Rahmadian, F., 2020. Dynamics of rural economy: a socio-economic understanding of oil palm expansion and landscape changes in East Kalimantan, Indonesia. *Land*, *9*(7), p.213. https://doi.org/10.3390/land9070213

Dib, J.B., Alamsyah, Z. and Qaim, M., 2018. Land-use change and income inequality in rural Indonesia. *Forest Policy and Economics*, *94*, pp.55-66. https://doi.org/10.1016/j.forpol.2018.06.010

Directorate General of Plantation, 2013–2018. Tree Crop Estate Statistics of Indonesia. *Jakarta, Indonesia: Ministry of Agriculture*

Donough, C.R., Witt, C. and Fairhurst, T.H., 2010, June. Yield intensification in oil palm using BMP as a management tool. In *International Conference on Oil Palm and the Environment* (pp. 23-27).

Dür, A., Eckhardt, J. and Poletti, A., 2020. Global value chains, the anti-globalization backlash, and EU trade policy: a research agenda. *Journal of European Public Policy*, *27*(6), pp.944-956. https://doi.org/10.1080/13501763.2019.1619802

Dwiyahreni, A.A., Fuad, H.A., Muhtar, S., Soesilo, T.B., Margules, C. and Supriatna, J., 2021. Changes in the human footprint in and around Indonesia’s terrestrial national parks between 2012 and 2017. *Scientific reports*, *11*(1), pp.1-14. https://doi.org/10.1038/s41598-021-83586-2

Edwards, R.B., 2019. *Export agriculture and rural poverty: evidence from Indonesian palm oil.* Dartmouth College: Hanover, Germany.

Egger, P. and Pfaffermayr, M., 2003. The proper panel econometric specification of the gravity equation: A three-way model with bilateral interaction effects. *Empirical Economics*, *28*(3), pp.571-580. https://doi.org/10.1007/s001810200146

Ekadinata, A. and Vincent, G., 2011. Rubber agroforests in a changing landscape: analysis of land use/cover trajectories in Bungo district, Indonesia. *Forests, Trees and Livelihoods*, *20*(1), pp.3-14. https://doi.org/10.1080/14728028.2011.9756694

Eklund, J., Blanchet, F.G., Nyman, J., Rocha, R., Virtanen, T. and Cabeza, M., 2016. Contrasting spatial and temporal trends of protected area effectiveness in mitigating deforestation in

Madagascar. *Biological Conservation*, *203*, pp.290-297. https://doi.org/10.1016/J.BIOCON.2016.09.033

Elhorst, J.P., 2003. Specification and estimation of spatial panel data models. *International regional science review*, *26*(3), pp.244-268. https://doi.org/10.1177/0160017603253791

Enrici, A.M. and Hubacek, K., 2018. Challenges for REDD+ in Indonesia. *Ecology and Society*, *23*(2). https://www.jstor.org/stable/26799084

Euler, M., Hoffmann, M.P., Fathoni, Z. and Schwarze, S., 2016. Exploring yield gaps in smallholder oil palm production systems in eastern Sumatra, Indonesia. *Agricultural Systems*, *146*, pp.111-119. https://doi.org/10.1016/j.agsy.2016.04.007

Euler, M., Krishna, V., Schwarze, S., Siregar, H. and Qaim, M., 2017. Oil palm adoption, household welfare, and nutrition among smallholder farmers in Indonesia. *World Development*, *93*, pp.219-235. https://doi.org/10.1016/j.worlddev.2016.12.019

Euler, M., Schwarze, S., Siregar, H. and Qaim, M., 2016. Oil palm expansion among smallholder farmers in Sumatra, Indonesia. *Journal of Agricultural Economics*, *67*(3), pp.658-676. https://doi-org.proxy-um.researchport.umd.edu/10.1111/1477-9552.12163

European Union Parliament news, 2018. Energy: new target of 32% from renewables by 2030 agreed by MEPs and ministers. Available from www.europarl.europa.eu/news/en/press-room/20180614IPR05810/energy-new-target-of-32-from-renewables-by-2030-agreed-by-meps-and-ministers

European Parliament, 2017. European Parliament resolution of 4 April 2017 on Palm oil and deforestation of rainforests. Available from https://www.europarl.europa.eu/doceo/document/TA-8-2017-0098_EN.html

FAO, 2011. AQUASTAT country profile – Indonesia. Food and Agriculture Organization of the United Nations. Available from www.fao.org/3/ca0393en/CA0393EN.pdf

FAO, 2017. Country fact sheet on food and agriculture policy trends – Indonesia. Food and Agriculture Organization of the United Nations. Available from www.fao.org/3/a-i7696e.pdf

FAO, 2021. Downloadable Data Sets. Food and Agriculture Organization of the United Nations. Visited in 2021 Dec. Available from https://www.fao.org/faostat/en/#data/QCL

Feintrenie, L., Chong, W.K. and Levang, P., 2010. Why do farmers prefer oil palm? Lessons learnt from Bungo district, Indonesia. *Small-scale forestry*, *9*(3), pp.379-396. https://doi.org/10.1007/s11842-010-9122-2

Ferraro, P.J., Hanauer, M.M., Miteva, D.A., Canavire-Bacarreza, G.J., Pattanayak, S.K. and Sims, K.R., 2013. More strictly protected areas are not necessarily more protective: evidence from Bolivia, Costa Rica, Indonesia, and Thailand. *Environmental Research Letters*, *8*(2), p.025011. https://doi.org/10.1088/1748-9326/8/2/025011

Field, R.D., Van Der Werf, G.R., Fanin, T., Fetzer, E.J., Fuller, R., Jethva, H., Levy, R., Livesey, N.J., Luo, M., Torres, O. and Worden, H.M., 2016. Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Niño-induced drought. *Proceedings of the National Academy of Sciences*, *113*(33), pp.9204-9209. https://doi.org/10.1073/pnas.1524888113

Fitzherbert, E.B., Struebig, M.J., Morel, A., Danielsen, F., Brühl, C.A., Donald, P.F. and Phalan, B., 2008. How will oil palm expansion affect biodiversity?. *Trends in ecology & evolution*, *23*(10), pp.538-545. https://doi.org/10.1016/j.tree.2008.06.012

Furumo, P.R. and Aide, T.M., 2017. Characterizing commercial oil palm expansion in Latin America: land use change and trade. *Environmental Research Letters*, *12*(2), p.024008. https://doi.org/10.1088/1748-9326/aa5892

Ganser, D., Denmead, L.H., Clough, Y., Buchori, D. and Tscharntke, T., 2017. Local and landscape drivers of arthropod diversity and decomposition processes in oil palm leaf axils. *Agricultural and forest entomology*, *19*(1), pp.60-69. https://doi.org/10.1111/afe.12181

Gatto, M., Wollni, M., Asnawi, R. and Qaim, M., 2017. Oil palm boom, contract farming, and rural economic development: Village-level evidence from Indonesia. *World Development*, *95*, pp.127-140. https://doi.org/10.1016/j.worlddev.2017.02.013

Gatto, M., Wollni, M. and Qaim, M., 2015. Oil palm boom and land-use dynamics in Indonesia: the role of policies and socioeconomic factors. *Land use policy*, *46*, pp.292-303. https://doi.org/10.1016/j.landusepol.2015.03.001

Gaveau, D.L., Curran, L.M., Paoli, G.D., Carlson, K.M., Wells, P., Besse-Rimba, A., Ratnasari, D. and Leader-Williams, N., 2012. Examining protected area effectiveness in Sumatra: importance of regulations governing unprotected lands. *Conservation Letters*, *5*(2), pp.142-148. https://doi.org/10.1111/J.1755-263X.2011.00220.X

Gaveau, D.L., Epting, J., Lyne, O., Linkie, M., Kumara, I., Kanninen, M. and Leader-Williams, N., 2009. Evaluating whether protected areas reduce tropical deforestation in Sumatra. *Journal of biogeography*, *36*(11), pp.2165-2175. https://doi.org/10.1111/J.1365-2699.2009.02147.X

Gaveau, D.L., Kshatriya, M., Sheil, D., Sloan, S., Molidena, E., Wijaya, A., Wich, S., Ancrenaz, M., Hansen, M., Broich, M. and Guariguata, M.R., 2013. Reconciling forest conservation and logging in Indonesian Borneo. *PloS one*, *8*(8), p.e69887. https://doi.org/10.1371/journal.pone.0069887

Gaveau, D.L., Sheil, D., Salim, M.A., Arjasakusuma, S., Ancrenaz, M., Pacheco, P. and Meijaard, E., 2016. Rapid conversions and avoided deforestation: examining four decades of industrial plantation expansion in Borneo. *Scientific reports*, *6*(1), pp.1-13. https://doi.org/10.1038/srep32017

Gaveau, D.L., Wich, S., Epting, J., Juhn, D., Kanninen, M. and Leader-Williams, N., 2009. The future of forests and orangutans (Pongo abelii) in Sumatra: predicting impacts of oil palm plantations, road construction, and mechanisms for reducing carbon emissions from deforestation. *Environmental Research Letters*, *4*(3), p.034013. https://doi.org/10.1088/1748-9326/4/3/034013

Geldmann, J., Barnes, M., Coad, L., Craigie, I.D., Hockings, M. and Burgess, N.D., 2013. Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. *Biological Conservation*, *161*, pp.230-238. https://doi.org/10.1016/j.biocon.2013.02.018

Geldmann, J., Manica, A., Burgess, N.D., Coad, L. and Balmford, A., 2019. A global-level assessment of the effectiveness of protected areas at resisting anthropogenic pressures. *Proceedings of the National Academy of Sciences*, *116*(46), pp.23209-23215. https://doi.org/10.1073/pnas.1908221116

George, B., Seals, S. and Aban, I., 2014. Survival analysis and regression models. *Journal of nuclear cardiology*, *21*(4), pp.686-694. https://doi.org/10.1007/s12350-014-9908-2

Germer, J. and Sauerborn, J., 2008. Estimation of the impact of oil palm plantation establishment on greenhouse gas balance. *Environment, Development and Sustainability*, *10*(6), pp.697-716. https://doi.org/10.1007/s10668-006-9080-1

Goetz, S.J., Hansen, M., Houghton, R.A., Walker, W., Laporte, N. and Busch, J., 2015. Measurement and monitoring needs, capabilities and potential for addressing reduced emissions from deforestation and forest degradation under REDD+. *Environmental Research Letters*, *10*(12), p.123001. https://doi.org/10.1088/1748-9326/10/12/123001

Gohari, A., Eslamian, S., Abedi-Koupaei, J., Bavani, A.M., Wang, D. and Madani, K., 2013. Climate change impacts on crop production in Iran's Zayandeh-Rud River Basin. *Science of the Total Environment*, *442*, pp.405-419. https://doi.org/10.1016/j.scitotenv.2012.10.029

Government Regulation no.57, 2016. Amending Government Regulation of the R.I. No. 71 of 2014 on Protection and Management of Ecosystem of Peat lands.

Groom, B., Palmer, C. and Sileci, L., 2022. Carbon emissions reductions from Indonesia's moratorium on forest concessions are cost-effective yet contribute little to Paris pledges. *Proceedings of the National Academy of Sciences*, *119*(5). https://doi.org/10.1073/pnas.2102613119

Guillaume, T., Damris, M. and Kuzyakov, Y., 2015. Losses of soil carbon by converting tropical forest to plantations: erosion and decomposition estimated by δ13C. *Global change biology*, *21*(9), pp.3548-3560. https://doi.org/10.1111/gcb.12907

Guillaume, T., Holtkamp, A.M., Damris, M., Brümmer, B. and Kuzyakov, Y., 2016. Soil degradation in oil palm and rubber plantations under land resource scarcity. *Agriculture, Ecosystems & Environment*, *232*, pp.110-118. https://doi.org/10.1016/j.agee.2016.07.002

Gunarso, P., Hartoyo, M. E., Agus, F. and Killeen, T. J., 2013. Oil palm and land use change in Indonesia, Malaysia and Papua New Guinea. *Reports from the Technical Panels of the 2nd greenhouse gas working Group of the Roundtable on Sustainable Palm Oil (RSPO)*

Hansen, M.C., Stehman, S.V., Potapov, P.V., Arunarwati, B., Stolle, F. and Pittman, K., 2009. Quantifying changes in the rates of forest clearing in Indonesia from 1990 to 2005 using remotely sensed data sets. *Environmental Research Letters*, *4*(3), p.034001. https://doi.org/10.1088/1748-9326/4/3/034001

Harrison, M.E., Ottay, J.B., D'Arcy, L.J., Cheyne, S.M., Belcher, C., Cole, L., Dohong, A., Ermiasi, Y., Feldpausch, T., Gallego-Sala, A. and Gunawan, A., 2020. Tropical forest and peatland conservation in Indonesia: challenges and directions. *People and Nature*, *2*(1), pp.4-28. https://doi.org/10.1002/pan3.10060

Haruna, A., Pfaff, A., Van den Ende, S. and Joppa, L., 2014. Evolving protected-area impacts in Panama: impact shifts show that plans require anticipation. *Environmental Research Letters*, *9*(3), p.035007. https://doi.org/10.1088/1748-9326/9/3/035007

Heino, M., Kummu, M., Makkonen, M., Mulligan, M., Verburg, P.H., Jalava, M. and Räsänen, T.A., 2015. Forest loss in protected areas and intact forest landscapes: a global analysis. *PloS one*, *10*(10), p.e0138918. https://doi.org/10.1371/JOURNAL.PONE.0138918

Henders, S., Persson, U.M. and Kastner, T., 2015. Trading forests: land-use change and carbon emissions embodied in production and exports of forest-risk commodities. *Environmental Research Letters*, *10*(12), p.125012. https://doi.org/10.1088/1748-9326/10/12/125012

Herold, M. and Skutsch, M., 2011. Monitoring, reporting and verification for national REDD+ programmes: two proposals. *Environmental Research Letters*, *6*(1), p.014002. https://doi.org/10.1088/1748-9326/6/1/014002

Hilton-Taylor, C., 2000. IUCN red list of threatened species. *IUCN http://www. redlist. org*.

Indonesia-Investments, 2017. Palm Oil. Available from https://www.indonesia-investments.com/business/commodities/palm-oil/item166

Hoffmann, M.P., Donough, C.R., Cook, S.E., Fisher, M.J., Lim, C.H., Lim, Y.L., Cock, J., Kam, S.P., Mohanaraj, S.N., Indrasuara, K. and Tittinutchanon, P., 2017. Yield gap analysis in oil palm: Framework development and application in commercial operations in Southeast Asia. *Agricultural Systems*, *151*, pp.12-19. https://doi.org/10.1016/j.agsy.2016.11.005

IIASA/FAO, 2021. Global Agro-ecological Zones (GAEZ v4). Laxenburg, Austria and Rome, Italy: IIASA and FAO. Available from https://gaez.fao.org/

Imron, M.A., Herzog, S. and Berger, U., 2010. The influence of agroforestry and other land-use types on the persistence of a Sumatran tiger (Panthera tigris sumatrae) population: an individual-based model approach. *Environmental management*, *48*(2), pp.276-288. https://doi.org/10.1007/S00267-010-9577-0

Indoensia-Investments, 2017. Palm oil. Available from www.indonesia-investments.com/business/commodities/palm-oil/item166

Indonesian President Instruction no. 10, 2011. New licensing moratorium and management improvement of primary forests and peatlands.

Indonesian President Instruction no. 6, 2013. New licensing moratorium and management improvement of primary forests and peatlands.

Inoue, M., Kawai, M., Imang, N., Terauchi, D., Pambudhi, F. and Sardjono, M.A., 2013. Implications of local peoples' preferences in terms of income source and land use for Indonesia's national REDD-plus policy: evidence in East Kalimantan, Indonesia. *International journal of environment and sustainable development*, *12*(3), pp.244-263. https://doi.org/10.1504/IJESD.2013.054951

IPCC guidelines for national greenhouse gas inventories. 2006. *Prepared by the national greenhouse gas inventories programme*, pp.10-1.Available from http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

Jones, K.R., Venter, O., Fuller, R.A., Allan, J.R., Maxwell, S.L., Negret, P.J. and Watson, J.E., 2018. One-third of global protected land is under intense human pressure. *Science*, *360*(6390), pp.788-791. https://doi.org/10.1126/SCIENCE.AAP9565

Irawan, S., Tacconi, L. and Ring, I., 2013. Stakeholders' incentives for land-use change and REDD+: The case of Indonesia. *Ecological Economics*, *87*, pp.75-83. https://doi.org/10.1016/j.ecolecon.2012.12.018

Irshad, M.S., Xin, Q., Hui, Z. and Arshad, H., 2018. An empirical analysis of Pakistan's bilateral trade and trade potential with China: A gravity model approach. *Cogent Economics & Finance*, *6*(1), p.1504409. https://doi.org/10.1080/23322039.2018.1504409

Ishak, K.J., Kreif, N., Benedict, A. and Muszbek, N., 2013. Overview of parametric survival analysis for health-economic applications. *Pharmacoeconomics*, *31*(8), pp.663-675. https://doi.org/10.1007/s40273-013-0064-3

Jackson, C.H., 2016. flexsurv: a platform for parametric survival modeling in R. *Journal of statistical software*, *70*. https://doi.org/10.18637/jss.v070.i08

Jafari, Y., Othman, J., Witzke, P. and Jusoh, S., 2017. Risks and opportunities from key importers pushing for sustainability: the case of Indonesian palm oil. *Agricultural and Food Economics*, *5*(1), pp.1-16. https://doi.org/10.1186/s40100-017-0083-z

Johnston, F.H., Henderson, S.B., Chen, Y., Randerson, J.T., Marlier, M., DeFries, R.S., Kinney, P., Bowman, D.M. and Brauer, M., 2012. Estimated global mortality attributable to smoke from landscape fires. *Environmental health perspectives*, *120*(5), pp.695-701. https://doi.org/10.1289/ehp.1104422

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J. and Ritchie, J.T., 2003. The DSSAT cropping system model. *European journal of agronomy*, *18*(3-4), pp.235-265. https://doi.org/10.1016/S1161-0301(02)00107-7

Jones, L.H. and Hughes, W.A., 1989. Oil palm (Elaeis guineensis Jacq.). In *Trees II* (pp. 176-202). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-61535-1_10

Joppa, L.N. and Pfaff, A., 2011. Global protected area impacts. *Proceedings of the Royal Society B: Biological Sciences*, *278*(1712), pp.1633-1638. https://doi.org/10.1098/rspb.2010.1713

Kepaptsoglou, K., Karlaftis, M.G. and Tsamboulas, D., 2010. The gravity model specification for modeling international trade flows and free trade agreement effects: a 10-year review of empirical studies. *The open economics journal*, *3*(1). https://doi.org/10.2174/1874919401003010001

Kerr, W.A., 2020. The COVID-19 pandemic and agriculture: Short-and long-run implications for international trade relations. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, *68*(2), pp.225-229. https://doi.org/10.1111/cjag.12230

Kinnaird, M.F., Sanderson, E.W., O'Brien, T.G., Wibisono, H.T. and Woolmer, G., 2003. Deforestation trends in a tropical landscape and implications for endangered large mammals. *Conservation Biology*, *17*(1), pp.245-257. https://doi.org/10.1046/j.1523-1739.2003.02040.x

Koh, L.P. and Butler, R.A., 2007. Can REDD make natural forests competitive with oil palm*?. ITTO Tropical Forest Update 19*, 9-10. Available from http://indiaenvironmentportal.org.in/files/REDD_1.pdf

Koh, L.P. and Ghazoul, J., 2010. Spatially explicit scenario analysis for reconciling agricultural expansion, forest protection, and carbon conservation in Indonesia. *Proceedings of the National Academy of Sciences*, *107*(24), pp.11140-11144. https://doi.org/10.1073/pnas.1000530107

Koh, L.P., Miettinen, J., Liew, S.C. and Ghazoul, J., 2011. Remotely sensed evidence of tropical peatland conversion to oil palm. *Proceedings of the National Academy of Sciences*, *108*(12), pp.5127-5132. https://doi.org/10.1073/pnas.1018776108

Koh, L.P. and Wilcove, D.S., 2008. Is oil palm agriculture really destroying tropical biodiversity?. *Conservation letters*, *1*(2), pp.60-64. https://doi.org/10.1111/j.1755-263X.2008.00011.x

Korinek, J. and M. Melatos, 2009. Trade Impacts of Selected Regional Trade Agreements in Agriculture. *OECD Trade Policy Papers, No. 87, OECD Publishing, Paris*, https://doi.org/10.1787/225010121752

Kotowska, M.M., Leuschner, C., Triadiati, T., Meriem, S. and Hertel, D., 2015. Quantifying above-and belowground biomass carbon loss with forest conversion in tropical lowlands of Sumatra (Indonesia). *Global change biology*, *21*(10), pp.3620-3634. https://doi.org/10.1111/gcb.12979

Lambin, E.F., Geist, H.J. and Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. *Annual review of environment and resources*, *28*(1), pp.205-241. https://doi.org/10.1146/annurev.energy.28.050302.105459

Lapola, D.M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C. and Priess, J.A., 2010. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the national Academy of Sciences*, *107*(8), pp.3388-3393. https://doi.org/10.1073/pnas.0907318107

Larch, M., Monteiro, J.A., Piermartini, R. and Yotov, Y., 2019. On the effects of GATT/WTO membership on trade: They are positive and large after all. *CESifo Working Paper No. 7721*. http://dx.doi.org/10.2139/ssrn.3421148

Laurance, W.F., Useche, D.C., Rendeiro, J., Kalka, M., Bradshaw, C.J., Sloan, S.P., Laurance, S.G., Campbell, M., Abernethy, K., Alvarez, P. and Arroyo-Rodriguez, V., 2012. Averting biodiversity collapse in tropical forest protected areas. *Nature*, *489*(7415), pp.290-294. https://doi.org/10.1038/nature11318

Lee, H. and Park, I., 2007. In search of optimised regional trade agreements and applications to East Asia. *World Economy*, *30*(5), pp.783-806. https://doi.org/10.1111/j.1467-9701.2007.01024.x

Lee, J.S.H., Abood, S., Ghazoul, J., Barus, B., Obidzinski, K. and Koh, L.P., 2014. Environmental impacts of large-scale oil palm enterprises exceed that of smallholdings in Indonesia. *Conservation letters*, *7*(1), pp.25-33. https://doi.org/10.1111/conl.12039

Lee, J.S.H., Garcia-Ulloa, J., Ghazoul, J., Obidzinski, K. and Koh, L.P., 2014. Modelling environmental and socio-economic trade-offs associated with land-sparing and land-sharing approaches to oil palm expansion. *Journal of applied ecology*, *51*(5), pp.1366-1377. https://doi.org/10.1111/1365-2664.12286

Lee, S.Y. and Lim, S.S., 2014. Determinants of the Korean agricultural trade with the LDCs and the OECD countries. *Agricultural Economics*, *60*(3), pp.110-122. https://doi.org/10.17221/118/2013-AGRICECON

Lewer, J.J. and Van den Berg, H., 2007. Religion and international trade: does the sharing of a religious culture facilitate the formation of trade networks?. *American Journal of Economics and Sociology*, *66*(4), pp.765-794. https://doi.org/10.1111/j.1536-7150.2007.00539.x

Lim, F.K., Carrasco, L.R., McHardy, J. and Edwards, D.P., 2019. Land rents drive oil palm expansion dynamics in Indonesia. *Environmental Research Letters*, *14*(7), p.074024. https://doi.org/10.1088/1748-9326/ab2bda

Linkie, M., Smith, R.J., Zhu, Y.U., Martyr, D.J., Suedmeyer, B., Pramono, J. and LEADER-WILLIAMS, N.I.G.E.L., 2008. Evaluating biodiversity conservation around a large Sumatran protected area. *Conservation Biology*, *22*(3), pp.683-690. https://doi.org/10.1111/j.1523-1739.2008.00906.x

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F. and Hansen, M.C., 2014. Primary forest cover loss in Indonesia over 2000–2012. *Nature climate change*, *4*(8), pp.730-735. https://doi.org/10.1038/NCLIMATE2277

Mascia, M.B. and Pailler, S., 2011. Protected area downgrading, downsizing, and degazettement (PADDD) and its conservation implications. *Conservation letters*, *4*(1), pp.9-20. https://doi.org/10.1111/J.1755-263X.2010.00147.X

Meehan, F. and Tacconi, L., 2017. A framework to assess the impacts of corruption on forests and prioritize responses. *Land Use Policy*, *60*, pp.113-122. https://doi.org/10.1016/j.landusepol.2016.10.021

Mertens, B. and Lambin, E.F., 2000. Land-cover-change trajectories in southern Cameroon. *Annals of the association of American Geographers*, *90*(3), pp.467-494. https://doi.org/10.1111/0004-5608.00205

Meyfroidt, P., Carlson, K.M., Fagan, M.E., Gutiérrez-Vélez, V.H., Macedo, M.N., Curran, L.M., DeFries, R.S., Dyer, G.A., Gibbs, H.K., Lambin, E.F. and Morton, D.C., 2014. Multiple pathways of commodity crop expansion in tropical forest landscapes. *Environmental Research Letters*, *9*(7), p.074012. https://doi.org/10.1088/1748-9326/9/7/074012

Miettinen, J., Shi, C. and Liew, S.C., 2011. Deforestation rates in insular Southeast Asia between 2000 and 2010. *Global Change Biology*, *17*(7), pp.2261-2270. https://doi.org/10.1111/j.1365-2486.2011.02398.x

Millo, G. and Piras, G., 2012. splm: Spatial panel data models in R. *Journal of statistical software*, *47*, pp.1-38. https://doi.org/10.18637/jss.v047.i01

Mokany, K., Raison, R.J. and Prokushkin, A.S., 2006. Critical analysis of root: shoot ratios in terrestrial biomes. *Global change biology*, *12*(1), pp.84-96. https://doi.org/10.1111/j.1365-2486.2005.001043.x

Molenaar, J.W., Persch-Orth, M., Lord, S., Taylor, C. and Harms, J., 2013. Diagnostic study on Indonesian oil palm smallholders: developing a better understanding of their performance and potential. *International Finance Corporation, World Bank Group, Washington, DC, USA.*

Mosnier, A., Boere, E., Reumann, A., Yowargana, P., Pirker, J., Havlík, P. and Pacheco, P., 2017. *Palm oil and likely futures: Assessing the potential impacts of zero deforestation commitments and a moratorium on large-scale oil palm plantations in Indonesia* (Vol. 177). CIFOR. https://doi.org/10.17528/cifor/006468

Murdiyarso, D., Hergoualc'h, K. and Verchot, L.V., 2010. Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proceedings of the National Academy of Sciences*, *107*(46), pp.19655-19660. https://doi.org/10.1073/pnas.0911966107

Murugesan, A., Umarani, C., Subramanian, R. and Nedunchezhian, N., 2009. Bio-diesel as an alternative fuel for diesel engines—a review. *Renewable and sustainable energy reviews*, *13*(3), pp.653-662. https://doi.org/10.1016/j.rser.2007.10.007

Myers, N., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A. and Kent, J., 2000. Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), pp.853-858. https://doi.org/10.1038/35002501

Myers, S.C. and Majluf, N.S., 1984. Corporate financing and investment decisions when firms have information that investors do not have. *Journal of financial economics*, *13*(2), pp.187-221.

https://doi.org/10.1016/0304-405X(84)90023-0

National Research Council. 1993. *Sustainable Agriculture and the Environment in the Humid Tropics*. Washington, D.C.: National Academies Press.

Nelson, G.C., Rosegrant, M.W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., Sulser, T.B., Ringler, C. and Msangi, S., 2010. *Food security, farming, and climate change to 2050: scenarios, results, policy options* (Vol. 172). Intl Food Policy Res Inst.

Nolte, C., Agrawal, A., Silvius, K.M. and Soares-Filho, B.S., 2013. Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon. *Proceedings of the National Academy of Sciences*, *110*(13), pp.4956-4961. https://doi.org/10.1073/PNAS.1214786110

Obidzinski, K., Dermawan, A. and Hadianto, A., 2014. Oil palm plantation investments in Indonesia's forest frontiers: limited economic multipliers and uncertain benefits for local communities. *Environment, Development and Sustainability*, *16*(6), pp.1177-1196. https://doi.org/10.1111/conl.12039

Ordway, E.M., Naylor, R.L., Nkongho, R.N. and Lambin, E.F., 2019. Oil palm expansion and deforestation in Southwest Cameroon associated with proliferation of informal mills. *Nature communications*, *10*(1), pp.1-11. https://doi.org/10.1038/s41467-018-07915-2

Pacheco, P., Schoneveld, G., Dermawan, A., Komarudin, H. and Djama, M., 2020. Governing sustainable palm oil supply: Disconnects, complementarities, and antagonisms between state regulations and private standards. *Regulation & Governance*, *14*(3), pp.568-598. https://doi.org/10.1111/rego.12220

Page, S.E., Morrison, R., Malins, C., Hooijer, A., Rieley, J.O. and Jauhiainen, J., 2011. Review of peat surface greenhouse gas emissions from oil palm plantations in Southeast Asia. *ICCT white paper*, *15*, pp.1-78.

Page, S.E., Rieley, J.O. and Banks, C.J., 2011. Global and regional importance of the tropical peatland carbon pool. *Global change biology*, *17*(2), pp.798-818. https://doi.org/10.1111/j.1365-2486.2010.02279.x

Paterson, R.R.M., Kumar, L., Shabani, F. and Lima, N., 2017. World climate suitability projections to 2050 and 2100 for growing oil palm. *The Journal of Agricultural Science*, *155*(5), pp.689-702. https://doi.org/10.1017/S0021859616000605

Petersen, R.A.C.H.A.E.L., Goldman, E.D., Harris, N., Sargent, S., Aksenov, D., Manisha, A., Esipova, E., Shevade, V., Loboda, T., Kuksina, N. and Kurakina, I., 2016. Mapping tree plantations with multispectral imagery: preliminary results for seven tropical countries. *World Resources Institute, Washington, DC*, *525*.

Phalan, B., Onial, M., Balmford, A. and Green, R.E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. *science*, *333*(6047), pp.1289-1291. https://www.science.org/doi/10.1126/science.1208742

Pirker, J., Mosnier, A., Kraxner, F., Havlík, P. and Obersteiner, M., 2016. What are the limits to oil palm expansion?. *Global Environmental Change*, *40*, pp.73-81. https://doi.org/10.1016/j.gloenvcha.2016.06.007

Poor, E.E., Frimpong, E., Imron, M.A. and Kelly, M.J., 2019. Protected area effectiveness in a sea of palm oil: A Sumatran case study. *Biological Conservation*, *234*, pp.123-130. https://doi.org/10.1016/J.BIOCON.2019.03.018

Purnomo, H., Okarda, B., Dermawan, A., Ilham, Q.P., Pacheco, P., Nurfatriani, F. and Suhendang, E., 2020. Reconciling oil palm economic development and environmental conservation in Indonesia: A value chain dynamic approach. *Forest Policy and Economics*, *111*, p.102089. https://doi.org/10.1016/j.forpol.2020.102089

Putter, H., Fiocco, M. and Geskus, R.B., 2007. Tutorial in biostatistics: competing risks and multi-state models. *Statistics in medicine*, *26*(11), pp.2389-2430. https://doi.org/10.1002/SIM.2712

Qaim, M., Sibhatu, K.T., Siregar, H. and Grass, I., 2020. Environmental, economic, and social consequences of the oil palm boom. *Annual review of resource economics*, *12*, pp.321-344. https://doi.org/10.1146/annurev-resource-110119-024922

Razzaque, M.A. and Ehsan, S.M., 2019. *Global Trade Turmoil: Implications for LDCs, Small States and Sub-Saharan Africa*. Commonwealth Secretariat.

Research and Markets, 2020. Global palm oil market: insights, trends and forecast (2020-2024). Available from www.researchandmarkets.com/r/fh7knt

Reuters Staff, 2019. Indonesia president makes moratorium on forest clearance permanent. *Reuters*. Available from https://www.reuters.com/article/us-indonesia-environment-forest-idUSKCN1UY14P

Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O. and Lutz, W., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global environmental change*, *42*, pp.153-168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Richards, P.D., Walker, R.T. and Arima, E.Y., 2014. Spatially complex land change: The Indirect effect of Brazil's agricultural sector on land use in Amazonia. *Global Environmental Change*, *29*, pp.1-9. https://doi.org/10.1016/j.gloenvcha.2014.06.011

Rifin, A., 2010. An analysis of Indonesia's palm oil position in the world market: a twostage demand approach. *Oil Palm Industry Economic Journal*, *10*(1), pp.35-42.

Rifin, A., 2020. Assessing the impact of limiting Indonesian palm oil exports to the European Union. *Journal of economic structures*, *9*(1), pp.1-13. https://doi.org/10.1186/s40008-020-00202-8

Robinson, S., van Meijl, H., Willenbockel, D., Valin, H., Fujimori, S., Masui, T., Sands, R., Wise, M., Calvin, K., Havlik, P. and Mason d'Croz, D., 2014. Comparing supply-side specifications in models of global agriculture and the food system. *Agricultural Economics*, *45*(1), pp.21-35. https://doi-org.proxy-um.researchport.umd.edu/10.1111/agec.12087

Rueda, O.M., Sammut, S.J., Seoane, J.A., Chin, S.F., Caswell-Jin, J.L., Callari, M., Batra, R., Pereira, B., Bruna, A., Ali, H.R. and Provenzano, E., 2019. Dynamics of breast-cancer relapse reveal late-recurring ER-positive genomic subgroups. *Nature*, *567*(7748), pp.399-404. https://doi.org/10.1038/s41586-019-1007-8

Rulli, M.C., Casirati, S., Dell'Angelo, J., Davis, K.F., Passera, C. and D'Odorico, P., 2019. Interdependencies and telecoupling of oil palm expansion at the expense of Indonesian rainforest. *Renewable and Sustainable Energy Reviews*, *105*, pp.499-512. https://doi.org/10.1016/j.rser.2018.12.050

Sayer, J., Ghazoul, J., Nelson, P. and Boedhihartono, A.K., 2012. Oil palm expansion transforms tropical landscapes and livelihoods. *Global Food Security*, *1*(2), pp.114-119. https://doi.org/10.1016/j.gfs.2012.10.003

Shah, P. and Baylis, K., 2015. Evaluating heterogeneous conservation effects of forest protection in Indonesia. *PloS one*, *10*(6), p.e0124872. https://doi.org/10.1371/JOURNAL.PONE.0124872

Sheil, D., Casson, A., Meijaard, E., Van Noordwijk, M., Gaskell, J., Sunderland-Groves, J., Wertz, K. and Kanninen, M., 2009. *The impacts and opportunities of oil palm in Southeast Asia: What do we know and what do we need to know?* (Vol. 51). Bogor, Indonesia: Center for International Forestry Research. https://hdl.handle.net/10535/5256

Shevade, V.S. and Loboda, T.V., 2019. Oil palm plantations in Peninsular Malaysia: Determinants and constraints on expansion. *PLoS One*, *14*(2), p.e0210628. https://doi.org/10.1371/journal.pone.0210628

Shimamoto, C.Y., Padial, A.A., da Rosa, C.M. and Marques, M.C., 2018. Restoration of ecosystem services in tropical forests: a global meta-analysis. *PloS one*, *13*(12), p.e0208523. https://doi.org/10.1371/JOURNAL.PONE.0208523

Spawn, S.A., and H.K. Gibbs. 2020. Global Aboveground and Belowground Biomass Carbon Density Maps for the Year 2010. *ORNL DAAC, Oak Ridge, Tennessee, USA*. https://doi.org/10.3334/ORNLDAAC/1763

Statistics Indonesia. 1997-2016. Statistical Yearbook of Indonesia.

Sodhi, N.S., Posa, M.R.C., Lee, T.M., Bickford, D., Koh, L.P. and Brook, B.W., 2010. The state and conservation of Southeast Asian biodiversity. *Biodiversity and Conservation*, *19*(2), pp.317-328. https://doi.org/10.1007/S10531-009-9607-5

Soliman, T., Lim, F.K.S., Lee, J.S.H. and Carrasco, L.R., 2016. Closing oil palm yield gaps among Indonesian smallholders through industry schemes, pruning, weeding and improved seeds. *Royal Society open science*, *3*(8), p.160292. https://doi.org/10.1098/rsos.160292

Sumarga, E. and Hein, L., 2016. Benefits and costs of oil palm expansion in Central Kalimantan, Indonesia, under different policy scenarios. *Regional Environmental Change*, *16*(4), pp.1011-1021. https://doi.org/10.1007/s10113-015-0815-0

Summit, U.N.C., 2014. New York Declaration. United Nations, New York, NY.

Sun, L. and Reed, M.R., 2010. Impacts of free trade agreements on agricultural trade creation and trade diversion. *American Journal of Agricultural Economics*, *92*(5), pp.1351-1363. https://doi.org/10.1093/ajae/aaq076

Syuaib, M.F., 2016. Sustainable agriculture in Indonesia: Facts and challenges to keep growing in harmony with environment. *Agricultural Engineering International: CIGR Journal*, *18*(2), pp.170-184.

Tacconi, L., Rodrigues, R.J. and Maryudi, A., 2019. Law enforcement and deforestation: Lessons for Indonesia from Brazil. *Forest policy and economics*, *108*, p.101943. https://doi.org/10.1016/j.forpol.2019.05.029

Taheripour, F., Hertel, T.W. and Ramankutty, N., 2019. Market-mediated responses confound policies to limit deforestation from oil palm expansion in Malaysia and Indonesia. *Proceedings of the National Academy of Sciences*, *116*(38), pp.19193-19199. https://doi.org/10.1073/PNAS.1903476116

The World Bank, Agriculture & rural development, 2021. Agriculture, forestry, and fishing, value added (current US$). Available from https://data.worldbank.org/indicator/NV.AGR.TOTL.CD

Therneau, T.M. and Lumley, T., 2014. Package 'survival'. *Survival analysis Published on CRAN*, *2*(3), p.119.

Tinbergen, J., 1962. Shaping the world economy; suggestions for an international economic policy.

Tubiello, F.N. and Fischer, G., 2007. Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000–2080. *Technological Forecasting and Social Change*, *74*(7), pp.1030-1056. https://doi.org/10.1016/j.techfore.2006.05.027

USDA, 2010. Commodity Intelligence Report: Indonesia: rising global demand fuels palm oil expansion. Available from https://ipad.fas.usda.gov/highlights/2010/10/Indonesia/

USDA, 2013. Commodity Intelligence Report: Indonesia: palm oil expansion unaffected by forest moratorium. Available from https://ipad.fas.usda.gov/highlights/2013/06/indonesia/

USDA, 2019a. Downloadable data sets. *Retrieved from United States Department of Agriculture Foreign Agricultural Service.* Visited in May 2020. Available from http://apps.fas.usda.gov/psdonline/download/psd_oilseeds_csv.zip

USDA, 2019b. Oilseeds: World Markets and Trade. *Approved by the World Agricultural Outlook Board/USDA.* Visited in May 2020. Available from https://apps.fas.usda.gov/psdonline/circulars/oilseeds.pdf.

USDA, 2021a. Downloadable data sets. *Retrieved from United States Department of Agriculture Foreign Agricultural Service.* Visited in December 2021. Available from https://apps.fas.usda.gov/psdonline/app/index.html#/app/downloads

USDA, 2021b. Oilseeds: World Markets and Trade. *Approved by the World Agricultural Outlook Board/USDA.* Visited in December 2021. Available from https://apps.fas.usda.gov/psdonline/circulars/oilseeds.pdf

USDA-FAS, 2021. Production, Supply and Distribution Online: Oilseeds. *Retrieved from United States Department of Agriculture Foreign Agricultural Service.* Visited in April 2022. Available from https://apps.fas.usda.gov/psdonline/downloads/psd_oilseeds_csv.zip

Valin, H., Frank, S., Pirker, J., Mosnier, A., Forsell, N., Havlik, P., Peters, D. and Hamelinck, C., 2014. Improvements to GLOBIOM for modelling of biofuels indirect land use change. *ILUC Quantification Consortium: Utrecht, The Netherland*.

Van der Laan, C., Budiman, A., Verstegen, J.A., Dekker, S.C., Effendy, W., Faaij, A.P., Kusuma, A.D. and Verweij, P.A., 2018. Analyses of land cover change trajectories leading to tropical forest loss: Illustrated for the West Kutai and Mahakam Ulu Districts, East Kalimantan, Indonesia. *Land*, *7*(3), p.108. https://doi.org/10.3390/LAND7030108

Van Noordwijk, M. and Leimona, B., 2010. Principles for fairness and efficiency in enhancing environmental services in Asia: payments, compensation, or co-investment?. *Ecology and Society*, *15*(4). http://www.jstor.org/stable/26268209

Vijay, V., Pimm, S.L., Jenkins, C.N. and Smith, S.J., 2016. The impacts of oil palm on recent deforestation and biodiversity loss. *PloS one*, *11*(7), p.e0159668. https://doi.org/10.1371/journal.pone.0159668

Vogt, S.C., 1994. The role of internal financial sources in firm financing and investment decisions. *Review of Financial Economics*, *4*(1), pp.1-24. https://doi.org/10.1016/1058-3300(94)90002-7

Von Geibler, J., 2013. Market-based governance for sustainability in value chains: conditions for successful standard setting in the palm oil sector. *Journal of Cleaner Production*, *56*, pp.39-53. https://doi.org/10.1016/J.JCLEPRO.2012.08.027

Von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E. and Kyle, P., 2014. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison. *Agricultural Economics*, *45*(1), pp.3-20. https://doi-org.proxy-um.researchport.umd.edu/10.1111/agec.12086

Wade, C.M., Austin, K.G., Cajka, J., Lapidus, D., Everett, K.H., Galperin, D., Maynard, R. and Sobel, A., 2020. What Is Threatening Forests in Protected Areas? A Global Assessment of Deforestation in Protected Areas, 2001–2018. *Forests*, *11*(5), p.539. https://doi.org/10.3390/F11050539

Walker, R., 2004. Theorizing land-cover and land-use change: the case of tropical deforestation. *International regional science review*, *27*(3), pp.247-270. https://doi.org/10.1177/0160017604266026

Wang, N., Brown, D.G., An, L., Yang, S. and Ligmann-Zielinska, A., 2013. Comparative performance of logistic regression and survival analysis for detecting spatial predictors of land-use change. *International Journal of Geographical Information Science*, *27*(10), pp.1960-1982. https://doi.org/10.1080/13658816.2013.779377

Watson, J.E., Dudley, N., Segan, D.B. and Hockings, M., 2014. The performance and potential of protected areas. *Nature*, *515*(7525), pp.67-73. https://doi.org/10.1038/nature13947

Weedon, G.P., Balsamo, G., Bellouin, N., Gomes, S., Best, M.J. and Viterbo, P., 2014. The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data. *Water Resources Research*, *50*(9), pp.7505-7514. https://doi.org/10.1002/2014WR015638

Wheeler, D., Hammer, D., Kraft, R., Dasgupta, S. and Blankespoor, B., 2013. Economic dynamics and forest clearing: A spatial econometric analysis for Indonesia. *Ecological Economics*, *85*, pp.85-96. https://doi.org/10.1016/j.ecolecon.2012.11.005

Westerlund, J. and Wilhelmsson, F., 2011. Estimating the gravity model without gravity using panel data. *Applied Economics*, *43*(6), pp.641-649. https://doi.org/10.1080/00036840802599784

Wicke, B., Sikkema, R., Dornburg, V. and Faaij, A., 2011. Exploring land use changes and the role of palm oil production in Indonesia and Malaysia. *Land use policy*, *28*(1), pp.193-206. https://doi.org/10.1016/j.landusepol.2010.06.001

Wicke, B., Sikkema, R., Dornburg, V., Junginger, M. and Faaij, A., 2008. Drivers of land use change and the role of palm oil production in Indonesia and Malaysia. *Overview of past developments and future projections. Copernicus Institute Science, Universiteit Utrecht, Utrecht, The Netherlands*.

Wiebe, K.D., Sulser, T., Pacheco, P., De Pinto, A., Mason d'Croz, D., Dermawan, A., Thomas, T.S., Li, M., Robinson, S. and Dunston, S., 2019. *The palm oil dilemma: Policy tensions among higher productivity, rising demand, and deforestation*. Intl Food Policy Res Inst. https://doi.org/10.2499/9780896296879

Wilcove, D.S., Giam, X., Edwards, D.P., Fisher, B. and Koh, L.P., 2013. Navjot's nightmare revisited: logging, agriculture, and biodiversity in Southeast Asia. *Trends in ecology & evolution*, *28*(9), pp.531-540. https://doi.org/10.1016/j.tree.2013.04.005

Woittiez, L.S., 2019. *On yield gaps and better management practices in Indonesian smallholder oil palm plantations*. Wageningen University and Research. https://doi.org/10.18174/470340

Woittiez, L.S., van Wijk, M.T., Slingerland, M., van Noordwijk, M. and Giller, K.E., 2017. Yield gaps in oil palm: A quantitative review of contributing factors. *European Journal of Agronomy*, *83*, pp.57-77. https://doi.org/10.1016/j.eja.2016.11.002

Wolf, J., West, T.O., Le Page, Y., Kyle, G.P., Zhang, X., Collatz, G.J. and Imhoff, M.L., 2015. Biogenic carbon fluxes from global agricultural production and consumption. *Global Biogeochemical Cycles*, *29*(10), pp.1617-1639. https://doi.org/10.1002/2015GB005119

Wooldridge, J.M., 2015. *Introductory econometrics: A modern approach*. Cengage learning.

World Health Organization, 2015. Eliminating trans fats in Europe: a policy brief. *WHO Regional Office for Europe*. Available from https://www.euro.who.int/__data/assets/pdf_file/0010/288442/Eliminating-trans-fats-in-Europe-A-policy-brief.pdf

World Resources Institute, 2014. Climate Analysis Indicators Tool (CAIT 2.0). http://cait2.wri.org/wri/.

World Integrated Trade Solution, 2021. UNCTAD TRAINS Database. Available from https://wits.worldbank.org/tariff/trains/country-byhs6product.aspx?lang=en.

WTO, 2021. Regional Trade Agreements Database. Available from http://rtais.wto.org/UI/PublicMaintainRTAHome.aspx

WWF, 2017. Which every day products contain palm oil? Available from www.worldwildlife.org/pages/which-everyday-products-contain-palm-oil#

Xin, Y., Sun, L. and Hansen, M.C., 2021. Biophysical and socioeconomic drivers of oil palm expansion in Indonesia. *Environmental Research Letters*, *16*(3), p.034048. https://doi.org/10.1088/1748-9326/abce83

Xin, Y., Sun, L. and Hansen, M.C., 2022. Land cover and land use change trajectory hopping facilitates estate crop expansion into protected forests in Indonesia [Manuscript submitted for publication]. Department of Geographical Sciences, University of Maryland.

Zhang, L., Jin, G., Wan, Q., Liu, Y. and Wei, X., 2018. Measurement of ecological land use/cover change and its varying spatiotemporal driving forces by statistical and survival analysis: a case study of Yingkou City, China. *Sustainability*, *10*(12), p.4567. https://doi.org/10.3390/SU10124567

Zidi, A. and Dhifallah, S.M., 2013. Trade creation and trade diversion between Tunisia and EU: analysis by gravity model. *International Journal of Economics and Finance*, *5*(5), pp.131-147. http://dx.doi.org/10.5539/ijef.v5n5p131

Zhong, H., Sun, L., Fischer, G., Tian, Z. and Liang, Z., 2019. Optimizing regional cropping systems with a dynamic adaptation strategy for water sustainable agriculture in the Hebei Plain. *Agricultural Systems*, *173*, pp.94-106. https://doi.org/10.1016/j.agsy.2019.02.005