Stretching perspectives on rubber sustainability: Ecological, economic, and social dimensions of tropical agriculture expansion and voluntary sustainability initiatives

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Thesis abstract

Agricultural expansion is a major source of tropical deforestation. In particular, export commodity crops are often associated with environmental and socioeconomic problems in producer countries. This thesis focused on natural rubber, applying a multi-disciplinary lens to study the potential for aligning ecological, economic, and social sustainability goals. Using quantitative spatial analyses methods, I identified strong trade-offs between biodiversity and economic interests for future rubber expansion in Africa, Asia, and New Guinea. There is little room for new plantations in the most suitable areas for growing rubber that do not also threaten vulnerable species. Next, I used a spatio-temporal economic model to study the interactions between market prices, agricultural rents, rubber expansion, and protected areas during the latest rubber price boom and bust cycle in mainland Southeast Asia. Agricultural rents, incorporating changes in market prices, explained much but not all of the rubber expansion patterns across all countries in the study, highlighting the influence of socio-political variables in land-use changes. Protected areas hindered rubber expansion, but even the strictest reserves could not fully prevent encroachment especially in the most suitable and accessible lands. Lastly, I examined the process and implications of more inclusive and participatory stakeholder engagement in a multi-stakeholder sustainability initiative for rubber. Using document analysis, I map out the evolution of inclusiveness in the Global Platform for Sustainable Natural Rubber (GPSNR). The qualitative case study highlighted changes in membership composition, geographical representation, governance of decision-making, and the quality of smallholder participation. I documented gradual improvements in each component of inclusiveness, but challenges remain around equity of pricing and full participation of smallholders. This thesis offers a diverse contribution of perspectives, demonstrating how deforestation, agricultural demand, and equitable livelihoods are inextricably linked and emphasising the importance of multi-disciplinary approaches in theory and practice.

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(I dedicate this thesis to all who have dedicated their lives to save what yet can be saved, and to restore what can be restored)

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Statement of contribution

I, the author, confirm that the thesis is my own work, except where work that has formed part of jointly authored publications has been included. The contribution of the other authors to this work has been explicitly indicated below. I confirm that appropriate credit has been given within the thesis where reference has been made to the work of others. I am aware of the University's Guidance on the Use of Unfair Means (www.sheffield.ac.uk/ssid/unfair-means). This work has not been previously presented for an award at this, or any other, university.

Chapter 2

This chapter has been published as:

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The manuscript is reproduced in full in this thesis, with minor alterations. The overall contribution of authors was as follows: Conceptualization, M.M.H.W. and D.P.E.; Methodology, M.M.H.W., D.P.E., and L.R.C.; Formal Analysis, M.M.H.W.; Data Curation, M.M.H.W.; Writing – Original Draft, M.M.H.W.; Writing – Review & Editing, M.M.H.W., D.P.E., and L.R.C.; Visualization, M.M.H.W; Supervision, D.P.E., and L.R.C.

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1 Thesis introduction

1.1 Sustainability and trade-offs in sustainability

What is sustainability? The term 'sustainability' reportedly has its roots in forestry, where the term was first used in the 1700s to describe how forests should be managed such that there was a balance between logging trees and leaving enough trees to maintain timber volumes (Du Pisani, 2006; Scoones, 2007). In the latter half of the 20th century, the emerging modern environmental movement led by the first environmental non-government organisations (NGOs) and anxieties about the limits to economic growth brought ecological concepts into mainstream discussions of economic development (Du Pisani, 2006; Scoones, 2007). The concept of sustainable development gained popularity in the 1980s, bridging the fields of development and ecological conservation as well as highlighting their interdependence (Du Pisani, 2006). The 1987 Brundtland report, commissioned by the United Nations (UN), solidified the commonly cited definition of sustainable development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987, p. 41). The report outlined a paradigm of the three interlinked dimensions of sustainability – environmental, social, and economic – prescribing that economic development must account for social equity and environmental concerns (WCED, 1987; Briant Carant, 2017).

The concept of sustainable development based around the three dimensions of sustainability gained even wider spread with the adoption of the UN Sustainable Development Goals (SDG) in 2015 (GRI, UNGC and WBCSD, 2015; UN, 2015; Hacking, 2019). The SDGs are a list of 17 broad goals, comprising 169 quantitative and qualitative socioeconomic and environmental targets (Pradhan *et al.*, 2017). In relation to this thesis, which looks at sustainability in the context of commodity crop supply chains and agricultural expansion, the most relevant goals include but are not limited to: Decent Work and Economic Growth (SDG8); Industry, Innovation, and Infrastructure (SDG9); Responsible Consumption and Production (SDG12); and Life on Land (SDG15) (UN, 2015). Promoting sustainable agriculture is also part of

SDG2 (Zero Hunger), with targets such as the doubling of agricultural productivity and incomes of small-scale producers (Target 2.3), sustainable food production systems and resilient agricultural practices (Target 2.4), and investments in rural infrastructure (Target 2.a) (UN, 2015).

Due to the integrated and interdependent nature of poverty alleviation, economic progress, and environmental protection goals, there are many interactions between the SDGs (ICSU, 2017). These interactions can be positive, where progress in one goal is correlated to progress in another, or negative, where progress in one goal leads to downgrading in another goal. Positive interactions among SDGs are termed 'synergies', while negative interactions are termed 'trade-offs' (Pradhan *et al.*, 2017). In their systematic study of correlations between changes in SDG indicators reported by UN member governments over time, Pradhan *et al.* (2017) found that for most countries synergies were more prevalent than trade-offs within and among the SDGs. Interestingly, the SDGs I identified as most relevant to this thesis (SDGs 8, 9, 12, and 15) were found by Pradhan *et al.* (2017) to be associated with a high number of trade-offs across SDGs. The authors explained that most of the observed trade-offs were tied to the unsustainable development paradigm where improvement in socioeconomic standards relies on economic growth, which comes with increases in carbon and material footprints (Pradhan *et al.*, 2017). In their modelling study, Scherer *et al.* (2018) found that pursuing social goals (SDG1 (No Poverty) and SDG10 (Reduced Inequalities)) is generally linked with higher carbon emissions, land stress, and water scarcity (SDG13 (Climate Action), SDG15 (Life on Land), and SDG6 (Life Below Water)) – although interactions vary widely among countries. This is because those social goals are linked to increasing household consumptions in developing countries (Pradhan *et al.*, 2017; Scherer *et al.*, 2018). Given increasing consumption, production, and trade of commodity crops globally, pursuit of sustainability must consider the trade-offs between the different dimensions of sustainability, to avoid undesirable outcomes for present and future generations of people living on the planet.

Murphy (2012, p. 20) presents equity as a central concept to define the social pillar of sustainability, defining equity as ‘the distribution of welfare goods and life chances on the basis of fairness’, including within nations, among nations, and between generations. Social sustainability and equity has been conceptualised in different ways by various authors (Murphy, 2012). Building on previous work assessing equity in sustainable development projects by Brown and Corbera (2003), McDermott, Mahanty and Schreckenberg (2013) proposed three dimensions for evaluating equity in conservation interventions: distributive, procedural and contextual. Distributive equity, or ‘equity in outcomes’ (Brown and Corbera, 2003), is concerned with the allocation of advantageous or disadvantageous outcomes, risks and responsibilities among different parties (McDermott, Mahanty and Schreckenberg, 2013). Procedural equity, or ‘equity in institutions and decision-making’ (Brown and Corbera, 2003), is concerned with the process of decision-making, such as conditions enabling fair participation and inclusion of all parties involved (McDermott, Mahanty and Schreckenberg, 2013). It concerns ‘the way in which projects and rules operate and whether all stakeholders are able to have a voice in the project’, such that equity is about participation as well as inclusion of different perspectives (Brown and Corbera, 2003, p. S46). Contextual equity, or ‘equity in access’ following Brown and Corbera (2003), is about socio-political or economic factors such as gender, ethnicity, and financial resources that impact both distributive and procedural equity, in terms of differentiated outcomes of sustainability interventions for different actors (distributive equity), or the abilities of different actors to access and participate in sustainability interventions and decision-making processes (procedural equity) (McDermott, Mahanty and Schreckenberg, 2013). Thus, all three dimensions of equity are interlinked and make up a comprehensive picture of social equity in sustainability interventions (McDermott, Mahanty and Schreckenberg, 2013). This conceptualisation of equity has subsequently been applied to study various commodity sustainability initiatives by other researchers (McDermott, 2013; Pinto and McDermott, 2013).

Equity forms a key concern in the Brundtland Report, which used the term ‘equity’ or ‘inequity’ thirteen times — not including one mention of equity in the financial sense[1] (WCED, 1987). The report recognises contextual equity as it emphasises the needs of the world's poor, stating that 'overriding priority should be given [to them]' while acknowledging that there are ecological limits to development (WCED, 1987, p. 41). The report also recognises the link between contextual/access equity and distributive equity. As explained by the report, inequitable access to resources can lead to worse environment and development outcomes for the poorer or less powerful classes (WCED, 1987). Moreover, the report describes how inequitable outcomes are exacerbated by ecological deterioration and climate change (WCED, 1987).

Despite the Brundtland Report's concern for equity, the subsequent SDGs have been criticised for not having justice at their core (Menton *et al.*, 2020). Krauss, Jiménez Cisneros and Requena-i-Mora (2022) argue that, among other problems, the indicators used to measure progress in SDGs obfuscate the greater material and carbon footprints of global north countries' lifestyles and consumption patterns, thus bringing into question the socio-ecological equity of SDGs in practice. Gupta and Vegelin (2016) found that the SDGs incorporated humanitarian concerns and had 'Reducing Inequality' as one of its goals (SDG10), but showed only vague commitment to securing equitable ecological outcomes and paid little attention to increasing participation of the poor in political processes that determine the trajectory of their development (i.e. procedural equity *a la* McDermott, Mahanty and Schreckenberg (2013)). Other researchers have also noted how the concept of sustainable development is too easily co-opted by businesses, enabling them to make claims of sustainability and social responsibility, but change very little in practice (Milne and Gray, 2013; Menton *et al.*, 2020).

International trade and global supply chains provide a mechanism for ecological inequities at the global scale (Murphy, 2012). One major issue is the outsourcing of the impacts of richer countries' production and extractive industries to poorer

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[1] Equity is also a financial term, referring to the value of assets after subtracting debts or the value of the company owned by shareholders (*'Equity'*, 2023). In this thesis, we refer to equity in the social sense.

countries (Murphy, 2012). Examples of this phenomenon include the relocation of industries in pursuit of greater profit margins to poorer, developing countries where environmental and labour regulations are neglected to protect their economic competitiveness in the global market (Faber and McCarthy, 2003), and the shifting of responsibility for carbon emissions from production of export goods to the producer countries (Pendrill *et al.*, 2019; Krauss, Jiménez Cisneros and Requena-i-Mora, 2022). FairTrade and Oxfam, two major international NGOs, argued that conventional trade models have massively increased inequality despite the growth of global markets, and have not been able to provide smallholder farmers and workers a living income (Fairtrade International, 2018; Willoughby and Gore, 2018). Due to their role in the global economy, provision of employment, and responsibility for social and environmental impacts, international supply chains and multinational corporations play key roles in addressing sustainability challenges across all three dimensions (Thorlakson, de Zegher and Lambin, 2018).

In particular, efforts to make commodity crop supply chains more sustainable and equitable need to pay attention to the roles and needs of smallholder farmers. Smallholder farmers have been defined as 'farmers with incomes generated primarily from natural resources whose property size is below the national average' (Grabs *et al.*, 2021, p. 6). Smallholders make up at least 75% of rural populations in Asia, Africa, and Latin America (Zimmerer, Lambin and Vanek, 2018). As 75-80% of the world's poor are rural dwellers and 50-65% of poor adults rely on agriculture for income, smallholder farmers and agricultural workers are demographically a key target for many SDGs covering goals on poverty, food security, health, and ecological conservation (Castañeda *et al.*, 2016; Zimmerer, Lambin and Vanek, 2018). Moreover, smallholders are important producers of tropical commodity crops: they are responsible for 46% and 28% of oil palm cropland in Indonesia and Malaysia (Bakhtary *et al.*, 2020), which make up 53% and 27% of global supply, respectively (Ritchie and Roser, 2021); over 90% of West African cocoa production, which makes up 75% of the global production (Bakhtary *et al.*, 2020); and 60% of coffee production globally (Rushton, 2019). Smallholder agriculture can play both negative and positive roles in ecological sustainability. On the one hand, smallholder agriculture can be a source of deforestation and land degradation – albeit typically due to wider political and economic factors (Grabs *et al.*, 2021). On the other hand, smallholder farms can harbour social-ecological systems supporting agrobiodiversity and 'critical interfaces' with wildlife habitat (Zimmerer, Lambin and Vanek, 2018, p. 30). Given their linkages to the global sustainability agenda, smallholder farmers should be included in discussions of social and ecological equity (Zimmerer, Lambin and Vanek, 2018; Grabs *et al.*, 2021; Krauss and Krishnan, 2021).

In this thesis, I use the terms 'sustainable' and 'sustainability' to describe the desired outcome of the process of sustainable development (Robertson, 2017). While the conceptualisation of sustainability as balancing the three dimensions of 'people, planet, and profit' is not without flaws (see critiques by Milne and Gray (2013) and Menton *et al.* (2020)), it is widely used by academics (Pereira and Martins, 2021), policymakers (Briant Carant, 2017), and businesses (WBCSD *et al.*, 2002; Milne and Gray, 2013). Thus, I continue to use this conceptualisation of sustainability to frame this thesis, cognisant of the challenges of managing sustainability trade-offs associated with this framing of sustainability. The following subsections of this introductory chapter will describe in greater detail the ecological and social impacts of tropical commodity agriculture and corporate sustainability initiatives developed to address these issues (1.2), introduce the context for the case study of natural rubber and sustainability initiatives for natural rubber (1.3), and how I approached the question(s) of sustainability in the natural rubber supply chain in this thesis (1.4).

1.2 (Un)sustainability of tropical commodity agriculture

Tropical forests harbour high concentrations of biodiversity (Dirzo and Raven, 2003) and one-fourth of global carbon stocks (Bonan, 2008), with the potential to continuing sequestering significant amounts of carbon despite global warming (Pennisi, 2020). The clearance and degradation of tropical forests have tremendous negative impacts on biodiversity across all taxonomic groups and regions (Gibson *et al.*, 2011), as well as major implications for avoiding and reducing carbon emissions (Maxwell *et al.*, 2019; Pennisi, 2020). Deforestation directly impacts biodiversity by removing habitat for forest-dependent species (Fitzherbert *et al.*, 2008; Symes *et al.*, 2018), while both deforestation and fragmentation intensifies anthropogenic disturbance such as hunting, trapping, logging, and fires in remaining forest patches (Barlow *et al.*, 2016). In monetary terms, tropical forests provide an average monetary value of $5264 per hectare (ha) per year (in international dollars at 2007 price levels) for their ecosystem services ranging from provision of food, raw materials, medicine, and genetic diversity, in addition to regulation of air and soil quality, pollination, and climate, as well as cultural values such as recreation (de Groot *et al.*, 2012).

Despite widespread recognition of their importance in maintaining biodiversity, mitigating climate change, and provisioning of other ecosystem services, tropical forests continue to be threatened by anthropogenic pressures and economic drivers (Turubanova *et al.*, 2018). Increasing demand for food, fuels and commodities as populations grow and develop contribute to pressures on tropical forests (Gibbs *et al.*, 2010; Phalan *et al.*, 2013). Agricultural cropland in the tropics expanded by more than 100 million hectares (ha) in the 1980s and 1990s, with more than half of this agricultural expansion occurring in tropical forests (Gibbs *et al.*, 2010). Tropical cropland continued to expand at a rate of approximately 4.8 million hectares per year from 1999-2008 (Phalan *et al.*, 2013). Tropical forest loss during a similar timeframe (2000-2010) was driven by commercial agriculture (including pasture) (40% of deforestation) and local/subsistence agriculture (33%), while urbanisation, infrastructure and mining together accounted for the remaining 27% of deforestation (Hosonuma *et al.*, 2012). Deforestation for agriculture exacerbates extinction risks for vulnerable tropical species (Tilman *et al.*, 2017) and undermines crucial, time-sensitive efforts to limit climate change (Mackey *et al.*, 2020).

Of particular concern are the expansion of globally-traded commodity crops like oil palm, rubber, soy bean, cocoa, and coffee. Tropical forest loss in the 2000s was positively correlated with growing urban populations and increased exports of agricultural products in 41 tropical countries and was not associated with rural population growth, suggesting that urban and global demand for agricultural goods were the underlying driver of deforestation (Defries *et al.*, 2010). Their findings indicate that the outsourcing of ecological impacts from the rich to the poor via international trade, i.e. the 'export of pollution' (Murphy, 2012) also occur at the sub-national level. More recently, a study quantified carbon emissions from deforestation due to agricultural expansion during 2010-2014, and found that international trade drove 26-39% of emissions attributed to deforestation (Pendrill *et al.*, 2019). Other studies have also demonstrated how the biodiversity impacts of agricultural expansion, typically in tropical developing countries, were quantifiably linked to export commodities consumed in developed countries (Lenzen *et al.*, 2012; Chaudhary, Pfister and Hellweg, 2016; Green *et al.*, 2019). Thus, policies and sustainability initiatives to prevent deforestation and biodiversity loss must account for rising resource consumption and associated demand for export-oriented agricultural commodities, as well as strategies on the production side, such as conservation land-use planning and increasing the coverage of protected areas (Defries *et al.*, 2010; Phalan *et al.*, 2013; Pendrill *et al.*, 2019).

Commodity crops are also linked to socioeconomic and equity issues in producer countries, which are usually developing countries (Page and Hewitt, 2001; Zoomers, 2010; Mithoefer *et al.*, 2017). While modernization of agriculture and global trade are important strategies for developing the economies of poor rural communities, they are often associated with negative socio-ecological impacts (Dou *et al.*, 2020). Land grabs by foreign investors or agribusinesses lead to the displacement of local communities and their livelihoods, violating or disrupting community and customary land-use rights, along with labour exploitation, environmental damage, and increased socio-political tensions (Zoomers, 2010; Malkamäki *et al.*, 2018). Volatile commodity prices worsen income insecurity for smallholder farmers, exacerbating global and national inequalities between the richer and the poorer classes (Brown and Gibson, 2006). Income insecurity also means food insecurity for the poorest households in the face of rising food prices (Häberli and Smith, 2014). Volatile commodity prices intensify inequities in the commodity value chain, as downstream players capture most of the profit from low commodity prices, while small farmers are less able to respond to market changes (Brown and Gibson, 2006). Moreover, in countries with weak governance, commodity booms increase incentives for corruption (van der Ploeg, 2011). In turn, socioeconomic stresses in producer countries tend to mean that environmental concerns take a backseat, creating a negative feedback loop for sustainability (Brown and Gibson, 2006).

In light of these issues, there is an urgent need to find ways to balance ecological, social, and economic needs in tropical commodity agriculture. As many sustainability considerations such as climate change transcend national boundaries, quantitative, spatially explicit analyses that analyse trade-offs at global or regional levels are useful for informing international policies and optimising targets of global conservation efforts. For example, Johnson *et al.* (2014) identified a strategy to minimise global carbon trade-offs from agricultural expansion via selectively expanding agriculture land on the margin of current cropland, which would conserve about 6 billion metric tons of carbon compared with unselective business-as-usual scenarios and still meet agricultural demand. In a different study, Carrasco *et al.* (2017) identified the spatial distribution of economic trade-offs between agricultural expansion and tropical deforestation. They identified areas across the tropics where the economic value of agricultural expansion exceeds the estimated ecosystem services value and carbon emissions of tropical forest conversion, suggesting that conservation schemes in these areas may not be economically efficient (Carrasco *et al.*, 2017).

At the same time, growing public awareness of sustainability issues in global agricultural commodity supply chains has inspired private sector actors to adopt burgeoning voluntary sustainability standards, which have been defined as ‘norms and standards designed to ensure that a product is produced, processed or transported sustainably in order to contribute to specific environmental, social and economic targets.’ (UNCTAD, 2020, p. VI). There are different types of voluntary sustainability standards, mostly led by private sector actors or non-governmental entities (UNCTAD, 2020). They can come in the form of individual company codes of conduct (e.g. Unilever’s Responsible Sourcing Policy), sectoral standards created by industry associations (e.g. GlobalGAP), certification schemes led by civil society organisations (e.g. Rainforest Alliance) or the public sector (e.g. United States Department of Agriculture (USDA) Organic), and multi-stakeholder initiatives (e.g. commodity sector roundtables like the Roundtable for Sustainable Palm Oil (RSPO)) (Lambin *et al.*, 2018; UNCTAD, 2020). Some certification schemes are also multi-stakeholder initiatives, such as Fairtrade and Forest Stewardship Council (FSC) (Lambin *et al.*, 2018; UNCTAD, 2020). Voluntary sustainability standards guide production by defining criteria for production processes to meet sustainability metrics (UNCTAD, 2020) and their coverage of social, environmental and economic goals vary (Krauss and Krishnan, 2021). Many companies rely on certification schemes to implement their sustainability policies or to verify their compliance to sectoral standards (Forest Trends, 2015).

Have voluntary sustainability standards been successful in meeting sustainability goals? In terms of adoption, companies embrace the economic incentives of adopting these standards, such as increased brand reputation, which allow them access to premium markets where consumers are willing to pay more for a more ethical or sustainable product (UNCTAD, 2020). While adoption of sustainability standards for agricultural commodities is increasing, much cropland is not yet covered by eco-certification schemes (Tayleur *et al.*, 2017; Willer *et al.*, 2019). A systematic review of tropical agricultural commodity certification schemes found that certification was associated with more positive outcomes than negative outcomes for the environment and small-scale producers (DeFries *et al.*, 2017). Another study systematically reviewed effects of certification schemes for agriculture on socio-economic outcomes in low and middle income countries, finding positive effects on prices and income from certified produce, but not on wages or household income (Oya *et al.*, 2017). Both studies noted that their conclusions were limited by the paucity of data (DeFries *et al.*, 2017; Oya *et al.*, 2017).

The political sciences literature tended to be more critical of voluntary sustainability standards and multi-stakeholder initiatives – various researchers argued and provided empirical case studies from different commodity supply chains to illustrate how these initiatives can or have favoured the voices and priorities of powerful actors over those of local peoples and smallholders (Schouten, Leroy and Glasbergen, 2012; Cheyns, 2014; Ponte, 2014; de Bakker, Rasche and Ponte, 2019), while benefits tend to be limited to a segment of farmers that have capabilities to participate in these initiatives (Nelson and Phillips, 2018; Krauss and Krishnan, 2021). Leakage of unsustainable practices due to incomplete coverage of sustainability standards (e.g. not all farms or companies have adopted these standards) is another major challenge to their effectiveness (Mithoefer *et al.*, 2017; Lambin *et al.*, 2018). Grabs *et al.* (2021) attempts to address some of these challenges by providing principles to design and evaluate supply chain policies that maximise synergies between environmental effectiveness and access equity. In their assessment of sustainability initiatives employed by the largest firms in the agricultural commodity sectors with highest deforestation risks (oil palm, soy, cattle, and cocoa), Grabs *et al.* (2021) found that initiatives typically favoured environmental effectiveness over access equity but also often addressed neither of the two, suggesting a gap between stated commitments and their implementation. In short, more research is needed to better understand ways in which sustainability initiatives can become more effective at addressing sustainability trade-offs and better advance equitable conservation outcomes for all (Mithoefer *et al.*, 2017; Lambin *et al.*, 2018; Nelson and Phillips, 2018).

1.3 Natural rubber

This thesis focuses on natural rubber, one of the less well-known tropical commodity crops. Natural rubber is sourced from the latex of the Pará rubber tree (*Hevea brasiliensis* Müll. Arg.), distinguishing it from synthetic rubber which is derived from petroleum. Due to its non-edible nature, natural rubber and its associated sustainability issues have received relatively less media and academic attention than other tropical crops (Kennedy, Leimona and Yi, 2017). Natural rubber was considered a ‘minor’ crop in regards to global distribution of cropland (Leff, Ramankutty and Foley, 2004). It was not included in the European Union (EU)’s list of critical raw materials until 2017 (ETRMA, 2020). However, natural rubber is a critical raw material for many industries including medical and industrial, but especially in transportation, due to the necessity of a certain percentage of natural rubber in tyres (about 40% in car tyres and up to 100% in high performance tyres for jets, airplanes, and trucks), which at the moment cannot be substituted by synthetic rubber (Cornish and Cherian, 2021).

Natural rubber (henceforth simply 'rubber') production area globally has expanded from 6.5 million ha in 1990 to 12.9 million ha in 2020 (Figure 1, Table 1). While the most rapid and extensive expansion of rubber occurred in the Mekong region in mainland Southeast Asia, rubber expansion has also accelerated in Africa in recent years particularly in Côte d'Ivoire (Figure 1, Table 1, Table 2; see also Gitz *et al.* (2020)). Thailand, Indonesia, Vietnam, Côte d'Ivoire, and China were the top five countries with the greatest expansion in terms of area from 1990 to 2020 (Table 2). Expansion accelerated in the Mekong region alongside a dramatic rubber price boom in the 2000s, but has slowed down since rubber prices fell in the mid-2010s (Hurni and Fox, 2018). While rubber demand declined in 2019-2020 due to the Covid-19 pandemic, industry models predict modest growth for the next 10 years, albeit with reduced demand until 2024 (Gitz *et al.*, 2020).

Rubber is a predominantly smallholder crop – the International Rubber Study Group reported that smallholdings make up 90% of global rubber production and area (IRSG, 2019, as cited in Gitz *et al.*, 2020). Fox and Castella (2013) reported that smallholders dominated rubber holdings in Malaysia (93%), Myanmar (90.5%), Thailand (90.5%), India (88.4%), Indonesia (85%), and Sri Lanka (64%) – although they also noted that the threshold for defining smallholders varied by country (<8 ha in Myanmar to <40.5 ha in Malaysia). In some non-traditional rubber producing countries, smallholders made up a smaller share of rubber holdings, e.g. 50% in China, 32% in Vietnam and Cambodia, and 23% in Laos (Fox and Castella, 2013). In the latter countries (Laos and Cambodia), and in some African countries, industrial-scale plantations or estates dominate production (Gitz *et al.*, 2020).

While rubber is typically not listed as a top deforestation-risk agricultural commodity (namely oil palm, soy, cattle, and sometimes timber, cocoa, or coffee – see Jopke and Schoneveld (2018) and Grabs *et al.* (2021)), rubber expansion in the past two decades

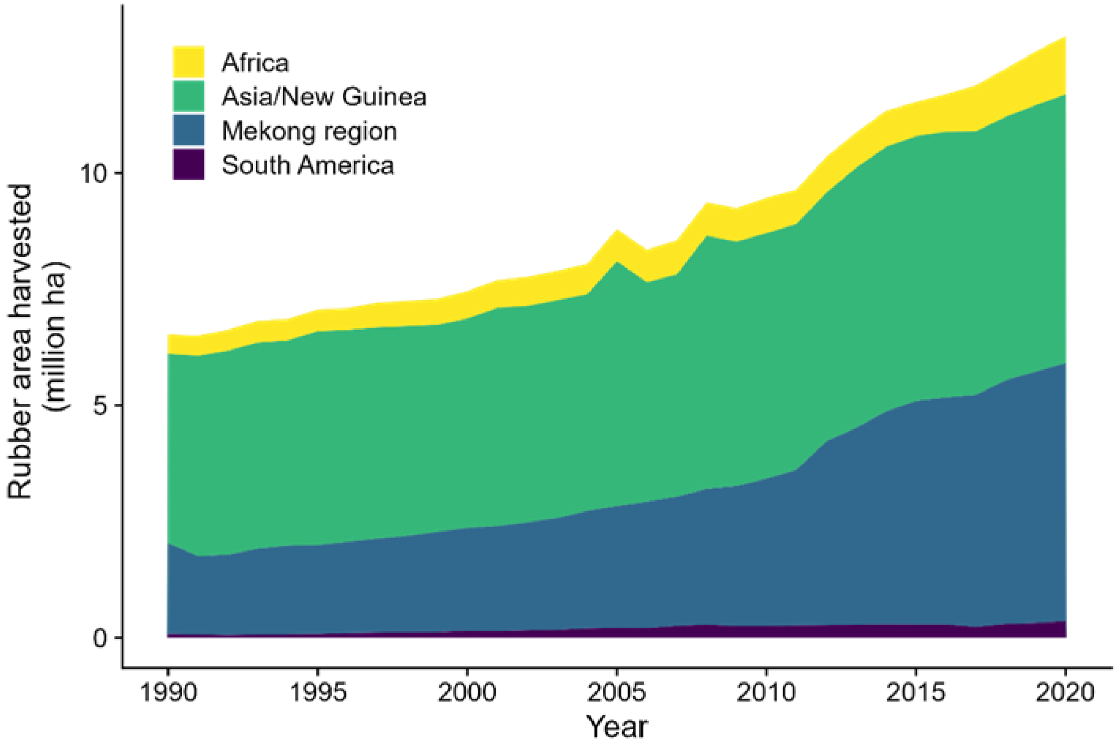

Figure 1. Rubber expansion patterns by region from 1990 to 2020, as measured by rubber area harvested. Countries included in the Mekong region category were Cambodia, China, Laos (data only available since 2013), Myanmar, Thailand, and Vietnam. Data from FAO (2022).

Table 1. Rubber area harvested in 1990 and 2020 (in million ha), rubber area expanded from 1990 to 2020 (in million ha), and annual rubber area expansion rates at different periods between 1990 and 2020 (in million ha per year), by region. Data from FAO (2022).

Region	Area harvested (million ha)		Area expanded 1990-2020 (mil. ha)	Annual expansion rate (million ha per year)			
	1990	2020		1990-2000	2000-2010	2010-2015	2015-2020
Africa	0.415	1.258	0.843	0.018	0.017	-0.005	0.104
Asia/New Guinea	4.077	5.780	1.704	0.043	0.078	0.083	0.017
Mekong region	1.946	5.549	3.603	0.026	0.096	0.327	0.149
South America	0.087	0.355	0.268	0.006	0.010	0.008	0.013
All	6.525	12.943	6.419	0.093	0.201	0.412	0.283

Table 2. Rubber area harvested in 1990 and 2020 (in thousand ha), rubber area expanded from 1990 to 2020 (in thousand ha), and annual rubber area expansion rates at different periods between 1990 and 2020 (in thousand ha per year), by country. Countries are sorted based on greatest area expanded from 1990 to 2020. 'NA' = no data available. Data from FAO (2022). DRC = Democratic Republic of the Congo; CAR = Central African Republic.

Country	Area harvested ('000 ha)		Area expanded 1990-2020 ('000 ha)	Annual expansion rate ('000 ha per year)			
	1990	2020		1990-2000	2000-2010	2010-2015	2015-2020
Thailand	1400.00	3292.67	1892.67	6.21	46.72	106.24	9.20
Indonesia	1865.61	3726.17	1860.57	53.44	104.51	50.88	2.90
Vietnam	81.10	728.76	647.66	15.04	20.71	161.06	20.59
Côte d'Ivoire	43.84	577.58	533.74	2.21	10.15	227.14	167.92
China	390.00	745.00	355.00	3.14	15.56	69.73	4.17
Myanmar	40.17	350.55	310.38	2.18	12.46	353.78	24.77
Cambodia	35.00	292.50	257.50	-0.09	0.43	226.24	162.96
Bangladesh	13.00	218.59	205.59	1.00	3.50	697.79	19.13
Philippines	86.33	230.72	144.39	-0.53	5.77	174.70	3.65
Nigeria	225.00	358.81	133.81	10.50	3.05	8.46	0.25
Brazil	59.34	163.25	103.91	3.47	3.09	53.16	13.39
Guatemala	15.26	110.40	95.14	2.53	6.04	155.46	6.44
Liberia	40.00	107.83	67.83	6.50	-3.05	NA	NA
Ghana	12.00	58.22	46.22	0.09	1.26	112.59	112.86
DRC	40.00	66.28	26.28	-2.10	3.10	152.12	38.36
India	289.10	314.90	25.80	11.09	7.70	14.00	-30.94
Mexico	10.03	33.04	23.01	0.23	0.36	85.87	44.59
Cameroon	37.00	58.71	21.71	0.29	1.39	39.86	5.26
Ecuador	2.36	12.87	10.51	-0.01	0.86	466.08	-0.11
Gabon	7.08	15.04	7.96	0.37	0.43	50.65	-7.01
Guinea	6.00	11.76	5.76	0.03	0.42	83.79	1.79
Papua New Guinea	6.40	9.44	3.04	0.24	0.43	31.59	-18.51
Brunei	3.17	4.17	1.00	0.01	0.05	21.85	3.66
Congo	2.52	2.58	0.06	-0.10	0.09	75.02	-3.45
CAR	1.22	1.22	0.00	-0.02	0.02	-5.41	26.74
Dominican Republic	0.06	0.05	-0.01	0.00	0.00	-38.57	6.98
Sri Lanka	199.05	137.29	-61.76	-4.10	-3.33	-23.46	13.48
Malaysia	1614.00	1139.14	-474.86	-18.33	-41.03	-24.90	6.03
Colombia	NA	35.82	NA	NA	NA	NA	419.10
Laos	NA	140.00	NA	NA	NA	NA	77.22

has been responsible for 5.2 million ha of forest loss in mainland Southeast Asia between 2003 and 2014 (Hurni and Fox, 2018) and nearly 21,000 ha of forest loss in the Congo Basin from 2011 to 2017 (Earthsight, 2018). From 2000 to 2020, nearly 52,000 ha of forest in Central and West Africa was converted to large-scale plantations owned by three international companies that supply rubber to tyre manufacturers (Global Witness, 2022). In comparison with other agricultural commodities, a recent analysis showed that 2.1 million ha of forest was replaced by rubber plantations from 2001 to 2015, on par with cocoa (2.3 million ha), coffee (1.9 million ha), and wood fibre (1.8 million ha), but less than forest conversion for cattle (45.1 million ha), oil palm (10.5 million ha), and soy (8.2 million ha) (Goldman *et al.*, 2020). Actual forest area replaced by rubber was likely much higher than 2.1 million ha, as the analysis only involved seven countries accounting for 40% of global rubber production while excluding other large producers like Thailand, Vietnam, and China due to lack of data (Goldman *et al.*, 2020). In 2022, the EU agreed to include rubber in its list of deforestation-risk commodities, requiring stricter due diligence by companies trading these commodities in the EU market (European Commission, 2022). Thus, there is wider consensus that deforestation is a key measure and a global concern for the ecological sustainability of rubber.

Deforestation for rubber drives negative impacts on biodiversity, including declines in bird, mammal, and invertebrate richness across Southeast Asia (Warren-Thomas, Dolman and Edwards, 2015; Cotter *et al.*, 2017), decreased plant species richness in China (Fu *et al.*, 2009; Meng *et al.*, 2012; Cotter *et al.*, 2014, 2017) and Sumatra, Indonesia (Beukema and van Noordwijk, 2004; Clough *et al.*, 2016), and replacement of forest specialists of conservation concern by widespread generalists in birds (Aratrakorn, Thunhikorn and Donald, 2006; Najera and Simonetti, 2010). While rubber trees are perennials and thus can sequester carbon, converting natural forest to rubber monoculture typically results in net carbon emissions especially from loss of soil carbon (Hauser *et al.*, 2015; Blagodatsky, Xu and Cadisch, 2016; Wang, Warren-Thomas and Wanger, 2020). Local-scale studies in Xishuangbanna, Southwest China, have also shown how rubber trees can deplete groundwater resources and increase surface water runoff (Hauser *et al.*, 2015; Ma *et al.*, 2019).

Socioeconomically, rubber expansion has played an important role in the development of rural economies (Fox and Castella, 2013; Min *et al.*, 2017). However, rubber expansion and production have also been linked to negative socioeconomic impacts, including income vulnerability, land conflicts, labour rights issues, and health risks (Kennedy, 2014; Aidenvironment, 2016), which are variously impacted by the social, political, institutional and economic contexts in which plantations are established (Gitz *et al.*, 2020). For example, estate rubber established by powerful or rich elites or foreign companies often results in land dispossession, or severe restrictions on access to land and forests, with little attention given to labour and living conditions of hired local or migrant tappers (Verité, 2012; Fox and Castella, 2013; Aidenvironment, 2016; Kenney-Lazar *et al.*, 2018). In contrast, smallholders who received adequate state support and who retained land rights, such as smallholders in Thailand and China, benefitted from increased incomes generated by rubber (Fox and Castella, 2013). Nevertheless, income vulnerability due to price volatility and the 6- to 7-year lag between planting and first harvest (Hauser *et al.*, 2015), inequitable market relations (Kopp and Sexton, 2019), and crop losses from environmental risks (e.g. weather, diseases) (Ahrends *et al.*, 2015; Min *et al.*, 2017), continue to be challenges for rubber smallholders worldwide. In short, while investors or owners of large scale rubber developments and downstream tyre manufacturers continue to reap the economic benefits of the demand for rubber products, local communities and smallholder farmers disproportionately bear the costs and risks of rubber expansion and production. In light of the above-defined understandings of equity in sustainable development (Brown and Corbera, 2003; McDermott, Mahanty and Schreckenberg, 2013), that means there are problematic and inequitable relations in the rubber supply chain which merit investigation.

Climate change is predicted to increase the economic and environmental risks of planting rubber in both traditional and non-traditional rubber planting regions – with non-traditional rubber regions having higher altitudes, typhoon risk, drought risk, and/or frost risk (Ahrends *et al.*, 2015). Warmer temperatures and drought are predicted to increase seedling mortality, delay tree growth and tapping commencement, reduce latex flow, and increase incidence of diseases (Jacob, 2020).

Increased unpredictability of rainfall disrupts latex harvesting routines and frequencies, reducing latex harvest (Ismail and Gohet, 2020). The rubber research institutes of major rubber producing countries as well as international agricultural research institutes are actively working to identify, breed, evaluate, and select clones that are tolerant to suboptimal climatic conditions and diseases while still maintaining high yield (Pinizzotto *et al.*, 2020). Promising clones adapted to country-specific conditions have been identified in India (Chaendaekattu *et al.*, 2021), Cambodia (Gohet, 2022), and China (He *et al.*, 2022), with ongoing work in Sri Lanka (Amarasekara, Withanage and Palihakkara, 2020). Climate-adapted agronomic practices such as increased mulching and decreased weeding to maintain soil moisture, increased irrigation, and intercropping young rubber with shade plants have also been identified and can be implemented immediately (Jacob, 2020). Nevertheless, the greater challenge will be how to effectively disseminate climate-adapted clones and information on best practices to both smallholders and industrial plantations.

To address the growing concern over environmental and social equity issues of rubber, several certification schemes and sustainability initiatives have been proposed over the past two decades, as reviewed by Kennedy (2014) and Kennedy, Leimona, and Yi (2017). Certification of rubberwood gained traction with the emergence of timber certification schemes like the Forest Stewardship Certification (FSC) in the mid-1990s (Kennedy, Leimona and Yi, 2017). A range of separate labels for different latex products emerged later to meet general consumer demand for ‘green’ products, but their standards and coverage of sustainability goals varied (Table 3) (Kennedy, 2014; Kennedy, Leimona and Yi, 2017). The most recent initiatives to emerge have been larger-scale efforts initiated by industry actors and targetting the whole rubber supply chain, namely the Sustainable Natural Rubber Initiative (SNR-i) by the International Rubber Study Group (IRSG), the Guidance for Sustainable Natural Rubber by the China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters (henceforth, the ‘CCCMC guidelines’), and the Global Platform for Sustainable Natural Rubber (henceforth, ‘GPSNR’) (Table 3).

Table 3. Non-exhaustive list of certification and sustainability initiatives for rubber and their targeted environmental and social criteria, expanding on Kennedy (2014).

Name	Product	Environmental criteria	Social criteria
GPSNR, founded by the Tire Industry Project – established 2018 (GPSNR, 2018a, 2018b)	Rubber supply chain	Founding principles include commitments to healthy, functioning ecosystems (avoid conversion, deforestation and degradation) and water management. Cross-cutting principles include traceability, transparent reporting, anti-corruption, grievance mechanism, auditing protocols, and support for training and education. Specific reporting requirements developed later (GPSNR, 2022).	Founding principles include commitments to land rights, labour rights, human rights (including poverty alleviation and improving smallholder livelihoods), and equity. Cross-cutting principles include traceability, transparent reporting, anti-corruption, grievance mechanism, auditing protocols, and support for training and education. Specific reporting requirements developed later (GPSNR, 2022).
Guidance for Sustainable Natural Rubber, by CCCMC – established 2017 (CCCMC, 2017)	Rubber supply chain	Pre-investment risk and impact assessment, including environmental suitability, presence of High Conservation Value (HCV) and High Carbon Stock (HCS) areas, and concerns about planting rubber on degraded land. Provides recommendations for risk prevention or management measures.	Pre-investment risk and impact assessment of social environment (country governance, civil society, community relations), land tenure rights (including indigenous rights), and economic stability. Provides recommendations for risk prevention or management measures.
Sustainable Natural Rubber Initiative (SNR-i), by the International Rubber Study Group (IRSG) – established 2014 (IRSG, 2014)	Rubber supply chain	Criteria includes: favouring natural fertilisers and biological pest control, minimising chemicals; not establishing plantations within protected areas or habitats of protected species and creating buffer zones; and complying with legal and customary water rights and treating wastewater.	Labour rights (no child or forced labour, freedom to unionise)
Global Organic Latex Standard (GOLS), by Control Union – established 2012 (Control Union, 2017)	Unprocessed raw latex, intermediate and final products made from latex	Waste and pollution management, wastewater treatment, and energy and water conservation.	Labour rights (including safe working conditions, no child or forced labour, freedom to unionise)
Fair Rubber Association – established 2012 (Fair Rubber, 2021, 2023a)	Mattresses, pillows, shoes, condoms, gloves, hot water bottles, balls, balloons, rubber bands	Criteria since 2018: Good tapping practices, soil productivity, waste management, forest impact assessment, biodiversity management plan, no illegal hunting.	Criteria since 2018: Land tenure rights, evaluate social impacts on local community, regular consultations with local community, grievance mechanism, transparency, detailed labour rights (health and safety, no child or forced labour, freedom to unionise, no discrimination, gender equality, living wages)

Name	Product	Environmental criteria	Social criteria
EU tyre labelling regulation – enacted 2009 (EU Parliament, 2009)	Tyres	Requires tyres to have labels displaying the fuel efficiency. The 2021 update emphasised the link between fuel efficiency and carbon emissions (EU Parliament, 2020).	Requires tyres to have labels for health and safety (wet grip and external rolling noise of tyres).
USDA Organic – established in 2002 (USDA, 2017)	Raw latex	Biodiversity (conserve wetlands, woodlands, and wildlife), soil and water quality; no synthetic fertilisers, sewage sludge, irradiation and genetic engineering.	N/A
eco-INSTITUT QLatex Label or QUL – established in mid-1990s (QUL, 2017)	Mattresses	Certified products are tested for absence of chemicals (e.g. volatile organic compounds (VOC), pesticides, heavy metals hazardous to health, PCP and nitrosamines). Not explicitly linked to environment.	Certified products are tested for absence of chemicals (e.g. volatile organic compounds (VOC), pesticides, heavy metals hazardous to health, PCP and nitrosamines), to meet consumer demand for 'safe for health' mattresses
Forest Stewardship Council (FSC) certified natural rubber – FSC established in 1993; unclear when they started certifying latex (FSC, 2017)	Latex, rubberwood	Criteria include 'maintaining, conserving and/or restoring ecosystem services and environmental values'; and 'avoiding, repair or mitigate negative environmental impacts'. Standards and evaluation procedures are provided in greater detail in different documents.	Criteria include social and economic wellbeing of workers and local communities; land rights; and long-term economic viability and social/environmental benefits. Standards and evaluation procedures are provided in greater detail in different documents.

In terms of the effectiveness of sustainability initiatives and certification schemes for rubber, most researchers are sceptical of their ability to create transformative change. Kennedy, Leimona, and Yi (2017) found that the business-oriented Global Organic Latex Standard (GOLS) created little additionality with their minimal environmental and social criteria, and that smallholders face prohibitive costs and barriers to qualify for certification without government support. Kenney-Lazar *et al.* (2018) reviewed both the Sustainable Natural Rubber Initiative and the CMCCC guidelines, finding the former guilty of greenwashing and not accounting for many socio-environmental impacts of rubber expansion and production. In contrast, the CMCCC guidelines have stronger language around socio-environmental sustainability, recognising the role of smallholders and power imbalances (Kenney-Lazar *et al.*, 2018). Nevertheless, the CMCCC guidelines have yet to gain foothold with its primary target audience, namely Chinese rubber companies with investments abroad (Yifan, 2022). Fair Rubber is a NGO-led certification scheme, which charges member companies a Fair Trade premium for latex produced by supplier partners who comply with its environmental and social criteria (Table 3). Similar to the CMCCC guidelines, Fair Rubber also suffers from having a very small market share and its Fair Rubber label is currently used by only about 30 companies to market their products despite having been established 10 years ago (Fair Rubber, 2022, 2023b). The limited uptake of CMCCC and Fair Rubber demonstrates the trade-off between stringent criteria and wider adoption that plagues voluntary sustainability standards (Lambin *et al.*, 2018).

The latest initiative, GPSNR, is a multi-stakeholder initiative but founded by industry actors, namely the Tire Industry Project (WBCSD, 2017). GPSNR departs from the other industry-led rubber supply chain sustainability initiatives by including smallholders in its decision-making body and having equity as a core principle in their vision of sustainability (GPSNR, 2020). With 70% of rubber used in tyres (Millard, 2019) and 65% of global tyre production capacity held by the 11 tyre-maker giants in the Tire Industry Project (WBCSD, 2017), GPSNR has larger potential for scaling up impact compared to Fair Rubber. However, GPSNR's impacts may be limited by selection bias, where only companies who are already compliant or close to compliance sign up to the initiative (Lambin *et al.*, 2018); or the leadership of powerful industry actors may influence the design of standards to suit their priorities rather than the priorities of the small-scale producers or smallholders (Krauss and Krishnan, 2021). GPSNR has not received much academic attention[2]. This literature gap suggests that there is opportunity for academic research to assess the ability of GPSNR to achieve different sustainability goals and address trade-offs, whether in terms of their stated goals or in their processes.

Other than rubber sustainability initiatives and certification schemes, previous studies have looked at the effectiveness of carbon payments to protect forests from rubber expansion (Yi *et al.*, 2014; Warren-Thomas *et al.*, 2018). Yi *et al.* (2014) estimated opportunity costs for carbon sequestration and reforestation by calculating the net present value (NPV) of rubber plantations in Xishuangbanna Province, China. Warren-Thomas *et al.* (2018) calculated the opportunity costs of not converting forest to rubber or other cash-crops in Cambodia for open and dense forests. Both studies concluded that carbon payments, at the carbon price levels when those studies were conducted, were hardly enough to halt rubber expansion into forests. Other studies have investigated intercropping and agroforestry practices as a way to mitigate environmental impacts (Chen *et al.*, 2017; Warren-Thomas *et al.*, 2020), diversify income sources (Min *et al.*, 2017; Stroesser *et al.*, 2018), build farmer capacity (Wibawa *et al.*, 2006; Wang, Warren-Thomas and Wanger, 2020), and reduce trade-offs between rubber production and loss of ecosystem services (Zheng *et al.*, 2019). However, in practice, uptake of rubber agroforestry practices has been generally limited, due to economic, labour, and policy constraints (Langenberger *et al.*, 2017; Wang, Warren-Thomas and Wanger, 2020). In short, there are still many open questions about how to address trade-offs and find synergies among the economic, ecological, and social dimensions of rubber expansion and production sustainability.

[2] A search on Scopus for "Global Platform for Sustainable Natural Rubber" on 12 January 2023 in the Title, Abstract, and Keywords yielded no articles.

Increasing the knowledge base around sustainability trade-offs in the context of rubber would also help inform existing rubber sustainability initiatives.

1.4 Thesis aims and overview

In this thesis, I consider the central question of how to meet ecological, economic, and social sustainability goals in rubber. I take a broad, multidisciplinary view, employing quantitative and qualitative methods to examine the interplay between biodiversity conservation concerns and economic concerns in rubber expansion as well as to investigate the role of equity in a multi-stakeholder initiative for the rubber industry.

I have chosen to focus on the sustainability of rubber cropland expansion and rubber production rather than end-of-life approaches. One reason is because the primary use for rubber is for manufacturing tyres, which both consume 70% of latex produced (Millard, 2019) and make up the bulk of rubber waste (Formela, 2021). However, vulcanised rubber is technically challenging and costly to reprocess for specific qualities required for making tyres; thus recycling rubber would have relatively minor impact on reducing demand for latex for making tyres (Araujo-Morera *et al.*, 2021; Formela, 2021). Another reason for focusing on the expansion and production phase of rubber is their more direct links to conservation impacts (e.g. deforestation, biodiversity loss, and pollution) (Ahrends *et al.*, 2015; Warren-Thomas, Dolman and Edwards, 2015) and social impacts (e.g. economic and equity issues related to land grabs and smallholder production) (Kenney-Lazar *et al.*, 2018; Gitz *et al.*, 2020), which are also the focus of most sectoral rubber sustainability initiatives (Table 3). Lastly, life cycle approaches typically rely on data for environmental impacts that are aggregated at the national level, not producing spatially resolved results (Mutel *et al.*, 2019). In contrast, spatially explicit approaches are able to marry rubber expansion data with other spatial datasets relevant to conservation concerns (e.g. biodiversity, carbon stocks, protected areas, and deforestation) and economic concerns (e.g. bioclimatic suitability for rubber production and accessibility of transport), allowing us to identify areas that have been or will be most impacted.

Working towards sustainability in tropical agriculture commodities requires that we address ecological, social, and economic aspirations in a more integrated manner by considering trade-offs and synergies as well as by considering different scales. Thus, this thesis aims to make conceptual and empirical contributions, using rubber as an example. The following paragraphs summarise the different approaches I took in each chapter to examine different combinations of rubber sustainability concerns.

In Chapter 2, I asked the question, ‘How can we simultaneously meet ecological and economic goals for sustainable rubber production and expansion?’ Previously, there was no information on which areas could provide opportunities to expand rubber without compromising biodiversity. This has been done for oil palm (Vijay *et al.*, 2016; Strona *et al.*, 2018), but not yet for rubber, despite projected expansion of rubber into regions of conservation concern (Ahrends *et al.*, 2015; Warren-Thomas, Dolman and Edwards, 2015). I conducted a feasibility assessment of reconciling rubber production with biodiversity conservation, by mapping out areas suitable for rubber cultivation and overlaying with extinction vulnerability, a composite index derived from IUCN Red List ranking of the extinction risk of birds, amphibians and mammals. I conducted this conservation spatial planning exercise for Africa, Asia, and New Guinea, identifying trade-offs between meeting market demand for new rubber plantations in the most productive lands and minimising biodiversity impacts for the most vulnerable species.

In Chapter 3, I asked the question, ‘Can rubber expansion be predicted based on market forces and other spatial/temporal factors?’ While previous studies have found links between rubber prices and rubber expansion models (Hurni and Fox, 2018; Grogan *et al.*, 2019), existing models attempting to predict or explain rubber expansion have not explicitly incorporated the role of markets (Li and Fox, 2012; Ahrends *et al.*, 2015; Xiao *et al.*, 2021). Using a spatial economic model of agricultural land rents, I simulated rubber expansion in mainland Southeast Asia from 2003-2014. The simulation comprised a period of dramatic rubber price boom and bust, allowing me to investigate the link between agricultural profits, rubber expansion, and deforestation at the national level for five countries. To gain further insight into the impact of conservation policies on rubber sustainability under market pressures, I also investigated the effectiveness of protected areas in preventing deforestation from rubber expansion, and how this might be affected by other factors such as the stringency of protected area categories, suitability for growing rubber, and accessibility to cities.

In Chapter 4, I shifted my focus towards the social dimensions of rubber sustainability, asking the question, 'How has inclusiveness evolved in a multi-stakeholder sustainability initiative for rubber?' With this question, I considered how corporate-led voluntary sustainability initiatives addressed issues of equity, especially in regards to smallholders. Focusing on the dimension of procedural equity (McDermott, Mahanty and Schreckenberg, 2013), also referred to as equity in institutions and decision-making (Brown and Corbera, 2003), I examined changes in inclusiveness in GPSNR, the latest industry-founded multi-stakeholder initiative for rubber sustainability. Here, inclusiveness refers to the degree of stakeholder inclusion and participation, thus enabling an assessment of procedural equity in the sustainability initiative (Schouten, Leroy and Glasbergen, 2012). Using document analysis, I conducted a qualitative case study of GPSNR, tracing the evolution of stakeholder inclusion and participation, paying particular attention to smallholders, in membership structures and decision-making processes of GPSNR over its first three years of operation. I chose GPSNR for my case study because it has not been studied in depth academically. It also claims to strive for greater inclusiveness by including smallholders along with civil society organisations and businesses in their membership, which calls for research attention to examine these claims.

Finally, in Chapter 5, I present a discussion of the findings from the previous chapters, highlighting overarching or recurrent themes, the linkages between chapters, and the implications of these findings for the literature and for the future of rubber agricultural sustainability. I reflect on the value and limitations of using a breadth of methods and disciplinary angles in this thesis, and provide examples of thinking more equitably for academics, businesses and policymakers.

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2 Reconciling rubber expansion with biodiversity conservation

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2.1 Summary

Over five million hectares of tropical forest were cleared across mainland Southeast Asia and sub-Saharan Africa for rubber plantations between 2003 and 2017 (Earthsight, 2018; Hurni and Fox, 2018). Millions of hectares of further clearance are predicted as rubber demand rises, with major consequences for biodiversity (Warren-Thomas, Dolman and Edwards, 2015). A key question is how to reconcile rubber expansion with biodiversity conservation. We assessed the feasibility of simultaneously meeting global future demand for rubber with conservation of extinction-threatened amphibians, birds, mammals, and reptiles. We compared the spatial congruence of rubber bioclimatic suitability with extinction vulnerability (Strona *et al.*, 2018) in Africa, Asia, and New Guinea, where large-scale rubber cultivation is viable, and simulated rubber expansion under different scenarios. We found no 'win-win' areas with highest rubber suitability and lowest extinction vulnerability. Projected rubber demand could be met by allowing expansion primarily in New Guinea and African Guinea. However, New Guinea has high ecosystem intactness and both regions are rich in endemics. Scenarios suggest converting only areas suitable for cultivation would cause the largest biodiversity losses, including endangered species, whereas prioritising conservation would result in only the conversion of highly unsuitable land. Compromise scenarios that balance production with conservation could cut biodiversity losses by two-thirds, protecting most threatened species, whilst maintaining high rubber suitability. Development of high-yielding hardy clones expands the amount of win-win areas, as well as suitable areas with high extinction vulnerability. These trade-offs reveal that clonal research and development, strategic corporate and government land-use policies, and rigorous impact assessments are required to prevent severe biodiversity losses from rubber development.

Keywords: Sustainable agriculture, sustainable agricultural production, tree plantations, land use change, tropical deforestation

2.2 Results and discussion

2.2.1 Rubber suitability and extinction vulnerability

We conducted a spatial assessment of whether future rubber expansion could be reconciled with biodiversity conservation by overlaying bioclimatic suitability for natural rubber (*Hevea brasiliensis*) with species extinction vulnerability. We generated the extinction vulnerability map using species distribution layers and IUCN Red List status of threatened amphibians, birds, mammals, and reptiles following the approach of Strona *et al.* (2018) (2.4 STAR Methods). We used this combined map to identify the extinction vulnerability of areas available for rubber expansion in Asia, which produces over 85% of global rubber, and New Guinea and Africa, which are both frontiers for new rubber developments. We excluded protected areas, unsuitable land cover categories, and known existing rubber from the areas available for expansion (2.4 STAR Methods). We did not include South America because the prevalence of rubber leaf blight (*Microcyclus ulei)* makes it unviable for large-scale expansion of rubber on the continent (Lieberei, 2007).

We found no 'win-win' areas for expansion that would serve both production and conservation needs. Of the land available for rubber expansion, just 0.1 Mha in Africa and none in Asia or New Guinea had high rubber bioclimatic suitability (> 0.8) (Figure 1). Among these highly suitable areas, none were minimal in extinction vulnerability (≤ 0.2) (Figure 1 and Table S1). To meet the projected rubber demand (2.45-3.90 Mha needed to fulfil demand to 2027 based on IRSG (2018); see 2.4 STAR Methods for estimation method), we would need to compromise on biodiversity by expanding into land with increased extinction vulnerability, or compromise on production by expanding into land with reduced suitability for rubber. We classified areas with medium suitability (> 0.4) and moderately low vulnerability (≤ 0.4) as 'areas of compromise', lands with potential for reconciling biodiversity with rubber expansion (Figure 1 and Table S1).

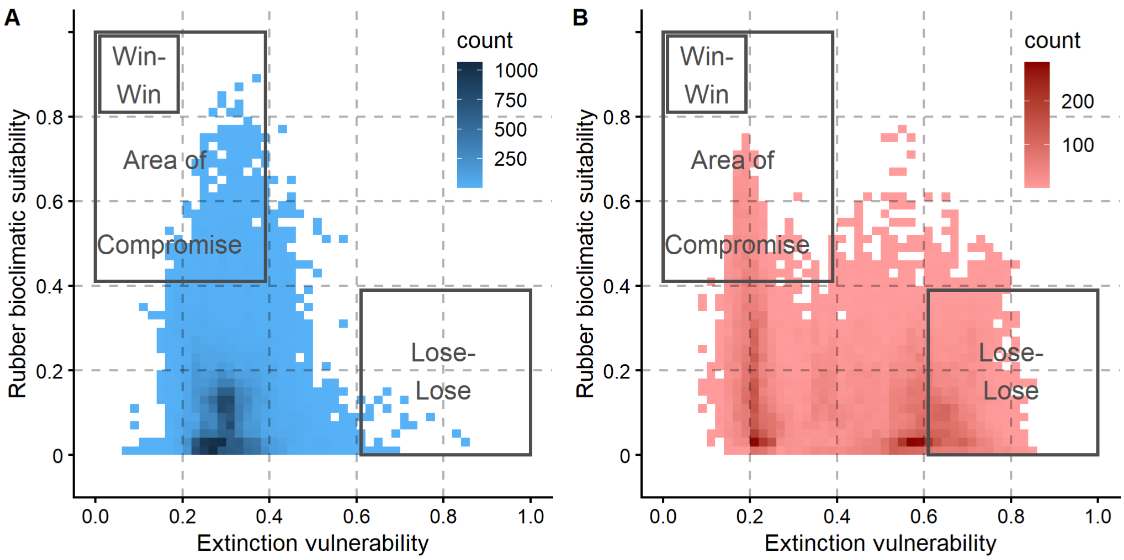

Figure 1. Distribution of rubber bioclimatic suitability and extinction vulnerability scores. Point density plot showing the number of 10 × 10 km grid cells available for rubber expansion as ranked by their suitability and vulnerability scores in Africa (A) and Asia and New Guinea (B). Dashed lines represent binning of the values into quintiles. We define 'win-win' areas as cells with suitability > 0.8 and vulnerability ≤ 0.2; 'area of compromise' as cells with suitability > 0.4 and vulnerability ≤ 0.4; and 'lose-lose' areas as cells with suitability ≤ 0.4 and vulnerability > 0.6. Only cells with suitability > 0.01 are shown (82,726 cells in (A) and 88,834 cells in (B) with suitability ≤ 0.01 were excluded from this plot for visual clarity).

We identified 18.8 Mha of land meeting our criteria for 'areas of compromise' (Table S1). Africa had fewer areas of compromise (7.3 Mha) compared to Asia and New Guinea (11.5 Mha), because Africa is less bioclimatically suitable for rubber (Table S1 and Figure 2). The largest areas of compromise were concentrated in southern New Guinea, particularly in Indonesian Papua. Next were areas of compromise in Africa, particularly in southern Guinea extending into Liberia, Central African Republic, southwest Ethiopia, and the southern Congolian forest-savannah region in the Democratic Republic of Congo (Figure 2 and Figure S1). Smaller areas of compromise were scattered across Asia (e.g. East Nusa Tenggara and Sumba Island, Indonesia; Sri Lanka) and in Africa (e.g. Ghana and Mozambique) (Figure 2 and Figure S1).

Mapping the approximate locations of documented rubber land concessions (The Land Matrix, 2018) suggests that many do not overlap with the identified areas of compromise (Figure S1). There are 213 concessions across Asia, 4 in New Guinea (all in Papua New Guinea), and 71 across Africa (The Land Matrix, 2018). Examples of areas of compromise with few or no existing concessions are: southern New Guinea (no concessions mapped), Central African Republic (none), southwest Ethiopia (one), and southwest Democratic Republic of Congo (one; Figure S1). In such areas of compromise, there is room for rubber expansion with reduced impact on biodiversity and an opportunity for rural development, particularly for smallholder farmers. To promote sustainable rubber expansion in these areas, farmers should be supported to uptake sustainable rubber cultivation practices via agricultural extension services and technological advances. In other areas of compromise, including Liberia and Guinea (four concessions; Figure S1), rubber is already frequently planted.

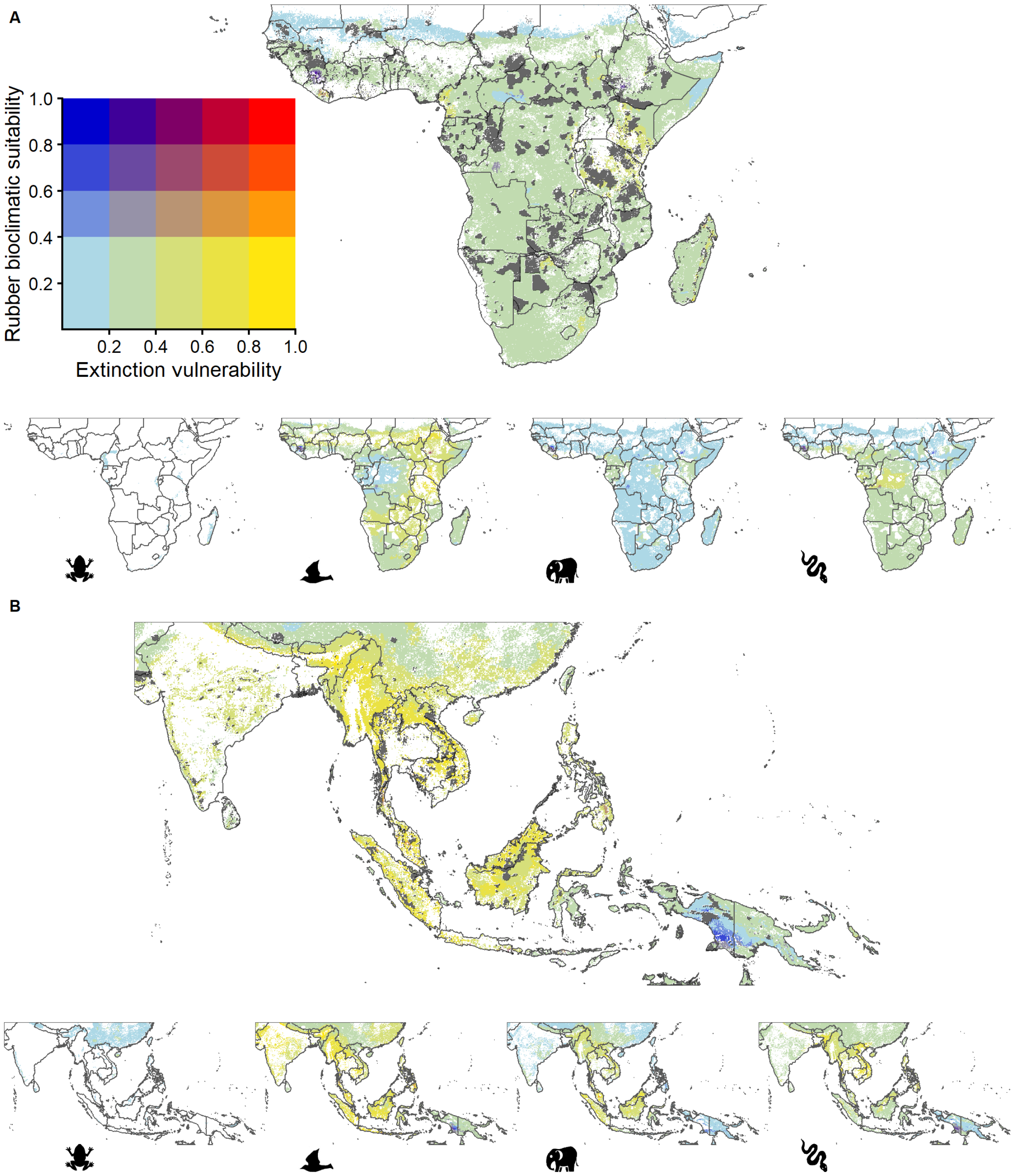

Figure 2. Spatial overlay of rubber bioclimatic suitability with extinction vulnerability. Map of rubber bioclimatic suitability and extinction vulnerability along two colour scales, divided into four classes for rubber suitability and five classes for extinction vulnerability for plotting. The main plots show extinction vulnerability scores aggregated for threatened amphibians, birds, mammals, and reptiles in Africa (A) and Asia and New Guinea (B). The subplots show extinction vulnerability scores for each taxonomic class separately. Protected areas are shaded in dark grey in the main plots.

While compromise areas are relatively low in extinction vulnerability, some are rich in presently unthreatened endemic species (WWF, 2012). New Guinea, Liberia, and the Congolian forest-savannah also represent less-disturbed areas with high ecosystem intactness, where developments should be avoided to maintain habitat integrity (Potapov *et al.*, 2017). Local- to national-level environment impact assessments should be conducted before any land clearing to avoid destruction of areas with high conservation values, which is likely to be required under the emerging Global Platform for Sustainable Natural Rubber (GPSNR) (GPSNR, 2019).

Although the area of compromise identified (18.8 Mha) is theoretically sufficient to meet rubber demand to 2027 (2.45-3.90 Mha, estimated from industry predictions (IRSG, 2018); 2.4 STAR Methods), this analysis does not account for competition with other crops. Expansion of other tropical crops, such as oil palm, cocoa, and coffee, would reduce the available area of compromise. Moreover, we have not considered climate change impacts on rubber productivity, which are predicted to worsen environmental conditions for > 50% of current and future rubber plantations in continental Southeast Asia (Ahrends *et al.*, 2015).

Large ‘lose-lose’ areas with high extinction vulnerability (> 0.6) and poor rubber suitability (≤ 0.4) were concentrated in Southeast Asia and Northeast India (109.5 Mha; Figure 1 and 2; Table S1). By contrast, Africa lacked substantial lose-lose areas (0.5 Mha). Mapping the approximate locations of known rubber land concessions suggests that such lose-lose areas have been the focus of rubber expansion (Figure S1), especially in Cambodia and Laos. This may reflect the development of drought- and cold-tolerant rubber clones (Ahrends *et al.*, 2015; Chen *et al.*, 2016), the distribution of high-value timber stocks that incentivise rubber conversion to obtain benefits from timber (Warren-Thomas *et al.*, 2018), or demonstrate the trend of more profitable oil palm plantations displacing rubber into marginal areas (Koh and Wilcove, 2008; Fox and Castella, 2013; Warren-Thomas, Dolman and Edwards, 2015). Government policies, weak governance, or political instability could also lead to rubber expansion in less suitable areas (Verité, 2012).

To account for the potential of drought- and cold-tolerant rubber clones enabling expansion into traditionally marginal areas, we produced a map of expanded suitability niche for rubber clones based on dry stress and cold stress conditions that, if met, should not reduce yields (Figure S2) (Ahrends *et al.*, 2015). We found 1,529 Mha in Africa and 457 Mha in Asia and New Guinea that, despite scoring low in suitability, should theoretically allow normal levels of rubber production (Figure S2). Relaxing bioclimatic constraints made areas available for rubber cultivation across West Africa, south of the Congo Basin, Mozambique, northern Madagascar, southern Africa, Indochina, Myanmar, and northeastern and western India. However, the resulting expanded niche map also identified some areas that are unlikely to be suitable for rubber cultivation, such as the Middle East and the high, dry plateaus in central Madagascar.

Overlaying the biodiversity maps with the expanded suitability niche suggests increased extinction vulnerability in some areas (e.g. Indochina and Northeast India) where hardy rubber clones can be cultivated without yield losses (Figure S3). Risk of areas with high vulnerability being converted also increases for birds in East Africa and birds, mammals, and reptiles throughout Indochina (Figure S3). However, in contrast with our original assessment where we found no win-win areas (Figure 2), expanding niches identified sufficient win-win areas to meet rubber demand: 22.6 Mha in Asia/New Guinea and 0.29 Mha in Africa met all dry/cold stress conditions and had low vulnerability (≤ 0.4) (Table S2 and Figure S3). This suggests that species impacts could be minimised by focusing on (1) developing high-yielding hardy clones that can be grown in less vulnerable areas; and (2) policy initiatives to restrict expansion in the most vulnerable areas.

2.2.2 Impact of rubber expansion on biodiversity

We simulated five scenarios of rubber expansion and compared their trajectories and biodiversity outcomes (2.4 STAR Methods). In Scenario 1 (*Production*), we optimised for rubber suitability and accessibility (travel time to the nearest city). In Scenario 2 (*Conservation*), we optimised for minimal extinction vulnerability of threatened species and low carbon loss (as measured by aboveground carbon stocks). In Scenario 3 (*Compromise*), we limited expansion to areas of compromise (Figure 1 and Figure S3). Within the areas of compromise, we determined the order of expansion by optimising for rubber suitability, accessibility, extinction vulnerability, and carbon. We did so following three varying sequences: compromise biodiversity first (Scenario 3a); compromise rubber suitability first (Scenario 3b); and compromise both simultaneously (Scenario 3c; Figure S4). As higher wages and competition for land from existing rubber and oil palm production might restrict expansion in Southeast Asia, we limited expansion in eleven Southeast Asian countries based on industry predictions of new rubber areas in those countries ('country-restricted' simulations; 2.4 STAR Methods). We then repeated the simulations without country restrictions ('unrestricted' simulations) in case economic conditions change in those eleven countries to enable a greater level of expansion.

Comparing the average rubber suitability of converted land across the different scenarios for the country-restricted simulations, Scenario 2 (*Conservation*) only converted land with extremely low rubber suitability (mean ± 1SE for first 7 Mha converted = 0.0001 ± 0.000004; Figure 3A). The conservation scenario is thus impractical for rubber expansion, with poor rubber suitability leading to lower yields and higher land area demands to meet production targets. While not as high as Scenario 1 (*Production*) (0.629 ± 0.012), the average suitability of land converted in Scenarios 3a-c (*Compromise*) were moderately high (3a = 0.595 ± 0.012; 3b = 0.529 ± 0.008; 3c = 0.591 ± 0.012; Figure 3A), suggesting higher acceptability to rubber producers. Average rubber suitability of converted land in Scenarios 1 and 3a-c was 6-8% higher in unrestricted simulations (Figure 3D).

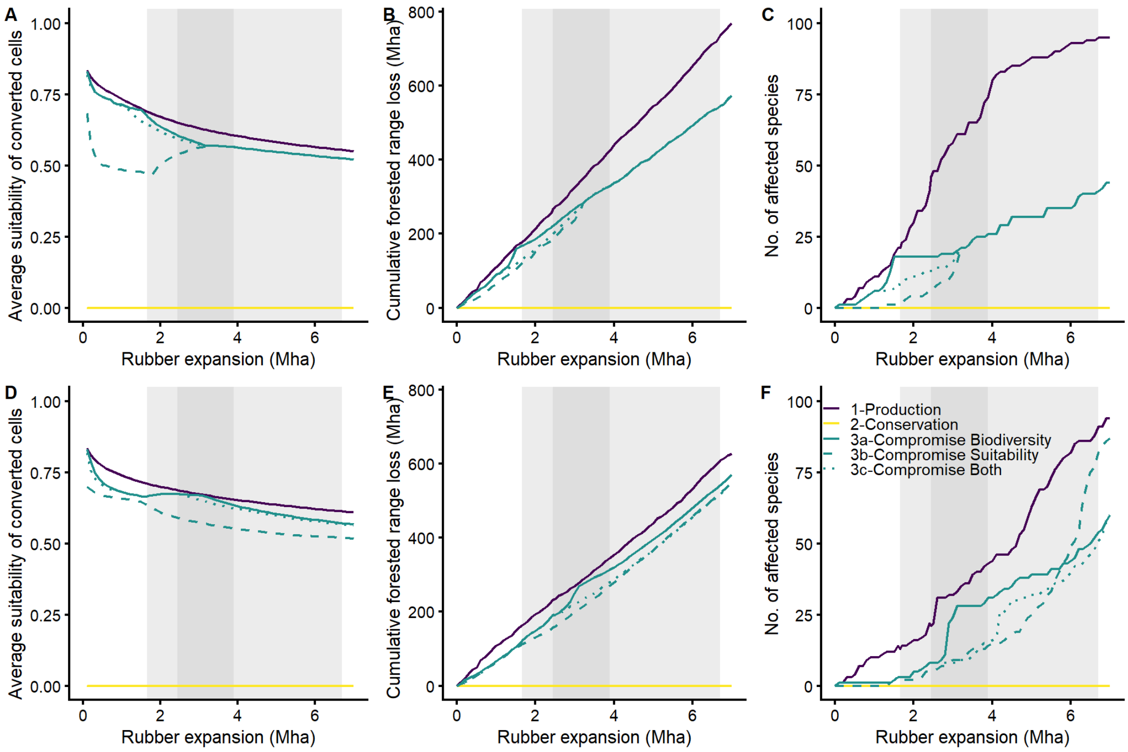

Figure 3. Impacts of rubber expansion scenarios. Impacts of five rubber expansion scenarios up to 7 Mha with country-restricted (A-C) and unrestricted (D-F) simulations, for average rubber bioclimatic suitability of converted cells (i.e. the projected new rubber area) (A, D); cumulative forested range loss in Mha, summed across all species (B, E); and cumulative number of species expected to lose ≥ 10% of their forested range (C, F). Average rubber suitability of projected new rubber area (A, D) was calculated from the suitability score of all the cells converted at each stage of the scenario. Cumulative forested range loss (B, E) was calculated by summing the range loss in Mha at each stage of the scenario, across 1155 forest-dependent amphibians, 2375 birds and 733 mammals whose ranges occur entirely within the study region. Cumulative number of species expected to lose ≥ 10% of their forested range (C, F) was calculated at each stage of the scenario from the same set of forest-dependent amphibians, birds, and mammals. Darker-grey background indicates the estimated land area needed to meet the rubber demand by 2027 (2.45-3.90 Mha); paler-grey background represents the lower and upper bound projections (1.66 and 6.70 Mha) from (Warren-Thomas, Dolman and Edwards, 2015), representing a precautionary indicator for recovering rubber prices (see 2.4 STAR Methods).

For both country-restricted and unrestricted simulations, Scenario 1 (*Production*) resulted in the highest habitat loss for forest-dependent species and the highest number of forest-dependent species affected (i.e. species losing ≥ 10% of their forested range), whereas Scenario 2 (*Conservation*) resulted in the lowest species impacts (Figure 3B, C, E, F). Scenarios 3a-c (*Compromise*) showed intermediate trajectories between Scenario 1 and 2 for both range loss and number of affected species (Figure 3B, C, E, F). Our results follow a similar trend to those of Strona *et al.* (2018), who found that integrating oil palm profit with conservation targets resulted in intermediate impacts on primates between their production and conservation scenarios.

Relative to country-restricted simulations, unrestricted simulations led to small to moderate reductions in species impacts under Scenario 1 (*Production*), but did not change trends under Scenario 2 (*Conservation*) (Figure 3E, F). The initial reduction in number of affected species could be attributed to conversion across tropical Africa being moved to relatively intact Indonesia (primarily West Papua) in unrestricted simulations. However, beyond ~6.70 Mha of expansion, differences between country-restricted and unrestricted simulations under Scenario 1 diminish (Figure 3F). Scenarios 3a-c (*Compromise*) trajectories showed that, initially, country-restricted compromise scenarios affected more species than the unrestricted ones; but beyond ~3 Mha of expansion, the trend gradually switched until the latter affected more species than the former (Figure 3C, F). This suggests that areas of compromise should not be used as blanket strategies for reconciling expansion and biodiversity, but conservation impacts must be analysed carefully on a case-by-case basis.

Taking a snapshot of species impacts for the country-restricted simulations at 3.90 Mha of expansion, which corresponds to the upper bound of industry projections (IRSG, 2018), 74 species (28 amphibians, 26 birds, 20 mammals) would lose ≥ 10% of their forested range under Scenario 1 (*Production*), of which six species would lose ≥ 50% of their forested range (Figure 4). No species were affected under Scenario 2 (*Conservation*). Scenarios 3a-c (*Compromise*) cut the number of affected species by 66% to 25, of which three species would lose ≥ 50% of their forested range (Figure 4). Unrestricted simulations at 3.90 Mha of expansion yielded similar patterns across scenarios: again, no species were affected under Scenario 2, whilst Scenarios 3a-c cut the number of affected species from 43 under Scenario 1 to 15-32.

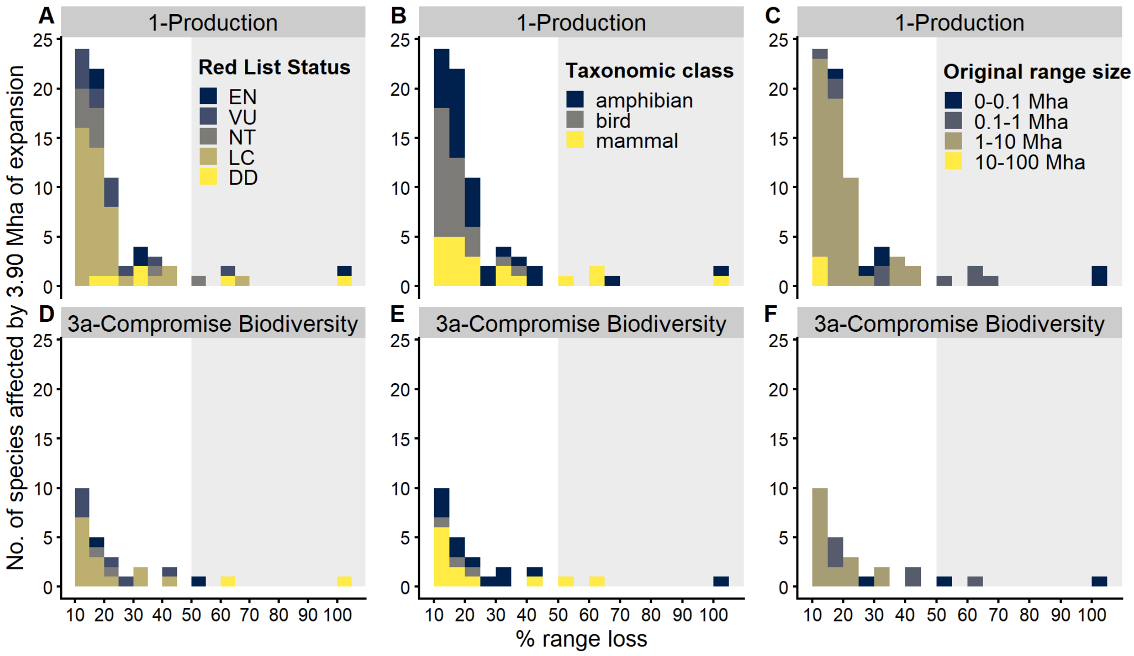

Figure 4. Number of species affected by 3.90 Mha of projected rubber expansion under different expansion scenarios. The histograms show the number of species expected to lose between 10% and 100% (in 5% bands) of their forested range under production (A-C) and compromise (D-F) scenarios. Species are divided by IUCN Red List threat status (A, D); taxonomic class (B, E); and original forested range size (C, F). The shaded area highlights species that lose ≥ 50% of their forested range. We present results for the country-restricted simulations for Scenarios 1 (*Production*) and 3 (*Compromise*), lumping Scenarios 3a-c together because their results were identical at 3.90 Mha of expansion. Scenario 2 (*Conservation*) did not cause any species to lose ≥ 10% of their forested range at 3.90 Mha of expansion and is not shown. EN = Endangered; VU = Vulnerable; NT = Near-threatened; LC = Least concern; DD = Data deficient.

In country-restricted simulations, less-impacted species tended to be of limited conservation concern (‘Least Concern’; Figure 4A, D) and with 1-10 Mha ranges (Figure 4C, F), whereas most-impacted species were of higher conservation concern (Figure 4A, D), mammals and amphibians (Figure 4B, E), and had smaller ranges (Figure 4C, F). The worst affected mammals were two bat species restricted to the Guinea and Liberia region, *Rhinolophus ziama* (endangered) and *Hipposideros marisae* (vulnerable); two shrews, *Crocidura zaphiri* (from Ethiopia and Kenya) and *Crocidura nimbae* (from lowland and submontane West Africa) (IUCN, 2018). The worst affected amphibians were *Amnirana fonensis*, a Guinean endemic frog, and the more broadly distributed *Amnirana occidentalis* (IUCN, 2018). If competition with other land uses necessitates rubber expansion beyond our projections, additional species will be threatened with larger range losses (Figure 3). Furthermore, predicted rubber expansion will likely overlap with Key Biodiversity Areas (Ahrends *et al.*, 2015), which in combination with our findings paints a dim picture for biodiversity conservation.

Our measures of extinction vulnerability and species impacts are limited by the quality of species range maps. As we were unable to differentiate between primary and secondary forest, all forested land is assigned the full complement of species as indicated by the range maps. However, primary and degraded forests close to access points (Harrison, 2011; Symes *et al.*, 2018), secondary forests (Alroy, 2017), and, to a lesser degree, selectively logged forests (Edwards *et al.*, 2011), are likely to have altered communities that lack high densities of over-hunted, large-bodied, or heavily traded species. While rubber demand projections are inherently uncertain, because our model assigns the order of conversion of cells in each scenario based on criteria not affected by rubber demand level, the conservation impacts of expansion can still be discerned from our analysis (Figure 3). Thus, whether rubber expansion is 3.90 or 6.70 Mha, there will be strong trade-offs between conservation and production.

Conservation organisations and the rubber industry continue to grapple with the on-going expansion of rubber plantations at the cost of forest habitat and biodiversity. Our broad-scale feasibility assessment can inform sustainability initiatives, including the GPSNR (GPSNR, 2019). Despite the lack of win-win areas, we found sufficient areas of compromise in southern New Guinea, southern Guinea (Africa), and scattered elsewhere across Asia and Africa to meet projected rubber demand, although these locations often harbour high diversity, localised endemic species, and high carbon stocks (WWF, 2012; Avitabile *et al.*, 2016; Potapov *et al.*, 2017). Given the precarious state of the world's biodiversity and increasing value of climate change-mitigating carbon stocks in tropical forests, it is also crucial to consider how rubber demand could be met via increasing rubber productivity within existing areas (Tilman *et al.*, 2011). Existing rubber production systems have an ageing farming population and are shifting from smallholder-dominated to agribusiness-owned estate plantations farmed by hired labour. This may represent an opportunity to improve yields on some lands, via higher planting densities, increased inputs, and higher-yielding hardy rubber clones.

Incorporating agroforestry and intercropping techniques into rubber production areas might mitigate biodiversity impacts, as jungle rubber, understorey vegetation, and some agroforests can better support forest specialists than monocultures (see reviews in Warren-Thomas, Dolman and Edwards (2015); Warren-Thomas *et al.* (2020); for jungle rubber see Beukema *et al.* (2007); Prabowo *et al.* (2016)). Studies assessing the biodiversity value of intensive rubber agroforests are scarce. One study showed that agroforestry with rubber clones had minimal positive impact on bird, butterfly, or reptile diversity (Warren-Thomas *et al.*, 2020). Rubber agroforests are subject to trade-offs not only between rubber yields and biodiversity, but also between yields of inter-planted crops, costs of additional labour and planting materials, and farmer perceptions of risk (Langenberger *et al.*, 2017). Additional research is required to identify the best practices to balance the trade-offs between yields, inputs, and biodiversity for rubber agroforests as well as monocultures. Hence, it remains likely, at least in the short term, that rubber production will continue to expand into new geographies with cheap labour costs and weaker governance.

Our analysis highlights inherent trade-offs between production targets and conservation priorities reinforcing the need for stronger corporate and government land-use policies, as well as closer monitoring to prevent severe biodiversity losses from rubber development (Yi *et al.*, 2014; Greenpeace, 2016, 2018; Earthsight, 2018; Cannon, 2019). Existing tools like the Integrated Biodiversity Assessment Tool (IBAT) are available for businesses or governments to incorporate legally protected or ecologically important areas into their planning (IBAT, 2019). Similarly, High Conservation Value (HCV) and High Carbon Stock (HCS) assessments can be used to identify locally important areas for biodiversity or carbon (Rosoman *et al.*, 2017; HCV Resource Network, 2019), and aid the design of rubber plantations to avoid forest fragmentation and ecologically sensitive areas. Development of high-yielding hardy clones that can be grown in less vulnerable areas provides more flexibility to use areas of potential rubber production and low biodiversity impacts. The expansion of these clones needs, however, to be combined with strategic land-use planning by governments and corporations, as well as careful impact assessments. These will be vital tools in reconciling rubber expansion with biodiversity conservation into the next decade.

2.3 Acknowledgments

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2.4 STAR Methods

2.4.1 Resource availability

2.4.1.1 Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Maria M. H. Wang (wang.mh.maria@gmail.com).

2.4.1.2 Materials availability

This study did not generate new unique reagents.

2.4.1.3 Data and code availability

Selected datasets and all code written for this chapter have been deposited on Zenodo (https://doi.org/10.5281/zenodo.3922296). A working version of the code can be accessed on GitHub (http://github.com/mmw590/rubberxbiodiversityCB). Some datasets are not available for redistribution due to licensing restrictions, but can be downloaded from the original sources as listed in the Key Resources Table.

2.4.2 Experimental model and subject details

2.4.2.1 Study area

We decided to focus on only Africa, Asia, and New Guinea for this study because the prevalence of the rubber leaf blight in South America makes it unlikely for large scale expansion of rubber on the continent (Lieberei, 2007). Following the methods of (Strona *et al.*, 2018), two 10 x 10 km reference raster grids were created from country polygons (GADM, 2018), one for the continent of Africa (37.9° N - 34.9° S, 3.8° W - 26.6° E) and one for South/Southeast Asia and New Guinea (35° N - 30° S, 72° E - 154° E; hereafter Asia and New Guinea for brevity) in Albers Equal Area Conic projection, with standard parallels and coordinates of centre points adjusted for each continental region.

2.4.2.2 Extinction vulnerability

To generate biodiversity maps, we downloaded georeferenced polygons of bird, amphibian, mammal and reptile species ranges (BirdLife International and Handbook of the Birds of the World, 2017; IUCN, 2018) and rasterised them on the 100 km^2 reference grids. For each taxonomic class, we generated a map of cumulative vulnerability. In developing the cumulative vulnerability map, we followed (Strona *et al.*, 2018), assigning a numerical 'threat score' to each species based on its IUCN Red List category following a geometric progression, i.e.: least concern (LC) = 2; near threatened (NT) = 4; vulnerable (VU) = 8; endangered (EN) = 16; and critically endangered (CR) = 32.

For data-deficient species, where available, we used the Red List categories predicted for these species from the literature – 36 birds (Butchart and Bird, 2010), 380 amphibians (González-del-Pliego *et al.*, 2019), and 301 mammals (Bland *et al.*, 2014; Jetz and Freckleton, 2015). Where there were disagreements within the literature (21 mammal species) we use Jetz and Freckleton (2015) as it is the most recent assessment. The predicted categories were scored as follows: 'not threatened' = 3 (intermediate between LC and NT); 'threatened' = 16 (intermediate between VU, EN, and CR); 'imperilled' = 24 (intermediate between EN and CR); and 'may be extinct already' = 32. Predicted categories were not available for five birds, 25 amphibians, and 104 mammals. For these data-deficient species, we assigned them the taxa-specific global average threat score, rounded up to the nearest integer (4 for birds, 9 for amphibians, 6 for mammals, and 5 for reptiles).

A cumulative extinction vulnerability score was obtained for each cell in the 100 km^2 reference grid by summing the threat score of threatened species whose range fell within the cell. This approach combines both the number of threatened species and their threat status. This resulted in an assessment of 789 amphibians, 737 birds, 1055 mammals, and 862 reptiles. Extinction vulnerability scores were rescaled to a 0-1 range. We also generated extinction vulnerability maps for all four taxonomic classes combined, by taking the mean of the rescaled scores to avoid skewing these scores by variation in species richness between taxa.

2.4.3 Method details

2.4.3.1 Areas for potential rubber expansion

For rubber suitability, we used a historical bioclimatic suitability map of rubber (continuous scale of 0-1) developed by Ahrends *et al.* (2015), and projected it onto the 100 km^2 reference grids using bilinear interpolation. For land cover, we used the 2015 land cover map from the European Space Agency (ESA) Climate Change Initiative (CCI), at a 300 m spatial resolution (ESA, 2017). We harmonised the maps to the 100 km^2 reference grids using the nearest neighbour algorithm. To identify potential areas for rubber expansion, we masked out the following land cover types from the rubber suitability maps: existing cropland; lichens and mosses; urban; bare; water bodies; and permanent snow and ice. We allowed rubber expansion into all types of tree cover (including flooded areas); shrubland (including flooded areas); grassland; mosaic tree/shrub/herbaceous cover; and sparse vegetation. For land classified as mosaic cropland/natural vegetation, we excluded areas with > 50% cropland, and included areas with < 50% cropland.

To refine the potential suitable rubber expansion areas, we also masked out protected areas from suitability maps. Protected areas (georeferenced polygons and points) were downloaded from the World Database on Protected Areas (WDPA) (IUCN and UNEP-WCMC, 2018). We first converted the point data in ArcMap ver. 10.4.1 by applying a geodesic buffer corresponding to the reported size of the protected area, as recommended in the WDPA User Manual (UNEP-WCMC, 2016). We excluded points with reported areas of zero. We combined and rasterised the polygon and buffered point data, and projected it onto the 100 km^2 reference grid.

Georeferenced data on existing rubber plantations were only available for a few countries in Asia, from three different sources (Li and Fox, 2012; Petersen *et al.*, 2016; Hurni and Fox, 2018): Indonesia, Malaysia, Cambodia, Laos, northern Thailand, Myanmar, Vietnam, and Xishuangbanna Prefecture and Hainan Island, China. We combined these rubber maps, rasterised them on the 100 km^2 reference grid, and masked out those existing rubber areas from areas of potential rubber expansion. We also obtained georeferenced point data for planned or existing rubber concessions in Africa and Asia, based on reported land deals for rubber plantations from the Land Matrix portal (The Land Matrix, 2018). For the point data, we only plotted them for visual reference because most of the reported locations were at the district or province level (Figure S1).

2.4.4 Quantification and statistical analysis

2.4.4.1 Feasibility assessment

All analyses were carried out in R version 4.0.0 (R Core Team, 2020) using custom code (Wang, 2020). We plotted bivariate choropleth maps by overlaying the rubber suitability map with extinction vulnerability maps, which allowed us to identify areas of compromise for rubber expansion and biodiversity. Suitability and extinction vulnerability values (on a 0-1 range) were each divided into deciles for plotting and into quintiles for analysis. We classified cells with suitability > 0.8 and extinction vulnerability ≤ 0.2 as 'win-win' areas, and cells with medium to high suitability > 0.4 and vulnerability ≤ 0.4 as 'areas of compromise' (Figure 1). We ranked areas of compromise from most ideal to least ideal in three ways: a) where we compromise biodiversity first and prioritise suitability, b) where we compromise suitability first and prioritise biodiversity, and c) where we compromise biodiversity and suitability simultaneously (Figure S4; also see the following section, 2.4.4.3 Simulating rubber expansion scenarios). We also identified 'lose-lose' areas as cells with extinction vulnerability > 0.6 and suitability ≤ 0.4 (Figure 1).

2.4.4.2 Expanded suitability niche for rubber clones

We also conducted a precautionary reanalysis in which we relaxed the environmental constraints of rubber to evaluate how potential new clones would affect the area suitable for rubber expansion. Using climate data from WorldClim (Fick and Hijmans, 2017) and Climate Research Unit (CRU) (Harris *et al.*, 2020), we mapped out areas meeting the three minimal dry stress and three minimal cold stress conditions for non-reduced yields as listed in Ahrends *et al.* (2015), harmonised the layer to the 100 km^2 reference grid. We classified each cell into one of six classes corresponding to the number of conditions met. The dry stress conditions are: (1) ≤ 5 months < 60 mm rainfall $month^{-1}$, and/or (2) ≥ 1200 mm rainfall $year^{-1}$, and/or (3) ≥ 20 mm rainfall during driest quarter). The cold stress conditions are: (1) ≤ 10 frost days per year, and/or (2) average temperatures ≥ 25°C during the wet season, and/or (3) temperature seasonality ≤ 50% higher than in humid tropics. We assume that at least one condition from the dry stress and one from the cold stress set of conditions must be met to avoid reduced yields; hence, the minimum number of conditions required is two, otherwise the cell would be reclassified to suitability = 0. Areas meeting zero conditions does not necessarily mean that rubber cultivation is not feasible there, only that reduced yields are likely. This differs from the suitability model from Ahrends *et al.* (2015) used for our main analysis, where we assume that a suitability score of 0 indicates that rubber cultivation is not feasible.

We then repeated the feasibility assessment using this map, and identified additional areas where rubber may represent a conservation risk, and those where rubber might be expanded with lower conservation cost.

2.4.4.3 Simulating rubber expansion scenarios

We simulated rubber expansion scenarios based on different criteria from 2017-2027, converting 100 km^2 grid cells across Africa, Asia, New Guinea, and associated islands based on different factors, until the projected demand to 2027 was met. Based on industry models, the demand for rubber in 2027 is projected to be 16.79 million tonnes, a 27% increase from the 2017 demand of 13.22 million tonnes (IRSG, 2018). Using the minimum and maximum yields of current plantations on mainland Southeast Asia as reported in Warren-Thomas, Dolman and Edwards (2015) and a 2017 baseline for existing rubber area (FAO, 2020), we estimate that 2.45-3.90 Mha of additional rubber area would be needed to meet the demand from 2017-2027. As a precautionary analysis, we also use the previously published projections for rubber demand in 2024 by Warren-Thomas, Dolman and Edwards (2015) (between 1.66 and 6.70 Mha from a 2017 baseline) to indicate potential impacts should rubber demand or prices recover in the near term.

We simulated (1) a production scenario, (2) a conservation scenario, and (3a-c) three ‘compromise’ rubber expansion scenarios. For the production scenario, we averaged the rubber bioclimatic suitability values (inversed) with accessibility values (shortest travel time to the nearest city), and converted cells to rubber area in increasing order of the averaged score. The accessibility data were downloaded from Weiss *et al.*

(2018) at a resolution of 30 arc-seconds, harmonised to the 100 km^2 reference grid using bilinear interpolation, and rescaled to 0-1. For the conservation scenario, we averaged extinction vulnerability scores with carbon stock values, and converted cells in increasing order of the averaged score. We used a global map of aboveground biomass at an original resolution of 30 arc-seconds (Avitabile *et al.*, 2016) as a proxy for carbon stock values, which we harmonised to the 100 km^2 reference grid using bilinear interpolation, and rescaled to 0-1.

For the 'compromise' scenarios, we restricted conversion to the 'areas of compromise', i.e. cells with suitability > 0.4 and vulnerability ≤ 0.4. We first ordered the cells to be converted according to the ranked areas of compromise (Figure S4), where Scenario 3a compromises biodiversity first (cells with higher suitability were prioritised for conversion), Scenario 3b compromises suitability first (cells with lower vulnerability were prioritised for conversion), and Scenario 3c compromises both simultaneously. Then for cells within the same ranked area of compromise we averaged their rubber bioclimatic suitability (inversed), accessibility, vulnerability, and carbon values. We converted those cells in order of the averaged score. Simulations requiring randomisation (e.g. when cells had identical values) were replicated 1,000 times and results were averaged across all replicates.

To account for the potential that higher wages and competition for land from existing rubber and oil palm production in Southeast Asia might restrict expansion in the region, we limited expansion in eleven Southeast Asian rubber producing countries (Indonesia, Thailand, India, Malaysia, Philippines, China, Sri Lanka, Vietnam, Cambodia, Laos, and Myanmar) based on industry predictions ('country-restricted' simulations). Predicted new rubber area from 2017 to 2027 in each country ranged from 0.01-0.09 Mha, summing to 0.407 Mha (IRSG, 2018). We performed the conversion simulation for each of the five scenarios as described above but capped conversion in these countries at the number of cells allocated per country. We repeated the simulations for each of the five scenarios without country restrictions ('unrestricted' simulations), in case economic conditions change in these eleven countries to enable a greater level of expansion.

For every 10 cells (0.10 Mha) converted under each scenario, we calculated the (1) average rubber suitability of all converted cells, (2) the cumulative percent species range loss, and (3) the number of species that were expected to lose ≥10% of their range. We then identified the species that were expected to lose range at 6.89 Mha of conversion — the upper limit of the projected 2016-2024 rubber land demand by Warren-Thomas, Dolman and Edwards (2015) — under each scenario and quantified their range losses. We considered only forest-dependent species whose ranges fell entirely or almost entirely (≥ 99%) within our study region. This also helps reduce the uncertainty in IUCN range maps regarding the area of occupancy of individual species (Hurlbert and Jetz, 2007) in addition to the filtering out of non-natural land cover types in the feasibility assessment, which was shown by Strona *et al.* (2018) to improve the IUCN range data. We also only considered the loss of forested cells as loss of range for these forest-dependent species. We used the list of forest-dependent species from Tracewski *et al.* (2016), who included birds, amphibians, and mammals with high dependency on forest, as well as birds with medium dependency. Species with high dependency were defined as those who almost always breed within forest but may persist in secondary forest and forest patches if it met their specific ecological needs. Species with medium dependency were defined as those who typically breed within forest, may occur within undisturbed forest, but are also found in forest strips, edges, and gaps. We also excluded 42 species that did not have any forested cells in their ranges.

We ran the conversion simulations on 1155 forest-dependent amphibian species, 2376 bird species, and 733 mammal species occurring in our study region. Our expansion scenarios are similar to those conducted for oil palm by Strona *et al.* (2018); however, ours differ in that we measure only forest loss experienced by forest-dependent species and that we include non-primate species. Like Strona *et al.* (2018), our scenarios were conceptually similar to the oil palm expansion scenarios in Koh and Ghazoul (2010), but our focus is on rubber production and biodiversity impacts, not on other factors such as food production.

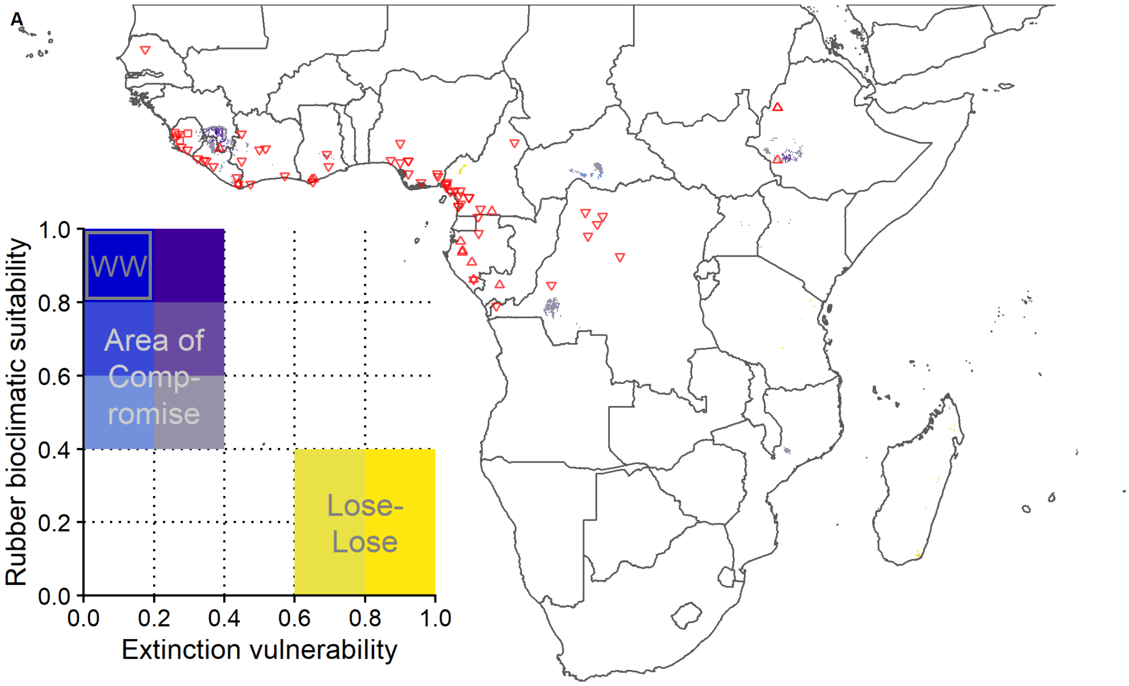
2.4.4.4 *Precautionary reanalysis with all species*

We conducted a precautionary reanalysis of the feasibility assessment and conversion simulations using extinction vulnerability scores calculated for all species (i.e. including those assigned a threat score of ≤ 4 (near threatened); 2534 amphibians, 6087 birds, 3136 mammals, and 3062 reptiles). For clarity, in the main text we present only results using extinction vulnerability calculated for threatened species. General conclusions were similar to the results presented in the main text, with the biggest difference being overall higher vulnerability scores in Africa − reducing the areas of compromise and increasing lose-lose areas in Africa (2.5.2 *Appendix 2*: Precautionary reanalysis using extinction vulnerability scores calculated for all species).

2.5 Supporting information

2.5.1 Appendix 1: Supplementary figures and tables

A



B

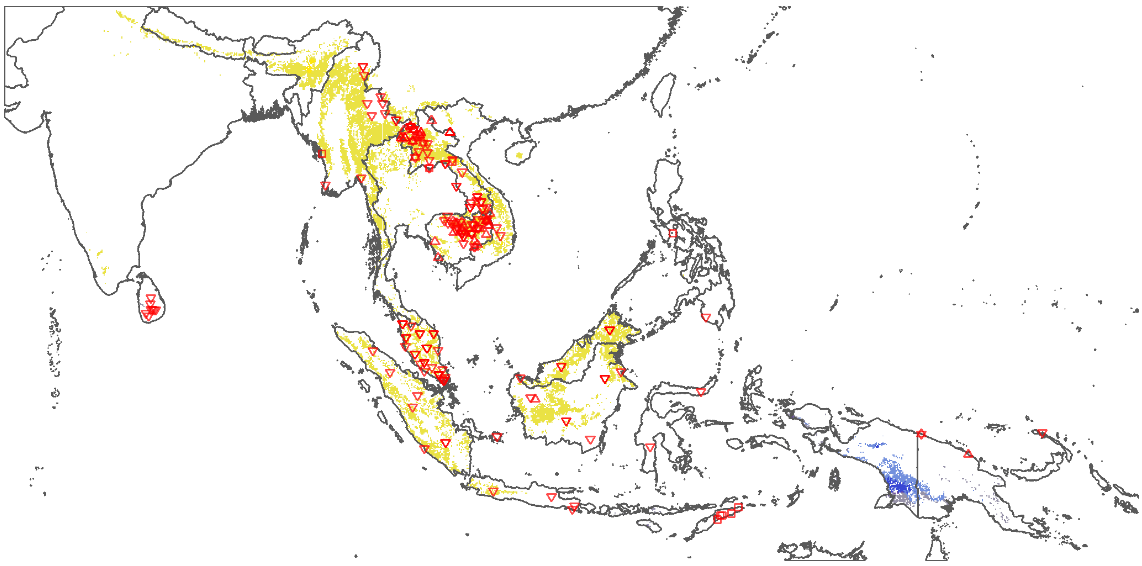


Figure S1. Locations of rubber concessions in Africa (A), and Asia and New Guinea (B), overlaid on areas of compromise and lose-lose areas. Georeferenced point data for reported rubber land concessions are mapped as red symbols (square: intended concessions; up triangle: startup phase; down triangle: in operation). Land concession data were obtained from the Land Matrix data portal (The Land Matrix, 2018). Only areas of compromise and lose-lose areas are coloured to improve visibility, following the bivariate colour scale as shown. 'WW' denotes 'win-win' areas, but there are no win-win areas on the map. Related to Figure 2.

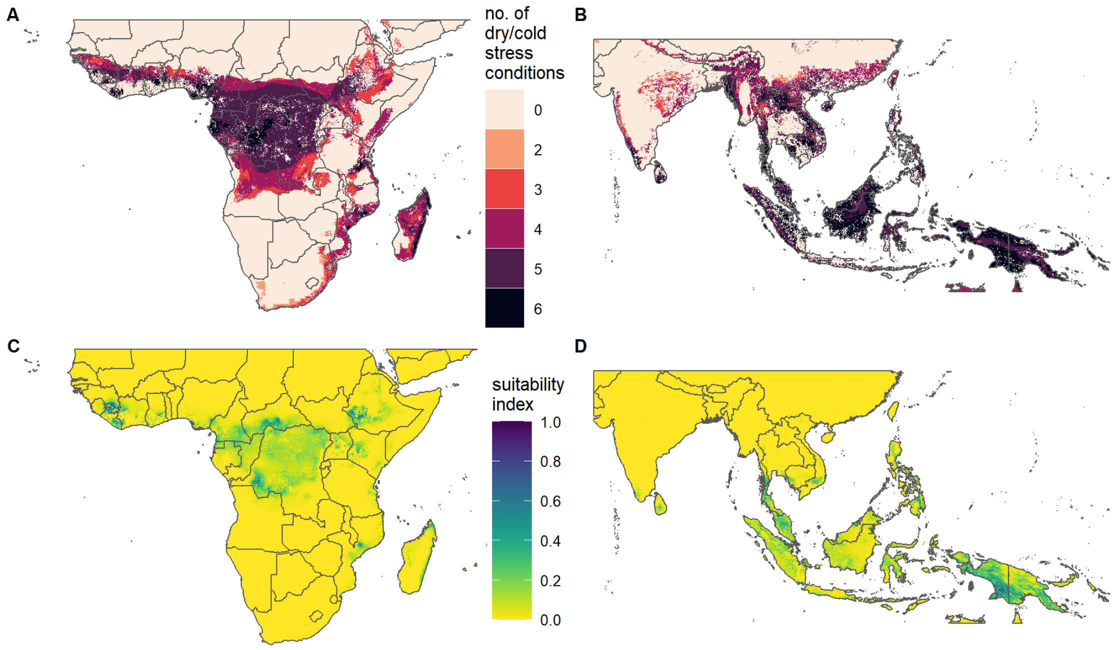


Figure S2. Comparison between expanded rubber bioclimatic suitability niche based on dry and cold stress conditions (A-B) and the rubber bioclimatic suitability layer modelled by Ahrends *et al.* (2015) (C-D). For our expanded suitability niche analysis, we relaxed the environmental constraints of rubber to evaluate how potential new clones would affect the area suitable for rubber expansion. (A-B) Expanded rubber bioclimatic niche showing areas meeting minimal dry and cold stress conditions for non-reduced rubber yields in Africa and Asia/New Guinea. (C-D) Rubber bioclimatic suitability model used in our main analysis, developed by Ahrends *et al.* (2015). See 2.4 STAR Methods for details. Unsuitable land uses were masked out in this figure but protected areas and existing rubber concessions were not. Related to Figure 1-2, Table S1-S2.

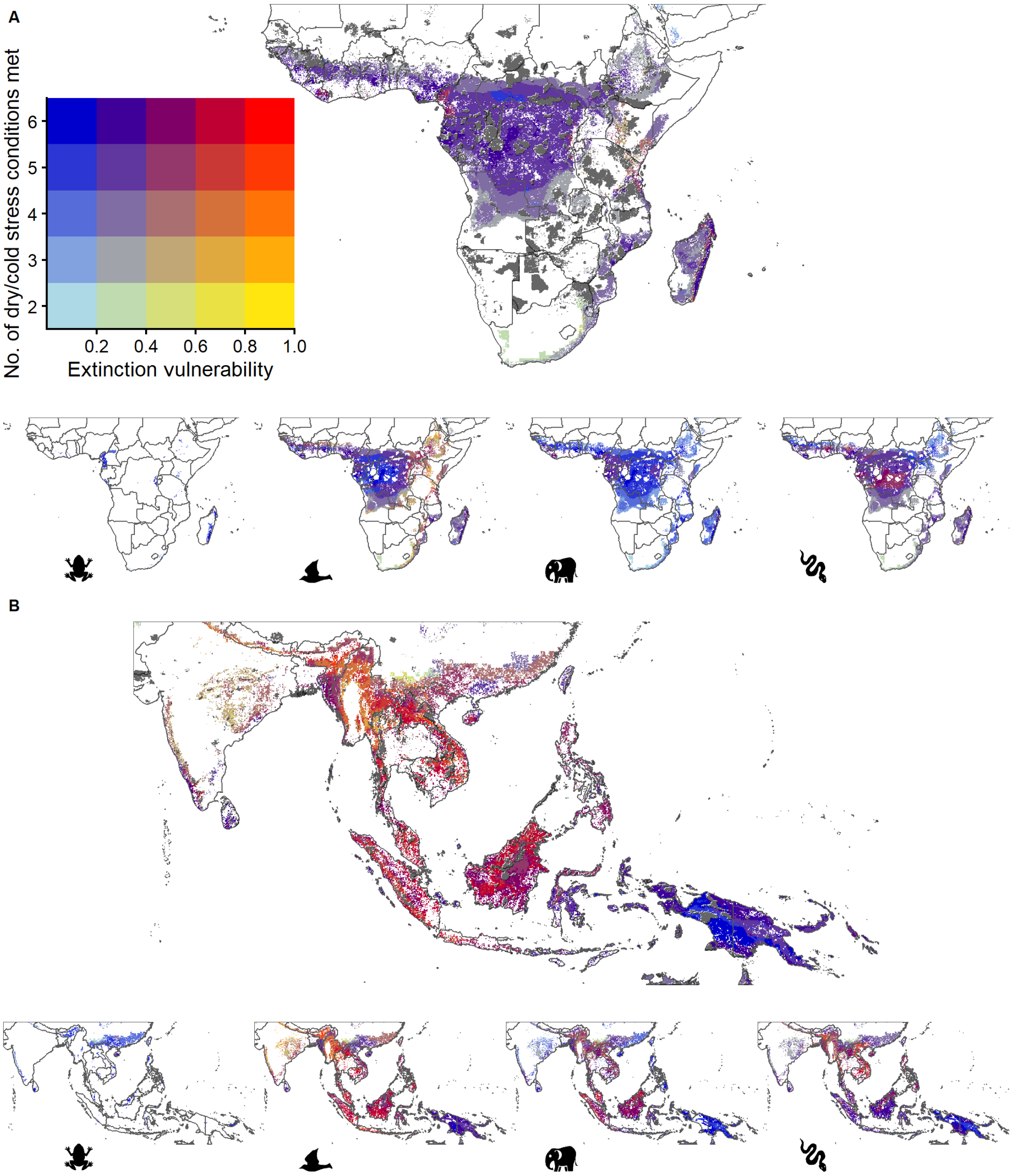


Figure S3. Spatial overlay of expanded rubber bioclimatic suitability niche based on dry and cold stress conditions with extinction vulnerability. We redid the feasibility assessment as shown in Figure 2 using the expanded suitability niche map to evaluate how potential new clones would affect the area suitable for rubber expansion. We overlaid the map of expanded rubber bioclimatic niche and extinction vulnerability along two colour scales, divided into quintiles for plotting. Uncoloured areas on the map indicate areas where reduced yields for rubber are likely. As in Figure 2, the main plots show extinction vulnerability scores aggregated for threatened amphibians, birds, mammals, and reptiles in Africa (A) and Asia and New Guinea (B). The subplots show extinction vulnerability scores for each taxonomic class separately. Protected areas are shaded in dark grey in the main plots. Related to Figure 2, Figure S2 and Table S2.

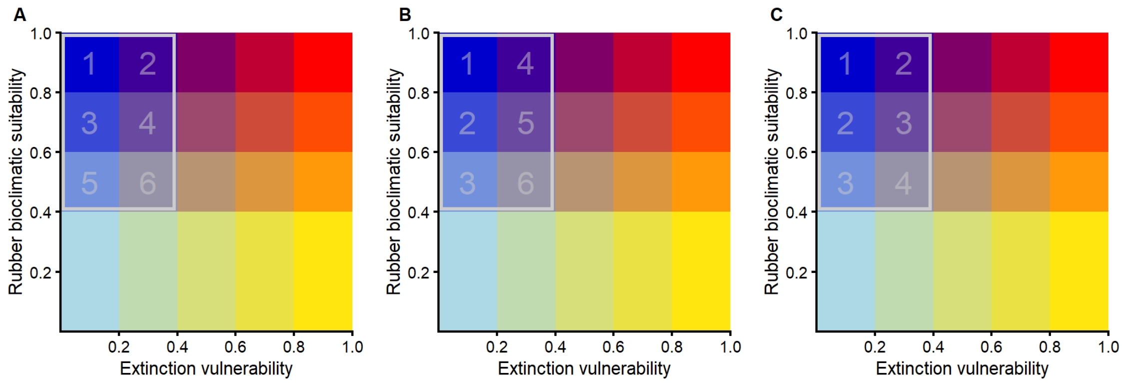


Figure S4. Sequence of ranking of areas of compromise for the three compromise scenarios. We simulated rubber expansion for the compromise scenarios 3a-c, where we ordered cells for conversion following the ranking as shown in the panel figures. (A) Scenario 3a: compromise biodiversity first (prioritising suitability), (B) Scenario 3b: compromise suitability first (prioritising biodiversity), and (C) Scenario 3c: compromise both biodiversity and suitability simultaneously. For cells falling within the same box, we converted them in order of averaged (un)suitability, vulnerability, accessibility, and carbon values (see 2.4 STAR Methods for details). Related to Figure 3 and Table S1.

Table S1. Size (in Mha) of win-win, compromise, and lose-lose areas in Africa and Asia/New Guinea. Related to Figure 1, Figure S4, and Appendix S2.

Suitability	Extinction vulnerability	Sequence of conversion in compromise scenarios*			Size of area in Africa (Mha)	Size of area in Asia/ New Guinea (Mha)	Total area (Mha)
		Compromise biodiversity	Compromise suitability	Compromise both			
0.8 < suit ≤ 1.0	0.0 < vuln ≤ 0.2	1 (win-win)	1 (win-win)	1 (win-win)	-	-	-
0.8 < suit ≤ 1.0	0.2 < vuln ≤ 0.4	2	4	2	0.13	-	0.13
0.6 < suit ≤ 0.8	0.0 < vuln ≤ 0.2	3	2	2	-	1.45	1.45
0.6 < suit ≤ 0.8	0.2 < vuln ≤ 0.4	4	5	3	1.28	0.21	1.49
0.4 < suit ≤ 0.6	0.0 < vuln ≤ 0.2	5	3	3	0.34	6.06	6.4
0.4 < suit ≤ 0.6	0.2 < vuln ≤ 0.4	6	6	4	5.58	3.77	9.35
0.0 < suit ≤ 0.4	0.6 < vuln ≤ 1.0	lose-lose			0.47	109.5	109.97

*This refers to the rubber expansion scenarios in 2.2.2 *Impact of rubber expansion on biodiversity*, see Figure S4 and 2.4 STAR Methods for details.

Table S2. Size of potential rubber expansion areas in Africa and Asia/New Guinea, based on map of extended rubber bioclimatic suitability niche (number of dry/cold stress conditions), broken down by extinction vulnerability classes. At least one condition each from the dry and cold stress set of conditions must be met to be considered suitable for rubber cultivation. See 2.4.4.2 *Expanded suitability niche for rubber clones* for details on the dry/cold stress conditions used. Related to Figure 1-2, Figure S2-S3 and Table S1.

No. of dry/cold stress conditions met	Extinction vulnerability				
	0.0 < vuln ≤ 0.2 (low)	0.2 < vuln ≤ 0.4 (low-moderate)	0.4 < vuln ≤ 0.6 (moderate)	0.6 < vuln ≤ 0.8 (moderate-high)	0.8 < vuln ≤ 1.0 (high)
			Size of area in Africa (Mha)		
6	0.29	39.81	3.21	0.01	-
5	6.91	258.73	10.72	0.32	0.03
4	1.53	190.37	7.93	0.06	-
3	2.18	90.12	5.28	0.04	0.01
2	1.89	9.45	0.55	-	-
			Size of area in Asia/New Guinea (Mha)		
6	22.6	39.28	41.88	43.01	0.23
5	7.4	35.94	50.29	39.83	1.08
4	0.3	20.14	43.27	20.18	0.33
3	0.01	3.88	15.39	3.33	0.01
2	0.01	2.95	2.29	0.04	-
			Total area (Mha)		
6	22.89	79.09	45.09	43.02	0.23
5	14.31	294.067	61.01	40.15	1.11
4	1.83	210.51	51.2	20.24	0.33
3	2.19	94	20.67	3.37	0.02
2	1.9	12.4	2.84	0.04	-

2.5.2 Appendix 2: Precautionary reanalysis using extinction vulnerability scores calculated for all species

We present a precautionary reanalysis using the cumulative extinction vulnerability calculated for all species (see 2.4.4.4 *Precautionary reanalysis with all species* for details). General conclusions were similar to the results presented in the main article, which uses extinction vulnerability calculated for only threatened species. The biggest difference was that the distribution of vulnerability scores was shifted to the right (i.e. higher vulnerability scores) for Africa, hence reducing the areas of compromise and increasing lose-lose areas in Africa.

2.5.2.1 Rubber suitability and extinction vulnerability

We found no 'win-win' areas for expansion that would serve both production and conservation needs. We identified 14.1 Mha of land meeting our criteria for 'areas of compromise' (Table I). Africa had fewer areas of compromise (2.5 Mha) compared to Asia and New Guinea (11.6 Mha) because Africa is less bioclimatically suitable for rubber (Table I and Figure II). The largest areas of compromise are concentrated in southern New Guinea, particularly in Indonesian Papua. Next were areas of compromise in Africa, particularly the southern Congolian forest-savannah region in the Democratic Republic of Congo and Central African Republic (Figure II). Smaller areas of compromise were scattered across Asia (e.g. East Nusa Tenggara Sumba Island, Indonesia; Sri Lanka) and in Africa (Figure II). Large 'lose-lose' areas with high extinction vulnerability (> 0.6) and poor rubber suitability (suitability ≤ 0.4) were concentrated in Southeast Asia and Northeast India (184.3 Mha; Figure I and II; Table I). By contrast, Africa had fewer lose-lose areas (20.9 Mha).

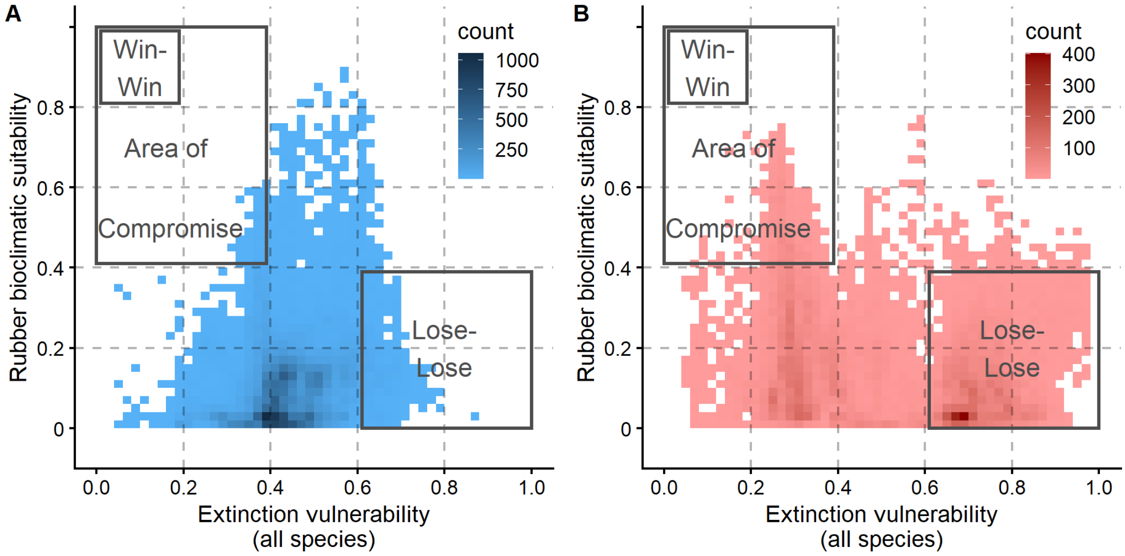


Figure I. Results of precautionary reanalysis: distribution of rubber bioclimatic suitability and extinction vulnerability scores calculated for all species (parallels Figure 1 in main text). Point density plot showing the number of 10 × 10 km grid cells available for rubber expansion as ranked by their suitability and vulnerability scores in Africa (A) and Asia and New Guinea (B). Dashed lines represent binning of the values into quintiles. We define 'win-win' areas as cells with suitability > 0.8 and vulnerability ≤ 0.2; 'area of compromise' as cells with suitability > 0.4 and vulnerability ≤ 0.4; and 'lose-lose' areas as cells with suitability ≤ 0.4 and vulnerability > 0.6. Only cells with suitability > 0.01 are shown.

Table I. Results of precautionary reanalysis: size (in Mha) of win-win, compromise, and lose-lose areas in Africa, Asia and New Guinea, using extinction vulnerability calculated for all species (parallels Table S1 in Supplemental Information).

Suitability	Extinction vulnerability (all species)	Sequence of conversion in compromise scenarios*			Size of area in Africa (Mha)	Size of area in Asia/ New Guinea (Mha)	Total area (Mha)
		Compromise biodiversity	Compromise suitability	Compromise both			
0.8 < suit ≤ 1.0	0.0 < vuln ≤ 0.2	1 (win-win)	1 (win-win)	1 (win-win)	-	-	-
0.8 < suit ≤ 1.0	0.2 < vuln ≤ 0.4	2	4	2	-	-	-
0.6 < suit ≤ 0.8	0.0 < vuln ≤ 0.2	3	2	2	-	0.03	0.03
0.6 < suit ≤ 0.8	0.2 < vuln ≤ 0.4	4	5	3	0.01	1.63	1.64
0.4 < suit ≤ 0.6	0.0 < vuln ≤ 0.2	5	3	3	-	0.17	0.17
0.4 < suit ≤ 0.6	0.2 < vuln ≤ 0.4	6	6	4	2.5	9.78	12.28
0.0 < suit ≤ 0.4	0.6 < vuln ≤ 1.0		lose-lose		20.87	184.28	205.15

*This refers to the rubber expansion scenarios in 2.2.2 *Impact of rubber expansion on biodiversity*, see Figure S4 and 2.4 STAR Methods for details.

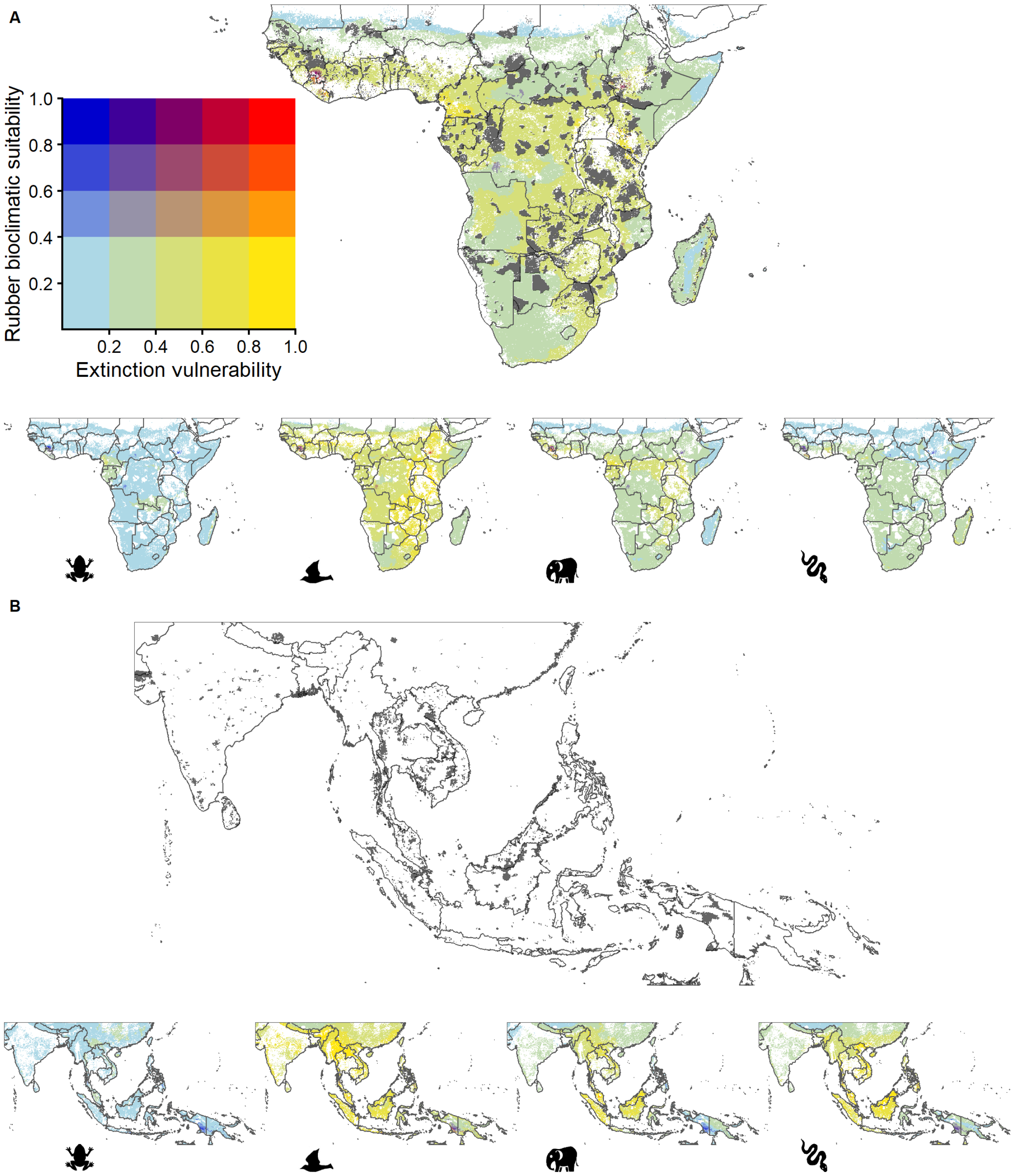


Figure II. Results of precautionary reanalysis: spatial overlay of rubber bioclimatic suitability with extinction vulnerability calculated for all species (parallels Figure 2 in main text). Map of rubber bioclimatic suitability and extinction vulnerability calculated for all species along two colour scales, divided into four classes for rubber suitability and five classes for extinction vulnerability for plotting. The main plots show extinction vulnerability scores aggregated for threatened amphibians, birds, mammals, and reptiles in Africa (A) and Asia and New Guinea (B). The subplots show extinction vulnerability scores for each taxonomic class separately. Protected areas are shaded in dark grey in the main plots.

2.5.2.2 Impact of rubber expansion on biodiversity

Comparing the average rubber suitability of converted land across the different scenarios for the country-restricted simulations, Scenario 2 (*Conservation*) only converted land with very low rubber suitability (mean ± 1SE for first 7 Mha converted = 0.0063 ± 0.0006; Figure III-A). The conservation scenario is thus impractical for rubber expansion, with poor rubber suitability leading to lower yields and higher land area demands to meet production targets. While not as high as Scenario 1 (*Production*) (0.629 ± 0.012), the average rubber suitability score of land converted in Scenarios 3a-c (*Compromise*) were moderately high (3a = 0.487 ± 0.008; 3b = 0.484 ± 0.007; 3c = 0.487 ± 0.008; Figure III-A), suggesting higher acceptability to rubber producers. Average rubber suitability of converted land in Scenarios 1 and 3a-c was 6% and 17-19% higher, respectively, in unrestricted simulations (Figure III-D).

For both country-restricted and unrestricted simulations, Scenario 1 (*Production*) resulted in the highest habitat loss for forest-dependent species and the highest number of forest-dependent species affected (i.e. species losing ≥ 10% of their forested range), whereas Scenario 2 (*Conservation*) resulted in the lowest species impacts (Figure III-B, C, E, F). Scenarios 3a-c (*Compromise*) showed intermediate trajectories between Scenario 1 and 2 for both range loss and number of affected species (Figure III-B, C, E, F).

Relative to country-restricted simulations, unrestricted simulations led to small to moderate reductions in species impacts under Scenario 1 (*Production*), but did not change trends under Scenario 2 (*Conservation*) (Figure III-E, F). The initial reduction in number of affected species could be attributed to conversion across tropical Africa being moved to relatively intact Indonesia (primarily West Papua) in unrestricted simulations. However, beyond ~6.70 Mha expansion, differences between country-restricted and unrestricted simulations under Scenario 1 diminish (Figure III-F). Scenario 3a-c (*Compromise*) trajectories showed that, initially, unrestricted compromise scenarios affected slightly more species than the country-restricted ones;

but beyond ~4 Mha expansion, the number of species affected in the former plateaued but continued to rise in the latter until the latter affected more species than the former (Figure III-C, F).

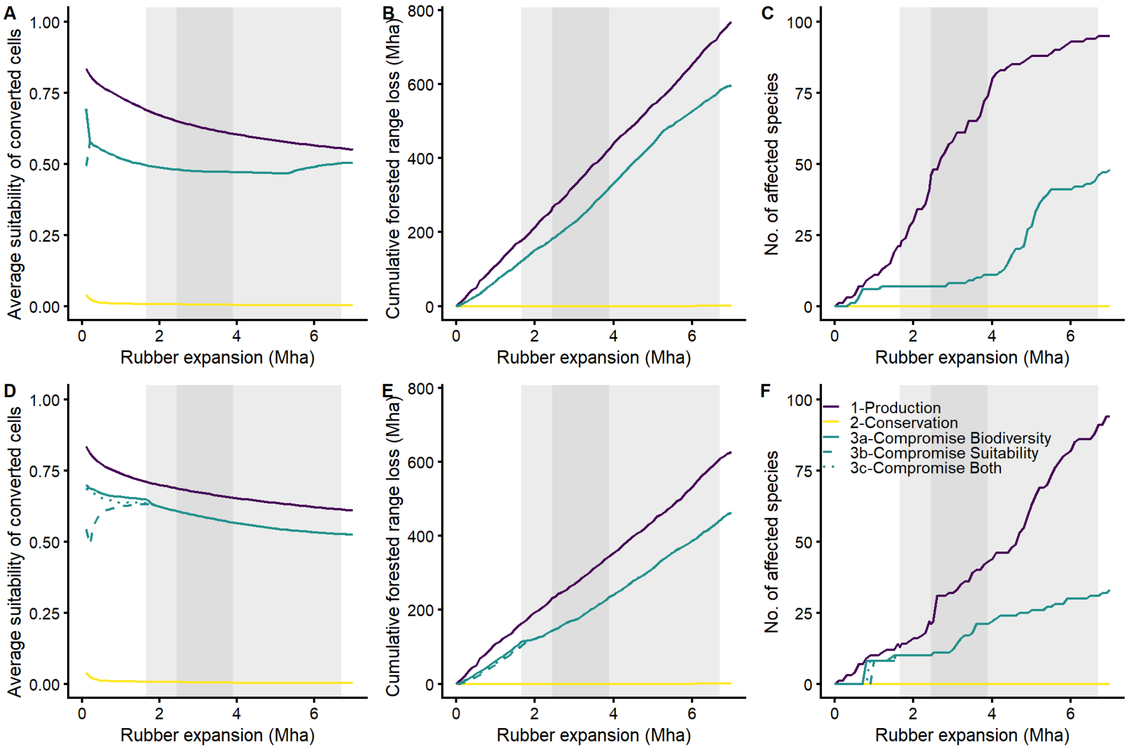


Figure III. Results of precautionary reanalysis: impacts of rubber expansion scenarios using extinction vulnerability calculated for all species (parallels Figure 3 in main text). Impacts of five rubber expansion scenarios up to 7 Mha with country-restricted (A-C) and unrestricted (D-F) simulations, for average rubber bioclimatic suitability of converted cells (i.e. the projected new rubber area) (A, D); cumulative forested range loss in Mha, summed across all species (B, E); and cumulative number of species expected to lose ≥ 10% of their forested range (C, F). Average rubber suitability of projected new rubber area (A, D) was calculated from the suitability score of all the cells converted at each stage of the scenario. Cumulative forested range loss (B, E) was calculated by summing the range loss in Mha at each stage of the scenario, across 1155 forest-dependent amphibians, 2375 birds, and 733 mammals whose ranges occur entirely within the study region. Cumulative number of species expected to lose ≥ 10% of their forested range (C, F) was calculated at each stage of the scenario from the same set of forest-dependent amphibians, birds, and mammals. Darker-grey background indicates the estimated land area needed to meet the rubber demand by 2027 (2.45-3.90 Mha); paler-grey background represents the lower and upper bound projections (1.66 and 6.70 Mha) from Warren-Thomas, Dolman and Edwards (2015), representing a precautionary indicator for recovering rubber prices (see 2.4 STAR Methods).

Taking a snapshot of species impacts for the country-restricted simulations at 3.90 Mha of expansion, which corresponds to the upper bound of industry projections (IRSG, 2018), 74 species (28 amphibians, 26 birds, 20 mammals) would lose ≥ 10% of their forested range under Scenario 1 (*Production*), of which six species would lose ≥ 50% of their forested range (Figure IV). No species were affected under Scenario 2 (*Conservation*). Scenarios 3a-c (*Compromise*) cut the number of affected species to 11, none of which would lose ≥ 50% of their forested range (Figure IV). Unrestricted simulations at 3.90 Mha of expansion yielded similar patterns across scenarios: again, no species were affected under Scenario 2, whilst Scenarios 3a-c cut the number of affected species under Scenario 1 by half from 43 to 21.

In country-restricted simulations, less-impacted species tended to be of limited conservation concern ('Least Concern'; Figure IV-A, D) and with 1-10 Mha ranges (Figure IV-C, F), whereas most-impacted species were of higher conservation concern (Figure IV-A, D), mammals and amphibians (Figure IV-B, E), and had smaller ranges (Figure IV-C, F). The worst affected mammals were two bat species restricted to the Guinea and Liberia region, *Rhinolophus ziama* (endangered) and *Hipposideros marisae* (vulnerable); two shrews, *Crocidura zaphiri* (from Ethiopia and Kenya) and *Crocidura nimbae* (from lowland and submontane West Africa) (IUCN, 2018). The worst affected amphibians were *Amnirana fonensis*, a Guinean endemic frog, and the more broadly distributed *Amnirana occidentalis* (IUCN, 2018). If competition with other land uses necessitates rubber expansion beyond our projections, additional species will be threatened with larger range losses (Figure III).

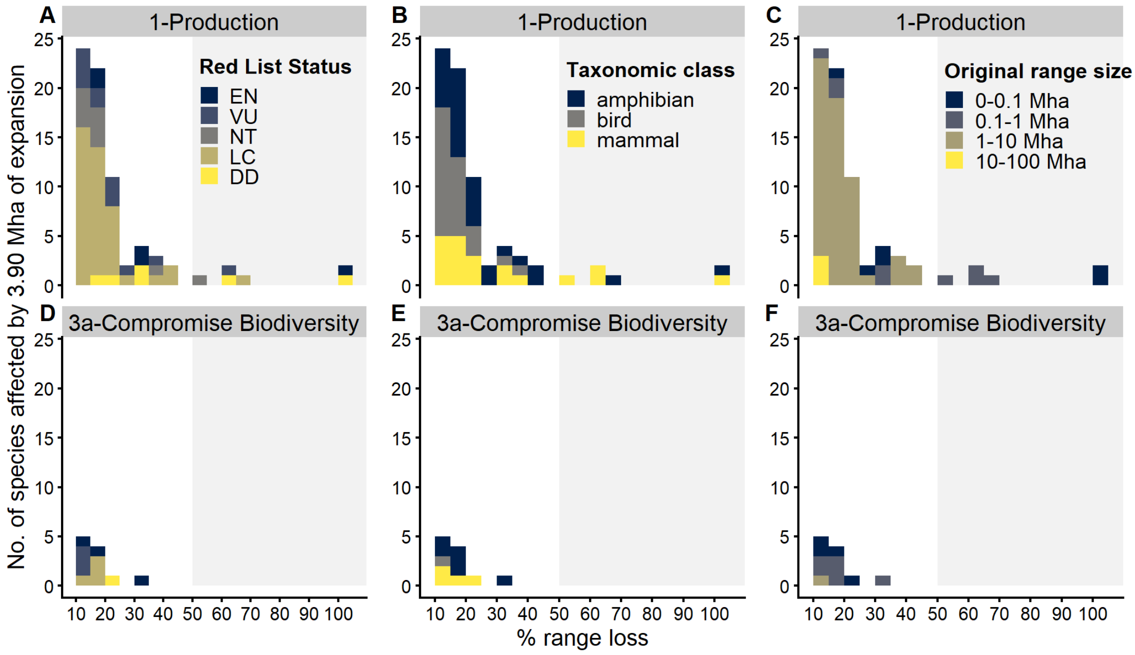


Figure IV. Results of precautionary reanalysis: number of species affected by 3.90 Mha of projected rubber expansion under different expansion scenarios, using extinction vulnerability calculated for all species (parallels Figure 4 in main text). The histograms show the number of species expected to lose between 10% and 100% (in 5% bands) of their forested range under production (A-C) and compromise (D-F) scenarios. Species are divided by IUCN Red List threat status (A, D); taxonomic class (B, E); and original forested range size (C, F). The shaded area highlights species that lose ≥ 50% of their forested range. We present results for the country-restricted simulations for Scenarios 1 (*Production*) and 3 (*Compromise*), lumping Scenarios 3a-c together because their results were identical at 3.90 Mha of expansion. Scenario 2 (*Conservation*) did not cause any species to lose ≥ 10% of their forested range at 3.90 Mha of expansion and is not shown. EN = Endangered; VU = Vulnerable; NT = Near-threatened; LC = Least concern; DD = Data deficient.

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3 Do agricultural rents, spatial contagion, and protected areas influence rubber expansion in mainland Southeast Asia?

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3.1 Abstract

Natural rubber is an important commodity and leading driver of tropical deforestation and biodiversity loss. Previous research had not accounted for agricultural rents in rubber expansion patterns, thus limiting our ability to identify areas susceptible to future conversion. We adopted an agricultural land rent contagion modelling framework to investigate drivers of rubber expansion across six countries in mainland Southeast Asia (MSEA) from 2003 to 2014, which spans a period of rubber price boom and bust. We also assessed whether expansion was prevented by protected areas (PAs). Our model shows that agricultural rents and rubber prices were important in explaining rubber expansion patterns in all countries, but also overestimated expansion in many areas. Spatial contagion within a 0.1° buffer was not informative in explaining rubber spread, although this does not rule out other forms of spatial clustering. Models that allowed expansion into PAs were better able to predict expansion within PAs than models not allowing conversion in PAs,

suggesting that PAs were not fully effective. Greater conversion in more accessible PAs (including in strict PAs) and environmentally suitable areas suggest that PAs cannot fully protect against economic incentives for conversion. Our study underscores the importance of market forces on crop expansion during crop booms.

Keywords: conservation planning, cropland expansion, *Hevea brasiliensis*, agricultural production, land use and land cover change, protected area

3.2 Introduction

Tropical forests are threatened by agricultural expansion (Laurance, Sayer and Cassman, 2014). In the past three decades, agriculture – particularly large-scale agribusiness – was responsible for > 80% of tropical forest conversion globally (Gibbs *et al.*, 2010; Hosonuma *et al.*, 2012). One of the main crops driving tropical habitat loss is natural rubber, *Hevea brasiliensis*, which is a critical raw material in several industries and a globally traded commodity that has replaced millions of hectares of natural habitat in Southeast Asia and Africa (Ziegler, Fox and Xu, 2009; Ordway, Asner and Lambin, 2017; Earthsight, 2018; Hurni and Fox, 2018). Natural rubber expansion has had negative repercussions for carbon stocks, biodiversity, hydrological systems, and other ecosystem services (Hauser *et al.*, 2015; Warren-Thomas, Dolman and Edwards, 2015; Blagodatsky, Xu and Cadisch, 2016).

Coupled with increasing demand and investments, especially from China, rising rubber prices led to an industry boom in the 2000s, with a rapid expansion of the areal extent of rubber, particularly in the Mekong region in mainland Southeast Asia (MSEA) and Côte d'Ivoire (Hurni and Fox, 2018; Kenney-Lazar *et al.*, 2018; Gitz *et al.*, 2020). Natural rubber prices increased steadily from the year 2000 (US$0.67/kg) to 2008 (US$2.59/kg), fell steeply after the 2008 economic crisis (US$1.92/kg in 2009), then rose sharply again, peaking at US$6.26/kg in early 2011 (World Bank, 2022a). Since 2011, rubber expansion has slowed as prices dropped (FAO, 2020; World Bank, 2022a). However, industry models predict that global rubber demand, largely from tyre manufacturing, will continue to grow at a modest rate of +2.4% per year into the next decade (IRSG, 2019, cited in Gitz *et al.*, 2020). This presents an opportunity for the rubber industry to strategically plan where to expand operations to maximise profit and minimise environmental impact. There is a significant emerging sector-wide commitment to drive more sustainable production and expansion of rubber (GPSNR, 2019). Nevertheless, given the mixed effectiveness of past eco-certification and sustainability standards for rubber and other commodity crops, more work is needed to ensure that sustainable policies are put into practice (Kennedy, Leimona and Yi, 2017; Jopke and Schoneveld, 2018).

Key to any strategic planning of rubber producers to meet sustainability goals is understanding the environmental, infrastructural, and economic factors affecting expansion as well as the links between these factors and deforestation. There have been few quantitative studies that investigated spatial factors explaining rubber expansion and projecting future expansion across MSEA (Li and Fox, 2012; Ahrends *et al.*, 2015; Xiao *et al.*, 2021). Li and Fox (2012) simulated land-cover change in montane MSEA from 2001 to 2025/2050 using the CLUE-S model, but they did not specify which variables affected rubber expansion. Using boosted regression trees, Ahrends *et al.* (2015) tested the ability of representative environmental and infrastructural variables (bioclimatic suitability, land cover, presence of protected areas, and distances to the nearest plantation, road, and major populated area) to explain rubber spread at the country level in MSEA from 2005 to 2010. They found that distance to nearest plantation was the most important predictor (36-59% contribution to the model) for all countries. Xiao *et al.* (2021) mapped and analysed spatial patterns of recent rubber plantations in MSEA (2013-2018), finding that plantations were expanding northwards into higher and lower elevations, and at transnational borders. Despite substantial evidence of agricultural prices stimulating deforestation and crop expansion in the tropics (Angelsen and Kaimowitz, 1999), and links noted between rubber prices and rubber expansion (Hurni and Fox, 2018; Grogan *et al.*, 2019), these studies did not explicitly account for the profitability of converting forest to rubber.

Other studies have found a spatial contagion or clustering effect in land clearing and crop expansion: for examples, land clearance for soy and cattle ranching in the Semiarid Chaco (Volante *et al.*, 2016); oil palm expansion in the Peruvian Amazon (Vijay *et al.*, 2018) and Indonesia (Lim *et al.*, 2019); and cocoa and oil palm expansion in Ghana (Asubonteng *et al.*, 2020). Theoretically, we expect a greater density of existing nearby plantations to increase agricultural rent and likelihood of conversion via increased transfer of knowledge of market conditions, availability of skilled labour, and lower transportation costs (Garrett, Lambin and Naylor, 2013), or via other mechanisms such as imitation behaviour and social transmission of perceived crop profitability (Junquera *et al.*, 2020). In rubber, Ahrends *et al.* (2015) found that distance to the nearest plantation was consistently the strongest predictor of expansion across MSEA countries. However, the effect of density of nearest plantations on rubber expansion has not been explored.

Understanding which areas are vulnerable to deforestation and conversion to agriculture is also useful for guiding conservation interventions, especially protected areas (PAs). Crop expansion has occurred inside PAs and currently crops take up 6% of PAs globally (Vijay and Armsworth, 2021). Despite their limitations, PAs are still moderately effective in reducing forest loss compared to non-PAs (Geldmann *et al.*, 2019; Shah *et al.*, 2021). Regarding rubber, strict PAs effectively prevented forest conversion to rubber in a small case study at the Laos-China border when enforced (Junquera *et al.*, 2020), whereas PAs in Xishuangbanna Prefecture, China, experienced similar or greater deforestation and rubber expansion rates as non-PAs regardless of the zonal stringency of the PAs (Sarathchandra *et al.*, 2018). During the rubber boom, rubber replaced 610 km^2 of PAs in MSEA, with 61% of the area converted in PAs highly unsuitable for rubber production (Ahrends *et al.*, 2015), presenting a lose-lose scenario for the ecological and economic sustainability of rubber (Wang, Carrasco and Edwards, 2020). Hence, investigating the links between PAs, agricultural land rents, and crop expansion is another important aspect of rubber sustainability.

In this study, we use a spatially explicit and temporally dynamic agricultural land rent modelling framework (Lim *et al.*, 2019) to simulate rubber expansion in MSEA. We investigate the role of market forces and spatial contagion in driving rubber expansion. To estimate the economic profitability of converting land to rubber, we use agricultural rents, i.e. the potential income from converting land for agricultural production (Angelsen, 2010). The calculation of agricultural rents in this modelling framework incorporates spatial variations in yield estimates, annual fluctuations in commodity prices, distance to markets, and production costs. This framework also allows us to investigate the influence of density of nearby plantations on conversion likelihood by testing for a spatial contagion effect. We also explore the interaction between agricultural rents and PAs to investigate the susceptibility of protected areas to conversion, as well as the effectiveness of protected areas in preventing rubber expansion. Using maps of the rubber-producing regions of six MSEA countries published by Hurni and Fox (2018) for the years 2001 through 2014, which cover the period of rubber price spikes and dips, we address the following research questions: (i) is rubber expansion governed by market forces (i.e. agricultural rents)? (ii) Is there a spatial contagion effect on rubber expansion? (iii) Is rubber expansion prevented by PAs?

3.3 Materials and methods

3.3.1 Data inputs

We obtained raster maps of land cover changes from 2001 to 2014 in rubber-producing regions of MSEA, spanning the whole of Cambodia and Laos, the Shan State of Myanmar, North/Northeast/part of Central Thailand, most of Vietnam, and Xishuangbanna Prefecture in China (Hurni and Fox, 2018). These were mapped as raster grid cells at a resolution of ~0.002°. We reclassified the land cover change categories to create separate maps for the years 2001/2002 (showing rubber plantations before 2003; for simplicity we assume this map is for the year 2002), 2005, 2008, 2011, and 2014. For each cell, we extracted values from other maps to obtain data on urban cover, rubber bioclimatic suitability, accessibility, and protected areas (Table S1). Prior to extracting values, we resampled all raster maps to the extent and resolution of the land cover map. We excluded cells that were classified as water or non-rubber cropland in 2002, urban in 2000, or were missing data for suitability and accessibility.

For the calculation of agricultural land rents and production costs, we used labour cost data from annual national minimum wages, annual national prices of fuel, fertiliser, rubber, and timber (data sources are detailed in Table S1). Temporal gaps in data were filled with the previous year's values. All input prices were adjusted to USD in 2015 prior to analysis.

3.3.2 Rubber expansion model

To simulate expansion of rubber production areas, we adapted a spatial economic model that uses an agricultural land rent approach to explain and predict crop expansion (Lim *et al.*, 2019). This model incorporates both spatial and temporal dynamics to assess crop expansion patterns, e.g. variations in crop yields across the landscape (spatial) and year-to-year fluctuations in crop and production prices (temporal). We applied this model to describe rubber spread in MSEA from 2002 to 2014. This model was programmed in R (R Core Team, 2018). We assumed that once cells were converted to rubber, they would remain as rubber for the rest of the modelled timespan. In this model, a cell was converted to rubber production if its agricultural rent (including timber harvests) exceeds the costs of conversion and production, as well as a minimum threshold representing opportunity costs of other land uses. This model assumes that the focal crop (i.e. rubber in this study) is likely to be the most profitable crop. Rubber was the largest boom crop during 2002-2014 in the study region, comprising 8% of the land cover in 2014, compared to cashews (1%), coffee (2%), pulp trees (4%), and fruit trees (2%) (Hurni and Fox, 2018). In addition, Hurni and Fox (2018) were not able to reliably classify the changes over time for these non-rubber crop land cover classes due to their fragmented nature. To obtain sufficient data, they had to group changes over time and present them as static land cover classes over the whole period. Hence, we excluded the non-rubber crop cover classes from cells available for rubber expansion in our model. The only non-rubber crop where the change over time could be reliably detected was sugarcane – cells classified as sugarcane in 2014 but not in 2002 were included among the cells available for rubber expansion in our model.

We calculate the agricultural net present value (NPV) annually for each cell in the raster map, starting from the year 2002 until the year 2013. As the six countries represented in the map (China, Cambodia, Laos, Myanmar, Thailand, Vietnam) had varying production costs and rubber yields, we ran the model separately for each country. We used country-level data whenever available; otherwise, we took the average of values from countries within the study region.

The NPV, or the predicted agricultural rent from converting each cell into rubber, discounted over a 25-year plantation cycle, was calculated as follows:

$$NPV_{i,t} = \sum_{t=0}^{24} \frac{(y_i \times p_t) + w_i - (f_t \times F) - (l_t \times L) - q_{i,t}}{(1+r)^t} \quad (1)$$

where y_i is rubber yield in tonnes per hectare per year in cell i; p_t is the annual national market price for rubber in year t; w_i is the timber profit from clearing the land in cell i; f_t is the cost of fertiliser in year t; F is the amount of fertiliser applied per hectare per year; l_t is wages in year t; L is the annual labour input per hectare needed for rubber cultivation; $q_{i,t}$ is the annual transportation costs for rubber in year t for cell i. Rubber yield was set as zero for the first six years before the trees reach maturity. We do not include the costs and profits of harvesting the rubber trees and selling the rubberwood timber at the end of the plantation cycle in this equation, as it is more often associated with the costs of replanting rubber in the next cycle (Shigematsu *et al.*, 2013). The discount rate, r, was set at 10% for all countries, following other studies estimating NPV for rubber plantations (Rodrigo *et al.*, 2001; Belcher *et al.*, 2004; RRISL, 2011; Warren-Thomas *et al.*, 2018). It falls within the range of social discount rates typically used by multilateral development banks (10-12%) and by developing countries (8-15%) (Zhuang *et al.*, 2007). Higher discount rates indicate that future benefits are valued lower than present benefits; thus, discount rates reflect the expectation of uncertainties or risks (Yi *et al.*, 2014).

To account for spatial differences in environmental suitability for growing rubber, suitability-scaled rubber yield per hectare per year, y_i, for cell i was calculated as follows:

$$y_i = \bar{y} \times \frac{u_i}{\bar{u}} \quad (2)$$

where $\bar{y}$ is the country-level rubber yield per hectare per year, averaged across all modelled years; u_i is the suitability value of cell i, and $\bar{u}$ is the mean suitability value of all cells in the country within the study region. The suitability values were obtained from a previous study of historically suitable environmental space for growing rubber (Ahrends *et al.*, 2015).

Timber profits, w_i are one-off and only calculated for the first year as follows:

$$w_i = W \times z_0 \times x_i \quad (3)$$

where W is the harvestable timber volume per hectare of forested land by country, reduced by 20% to account for wastage (Putz *et al.*, 2008); z_0 is the export price of timber in year t = 0; and x_i is a binary variable which indicates whether cell i is forested (1) or not (0) based on the land cover map. If the cell is not forested, then timber profits are assumed to be zero. For years t > 0, w_i = 0.

Transportation cost includes driver cost and fuel costs, and is based on the yield, as follows:

$$q_{i,t} = 2 \times \frac{y_i}{C} \times d_i \times (l_t + v_t \times M \times V) \quad (4)$$

where the suitability-scaled rubber yield, y_i, for cell i, is divided by C, the maximum payload capacity of the truck minus the weight of one driver, to determine the number of trips required to transport per hectare of rubber product. Assuming round trips are made, the number of trips is multiplied by two. Then d_i is the travel time in hours from cell i to the nearest city, a measure of accessibility; l_t is driver's wages per hour in year t; v_t is the diesel price in USD per litre in year t; M is the fuel consumption in litre per km; and V is average truck speed in km per hour.

To express the NPV in annual terms (USD per hectare per year), NPV was converted to equivalent annual cost (EAC), following the same discount rate as before (r = 10%), using the equation below:

$$EAC_{i,t} = \frac{NPV_{i,t} \times r}{1 - (1 + r)^{-25}} \quad (5)$$

The EAC was further adjusted based on two additional parameters as follows:

$$EACadj_{i,t} = EAC_{i,t} - K - S \times A_{i,t} \quad (6)$$

Firstly, we include a national rent threshold, K, which is subtracted from the EAC to account for additional costs not included in the NPV calculation, such as capital costs, depreciation, and legislation. The national rent threshold parameter K represents the minimum agricultural rent at which it is profitable for new plantations to be established, which varies among countries due to differences in government legislation and financial or technical resources provided (e.g. subsidies, training in rubber growing and tapping practices). Secondly, we incorporate a 'spatial contagion' parameter, $S \times A_{i,t}$, as we expect the density of established rubber plantations nearby to indirectly reduce establishment costs for new plantations; for example, due to presence of existing necessary infrastructure like roads and skilled labour. $A_{i,t}$ is the percentage of cells classified as rubber plantations within a 0.1° buffer (about 11 km at the equator) surrounding cell i in year t. $A_{i,t}$ is recalculated every year in the model, as additional cells are predicted by the model to be converted to rubber. S is a weight parameter to calibrate $A_{i,t}$.

If $EACadj$ for cell i is > 0, the model predicts that cell i will be converted to rubber in the following year. In practical terms, if estimated agricultural rents and timber profits from initial forest clearing for rubber are high enough on a given piece of land, the model predicts that the piece of land will be converted into a rubber plantation.

Cells with $EACadj$ > 0 in year t are classified as 'rubber' in the following year $(t + 1)$, generating an updated raster map of rubber areas for year $(t + 1)$. This output raster will be used as the input raster for predicting rubber expansion in year $(t + 2)$ and $EACadj$ will be recalculated for the remaining unconverted cells using parameters for the year $(t + 1)$. By iterating this model for all years, we generated annual maps of projected rubber expansion which can then be compared to the maps of observed rubber expansion.

3.3.3 Macro-averaged recall and precision

For both model fitting (3.3.4) and selection (3.3.5), we used macro-averaged recall as the primary metric following Lim *et al.* (2019). Recall measures the proportion of known instances of one class (e.g. cells converted to rubber) that were correctly classified by the model (Lever, Krzywinski and Altman, 2016). Macro-averaged recall simply means the class-wise arithmetic mean of recall (Takahashi *et al.*, 2022), calculated as follows:

$$\frac{1}{2}\left(\frac{true\ positives}{true\ positives\ +\ false\ negatives} + \frac{true\ negatives}{true\ negatives\ +\ false\ positives}\right)$$

Or, in the context of our study:

$$\frac{1}{2}\left(\frac{correctly\ predicted\ as\ converted}{observed\ rubber\ plantations} + \frac{correctly\ predicted\ as\ unconverted}{observed\ unconverted}\right)$$

Alongside recall, we also calculated precision. Precision measures the proportion of predicted instances of one class (e.g. cells predicted to be profitable) that were correctly classified (Lever, Krzywinski and Altman, 2016). Macro-averaged precision was calculated as follows:

$$\frac{1}{2}\left(\frac{true\ positives}{true\ positives\ +\ false\ positives} + \frac{true\ negatives}{true\ negatives\ +\ false\ negatives}\right)$$

Or, in the context of our study:

$$\frac{1}{2}\left(\frac{correctly\ predicted\ as\ converted}{predicted\ to\ be\ converted} + \frac{correctly\ predicted\ as\ unconverted}{predicted\ to\ be\ unconverted}\right)$$

In cases where true positives + false positives = 0 (i.e. no cells predicted to be converted) or true negatives + false negatives = 0 (i.e. no cells predicted to be unconverted), we assumed precision to be zero to avoid errors of division-by-zero before calculating macro-averaged precision.

Recall and precision values range from 0 to 1, with 0 indicating zero correct predictions and 1 indicating perfect performance. They can also be expressed as percentages, which we will adopt in this study for ease of interpretation. Essentially, the model that returns the highest macro-averaged recall is the model that returns the highest average proportion of both correctly predicted converted and unconverted cells (Lim *et al.*, 2019). There is a trade-off between recall and precision, as improving recall typically reduces precision and vice versa (Buckland and Gey, 1994). In our case, we prioritised recall over precision because we are more concerned about minimising false negatives (i.e. failing to predict conversions). We are less concerned about precision or minimising false positives because cells predicted to be profitable enough to convert could still be converted in the future. Nevertheless, we still report macro-averaged precision alongside macro-averaged recall during the model selection process as both metrics provide a fuller picture of model performance.

3.3.4 Model fitting and validation

We define model fitting as the process where we identified optimal values for parameters K (minimum rent threshold for conversion) and S (spatial contagion weight) in the models that would return the highest macro-averaged recall. For computational feasibility, we fitted models on a 10% subset of cells (training set) stratified-randomly sampled by province. For each country, we individually fitted models via a manual grid search process.

For each set of K and S values being tested, we ran models simulating rubber expansion from 2002 to 2014. From the simulation outcomes, we calculated confusion matrices comparing predictions of converted/unconverted cells for 2014 with actual converted/unconverted cells in 2014, then calculated the macro-averaged recall. Cells classified as rubber in 2002 were excluded from cells available for conversion and were not incorporated into the confusion matrices. We first tested models with a broad range of values for K at $S = 0$ and calculated recall scores for each iteration. We gradually narrowed the range of K being tested until we identified the best value for K that returned the highest macro-averaged recall. Next, we held K constant at the best value and repeated the manual grid search process for S. Once we identified the best values for K and S for each model, we then validated the fitted models against a separate 10% subset of cells (no overlap with training subset). We found very little difference in the results between training and validation models, so we proceeded with model selection using outputs of the validation models.

3.3.5 Model selection

Following Lim *et al.* (2019)'s protocol, we ran the fitted validation models under different model specifications, as follows:

Model 0a: all cells converted (baseline model)
Model 0b: zero cells converted (baseline model)
Model 1: EAC only
Model 2: $EAC - K$
Model 3: $EAC - K - S \times A_{i,t}$
Model 4: $EAC - K - S \times \sqrt{A_{i,t}}$

After running the models, we built four confusion matrices from the results of each model specification. The confusion matrices compared predictions of cells converted/unconverted since 2002 for the years 2005, 2008, 2011, and 2014 versus observed converted/unconverted cells in the corresponding years. Cells classified as rubber in 2002 were excluded from cells available for conversion and were not incorporated into the confusion matrices. From the four confusion matrices, we calculated macro-averaged recall and precision. We then calculated the mean and standard error of macro-averaged recall and precision across years.

To identify the influence of agricultural rents on rubber expansion, we qualitatively compared the macro-averaged recall of Models 1 and 2 to the baseline models. To identify the influence of spatial contagion, we qualitatively compared the macro-averaged recall of Models 3 and 4 to Model 2. Models 3 and 4 differ in the functional form of the spatial contagion effect – Model 3 shows a linear effect, whereas Model 4 square-root transforms $A_{i,t}$ to capture a convex effect, i.e. agricultural rents decrease with higher density of existing plantations within a 0.1° buffer but at a diminishing rate. Following the protocol by Lim *et al.* (2019), for every country we selected the model specification with the highest macro-averaged recall as the best performing model.

3.3.6 Evaluation of best performing models

For the model evaluation process, we also calculated accuracy, true positive rate, false negative rate, and false positive rate, in addition to macro-averaged recall and precision, as defined by Lever, Krzywinski and Altman (2016). Accuracy is the proportion of correct predictions (true positives + true negatives) over all cells in the model. True positive rate is equivalent to the recall of the positive class, i.e. the proportion of true positives (correctly predicted as converted) over all positive instances (all converted cells). False negative rate is the proportion of false negatives (incorrectly predicted as unconverted) over all converted cells. False positive rate is the proportion of false positives over all negative instances (all unconverted cells). These metrics all range from 0 to 1 (or 0% to 100%, expressed as percentages).

For evaluation purposes, we did not average metrics across years. To maintain consistency with Lim *et al.* (2019)'s evaluation process, we built confusion matrices comparing only the final model predictions (i.e. for the year 2014) to actual distribution of rubber plantations in 2014. We calculated evaluation metrics for all cells, protected cells (‘PA cells’) only and non-protected cells (‘non-PA cells’) only. We then quantitatively assessed and compared model performances across countries and across cell types, using the evaluation metrics as a guide.

To gain further insight into performances of the best models for each country, we plotted model results on maps of each country. We visualised the distribution of true positives, false negatives, and false positives over the landscape as a form of qualitative assessment. On these maps, we also overlaid polygons of protected areas established before 2003, during 2003-2014, and after 2014 (UNEP-WCMC and IUCN, 2020).

We caution that accuracy is not a suitable metric for datasets with class imbalance because of its sensitivity to skew (Lever, Krzywinski and Altman, 2016; Larner, 2022). Class imbalance means that the number of cases in one class is much higher than in the other class(es). Our dataset was highly imbalanced, as there were many more unconverted cells than converted cells (97% unconverted compared to 3% converted in 2014). Because of this, our baseline model, where none of the cells were converted (Model 0b), will always have an accuracy close to 100% despite having zero true positives. On the other hand, macro-averaged recall (equivalent to ‘balanced accuracy’ for binary classifications), is appropriate for imbalanced datasets (Larner, 2022). Hence, for model fitting and selection, we focus solely on maximising macro-averaged recall scores. Nevertheless, for evaluating performance of the final models we still report accuracy and the other metrics. We chose to do this because these metrics are more intuitive and easier to interpret, as well as to provide points of comparison with the previous application of the agricultural land rents framework (Lim *et al.*, 2019).

3.3.7 Protected Areas (PAs) analysis

To investigate the role of protected areas (PAs) in hindering expansion, we recalculated confusion matrices for an alternative model where cells within PAs were not allowed to be converted (‘effective PA’). For every year in the model, cells designated as PAs before the modelled year were classified as unconverted. Cells that were not yet designated as PAs before or during the modelled year were allowed to be converted. For example, during the modelled year 2005, conversion would not be allowed in cells designated as PAs in 2005 and earlier. However, during that same year, conversion would be allowed in cells designated as PAs in 2006 and later.

We then noted changes in model performances (mean of macro-averaged recall and macro-averaged precision across years) between the 'effective PA' model and the original model, where conversion was allowed in PAs. We also looked at changes in evaluation metrics calculated for all cells, protected cells ('PA') only, and non-protected cells ('non-PA') only. We conducted an exact McNemar's test, a paired, non-parametric statistical test to compare if the two models differed in their 2014 prediction errors on all cells (Dietterich, 1998). We used the exact version of the McNemar's test, which is more conservative and suitable for small sample sizes (Pembury Smith and Ruxton, 2020), as implemented in the R package 'exact2x2' which also provides confidence intervals (Fay, 2010).

We also conducted descriptive analysis on data obtained from maps of rubber distribution, PAs, rubber bioclimatic suitability, and accessibility (Table S1) to compare: (i) rubber expansion in PA versus non-PA cells; (ii) suitability for rubber cultivation and accessibility of PA versus non-PA cells, to see whether suitability and accessibility affected PA effectiveness; and (iii) rubber encroachment rates between PA categories, to see whether stringency of categories affected PA effectiveness. PAs in Xishuangbanna Prefecture, China, were classified as non-PAs as recommended by the World Database of Protected Areas guidelines because they included buffer and transition zones (UNEP-WCMC and IUCN, 2020). Thus, China was excluded from most of the PA analyses. We found 24 PA cells falling within Chinese borders, which belonged to the Nam Ha National PA of Laos – these cells were left as part of the China dataset for consistency with other analyses in this study. PAs degazetted before 2020 were also excluded.

3.4 Results

3.4.1 Model selection: Influence of agricultural rents and spatial contagion on predictability of rubber expansion

Across all countries, model specifications incorporating a national rent threshold K (Models 2-4) were better at predicting rubber expansion than either of the baseline models (Model 0) or the model based on unadjusted agricultural rents (Model 1) (Figure 1; Table S2). Model specifications based on unadjusted agricultural rents (Model 1) predicted that 98-100% of cells in each country would be converted by 2014, thus performing very similarly to Model 0a (All cells converted) (Figure 1; Table S2). Comparing Model 2 to Model 1, the addition of the national rent threshold parameter K improved mean macro-averaged recall by 22% for Myanmar, 16% for Vietnam, 8% for China, 6% for Laos and Thailand, and 5% for Cambodia (Figure 1; Table S2). This suggests that our agricultural rents framework may better explain rubber spread in Myanmar and Vietnam (mean macro-averaged recall up to 73% and 78% respectively) than in the other countries (mean macro-averaged recall up to 56%-60%).

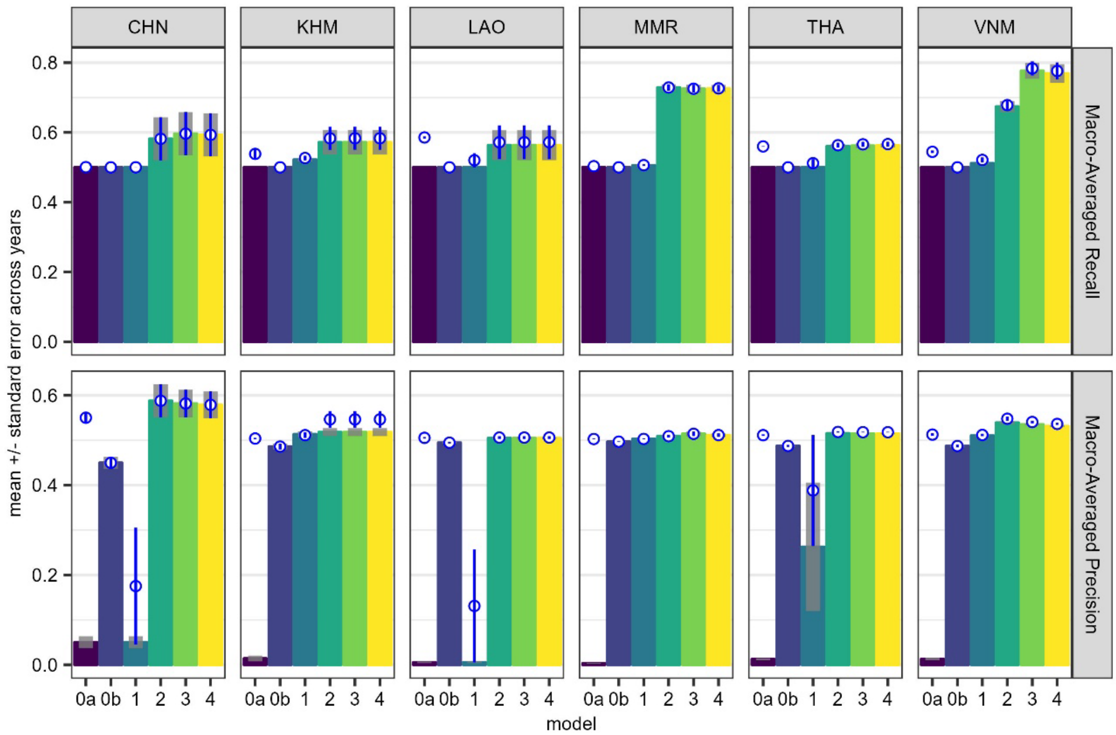

Figure 1 (previous page). Selection of best performing model for each country via comparison of macro-averaged recall and precision for different model specifications. Macro-averaged recall and precision were calculated from confusion matrices comparing model predictions to observed rubber distributions for the years 2005, 2008, 2011, and 2014, then averaged across years. Circles are metric scores for 'effective PA' models where conversion was not allowed in PAs, while coloured bars are the scores for the original models. Error bars (grey bars for original models and blue lines for 'effective PA' models) indicate the standard errors. Country abbreviations: China (CHN), Cambodia (KHM), Laos (LAO), Myanmar (MMR), Thailand (THA), and Vietnam (VNM). Model specifications: All cells converted (Model 0a); Zero cells converted (Model 0b); EAC only (Model 1); EAC adjusted by national rent threshold K (Model 2); EAC adjusted by K and linear spatial contagion effect S (Model 3); and EAC adjusted by K and square root transformed S (Model 4). For more details on model specifications, see Table S2.

Due to the trade-off between recall and precision, we did not rely on macro-averaged precision in the model selection process. Across all countries and model specifications, mean macro-averaged precision never exceeded 60%. Low macro-averaged precision indicates that our models tend to predict much more conversion than was actually converted, which is to be expected given that we favoured recall during model fitting. Models incorporating national rent thresholds (Models 2-4) improved macro-averaged precision from the best baseline (Model 0b: Zero cells converted) by about 13% for China, but only 1-5% for other countries.

We did not find a consistent effect of spatial contagion across all countries over the modelled years (2002-2014). When we added a spatial contagion parameter to the model specification (Models 3 and 4), macro-averaged recall improved by 10% for Vietnam, but hardly made a difference for the other countries (Figure 1; Table S2). For Vietnam, adding spatial contagion to the model improved macro-averaged recall but at the cost of decreased macro-averaged precision (Figure 1; Table S2). For Shan State in Myanmar, having a negative value for the spatial contagion parameter was better for macro-averaged recall than a positive contagion effect (Table S2). This suggests that in Shan State, cells with fewer existing nearby plantations were more likely to be converted. The difference between linear or square root spatial contagion model specifications was negligible (Figure 1; Table S2).

The best performing models for each country were selected based on the model specification that returned the highest mean macro-averaged recall across years. Model 3 was selected as the best performing model for China, Cambodia, and Vietnam. Model 4 was the best performing model for Laos and Thailand. For Myanmar, Model 2 without a spatial contagion parameter was selected as the best performing model.

3.4.2 Evaluation of best performing models

The ability of the best models to predict rubber conversion outcomes in 2014 varied considerably among countries (Table 1; Figure 2). The models correctly identified 71.7% of cells converted to rubber in 2014, with rates of > 90% in China (Xishuangbanna Prefecture) and Cambodia, 78% in Laos, and 73.4% in Myanmar (Shan State) (true positive rate, Table 1). Overall, the models also correctly identified 82.5% of PAs converted into rubber plantations by 2014, especially in Cambodia and Myanmar (true positive rate in PA cells, Table 1). Among countries, the model for Thailand performed worst based on macro-averaged recall, true positive rate, and false negative rate. Although boasting the highest accuracy (80.8%), the model for Thailand correctly identified only 30.8% of converted cells and 23.6% of converted PAs. From the maps, we can observe clusters of true positives in each country, usually surrounded by false positives (Figure 2).

Figure 2 (following page). Performance of the best country models in predicting conversions to rubber from 2002 to 2014, compared against observed rubber distributions in 2014. Cells are colour-coded, indicating whether the model prediction was a true positive, true negative, false positive, or false negative. PAs are shown as translucent polygons, with different outlines indicating when they were established. Models presented are those returning the highest recall out of the four models fitted per country, as follows: Model 3 for Xishuangbanna Prefecture, Cambodia, and Vietnam; Model 4 for Laos and Thailand; Model 2 for Shan State, Myanmar.

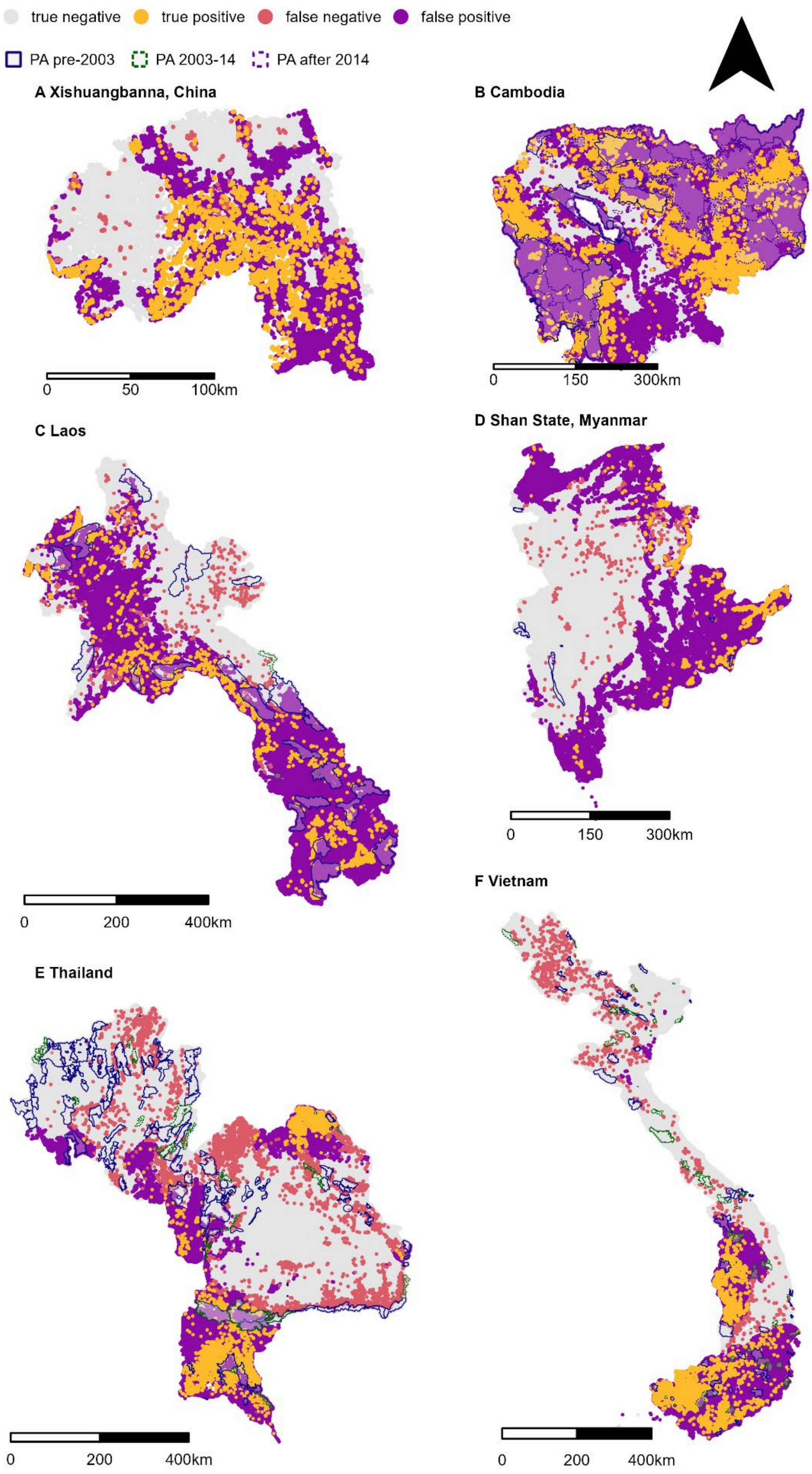
true negative
true positive
false negative
false positive
PA pre-2003
PA 2003-14
PA after 2014
A Xishuangbanna, China
0
50
100km
B Cambodia
0
150
300km
C Laos
0
200
400km
D Shan State, Myanmar
0
150
300km
E Thailand
0
200
400km
F Vietnam
0
200
400km

Table 1. Summary of the results and evaluation metrics for the best performing models for each country, broken down by all cells, cells within protected areas (PA), and non-protected cells (non-PA). The confusion matrices and evaluation metrics reported here were obtained from comparing final model predictions in 2014 with actual rubber distribution in 2014. The best performing models were those returning the highest macro-averaged recall (mean across years; reported in Figure 1 and Table S2) out of the four model specifications fitted per country, as follows: Model 3 ('EAC adjusted by K and linear spatial contagion effect S') for China (Xishuangbanna Prefecture), Cambodia, and Vietnam; Model 4 ('EAC adjusted by K and square root transformed S') for Laos and Thailand; Model 2 ('EAC adjusted by national rent threshold K') for Shan State, Myanmar. Abbreviations: n = number of cells, TP = true positive, TN = true negative, FP = false positive, FN = false negative, TPR = true positive rate, FNR = false negative rate, FPR = false positive rate.

Country	Cell type	n	TP	TN	FP	FN	Macro-averaged recall	Macro-averaged precision	Accuracy	TPR	FNR	FPR
China	All	24397	2863	13026	8243	265	76.4%	61.9%	65.1%	91.5%	8.5%	38.8%
	PA	24	0	0	24	0	NA	NA	0.0%	NA	NA	100.0%
	non-PA	24373	2863	13026	8219	265	76.4%	61.9%	65.2%	91.5%	8.5%	38.7%
Cambodia	All	287987	16442	97353	173836	356	66.9%	54.1%	39.5%	97.9%	2.1%	64.1%
	PA	41332	2266	6592	32473	1	58.4%	53.3%	21.4%	100.0%	0.0%	83.1%
	non-PA	246655	14176	90761	141363	355	68.3%	54.4%	42.5%	97.6%	2.4%	60.9%
Laos	All	307104	4056	156061	145840	1147	64.8%	51.0%	52.1%	78.0%	22.0%	48.3%
	PA	62184	147	33522	28453	62	62.2%	50.2%	54.1%	70.3%	29.7%	45.9%
	non-PA	244920	3909	122539	117387	1085	64.7%	51.2%	51.6%	78.3%	21.7%	48.9%
Myanmar	All	241071	1692	164762	74004	613	71.2%	50.9%	69.0%	73.4%	26.6%	31.0%
	PA	1619	1	1373	245	0	92.4%	50.2%	84.9%	100.0%	0.0%	15.1%
	non-PA	239452	1691	163389	73759	613	71.1%	50.9%	68.9%	73.4%	26.6%	31.1%
Thailand	All	514957	4692	411539	88181	10545	56.6%	51.3%	80.8%	30.8%	69.2%	17.6%
	PA	80240	134	65552	14120	434	52.9%	50.1%	81.9%	23.6%	76.4%	17.7%
	non-PA	434717	4558	345987	74061	10111	56.7%	51.5%	80.6%	31.1%	68.9%	17.6%
Vietnam	All	270014	7820	174439	85861	1894	73.8%	53.6%	67.5%	80.5%	19.5%	33.0%
	PA	32153	68	19294	12735	56	57.5%	50.1%	60.2%	54.8%	45.2%	39.8%
	non-PA	237861	7752	155145	73126	1838	74.4%	54.2%	68.5%	80.8%	19.2%	32.0%
Overall	All	1645530	37565	1017180	575965	14820	67.8%	52.3%	64.1%	71.7%	28.3%	36.2%
	PA	217552	2616	126333	88050	553	70.7%	51.2%	59.3%	82.5%	17.5%	41.1%
	non-PA	1427978	34949	890847	487915	14267	67.8%	52.6%	64.8%	71.0%	29.0%	35.4%

Conversely, the models failed to identify 28.3% of converted cells as being profitable enough for conversion to rubber (false negative rate, Table 1). Concerningly, we failed to predict the conversion of 76.4% and 45.2% of PA cells in Thailand and Vietnam, respectively (false negative rate in PA cells, Table 1). These false negatives were concentrated in northern Vietnam and northern Thailand, particularly at the borderlands with Cambodia, Laos, and Myanmar (Figure 2).

Across the entire study area, the best performing models predicted 37% of cells to be profitable for conversion, although only 6% of those were actually converted to rubber by 2014 (Table 2). Overall, our model overestimated conversions for 36.2% of the unconverted cells (false positive rate, Table 1). False positives were prevalent in all countries, with the highest rates in Cambodia (64.1%) and Laos (48.3%), followed by China (38.8%), Vietnam (33%), and Myanmar (31%) (Table 1; Figure 2). Thailand had the lowest false positive rate (17.6%), at the expense of having the lowest macro-averaged recall, lowest true positive rate, and highest false negative rate. The false positive rate was very high (83%) in Cambodian PA cells, indicating that many Cambodian PAs were predicted to be profitable for conversion but were not converted by 2014 (Table 1; Figure 2).

Among countries, calculated agricultural rents (EACs) varied widely, with Thailand having much higher agricultural rents than the other countries (Figure S1). Agricultural rents were primarily driven by rubber profits, while timber profits and other agricultural costs had a limited role in determining agricultural rents (Figure S1). Country differences in our estimates of agricultural rents were driven by national differences in rubber yield (FAO, 2020). In all countries except Vietnam, our models predicted surges in rubber expansion during the periods 2007-2009 and 2011-2012, which follow the rubber price trajectories (Figure S1). In all countries, our models predicted much more rubber expansion by 2014 than was observed (Figure 2); although in China (Xishuangbanna Prefecture) our model under-estimated conversions until 2011 - actual conversions occurred earlier than predicted (Figure S2). Peak expansion was around 2006-2008 in China, Thailand, Laos, and Myanmar, rather than around 2011-2012 when rubber prices were at their highest (Figure S2).

Table 2. Composition of cells predicted by the best performing country models to be profitable for conversion to rubber (validation dataset, 10% of cells), including the percentage actually converted to rubber by 2014 (equivalent to precision of the positive class), number of profitable cells not converted to rubber (i.e. false positives), and a breakdown of false positives by land cover type in 2014. LVA: low vegetation area comprising annual crops, shrubs, and grass; may have been deforested in the past; includes urban cells. PA: protected areas established up to 2014; includes forested and non-forested cells. Urban: data for 2010; only includes cells classified as LVA and urban. Sugarcane: not a subset of LVA; the only non-rubber crop where the change over time could be reliably detected in the land cover map (Hurni and Fox, 2018).

Country	n cells available for conversion	% cells predicted profitable	% profitable cells converted to rubber	n profitable cells not converted to rubber (false positives)	Actual land cover in 2014 (% false positives)				
					Forest	LVA	PA	Urban	Sugarcane
China	24397	45.52	25.78	8243	91.60	8.40	0.29	0.05	0.00
Cambodia	287987	66.07	8.64	173836	86.18	13.80	18.68	0.04	0.02
Laos	307104	48.81	2.71	145840	78.80	21.14	19.51	0.07	0.06
Myanmar	241071	31.40	2.24	74004	91.50	8.50	0.33	0.03	0.00
Thailand	514957	18.04	5.05	88181	25.76	74.23	16.01	0.30	0.00
Vietnam	270014	34.69	8.35	85861	61.27	38.69	14.83	0.56	0.04
Overall	1645530	37.28	6.12	575965	72.11	27.86	15.29	0.16	0.03

3.4.3 Protected areas and rubber expansion

To investigate how PAs might influence the rubber expansion model, we simulated rubber expansion under the condition where conversion was not allowed within PAs (‘effective PA’ model). Considering only the more realistic model specifications (Models 2-4), the ‘effective PA’ model made very little difference to the mean macro-averaged recall (changes of 0.002%-1.2%) and macro-averaged precision (changes of 0.005%-2.84%) of each country (Figure 1; Models 2-4). The biggest observable difference was in Cambodia, where the ‘effective PA’ model increased macro-averaged precision by 3% with no overlap in standard errors (Figure 1).

A more revealing comparison could be made by comparing evaluation metrics within PAs between the original model and the ‘effective PA’ model (Figure 3; Table S3). Across all countries, the ‘effective PA’ model reduced false positive rates within PAs to low levels (< 10%), but at the cost of greatly reduced true positive rates (ranging from 0% to 12.9%) and very high false negative rates (ranging from 87.1% to 100%) (Figure 3; Table S3). Macro-averaged precision did not change or only decreased slightly (Table S3). Taken together, the ‘effective PA’ model performed worse within PA cells compared to the original model as the macro-averaged recall fell to around 50% (i.e. baseline levels). The differences between the two models were significant (Table 3). This result indicates that our original model which allows conversion in PAs is more realistic than the ‘effective PA’ model. For some countries, even our original model was conservative. As noted in the previous section (3.4.2), our model already under-predicted profitability of conversion for 76.4% and 45.2% of PA cells in Thailand and Vietnam (Table 1). Meanwhile, there was little change in model performances in non-PA cells with the ‘effective PA’ model (differences in false positive rates never exceeded 0.4%) (Table S3).

Table 3. Results of exact McNemar’s test, based on a contingency table comparing the predictions of our original model to those of the ‘effective PA’ model. Predictions for both PA and non-PA cells were included. ‘b’ is the number of cells misclassified by original model but not by ‘effective PA’ model. ‘c’ is the number of cells misclassified by ‘effective PA’ model but not by original model. Odds ratio (calculated as ‘b’ divided by ‘c’) is the main test statistic, with 95% confidence intervals as implemented by Fay (2010). For all models, the null hypothesis that the true odds ratio is equal to 1 was rejected. This indicates that there were significant differences between two models.

Country	b	c	p-value	Odds ratio	95% CI (lower)	95% CI (upper)
Cambodia	32468	2267	< 0.001	14.32	13.72	14.95
Laos	28449	147	< 0.001	193.53	164.58	229.16
Myanmar	245	1	< 0.001	245.00	43.56	9715.98
Thailand	13289	134	< 0.001	99.17	83.66	118.46
Vietnam	11017	66	< 0.001	166.92	131.10	215.99
Entire study area	85492	2615	< 0.001	32.69	31.44	34.00

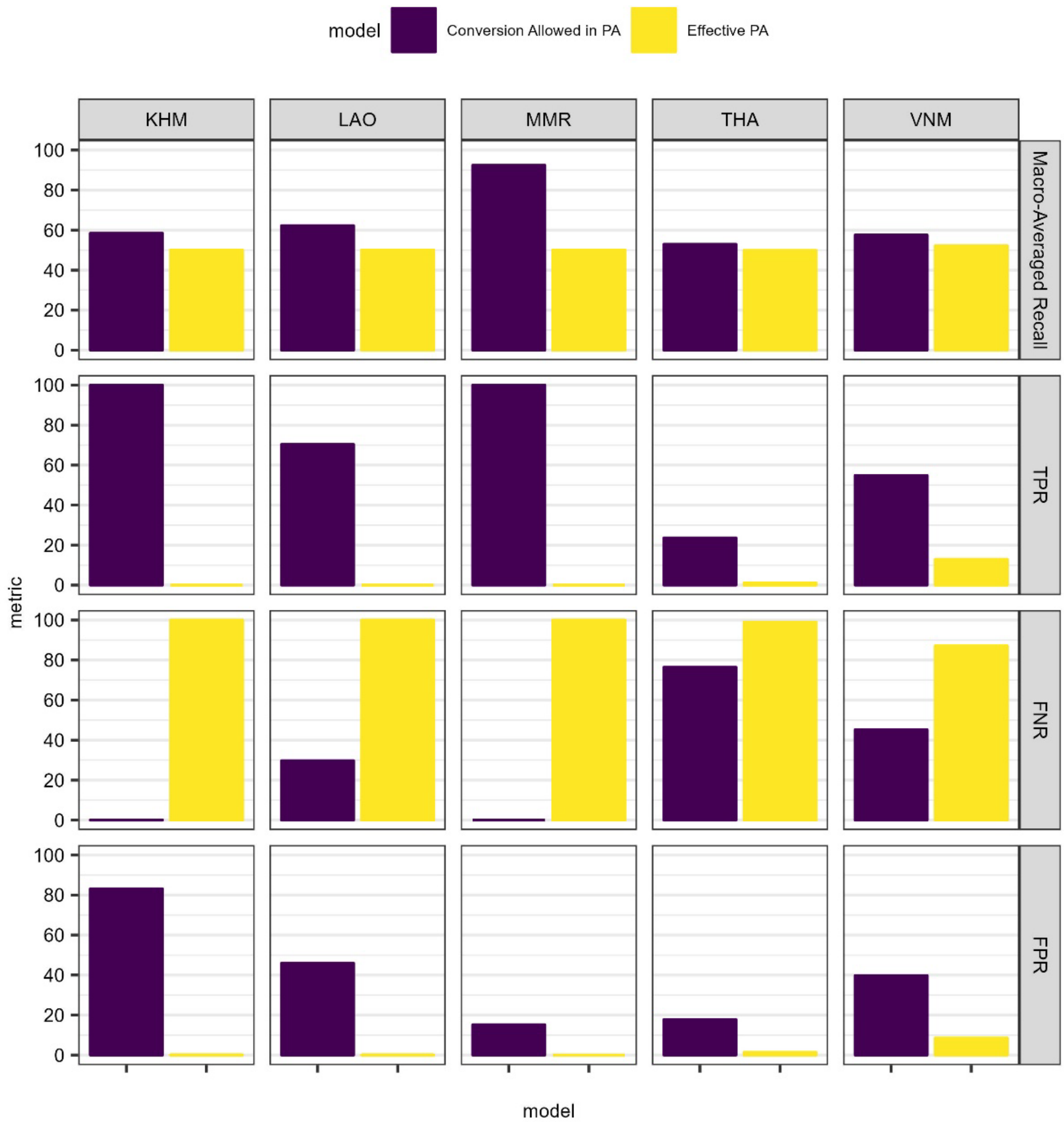

Figure 3. Comparison of model performances within PAs, by country, between the original model where conversion was allowed in PAs and the 'effective PA' model. Only the four most informative evaluation metrics are presented, namely macro-averaged recall, true positive rate (TPR), false negative rate (FNR), and false positive rate (FPR). Other metrics were not useful for model comparison but are reported in Table S3. Country abbreviations: Cambodia (KHM), Laos (LAO), Myanmar (MMR), Thailand (THA), and Vietnam (VNM).

Based on descriptive analysis of data obtained from rubber and PA maps, it is clear that PAs were not fully effective against encroachment by rubber. About 462 km^2 (0.25%) of all PAs established by 2020 across the entire study area had already been converted to rubber before 2003 (Table 4). An additional ~2,308 km^2 (1.25%) were converted between 2003 and 2014 (Table 4). PA encroachment before 2003 totalled ~302 km^2, and increased dramatically during 2003-2014, particularly in Cambodia (~1237 km^2, 4.9% of Cambodian PAs) and Thailand (~556 km^2; Figure 4A; Table 4). In Cambodia, ~46,574 km^2 of new PAs were established in 2015-2020, but 1.4% of these new PAs (~659 km^2) had already been converted to rubber.

Overall, there were no clear differences between PAs and non-PAs in their rubber cultivation suitability, but converted cells had higher mean suitability than unconverted cells regardless of their protection status (Figure 4B). The only exception was Cambodia, where cells converted during 2003-2014 had lower mean suitability than unconverted cells, suggesting decoupling of rubber expansion from suitability. In Thailand and Vietnam, the 'pecking order' trend is evident, with the most suitable areas in both PAs and non-PAs converted before 2003, and the least suitable cells left unconverted by 2014. Countries with higher mean rubber suitability experienced higher levels of conversion in both PA and non-PAs (Thailand, Cambodia, and Vietnam), while countries (Laos and Myanmar) with very low suitability were converted less (Figure 4A, B). Taken together, our findings suggest PAs had limited effectiveness in protecting the most suitable areas from rubber conversion.

PAs were, on average, more remote than non-PAs, except in Shan State, Myanmar, where the converse was true (Figure 4B). Encroached PAs were up to 4 hours closer to cities than PAs that remained unconverted. The 'pecking order' trend for accessibility held true for PAs in Cambodia, Thailand, and Vietnam, plus also for non-PAs in Myanmar and Vietnam. This suggests that PAs located closer to cities were more susceptible to agricultural conversion. However, in Laos, rubber expansion first occurred in the remotest locations, suggesting targeted 'pioneering' development of rural, heavily forested areas.

Table 4. Extent of protected areas (PAs) and rubber encroachment within PAs, by country and across the study area overall. Rubber encroachment within PAs was further broken down by the time period they were encroached. For the time period 2003-2014, we were also able to quantify the extent of rubber encroachment occurring before and after the PAs were established. Descriptive statistics were derived from all cells in the data. Number of cells (n cells) may not add up exactly and may depart from area estimations due to PAs at cross-border areas. PA sizes (km^2) were approximated from rasterised data.

Country	Cambodia	Laos	Myanmar	Thailand	Vietnam	Overall
			PAs established before 2003			
(n cells)	461345	705969	21171	778055	206095	2172961
(km^2)	25,286	37,741	1,082	41,736	11,069	116,721
% encroached before 2015	5.061	0.349	0.076	1.065	0.814	1.647
% encroached before 2003	0.168	0.045	0	0.484	0.374	0.259
			PAs established 2003-2014			
(n cells)	204	12692	71	203261	166283	382511
(km^2)	0	594	0	11,009	9,014	20,618
% encroached before 2015	0	0.087	0	1.393	0.401	0.918
% encroached before 2003	0	0.071	0	0.92	0.191	0.574
% encroached before PA established	0	0.071	0	1.208	0.38	0.81
% encroached after PA established	0	0.016	0	0.185	0.021	0.108
			PAs established 2015-2020			
(n cells)	849120	1082	1100	54	386	851742
(km^2)	46,575	0	58	0	0	46,553
% encroached before 2015	1.414	0	0	0	1.036	1.41
% encroached before 2003	0.086	0	0	0	0	0.085
			All PAs up to 2020			
(n cells)	1310669	719743	22342	981370	372764	3407214
(km^2)	71,861	38,335	1,140	52,745	20,083	183,891
% encroached before 2015	2.697	0.344	0.072	1.133	0.63	1.506
% encroached before 2003	0.115	0.045	0	0.575	0.292	0.251

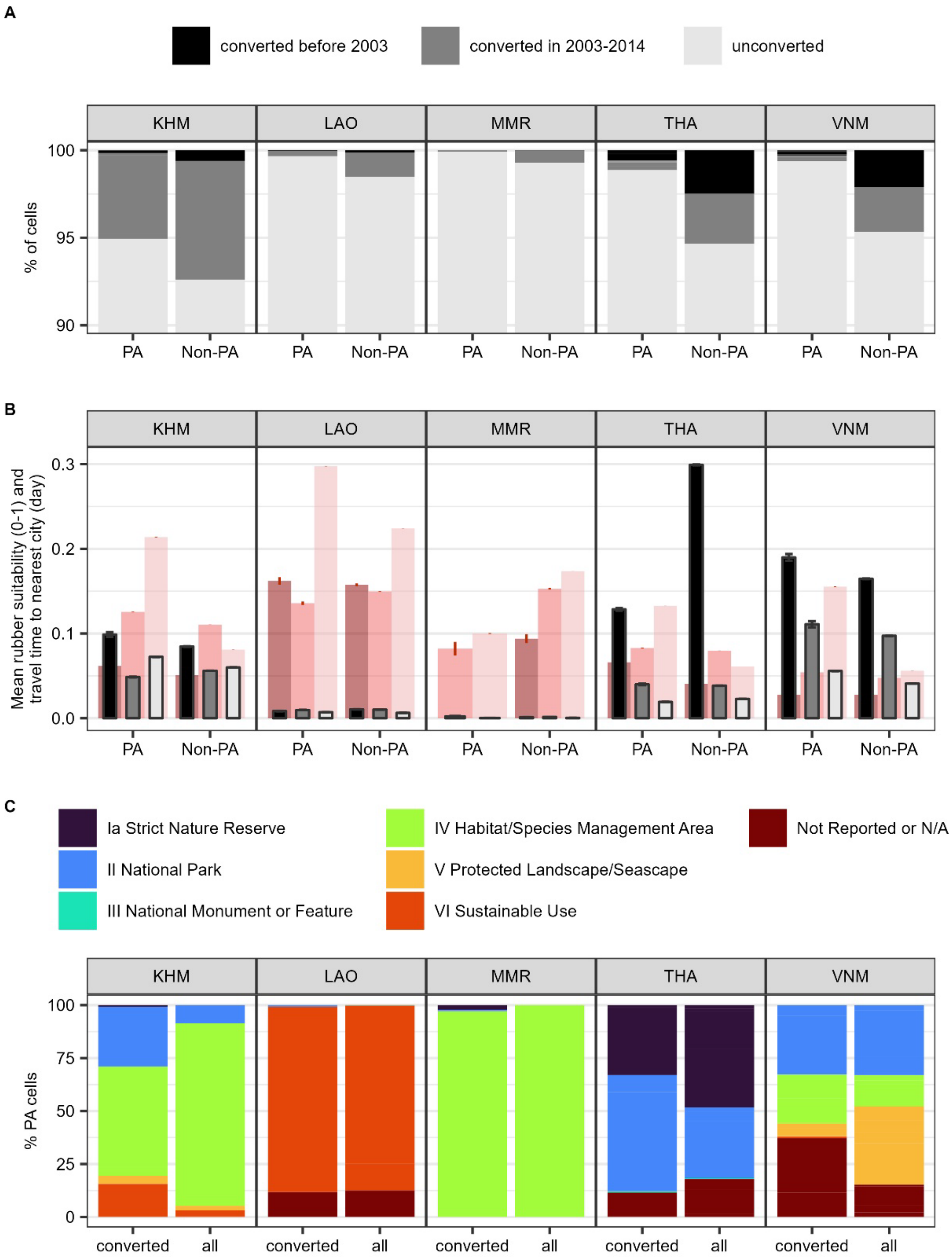

Figure 4. Encroachment of rubber into PAs. (A) Conversion (%) in PA/non-PA cells; y-axis begins at 0.90 for better visualisation as > 90% of cells were unconverted. (B) Suitability (grey-tone, bordered bars) and accessibility (red-tone, borderless bars) of converted/ unconverted and PA/non-PA cells. We show the mean ± standard error of rubber suitability (scale of 0-1) and travel time to nearest city in days. (C) PA categories of converted PAs compared to all PAs. Descriptive statistics for this figure were derived from all cells.

Composition of PA categories varied among countries, but none of the categories were 100% effective at preventing encroachment from rubber (Figure 4C). The stringency of PA categories did not impact the level of protection. Categories Ia and II, which strictly exclude human inhabitation and use of resources, were encroached at similar or sometimes greater levels than the less stringent categories III and IV or even the least strict categories V and VI (Figure 4C). In particular, the disproportionate levels of encroachment in Category II National Parks in Cambodia and Thailand are a cause for concern.

3.5 Discussion

Using an agricultural land rents framework, we modelled and simulated rubber expansion across MSEA from 2003 to 2014. We showed that agricultural rents played a partial but important role in explaining rubber spread across all six MSEA countries, although model performance varied widely by country. We found little evidence of the role of contagion effects and transport costs in expansion patterns, potentially explained by the low costs of transporting non-perishable latex. Predictions of rubber expansion within PAs worsened when we did not allow any conversion within PAs in our 'effective PA' simulations, indicating that PAs were not a sufficient condition to fully prevent rubber expansion. The most environmentally suitable and accessible areas for rubber in both PAs and non-PAs were already converted before 2003.

3.5.1 Is rubber expansion governed by agricultural rents?

Given lucrative profits during high rubber prices, our agricultural land rent model predicted substantial rubber expansion in each MSEA country by 2014, but observed expansion was much less than predicted. This may reflect impacts of the 2008 financial crisis on smallholders and agribusinesses, reducing their incentive or capacity to expand rubber plantations, even as prices soared from 2009 to 2011 (Hurni and Fox, 2018). Nevertheless, smallholders may still plant rubber during declining prices for economic reasons, anticipating prices to rebound when new plantations are ready for tapping or because rubber remains more profitable than other crops (Junquera *et al.*, 2020).

Our findings suggest that additional factors moderate the effects of agricultural rents, restricting rubber expansion in profitable areas or stimulating conversion in less-profitable locations. Land-use policies, political interests, weak governance, and differences between smallholders versus estates could explain contrasting patterns of rubber expansion across and within individual MSEA countries (Fox and Castella, 2013; Byerlee, 2014; Hurni and Fox, 2018; Kenney-Lazar *et al.*, 2018; Kissinger, 2020). Moratoria on concessions in Laos and Cambodia, and civil unrest in Shan State, Myanmar, likely restricted rubber expansion in otherwise profitable areas (Burke *et al.*, 2017; Lu, 2017; Hurni and Fox, 2018). Conversely, the 2004 Thai government scheme to promote rubber cultivation in new areas (e.g. Northeast and Southwest) likely lowered the national rent threshold for conversion (e.g. by increasing financial assistance, creating markets, etc.), driving an upsurge of rubber in non-traditional growing areas outside our model predictions (Sakayarote and Shrestha, 2017).

Cambodia had the lowest agricultural rents for conversion to rubber – with land converted to rubber during 2003-2014 less suitable for rubber than unconverted land – but the highest predicted returns from timber exports. Between 2001 and 2011, many large rubber concessions were granted to companies backed by political elites and foreign investors (Byerlee, 2014; Hurni and Fox, 2018). These concessions often overlapped with evergreen forests, reservoirs of extremely lucrative rosewood (*Dalbergia* spp.) and native hardwoods (*Dipterocarpus* spp.) (Milne, 2015), and concessionaires often sought timber rather than rubber development (Oldenburg and Neef, 2014). Similarly, in southern Myanmar, most oil palm concessions were left undeveloped, implying that investors were more interested in timber extraction or land speculation (Byerlee *et al.*, 2014). Since forests constitute 68% of the area predicted by our model to be profitable for conversion, the risk of deforestation looms large in MSEA.

3.5.2 Is there a spatial contagion effect on rubber expansion?

After accounting for agricultural rents, spatial contagion had little effect on the models (except in Vietnam). This was unexpected because previous research uncovered a consistent relationship between rubber expansion and distance to existing plantations across MSEA (Ahrends *et al.*, 2015). One explanation is that rubber latex can be stored for months before being processed and is typically delivered to processing facilities via multiple intermediaries, in contrast to oil palm fruit bunches that must be transported to mills within 24 hours and where spatial contagion explained expansion in Indonesia (Lim *et al.*, 2019). Given that rubber production is less reliant on large, shared infrastructure close by, increasing the spatial contagion buffer (e.g. to 0.5°) may improve model results.

Our measure of spatial contagion did not account for existing plantations across national borders, which could obscure transboundary spatial contagion effects. The increased rubber cultivation at cross-border regions (Xiao *et al.*, 2021) likely reflects the availability of cheap migrant labour (Byerlee, 2014; Rungmanee, 2014). Rubber expansion may occur in areas with few to no plantations because concessions are frequently granted in sparsely populated areas (‘vacant’ land) to reduce conflict with existing land users and local communities (Byerlee, 2014), as well as promote timber exploitation. Lastly, spatial contagion may be linked to the density of other crop plantations besides rubber; unpredicted rubber expansion in northern Vietnam may be linked to pulp-tree plantations dominating the region (Hurni and Fox, 2018).

3.5.3 Is rubber expansion prevented by protected areas (PAs)?

Compared to models that allowed expansion into PAs, our ‘effective PA’ models, which simulated full enforcement of PAs, produced poorer predictions of rubber expansion within PAs. PAs did not completely prevent rubber expansion. Our study supports the previous finding by Ahrends *et al.* (2015) that PAs were generally not a useful predictor of rubber spread in MSEA. Nevertheless, our descriptive analyses suggest that PA presence can hinder the conversion of profitable cells, with conversion rates lower in PAs than non-PAs. While this simple comparison did not take counterfactuals into account, our observation is consistent with other studies showing that forest loss and crop expansion are lower within PAs (Geldmann *et al.*, 2019; Shah *et al.*, 2021; Vijay and Armsworth, 2021). PAs are often established in areas with low opportunity cost and questionable additionality (Joppa and Pfaff, 2009), and we found that PAs were generally less accessible than non-PAs (except in Shan State, Myanmar), but not less suitable for rubber than non-PAs. In addition, PAs degazetted before 2020 were not included in our dataset, so our study may have underestimated PA encroachment.

The extent of rubber encroachment in Cambodia's PAs and Thailand's strict PAs confirms that PAs are subject to persistent deforestation pressures (Geldmann *et al.*, 2019; Vijay and Armsworth, 2021). Recent analysis suggests that tree cover loss in Cambodian PAs has not slowed down after the rubber boom (Kresek, 2019). Moreover, protection against forest loss does not necessarily prevent habitat degradation and biodiversity loss (Junquera *et al.*, 2020). For PAs to be effective, we need to consider both where to establish PAs and which locations are susceptible to specific anthropogenic threats, as PAs in highly suitable and accessible areas may require additional measures. In turn, a better understanding of the local pressures on PAs and whether these pressures are influenced by economic factors should facilitate implementation and enforcement of PAs.

3.5.4 Study limitations

In contrast with Lim *et al.* (2019), who used the same agricultural rents modelling framework to predict oil palm expansion in Indonesia from 2000 to 2015 with high accuracy (85.8%) and macro-averaged recall (75.8%), the performance of our models fell short. Comparing final model predictions in 2014 with actual rubber distribution in 2014 over the entire study region, our best models produced an overall accuracy of only 52.3% and an overall macro-averaged recall of 67.8% (Table 1). Looking at other metrics, our best models produced an overall true positive rate and overall false negative rate very close to those reported by Lim *et al.* (2019) (71.7% and 28.3%

compared to 70.7% and 29.9%) (Table 1). However, our overall false positive rate (36.2%) was almost three times as high as their false positive rate (13.53%).

The differences between their model performance and ours may be due to limitations in data quality – for example, Lim *et al.* (2019) used a potential yield map for oil palm, whereas we estimated variation in yields from historical rubber suitability. This may have led to overestimations in potential rubber yield for many cells, leading to a higher false positive rate. Other differences between the oil palm system and rubber system, such as greater labour requirements for rubber and greater need for access to processing mills for oil palm, may also lead to divergences in expected performance of the crop expansion model.

Overall, our results demonstrate the challenge of capturing underlying spatial heterogeneity across each country and the temporal dynamics of market forces and land-use change over 12 years in a single variable: agricultural rents. The national minimum threshold for conversion, K, represents establishment costs and opportunity costs of alternative land uses, which could be influenced by regional policies, suitability for other land uses, and the behaviour of different land-use decision makers (Lim *et al.*, 2019). Although we held the threshold (K) constant for each country and across the whole time period, substantial subnational and temporal variation in model performances suggest that the true conversion threshold could vary spatially and over time. In addition, discount rates can vary widely for different countries and different years based on different inflation and interest rates (i.e. market lending rate). The average inflation adjusted interest rates during 2002-2014 were as follows: China (1.5%), Cambodia (no data), Laos (18%), Myanmar (4.2%), Thailand (1.8%), and Vietnam (-0.9%) (World Bank, 2022b). Different discount rates may lead to substantial variations in estimated NPVs (Warren-Thomas *et al.*, 2018). Thus, applying a variable discount rate based on the market interest rate could help improve NPV estimations and model predictions. The model also does not account for a multitude of other factors influencing agricultural rents and land-use outcomes (infrastructure, tax and tenure, financial policies like government subsidies, capital assets, etc.) nor interactions with other crops (Lim *et al.*, 2019). Regardless of the many simplifying assumptions, we believe that it remains a useful mechanistic model for testing different hypotheses on factors influencing rubber expansion.

3.6 Conclusion

Our mechanistic model revealed that agricultural land rents helped to explain rubber expansion patterns over a 12-year timescale. Overall, our model correctly predicted 72% of conversions, balancing a false negative rate of ~28% and false positive rate of ~36%. Nevertheless, there was substantial variation in model performances among and within countries, which is perhaps unsurprising given the relative simplicity of our model compared to the complex realities of land-use changes. Contrary to expectations, we did not find a consistent spatial contagion effect, suggesting that the clustering of rubber spread needs to be modelled differently to account for the dispersed nature of rubber production and transport. While projecting land-use and land-cover change over a long timescale is fraught with challenges, our findings indicate which areas are potentially profitable for conversion, including within PAs, especially under high rubber prices. PAs could not fully prevent rubber encroachment in the most suitable and accessible locations, even those under strict PA categories.

Despite the sustainability risks of commodity crop expansion, when rubber is anticipated to be more profitable than other options, then expansion remains likely. Our analysis highlights the dangers of a profit maximisation approach to development, as large swathes of forest and PAs may be targeted for conversion based on their projected returns especially during periods of high commodity prices. Nevertheless, our analysis also showed that high agricultural rents alone do not dictate all land-use decisions. Protected areas and moratoria, if enforced, can stem the tide of unabated crop expansion. However, combating corruption among powerful actors who flout environmental and human rights for private gain is a much bigger challenge requiring political will, government cooperation, and international support. Ideally, markets will account for ecological externalities, i.e. the value of ecosystem services, to better align economic land-use decisions with sustainability goals. Increased efforts by governments, industry, civil society, and researchers to improve traceability and transparency in the commodity crop value chains can also help prevent unsustainable ecological losses due to commodity crop expansion.

3.7 Data statement

R scripts are currently hosted in a private repository (URL: https://github.com/mmw590/rubber-expansion-model) and are available upon request by emailing the corresponding author.

3.8 Acknowledgements

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3.10 Supporting information

Table S1. Sources of data inputs for rubber expansion model. Raster maps were resampled to the extent and resolution of the rubber distribution map before extracting values.

Data	Description	Source
	Maps	
Rubber and land cover map	Raster map of land cover changes, including rubber, of montane mainland Southeast Asia from 2001 to 2014. The geographical coverage includes the whole of Cambodia and Laos, and portions of Myanmar, Vietnam, Thailand, and China.	(Hurni and Fox, 2018)
Urban area distribution map	Raster map of urban areas in 2000 and 2010, downloaded for the six studied countries. As the land cover map did not differentiate between urban areas and low vegetation areas (LVA), we used a separate map of urban areas as a mask. We only classified raster cells as 'urban' where the urban cells in the year 2000 intersected with LVA in the year 2001 in the land cover map.	(Schneider, Friedl and Potere, 2009, 2010)
Rubber bioclimatic suitability map	Raster map of a global bioclimatic model of the environmental space where rubber would naturally occur, represented by a 'suitability index' ranging from 0 to 1. Includes edaphic factors.	(Ahrends *et al.*, 2015)
Accessibility, d_i (hour)	Raster map of travel time to nearest city, converted from minutes to hours.	(Weiss *et al.*, 2018)
Protected areas	Point and polygon maps of protected areas, rasterised prior to extracting values. Point data was converted into polygon data using buffers, following best practices as implemented in the R package 'wdpar' (Hanson, 2020).	(UNEP-WCMC and IUCN, 2020)
	Datasets	
Exchange rate	Official exchange rate (LCU/USD, period average), last updated 2 May 2018, by country and by year.	(World Bank, 2018)
Price deflator	GDP deflator for inflation adjustment. Linked series (base year varies by country), last updated 2 May 2018, by country and by year. Base year for USD was 2010.	(World Bank, 2018)
Length of rubber plantation cycle	Set at 25 years, constant for all countries.	(Yi *et al.*, 2014; Warren-Thomas *et al.*, 2018)

Data	Description	Source
Rubber yield, $\bar{y}$ (tonne/ha-year)	FAOSTAT: Crops – Yield, by country, averaged over modelled years.	(FAO, 2020)
Rubber price, p_t (USD/tonne)	FAOSTAT: Producer Prices – Annual/Producer Price, by country and by year. This is the farm-gate price.	(FAO, 2020)
Fertiliser price, f_t (USD/tonne)	Fertiliser price was estimated by dividing fertiliser import value (USD) by import quantity (tonne), by country and by year. For Xishuangbanna, the price of 361 USD/tonne was used (the price of 15-15-15 NPK CL-base fertiliser from Hubei Sanning Chemical, China) (Alibaba, 2018); fertiliser brand from Zhou *et al.* (2016).	(Alibaba, 2018; Zhou *et al.*, 2016)
	Fertiliser import value FAOSTAT: Fertilizers – Trade Value – Nitrogenous Fertilizers – Import Value (1000 USD), by country and by year.	(FAO, 2020)
	Fertiliser import quantity FAOSTAT: Fertilizers by Nutrient – Nutrient Nitrogen N (total) – Import Quantity (tonne), by country and by year.	(FAO, 2020)
Fertiliser input, F (tonne/ha-year)	Recommended or reported annual fertiliser input per ha of rubber plantation, averaged across the rubber plantation cycle. Constant for all countries. In cases where fertiliser input per tree was reported, the reported tree planting density was used to converted to input per ha. All values found were averaged to produce one value for F.	(Purcell and Rauniyar, 2005; Jawjit, Kroeze and Rattanapan, 2010; Clermont-Dauphin *et al.*, 2013; Petsri *et al.*, 2013; van Asselt, Htoo and Dorosh, 2016; Zhou *et al.*, 2016; Roberson, 2018)
Wages, l_t (USD/day) or (USD/hour)	ILOSTAT: Mean monthly minimum wage, by country and by year. Converted from USD/month to USD/day, assuming working times as follows: 4 weeks/month, 6 working days/week. For driver's wages in calculation of transportation costs, this was converted from USD/day to USD/hour, assuming 8 working hours/day.	(ILO, 2020)
Labour input, L (day/ha-year)	L = average of $L1$, $L2$ and $L3$. Constant for all countries.	
	$L1$ = average planting density divided by number of trees a person can tap per day multiplied by frequency of tapping per week (set at 2).	(Vuthy *et al.*, 2007; Hing and Thun, 2009; Simien and Penot, 2011; Lai and Yamazaki, 2014; van Asselt, Htoo and Dorosh, 2016; Priyadarshan, 2017; Roberson, 2018)
	$L2$ = labour input, in day/ha-year, for rubber in Xishuangbanna, China. Yi *et al.* (2014) reported that smallholder farmers can manage 1.3 ha of rubber trees per day, but an experienced state-farm worker can manage 3.1 ha rubber trees per day.	(Yi *et al.*, 2014)
	$L3$ = labour input, in day/ha-year, for rubber in Cambodia (Table 61, p. 170).	(Purcell and Rauniyar, 2005)

Data	Description	Source
Harvestable timber volume, W (m^3/ha-year)	Forest timber volume (Table 7, Appendix 3), by country.	(FAO, 2000)
Timber price, z_0 (USD/m^3)	FAOSTAT: Forestry – Forestry Production and Trade – Export Quantity (m^3) and Export Value (1000 USD), by country and by year.	(FAO, 2020)
Maximum payload capacity, C (tonne)	The specification for a Ford Ranger XL pickup truck (2.2 Duratorq TDCi (160PS (118 kW)) 4x4) was used. Constant for all countries. Maximum payload = 1232 kg, after subtracting 75 kg for one driver (industry standard for the weight of one person) (p. 33).	(Ford Motor Company Ltd., 2017)
Diesel price, v_t (USD/litre)	Pump price for diesel fuel, by country.	(World Bank, 2018)
Truck speed, V (km/hour)	Average truck speed on the road, from Table S2. Constant for all countries.	(Phelps *et al.*, 2013)
Mileage or fuel consumption, M (litre/km)	The fuel consumption for a Ford Ranger XL pickup truck (2.2 Duratorq TDCi (160PS (118 kW)) 4x4) was used. Constant for all countries. M = 43.5 litres/100km (p. 35).	(Ford Motor Company Ltd., 2017)

Table S2. Summary of fitted country-level rubber expansion models and model performances (mean ± standard errors across years) on the validation dataset. Macro-averaged recall, macro-averaged precision, accuracy, true positive rate (TPR), false negative rate (FNR), false positive rate (FPR) were calculated from confusion matrices comparing model predictions to observed rubber distributions for the years 2005, 2008, 2011, and 2014, then averaged across years. Models with the best macro-averaged recall score are highlighted in bold for each country. K is the minimum rent threshold for conversion and S is the spatial contagion weight. 'Linear S' = linear spatial contagion effect and 'sqrt S' = square-root spatial contagion effect.

Country	Model specification	K (1000 USD)	S (USD)	Macro-averaged recall	Macro-averaged precision	Accuracy	TPR	FNR	FPR
China	0a: All cells converted	-	-	50 ± 0	5.02 ± 1.34	10.04 ± 2.67	100 ± 0	0 ± 0	100 ± 0
	0b: No cells converted	-	-	50 ± 0	44.98 ± 1.34	89.96 ± 2.67	0 ± 0	100 ± 0	0 ± 0
	1: EAC only	-	-	50 ± 0	5.02 ± 1.34	10.04 ± 2.67	100 ± 0	0 ± 0	100 ± 0
	2: EAC - K	86	-	58.16 ± 6.16	58.79 ± 3.65	83.75 ± 6.51	27.49 ± 21	72.51 ± 21	11.17 ± 8.69
	3: EAC - K - linear S	**86**	**330**	**59.64 ± 6.18**	**58.18 ± 3.09**	**82.95 ± 6.85**	**32.01 ± 21.39**	**67.99 ± 21.39**	**12.74 ± 9.08**
	4: EAC - K - sqrt S	86	1680	59.29 ± 6.17	57.88 ± 2.99	83.01 ± 6.87	31.11 ± 21.44	68.89 ± 21.44	12.54 ± 9.13
Cambodia	0a: All cells converted	-	-	50 ± 0	1.4 ± 0.64	2.8 ± 1.27	100 ± 0	0 ± 0	100 ± 0
	0b: No cells converted	-	-	50 ± 0	48.6 ± 0.64	97.2 ± 1.27	0 ± 0	100 ± 0	0 ± 0
	1: EAC only	-	-	52.21 ± 0.51	51.36 ± 0.63	7.46 ± 0.5	99.65 ± 0.16	0.35 ± 0.16	95.23 ± 1.03
	2: EAC - K	8	-	57.16 ± 3.53	51.81 ± 0.89	79.32 ± 13.57	34.99 ± 21.56	65.01 ± 21.56	20.67 ± 14.67
	3: EAC - K - linear S	**8**	**1**	**57.17 ± 3.53**	**51.81 ± 0.89**	**79.29 ± 13.57**	**35.03 ± 21.55**	**64.97 ± 21.55**	**20.7 ± 14.67**
	4: EAC - K - sqrt S	8	1	57.16 ± 3.53	51.81 ± 0.89	79.31 ± 13.57	35 ± 21.56	65 ± 21.56	20.68 ± 14.67
Laos	0a: All cells converted	-	-	50 ± 0	0.53 ± 0.18	1.07 ± 0.37	100 ± 0	0 ± 0	100 ± 0
	0b: No cells converted	-	-	50 ± 0	49.47 ± 0.18	98.93 ± 0.37	0 ± 0	100 ± 0	0 ± 0
	1: EAC only	-	-	50 ± 0	0.53 ± 0.18	1.07 ± 0.37	100 ± 0	0 ± 0	100 ± 0
	2: EAC - K	64	-	56.34 ± 4.31	50.49 ± 0.24	72.89 ± 8.21	39.7 ± 16.77	60.3 ± 16.77	27.01 ± 8.35
	3: EAC - K - linear S	64	1	56.35 ± 4.3	50.49 ± 0.24	72.89 ± 8.21	39.71 ± 16.77	60.29 ± 16.77	27.02 ± 8.35
	4: EAC - K - sqrt S	**64**	**1**	**56.35 ± 4.31**	**50.49 ± 0.24**	**72.9 ± 8.21**	**39.71 ± 16.77**	**60.29 ± 16.77**	**27 ± 8.35**

Country	Model specification	K (1000 USD)	S (USD)	Macro-averaged recall	Macro-averaged precision	Accuracy	TPR	FNR	FPR
Myanmar	0a: All cells converted	-	-	50 ± 0	0.3 ± 0.1	0.61 ± 0.21	100 ± 0	0 ± 0	100 ± 0
	0b: No cells converted	-	-	50 ± 0	49.7 ± 0.1	99.39 ± 0.21	0 ± 0	100 ± 0	0 ± 0
	1: EAC only	-	-	50.54 ± 0.3	50.3 ± 0.1	1.71 ± 0.42	99.98 ± 0.02	0.02 ± 0.02	98.9 ± 0.6
	2: EAC - K	**15**	**-**	**72.88 ± 0.94**	**50.91 ± 0.3**	**83.05 ± 5.24**	**62.63 ± 4.23**	**37.37 ± 4.23**	**16.87 ± 5.27**
	3: EAC - K - linear S	15	-710	72.52 ± 1.15	51.43 ± 0.51	89.51 ± 4.35	55.34 ± 4.38	44.66 ± 4.38	10.31 ± 4.36
	4: EAC - K - sqrt S	15	-1350	72.64 ± 1	51.15 ± 0.39	87.16 ± 4.84	57.97 ± 4.35	42.03 ± 4.35	12.7 ± 4.86
Thailand	0a: All cells converted	-	-	50 ± 0	1.25 ± 0.22	2.51 ± 0.43	100 ± 0	0 ± 0	100 ± 0
	0b: No cells converted	-	-	50 ± 0	48.75 ± 0.22	97.49 ± 0.43	0 ± 0	100 ± 0	0 ± 0
	1: EAC only	-	-	50 ± 0	26.26 ± 14.31	2.51 ± 0.43	100 ± 0	0 ± 0	100 ± 0
	2: EAC - K	264	-	56.04 ± 0.68	51.53 ± 0.13	87.89 ± 2.26	22.53 ± 2.09	77.47 ± 2.09	10.45 ± 2.14
	3: EAC - K - linear S	264	2100	56.18 ± 0.68	51.46 ± 0.07	87.05 ± 2.49	23.71 ± 2.66	76.29 ± 2.66	11.35 ± 2.41
	4: EAC - K - sqrt S	**264**	**10900**	**56.28 ± 0.64**	**51.46 ± 0.07**	**86.88 ± 2.51**	**24.09 ± 2.68**	**75.91 ± 2.68**	**11.53 ± 2.44**
Vietnam	0a: All cells converted	-	-	50 ± 0	1.27 ± 0.29	2.54 ± 0.59	100 ± 0	0 ± 0	100 ± 0
	0b: No cells converted	-	-	50 ± 0	48.73 ± 0.29	97.46 ± 0.59	0 ± 0	100 ± 0	0 ± 0
	1: EAC only	-	-	51.15 ± 0.12	51.05 ± 0.24	5.26 ± 0.46	99.49 ± 0.17	0.51 ± 0.17	97.2 ± 0.19
	2: EAC - K	81	-	67.41 ± 1.59	53.93 ± 0.34	88.24 ± 1.45	45.44 ± 2.34	54.56 ± 2.34	10.62 ± 1.22
	3: EAC - K - linear S	**81**	**5290**	**77.66 ± 2.27**	**53.52 ± 0.23**	**76.76 ± 4.06**	**78.68 ± 1.48**	**21.32 ± 1.48**	**23.36 ± 4.18**
	4: EAC - K - sqrt S	81	19300	76.91 ± 2.67	53.16 ± 0.2	73.94 ± 4.26	80.11 ± 1.53	19.89 ± 1.53	26.29 ± 4.38

Table S3. Summary of the ‘effective PA’ model results and evaluation metrics for the best performing models for each country, broken down by all cells, cells within protected areas (PA), and non-protected cells (non-PA). The confusion matrices and evaluation metrics reported here were obtained from comparing final model predictions in 2014 with actual rubber distribution in 2014. See Table 1 for original model results and Figure 3 for a visual comparison of selected metrics. Abbreviations: n = number of cells, TP = true positive, TN = true negative, FP = false positive, FN = false negative, TPR = true positive rate, FNR = false negative rate, FPR = false positive rate.

Country	Cell type	n	TP	TN	FP	FN	Macro-averaged recall	Macro-averaged precision	Accuracy	TPR	FNR	FPR
China	All	24397	2863	13050	8219	265	76.4%	61.9%	65.2%	91.5%	8.5%	38.6%
	PA	24	0	24	0	0	NA	NA	0.0%	NA	NA	0.0%
	non-PA	24373	2863	13026	8219	265	76.4%	61.9%	65.2%	91.5%	8.5%	38.7%
Cambodia	All	287987	14175	129821	141368	2623	66.1%	53.6%	50.0%	84.4%	15.6%	52.1%
	PA	41332	0	39054	11	2267	50.0%	47.3%	94.5%	0.0%	100.0%	0.0%
	non-PA	246655	14175	90767	141357	356	68.3%	54.4%	42.5%	97.6%	2.4%	60.9%
Laos	All	307104	3909	184510	117391	1294	68.1%	51.3%	61.4%	75.1%	24.9%	38.9%
	PA	62184	0	61971	4	209	50.0%	49.8%	99.7%	0.0%	100.0%	0.0%
	non-PA	244920	3909	122539	117387	1085	64.7%	51.2%	51.6%	78.3%	21.7%	48.9%
Myanmar	All	241071	1691	165007	73759	614	71.2%	50.9%	69.1%	73.4%	26.6%	30.9%
	PA	1619	0	1618	0	1	50.0%	50.0%	99.9%	0.0%	100.0%	0.0%
	non-PA	239452	1691	163389	73759	613	71.1%	50.9%	68.9%	73.4%	26.6%	31.1%
Thailand	All	514957	4558	424828	74892	10679	57.5%	51.6%	83.4%	29.9%	70.1%	15.0%
	PA	80240	6	78571	1101	562	49.8%	49.9%	97.9%	1.1%	98.9%	1.4%
	non-PA	434717	4552	346257	73791	10117	56.7%	51.5%	80.7%	31.0%	69.0%	17.6%
Vietnam	All	270014	7754	185456	74844	1960	75.5%	54.2%	71.6%	79.8%	20.2%	28.8%
	PA	32153	16	29296	2733	108	52.2%	50.1%	91.2%	12.9%	87.1%	8.5%
	non-PA	237861	7738	156160	72111	1852	74.5%	54.3%	68.9%	80.7%	19.3%	31.6%
Overall	All	1645530	34950	1102672	490473	17435	68.0%	52.5%	69.1%	66.7%	33.3%	30.8%
	PA	217552	22	210534	3849	3147	49.4%	49.5%	96.8%	0.7%	99.3%	1.8%
	non-PA	1427978	34928	892138	486624	14288	67.8%	52.6%	64.9%	71.0%	29.0%	35.3%

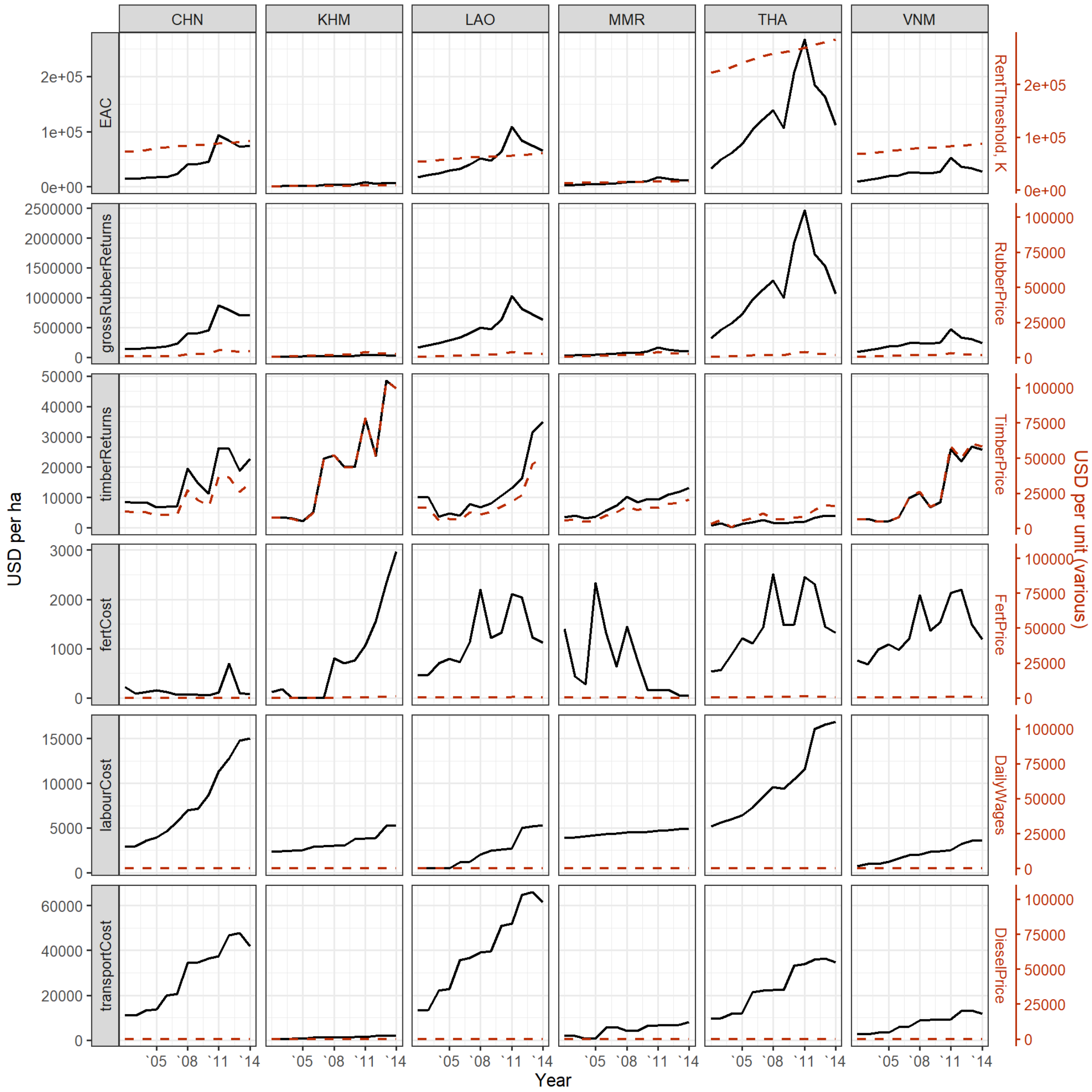

Figure S1. Agricultural rents and components of agricultural rents from 2002 to 2014, by country. Values shown are the mean of all cells available for conversion in each country. Commodity prices (deflated to USD 2015) are shown on the secondary y-axis in red and dashed lines. EAC and K (the minimum rent threshold) are in units of USD per ha per year. EAC is derived from NPV, which is the summation of the rent components discounted over time, as shown in eq. 1 and eq. 5 in 3.3 Materials and methods.

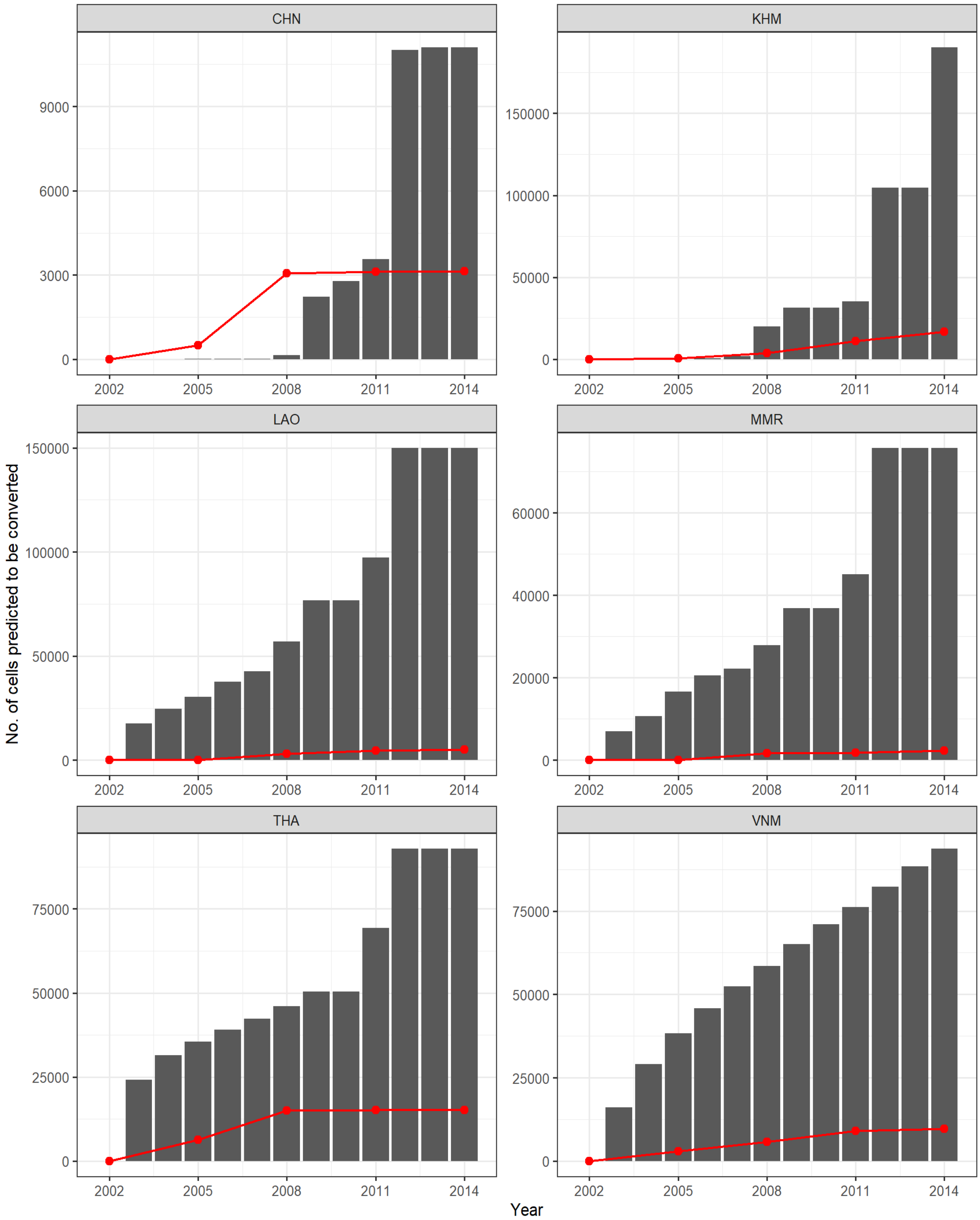

Figure S2. Number of cells profitable enough to be converted into rubber from 2002 to 2014 (grey bars), and number of cells actually converted (red points) in 2005, 2008, 2011, and 2014. See Hurni and Fox (2018) for a breakdown of rubber expansion trends over time.

3.10.1 Supporting information references

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4 Evolution of inclusiveness in a multi-stakeholder initiative for sustainable natural rubber

4.1 Abstract

Despite over 85% of rubber being produced by smallholders, they face inequities in the value chain, creating livelihood insecurities. This case study is the first academic analysis of a relatively young multi-stakeholder initiative (MSI) for rubber, the Global Platform for Sustainable Natural Rubber (GPSNR), focusing on changes in inclusiveness during its inception and developments over three years. Using document analysis, I examined the evolving GPSNR's stakeholder – particularly smallholder – inclusiveness as reflected in its membership composition, geographical representation, governance of decision-making, and quality of smallholder participation. I found that after initial exclusionary practices and limited representation from producer countries, GPSNR proceeded to include civil society and smallholders in membership and governance roles, which helped to balance representation from producer and non-producer countries. While GPSNR actively supported smallholders' participation and allotted opportunities for smallholders to voice their interests, various equity challenges remain to full inclusiveness. These challenges include unequal resources for all smallholders to participate effectively, lack of self-organisation by smallholders, industry's indifference towards fair pricing concerns, and the limitations of inclusiveness. By demonstrating how involvement of different stakeholders variously affected GPSNR's membership, governance structures, and priority issues, this study aims to contribute to a better understanding of the dynamic process of making MSIs more inclusive.

Keywords: multi-stakeholder initiatives, rubber sustainability, smallholders, inclusiveness, inclusion, participation, sustainable agriculture

Abbreviations:

GPSNR	Global Platform for Sustainable Natural Rubber
MSI	Multi-stakeholder initiative

NGO	Non-governmental organization
RSPO	Roundtable on Sustainable Palm Oil
RTRS	Round Table on Responsible Soy

4.2 Introduction

There is growing acknowledgement from the private sector that more needs to be done to address the pressing environmental and social issues plaguing global agricultural value chains. Among various types of private voluntary sustainability standards, multi-stakeholder initiatives (MSIs) have been proliferating since the 1990s as a strategy to address these complex, wide-ranging problems with contributions from diverse stakeholder types (Dentoni and Peterson, 2011; Cheyns and Riisgaard, 2014). MSIs are forums that bring together various stakeholders, ranging from businesses, non-governmental organisations (NGOs), and governmental bodies to create sustainability standards. They are also referred to by different terms such as 'cross-sector partnerships', 'multi-stakeholder platforms', 'alliances', or 'roundtables' (Dentoni and Peterson, 2011; Bitzer, Glasbergen and Leroy, 2012; de Bakker, Rasche and Ponte, 2019). Due to their multi-stakeholder nature, MSIs are seen as having the feature of 'inclusiveness', meaning that all relevant groups have a voice in matters that affect them (Fransen and Kolk, 2007). However, some MSIs have been criticised for inadequate inclusiveness of smallholder farmers, such as by not having direct representation by smallholders, repressing contesting viewpoints, and not addressing smallholders' lack of resources to participate effectively in MSIs' processes (Cheyns, 2014; de Bakker, Rasche and Ponte, 2019; Brandi, 2020).

Inadequately including smallholders in MSIs is problematic for various reasons. Smallholder farmers are those who rely primarily on small-scale agriculture for income, with farm sizes below the national average (Grabs *et al.*, 2021). They are a key stakeholder group as important producers of many globally traded tropical commodity crops (Byerlee and Rueda, 2015, chap. 1). Moreover, smallholders can play a role in deforestation and land degradation via land-use decisions and environmentally harmful farming practices (Brandi, 2020; Grabs *et al.*, 2021), but they are also key actors for food security and agro-biodiversity conservation (Rueda *et al.*, 2018; Zimmerer, Lambin and Vanek, 2018). At the same time, smallholders are typically at the losing end in global value chains, as they continue to face livelihood insecurities, worsened by volatile commodity prices, disregard for their land and labour rights, and climate change (Fox and Castella, 2013; Ahrends *et al.*, 2015; Lanka, Khadaroo and Böhm, 2017). Smallholders may also be disadvantaged by eco-certification schemes that result in market exclusion for them due to the costs of certification compliance and auditing (Brandi, 2020). In order to ensure that MSIs meet the equity goals of sustainable development (Brown and Corbera, 2003; McDermott, Mahanty and Schreckenberg, 2013), it is thus important to include smallholders' voices in MSIs (Cheyns, 2014; Nelson and Phillips, 2018; Brandi, 2020).

One recent MSI that aspires to be inclusive is the Global Platform for Sustainable Natural Rubber (GPSNR). This MSI was initiated by a group of tyre-makers, and was officially launched in March 2019 (GPSNR, 2019a). It currently boasts a membership comprising diverse stakeholders, including smallholder farmers, industrial producers, processors, traders, tyre-makers, car makers and civil society organisations (GPSNR, 2020g). As publicised on their website, GPSNR claims to 'bring[] together various stakeholders to a common ground based on fairness, equity and environmental sustainability', and that it 'value[s] smallholder inclusivity through representation within GPSNR' (GPSNR, 2020g, paras 1, 3). GPSNR uses the terms 'inclusion', 'inclusive', and 'inclusivity' seemingly interchangeably, in the context of 'ensur[ing] the voice of rubber smallholders is meaningfully represented within the platform's governance model' (WBCSD, 2019a, para. 3). This is consistent with the concept of inclusiveness in MSIs as described above, relating to the inclusion of stakeholder voices in issues that affect them (Fransen and Kolk, 2007). However, given shortcomings in including smallholders in other MSIs (FAO, 2014; de Bakker, Rasche and Ponte, 2019), it is important to examine to what extent GPSNR has lived up to these public statements in favour of inclusiveness.

This chapter traces whether and how smallholders, over time, have become included in GPSNR activities and the limitations they have faced. This study addresses a few research gaps. Firstly, MSIs have been much better explored for other key tropical commodities such as palm oil and soy (Cheyns, 2011; Schouten, Leroy and Glasbergen, 2012), cocoa (Bitzer, Glasbergen and Leroy, 2012; Nelson and Phillips, 2018), and coffee (Reinecke, 2010). Yet, rubber sustainability has been largely neglected by industry and the public until recently (Millard, 2019). Moreover, given that GPSNR is relatively young, this MSI has received little research attention (Chapter 1). Secondly, this study also addresses the call for more research on MSIs' abilities to be inclusive (Cheyns and Riisgaard, 2014). Lastly, a better understanding of stakeholder and smallholder inclusion in GPSNR could provide useful insights for the platform itself and for other MSIs aiming for greater inclusiveness.

In this longitudinal and qualitative case study based on document analysis, I address the question: 'How has stakeholder, particularly smallholder, inclusiveness evolved in GPSNR's first three years of operation?' More specifically, I trace changes in stakeholder inclusion and participation across different phases of GPSNR's formation and operation, focusing on the range of stakeholder categories present or absent in membership and decision-making roles, the geographical composition of membership, and the opportunities available for smallholders to participate in and influence decision-making and priorities of GPSNR. I found that GPSNR has created a platform that, over time, has become more inclusive in membership composition and decision-making procedures. However, barriers to full inclusiveness remain, particularly with regards to setting agendas and deciding what is or is not a priority for GPSNR.

This chapter is structured as follows: first, I define my conceptual framings, reviewing the concept of inclusiveness in MSIs and operationalising inclusiveness in terms of stakeholder inclusion in membership, geographical representation, governance of decision-making, and quality of participation for this case study. Secondly, I provide a brief overview of the rubber sector, smallholders' role in rubber production, a review of previous rubber sustainability initiatives before GPSNR, and a brief context about the group of tyre-makers who founded GPSNR. Thirdly, I introduce the research strategy, data analysis methods, and explain how I applied the inclusiveness framework to the data. Next, in the Findings section, I describe the governance structure of GPSNR, followed by a chronological narrative that addresses the relevant changes in components of inclusiveness that have occurred within GPSNR, along with rich contextual details. This narrative is followed by a critical evaluation of the findings, linked to the wider literature on inclusiveness and equity in other MSIs as well. Lastly, I discuss the limitations of this study and conclude with a summary of the main findings.

4.3 Conceptual framings

In examining the multi-stakeholder initiative of GPSNR, it is important to first define what stakeholders are. Stakeholders are defined as 'all those who affect, and/or are affected by, the policies, decisions and actions of the system; they can be individuals, communities, social groups or institutions of any size, aggregation or level in society' (Brown and Corbera, 2003, p. S48). Based on this definition, stakeholders in a commodity value chain can include any individual or firm who deals with the commodity, such as buyers, suppliers, shareholders, and investors, as well as broader stakeholders like consumers, the media, civil society, and workers (Thorlakson, 2018). In an MSI, different stakeholder groups or categories are formed based on each group having different interests to defend (Cheyns and Riisgaard, 2014). Different MSIs have different ways of organising stakeholder interest groups (Vallejo and Hauselmann, 2004). For example, the Forest Stewardship Council is organised based on three broad interest groups – social, environmental, and economic – with voting split equally across the three groups (Pinto and McDermott, 2013). Within each group, votes are distributed equally between global north and global south members (Pinto and McDermott, 2013). Other MSIs organise their stakeholder interest groups by their role in the supply chain (Vallejo and Hauselmann, 2004), such as the Roundtable on Sustainable Palm Oil (RSPO), which classified their stakeholders into the following categories: growers, processors and traders, consumer goods manufacturers, retailers, banks and investors, environmental NGOs, and social NGOs (RSPO, 2023c).

The literature provides several rationales for MSIs to be inclusive of various stakeholders and incorporating different voices (Ansell *et al.*, 2020). This includes the potential of inclusive processes to enrich discussions and learning opportunities between different actors (Boström, 2006; Fransen and Kolk, 2007), to cover all relevant issues and opportunities for actions (Fransen and Kolk, 2007; Mena and Palazzo, 2012), and to create legitimacy and procedural equity (Mayntz, 2010; Mena and Palazzo, 2012; Schouten, Toonen and Leeuwerik, 2022). Legitimacy refers to the level of acceptance of the MSI as a justified or credible institution by directly involved stakeholders and external audiences (Vallejo and Hauselmann, 2004). Including key stakeholders and their views in decision-making processes is said to increase their acceptance of the decisions made (Mena and Palazzo, 2012), as well as create a sense of ownership over joint decisions (Bäckstrand, 2006; Beisheim and Dingwerth, 2008). Instrumentally, more inclusive voluntary sustainability initiatives that substantially involve more producers and smallholders are more likely to achieve goals of preventing deforestation in production landscapes (Garrett *et al.*, 2018; Grabs *et al.*, 2021). Conversely, exclusion of key stakeholders can reduce the effectiveness and legitimacy of MSIs by omitting important knowledge or resources and disenfranchising stakeholders from supporting MSI standards and zero-deforestation commitments (Ansell *et al.*, 2020; Grabs *et al.*, 2021). Procedural equity, also known as equity in institutions and decision-making, is a key dimension of social equity, alongside distributional equity (i.e. equity in outcomes) and contextual equity (social, political, and economic factors that affect actors' access to opportunities) (Brown and Corbera, 2003; McDermott, Mahanty and Schreckenberg, 2013). Since equity is a core principle of sustainable development (WCED, 1987), MSIs should aim to enhance all dimensions of equity. While procedural equity alone does not guarantee equitable outcomes or neutralise all pre-existing inequitable conditions for all marginalised stakeholders, ensuring fairness in decision-making processes at least gives them a seat at the table to influence decisions that affect them and thereby improving potential outcomes.

Inclusiveness of MSIs has been operationalised in terms of stakeholder inclusion in membership, balanced geographical representation, inclusive governance, and the quality of stakeholder participation (Fransen and Kolk, 2007; Schouten, Leroy and Glasbergen, 2012; Schleifer, 2019; Bitzer and Marazzi, 2021; Schönherr, 2022; Schouten, Toonen and Leeuwerik, 2022). I will discuss each of the dimensions in turn in the following paragraphs.

Stakeholder inclusion means the extent to which stakeholders affected by the issue are enabled to be present and involved in the structures and processes of MSIs (Bitzer and Marazzi, 2021). For most MSIs, the first step towards formal inclusion of stakeholders is membership (Fransen and Kolk, 2007; Schouten, Leroy and Glasbergen, 2012). Drawing from the literature, inclusiveness in membership concerns questions such as: which stakeholder interest groups are present or absent in membership (Fransen and Kolk, 2007; Schouten, Leroy and Glasbergen, 2012); and whether there is an outreach program or support structure to make membership more accessible to disadvantaged groups (like smallholders) (Bitzer and Marazzi, 2021; Schouten, Toonen and Leeuwerik, 2022). Additionally, the assessment of stakeholder inclusion in membership should also pay attention to geographical representation, i.e. the country or region of origin of stakeholders and the accessibility of MSI membership and governance roles to stakeholders from different regions (Fransen and Kolk, 2007; Biermann and Gupta, 2011; Schouten, Leroy and Glasbergen, 2012). Studies have found that most agricultural commodity MSIs have been founded and led by actors from developed nations, with comparatively lesser involvement of actors from southern producer countries (Fransen, 2012; Bitzer and Glasbergen, 2015; Moog, Spicer and Böhm, 2015). Schouten, Toonen and Leeuwerik (2022) argued that inadequate inclusion of southern producers will lead these important stakeholders to not accept the MSI as legitimate, as has been shown by empirical case studies (Cheyns, 2011; Partzsch, 2011; Elgert, 2012).

Inclusive governance has been defined as ‘equal representation and decision-making power for stakeholders’ (Schönherr, 2022, p. 5). Governance in MSIs refers to the organisational structures and procedures around decision-making and rule-setting, typically referring to the central decision-making body in the MSI (Schönherr, 2022), which can be termed 'executive board', 'management board', or 'board membership' (Fransen and Kolk, 2007; Schouten, Leroy and Glasbergen, 2012). Drawing from the literature, inclusiveness in governance concerns questions such as which stakeholder interest groups are included in governance (decision-making) roles (Fransen and Kolk, 2007; Schouten, Leroy and Glasbergen, 2012; Schönherr, 2022), whether all stakeholders have formal voting rights in the central-decision making body (Schönherr, 2022), and whether voting rights are structured equitably among different stakeholder groups (Schouten, Leroy and Glasbergen, 2012).

Another crucial and closely related dimension of MSI inclusiveness is stakeholder participation, which refers to 'a process where individuals, groups and organisations choose to take an active role in making decisions that affect them' (Reed, 2008, p. 2418). Stakeholder participation is frequently conceptualised as a 'continuum' based on varying 'degrees of participation' (Reed, 2008, p. 2419). For example, participation can range from passive (such as stakeholders being consulted but not given access to decision-making roles) to active (such as co-creation of priorities and co-implementing strategies throughout all stages of decision-making, and self-mobilisation) (Adeyeye, Hagerman and Pelai, 2019). Fransen and Kolk (2007) describe how MSIs can limit the participation of certain stakeholders to merely occasional consultations and annual attendance at general assemblies, as opposed to opportunities to participate in governance roles (i.e. inclusive governance) and other agenda-setting roles such as working groups. Hence, in assessing inclusiveness, it is important to study the quality of participation in MSIs, such as the equality of opportunities available to different stakeholders to participate in MSI processes, the extent to which different stakeholders are able to influence decisions being made, and factors hampering stakeholders' participation (Mena and Palazzo, 2012; Schouten, Leroy and Glasbergen, 2012; Schouten, Toonen and Leeuwerik, 2022).

Building on the discussions above, this case study will analyse inclusiveness in MSIs as captured by (1) stakeholder composition of membership, (2) geographical representation, (3) inclusive governance of decision-making, and (4) quality of stakeholder participation. This case study will focus on inclusiveness towards non-industry stakeholders, especially smallholders. As GPSNR was initiated by industry actors, industry stakeholders have the upper hand in defending their interests and determining how they will include (or exclude) non-industry stakeholders in this MSI. Moreover, smallholders are often inadequately included in supply chain sustainability initiatives and face additional barriers to participation, for reasons such as language barriers, lack of time, and being difficult to reach due to lack of access to international networks of contacts (de Bakker, Rasche and Ponte, 2019; Schouten, Toonen and Leeuwerik, 2022). In addition, studies have found how industry actors dismissed smallholders for being too ‘political’ or for lacking technical expertise (Cheyns, 2014; Nelson and Tallontire, 2014). Thus, the case study will examine whether smallholders are adequately included in GPSNR in terms of membership, geographies, governance, and the quality of their participation in GPSNR activities.

4.4 Research context: Rubber and rubber sustainability initiatives

Even with transportation systems rapidly transforming across the globe, one thing that has hardly changed is the critical raw material for tyres. Natural rubber (henceforth, ‘rubber’) is sourced from the latex of the Pará rubber tree (*Hevea brasiliensis* Müll. Arg.), which can only grow in the tropics. It is used to make tyres and other automotive parts, latex gloves, shoes, machinery parts, and many other products. The top rubber producer countries in 2020 were Thailand (34%), Indonesia (22%), Vietnam (9%), Côte d’Ivoire (7%), China (5%), and India (5%) (Table S1; FAO, 2022). Meanwhile, the top rubber consumers were China (43%), EU (8%), India (8%), USA (6%), Thailand (6%), and Japan (5%) (ETRMA, 2021, p. 44). Tyres make up 70% of rubber consumption (Millard, 2019).

Natural rubber is primarily produced by smallholders – globally, 90% of rubber production volume and rubber area are under smallholdings (IRSG, 2019, as cited in Gitz *et al.*, 2020). A typically cited statistic is that there are 6 million smallholders around the world who are responsible for producing rubber (Schwartz, 2018; ETRMA, 2019; GPSNR, 2020j). Smallholders manage over 90% of rubber holdings in Malaysia, Myanmar, and Thailand, over 85% in Indonesia and India, 64% in Sri Lanka, 50% in China, 32% in Vietnam and Cambodia, and 23% in Laos (Fox and Castella, 2013). However, the threshold farm size used to define smallholders varies widely by country – for example, the threshold is 8 ha for Myanmar, 20 ha for India and Sri Lanka, 25 ha for Indonesia and Laos, 40 ha for Thailand, and 40.5 ha for Malaysia. Industry or state-owned plantations make up the rest of the holdings. Smallholders can operate independently or by contract to companies, and different systems exist for different countries (Gitz *et al.*, 2020). Given the heterogeneity of smallholders by geographical regions, being inclusive of all types of smallholders is a complex issue.

As a commodity, rubber suffers from price volatility. The rubber price boom in the 2000-2010s led to considerable deforestation due to expansion of rubber plantations, while smallholders bore the brunt of the subsequent bust (Hurni and Fox, 2018). Smallholders who expanded their rubber plantations during the boom could only begin to harvest latex after 6-7 years when prices had already fallen, and those who relied on rubber as their main crop suffered a drop in income and had to seek alternative income sources such as off-farm employment or planting other crops (Andriesse and Tanwattana, 2018; Jin, 2020). Currently, rubber prices are still low, driving some smallholders to abandon rubber (Warren-Thomas, Dolman and Edwards, 2015; Meyer, 2019). As such, there is an economic incentive for downstream players relying on a stable supply of rubber latex to help smallholders to stay in rubber production (Meyer, 2019). There are also wider inequitable dynamics affecting smallholders in the rubber value chain, where rubber traders, processors and tyre-makers display oligopsony market power (i.e. many suppliers but few buyers) (Trangadisaikul, 2009; Kopp and Sexton, 2019). These factors illustrate the need for MSIs in the rubber sector to be inclusive towards smallholders.

Due to the non-edible nature of rubber products, the commodity has received less media and public attention as compared to other crops like oil palm, coffee, and cocoa (Kennedy, Leimona and Yi, 2017; Millard, 2019). Therefore, rubber sustainability initiatives are relatively young, compared to other commodity MSIs –

e.g. the Roundtable on Sustainable Palm Oil (RSPO) was formed in 2004, while the Round Table on Responsible Soy (RTRS) was formed in 2005 (RSPO, 2023b; RTRS, 2023). While certification for rubberwood had begun since the mid-90s, sustainability initiatives for latex emerged from around 2007 (Kennedy, 2014; Kennedy, Leimona and Yi, 2017). Industry standards were more concerned with end-consumer health concerns than with plantation or smallholder-level environmental or social impacts (Kennedy, Leimona and Yi, 2017). These schemes were also limited in scope and uptake, and had little market demand (Kennedy, Leimona and Yi, 2017). Around the same time, the NGO Global Witness began to publish exposes of land rights abuses and deforestation related to rubber plantation development in Cambodia, Laos, and Myanmar (Global Witness, 2007, 2013, 2015).

In 2012, Fair Rubber, an eco-certification model based on FairTrade, was established as a non-profit based in Germany (Fair Rubber, 2022b). It is the only MSI offering a price premium for latex (0.50 € per kg of dry rubber content), paid by companies for use of the Fair Rubber label, which is passed directly onto supplier partners that agree to comply to their sustainability criteria (Fair Rubber, 2022a). The premium may only be used to improve living and working conditions of rubber workers, but the supplier partners themselves decide via democratic processes how to use the premium (Fair Rubber, 2021). Supplier partners could be industrial plantations that hire tappers or smallholder associations (Fair Rubber, 2022a). However, Fair Rubber is limited in its market share and only about thirty companies have signed up to the label even after ten years (Fair Rubber, 2023).

In 2013, the International Rubber Study Group announced plans for the first industry-wide MSI for rubber (IRSG, 2013). The International Rubber Study Group is an inter-governmental organisation with the primary aims of providing a platform to discuss the production, consumption, and trade of natural or synthetic rubber as well as to synthesise and publish rubber markets statistics (EU Monitor, 2017). Their membership consists of member governments and companies or industry organisations involved in the rubber industry (IRSG, 2023). Their MSI, later named 'Sustainable Natural Rubber Initiative', is based on voluntary self-declarations by organisations to indicate compliance with a set of sustainability guidelines, although it is unclear to what extent these self-declarations were vetted by the International Rubber Study Group or a third party (IRSG, 2014). The IRSG was well-placed to lead an MSI given its many connections with industry and governments. However, their initiative was criticised for being 'extremely weak and lack[ing] stakeholder input' (BirdLife International, 2016, p. 23), for interpreting sustainability in narrow ways that favoured industry (Kenney-Lazar *et al.*, 2018), and for failing to prevent deforestation and dispossession of land (Otten *et al.*, 2020).

In 2014, a government-backed industry association, the China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters, began research for a due diligence guide for Chinese companies investing in rubber plantations and processing plants abroad (Yifan, 2022). In 2017, they published the 'Guidelines for sustainable development of rubber', which received input from a range of stakeholders including Global Witness (2017), another international NGO, Chinese industry experts, corporate social responsibility specialists, and Chinese academics (Yifan, 2022). It is said to be more robust than the Sustainable Natural Rubber Initiative (Kenney-Lazar *et al.*, 2018). Its criteria included respect for land tenure and indigenous rights, and it acknowledged the role of smallholders and power dynamics (Kenney-Lazar *et al.*, 2018). Its main target audience was Chinese companies investing in rubber plantations abroad (Kenney-Lazar *et al.*, 2018), but even after five years it has not yet been widely adopted (Yifan, 2022). This initiative also faced competition from the Tire Industry Project, which was also planning to develop a new industry-wide MSI for rubber – which would later be named GPSNR (Yifan, 2022).

Founded under the umbrella of the World Business Council for Sustainable Development (WBCSD) in 2005, the Tire Industry Project is a voluntary initiative led by CEOs of the world's major tyre manufacturers to 'identify and offer solutions to sustainability challenges associated with the life cycle of tires' (WBCSD, 2017, para. 2). Prior to GPSNR, their sustainability concerns had included pollution from road wear of tyres, safety of new materials for tyres, guidelines for conducting life cycle assessments, reporting environmental impact indicators (e.g. carbon emissions, energy and water use), and management of end-of-life tyres (WBCSD, 2017). The Tire Industry Project had a large market influence, with its then eleven member companies making up 65% of tyre manufacturing capacity globally (WBCSD, 2017). Perhaps, due to its market power, the Tire Industry Project and GPSNR effectively replaced the role of the IRSG and the Sustainable Natural Rubber Initiative as the leading rubber MSI. In April 2018, the Tire Industry Project formally announced their commitment to develop a roundtable (Beaumont, 2018).

4.5 Methods

4.5.1 Research strategy and data analysis

In terms of research design, this qualitative case study is inductive, as there was no pre-defined theoretical or conceptual framework, hypothesis, or well-defined research questions before the research and analysis process was initiated. This ‘inductive, open-ended strategy’ is well suited for my initial broad goals of understanding the perspectives of different stakeholders, the influence of particular contexts on stakeholders’ actions, and the processes by which changes in GPSNR occurred (Maxwell, 2012, pp. 30–31). I adopted a flexible, non-linear, and interactive research design, whereby my research goals, research questions, and conceptual framework were iteratively refined by insights generated by data analysis and readings of existing literature (Maxwell, 2012; Smith and Besharov, 2019).

I chose document analysis as the primary research method because it is well suited to qualitative case studies, which are ‘intensive studies producing rich descriptions of a single phenomenon, event, organisation, or program’ (Bowen, 2009, p. 29). This is because document analysis provides data to place events in context and a method to follow changes in the study subject over time (Bowen, 2009). Document analysis also has the advantage of being unobtrusive and is not subject to reactivity, i.e. in contrast to an interview or participant observation, the contents of documents do not change or react to the presence or behaviour of the researcher (Bowen, 2009). The data sources comprised primarily of publicly-available written material from GPSNR’s website (e.g. news articles, statutes, code of conduct, commissioned consultant reports, and other organisational documents) and audio-visual material (e.g. videos published by GPSNR) (Table S2). To obtain perspectives of different stakeholders and alternative accounts of events, I also collected documents from a range of sources: the initiators of GPSNR (World Business Council for Sustainable Development and the Tire Industry Project), GPSNR member companies, NGOs, other rubber sustainability initiatives, and other non-GPSNR websites reporting on GPSNR and rubber sustainability issues. I transcribed videos into text. Guided by my prior knowledge of GPSNR and interactions with stakeholders involved with GPSNR, I used these public data sources to construct a case study of GPSNR and follow reported changes in GPSNR over time.

My approach to conducting content analysis of the collected documents followed a process based on Smith and Besharov (2019): a non-linear, iterative process between data collection, coding, analysis, and referring to existing literature to develop insights from textual material. They summarised their approach as: (1) developing an in-depth case study involving a rich chronological narrative that describes how events unfolded over time with contextual detail; (2) 'temporal bracketing' (Langley, 1999) and identifying themes in light of the identified conceptual framework; and (3) examining relationships among themes and integrating existing literature. The following paragraphs describe my process in greater detail. Alongside this process, I also followed a general coding procedure described by Mikkelsen (2005), consisting of three steps of 'open coding', 'axial coding', and 'selective coding'.

In a first round of 'open coding' (Mikkelsen, 2005), I read documents and scanned for relevance to the initial topics of interest, i.e. (1) the events surrounding and leading to the formation of GPSNR, and (2) changes in GPSNR in relation to stakeholder inclusion and participation. Synthesising the various data sources, I created a detailed chronological narrative describing events in GPSNR (Smith and Besharov, 2019). Descriptive narratives, rich in contextual detail (also referred to as 'thick description'), have been used by management researchers as a tool to organise data into a coherent structure for subsequent analysis, as well as to propose linkages between sequences of events and establish early analytical themes (Langley, 1999). A thick description of results, with rich detail and varied data including direct quotes, is also a recommended practice to improve validity and reduce bias in qualitative research (Mikkelsen, 2005; Maxwell, 2012).

While refining the chronological narrative, I conducted the second coding step of ‘axial coding’ (Mikkelsen, 2005), identifying key events and phases, potential causal conditions and linkages, contexts surrounding the events, prevailing conditions or actions by stakeholders that influenced the events, and the consequences of those actions. To structure the narrative timeline, I applied the ‘temporal bracketing’ strategy used by Smith and Besharov (2019). ‘Temporal bracketing’ refers to breaking down a timeline into discrete periods or phases (Langley, 1999). Temporal bracketing also facilitates analysis of how context affects changes and consequences of these changes within and between phases (Langley, 1999).

Following Smith and Besharov (2019), these prior analytical steps helped identify the conceptual lenses and analytical frameworks for grounding the case study. Informed by the wider literature around stakeholder inclusion, participation, and inclusiveness in MSIs, as detailed earlier in Conceptual Framings, I analysed inclusiveness in GPSNR around (1) stakeholder composition and geographical representation of membership, (2) governance of decision-making, and (3) extent, degree, and quality of stakeholder participation. At this point, I made additional passes through the data in the ‘selective coding’ step (Mikkelsen, 2005), whereby I conducted selective searches for specific examples to contribute to the process of integrating and refining the main findings relating to the evolution of inclusiveness in GPSNR. In addition to selective coding, I also referred to the chronological narrative and temporal bracketing structure I had developed earlier to identify and analyse data relevant to each component of MSI inclusiveness. With data spanning the period before GPSNR’s inception through its first three years of operation, I was also able to track changes in each component of MSI inclusiveness over time.

I operationalised the components of MSI inclusiveness as follows. To analyse stakeholder composition of membership, I identified the range of stakeholder categories represented in GPSNR membership and the number of members in each category at different time points. I also obtained publicly available information on membership fees and assessed the process of smallholder inclusion into GPSNR over time. For geographical representation, I looked up the countries of origin of the headquarters of each GPSNR member organisation or company, combined with data of smallholder members' countries of origin (Fransen and Kolk, 2007; Schouten, Leroy and Glasbergen, 2012; Schouten, Toonen and Leeuwerik, 2022). To analyse governance of decision-making, I looked at the governance structure of GPSNR, which includes the voting system and the structure of its executive committee. I classified the countries of origin into rubber producer countries and non-rubber producer countries. Following Schouten, Leroy and Glasbergen (2012), I then compared the geographical composition of GPSNR membership to the global rubber production and consumption trends by country (see 4.4 Research context: Rubber and rubber sustainability initiatives; Table 3). Lastly, to assess the quality of stakeholder participation, I qualitatively examined the opportunities available to different stakeholders, especially smallholders, to participate in various GPSNR processes at different times. These opportunities included stakeholder consultations prior to the launch of GPSNR, smallholder recruitment workshops, election of representatives to governance roles, and working groups. I also considered the extent to which stakeholders were able to influence GPSNR's decisions and priority issues, changes in the perceived role of smallholders, and potential factors hampering stakeholders' participation. In light of these refined themes, I revised the chronological narrative to highlight the findings relevant to changes in membership composition, geographical representation, governance, and participation, situating the findings within the overall context of evolving stakeholder interactions within GPSNR.

4.5.2 Positionality and addressing bias

The ideas for this qualitative case study were gradually developed from my engagement with GPSNR as part of my professional development activities during my doctoral program and my university's affiliate membership in GPSNR. My prior knowledge of and background engagement with GPSNR have led to my interest in documenting the circumstances in which GPSNR was formed and the evolution of GPSNR as an MSI over time. In April 2021, I volunteered to become a member of the GPSNR Capacity Building Working Group, an opportunity afforded by the University of Sheffield being an affiliate member of GPSNR. In August 2022, after my viva, building on continuous engagement with GPSNR, the organisation hired me as one of two consultants to coordinate pilot agroforestry training workshops for rubber smallholders. The work was funded by an external grant, the Partnership for Forests (P4F) grant, funded by the UK's Foreign Commonwealth and Development Office.

Although the focus of my consultancy was not on the subject of my PhD chapter, given my relationship with GPSNR, I was aware that my positionality places my research at risk of being biased towards perspectives that are favourable to GPSNR. This has been described as ‘the risk of “going native,” namely, being too close and essentially adopting the informant’s view’ (Gioia, Corley and Hamilton, 2013, p. 19). To reduce researcher bias in the selection and interpretation of data, I have taken the following precautions as suggested by Maxwell (2012); Gioia, Corley and Hamilton (2013); and Mikkelsen (2005): (1) analysing only publicly available documents, i.e. secondary data, such that the data collected are not coloured by my own subjectivity; (2) including non-GPSNR data sources as well as critical sources involved in GPSNR, such as civil society, where available, such that diverging perspectives are presented (see 4.5.1 Research strategy and data analysis, Table S2); (3) making clear the sources of the documents I used (Table S2 and individual citations in 4.6 Findings); (4) analysing the documents cognisant of authorship and intended audience and related potential biases; and (5) to widen my perspectives and analysis through discussions with others who have critical or diverging viewpoints. This includes two co-supervisors who have not been involved with GPSNR, other researchers not involved with GPSNR, GPSNR members, and non-GPSNR members. Gioia, Corley and Hamilton (2013, p. 19) suggests having ‘one member of the collaborative team adopt an outsider perspective…whose role it is to critique interpretations that might look a little too gullible’. In this study, this role is played primarily by my co-supervisors. Smith and Besharov (2019) also adopted a similar strategy of obtaining feedback from colleagues during analysis to improve the reliability and validity of their interpretations.

4.6 Findings

The Findings section is structured into four parts: First, in 4.6.1 Overview of GPSNR membership and governance structure, I give an overview of the governance structure of GPSNR as of the 3rd General Assembly (December 2021, i.e. the end of my study period), including membership structure, membership fees, voting system, the executive committee, and working groups. These aspects of the governance structure are important for understanding the different components of MSI inclusiveness, particularly around governance of decision-making (Fransen and Kolk, 2007; Schouten, Leroy and Glasbergen, 2012; Schouten, Toonen and Leeuwerik, 2022). A basic understanding of the current governance structure will also aid in understanding the relevant changes in inclusiveness that have taken place within GPSNR, which will be covered in the subsequent subsection.

In 4.6.2 Evolution of inclusiveness in GPSNR, I present an in-depth chronological narrative to address the research question in a qualitative way, ‘How has stakeholder, particularly smallholder, inclusiveness evolved in GPSNR's first three years of operation?’ In this narrative, I break down the timeline of the evolution of inclusiveness in GPSNR into a few time periods or phases in keeping with Smith and Besharov's (2019) temporal bracketing approach. Within each phase, I analyse relevant events and context that surround the changes in inclusion and participation, which is important for understanding the processes that may have led to these changes in inclusiveness. I highlight changes in membership composition, geographical representation, governance board composition, and smallholder participation in working groups or other GPSNR processes, which are directly relevant to the components of inclusiveness. I discuss events that are important for a fuller understanding of the quality of stakeholder participation, such as events where non-industry stakeholders were excluded, as well as the events where feedback from non-industry stakeholder inputs were sought.

In 4.6.3 Components of inclusiveness and other themes, I discuss the main findings for changes in each component of inclusiveness, making links to other MSIs and the wider literature around MSI inclusiveness and the different dimensions of equity. Additional details about GPSNR relevant to each discussion theme that were not covered earlier are integrated throughout, as appropriate.

Lastly, I discuss the limitations of this study in 4.6.4 Limitations of this study.

4.6.1 Overview of GPSNR membership and governance structure

The structure of GPSNR consists of a General Assembly, an Executive Committee, a Secretariat to oversee daily operations, and Working Groups (GPSNR, 2021m). For administrative and legal purposes, GPSNR is hosted by the Asia Pacific branch of the World Business Council for Sustainable Development[3], which is registered as a non-profit entity in Singapore (GPSNR, 2019b). Singapore is located in Southeast Asia, close to many rubber producer countries, but does not itself produce rubber (Table S1).

The General Assembly is divided into 'Ordinary Members' with voting rights and 'Affiliate Members' with no voting rights (GPSNR, 2021m). Ordinary Members are members who fall under one of the following stakeholder categories: (1) industrial producers, processors, and traders, (2) tyre-makers and other rubber makers/buyers, (3) car-makers, other downstream users, and financial institutions, (4) civil society organisations, and (5) smallholders. These stakeholder categories are based on their roles in the value chain, although GPSNR also recognises civil society organisations (CSOs) as a category of equal standing as the other value chain stakeholder categories. CSOs are defined by GPSNR as 'non-governmental organizations and institutions that manifest interests and will of citizens and with an express interest in

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[3] As discussed in 4.4 Research context: Rubber and rubber sustainability initiatives, the World Business Council for Sustainable Development also hosts the Tire Industry Project. The World Business Council for Sustainable Development is a CEO-led network of over 200 businesses interested in pursuing sustainable development (WBCSD, 2023).

the Mission of the Platform', including environmental and social NGOs and certification bodies (GPSNR, 2021m, p. 2). To join GPSNR as a smallholder member, applicants must be individual rubber farmers who meet three conditions: (1) their primary source of income comes from the farm (which may have crops other than rubber); (2) have a rubber production area of < 50 ha (although the farm may be larger); and (3) the farm income goes primarily to the farm-owner and their family (GPSNR, 2019c). Affiliate Members are members who do not fall under the listed stakeholder categories, such as industry associations, academic or research institutions, governments and governmental organisations, and for-profit consultants (GPSNR, 2021m). Affiliate Members cannot vote but can participate as observers in the General Assembly and Working Groups (GPSNR, 2021m).

The annual membership fees range from USD 2000 to USD 20,000 for companies, depending on their revenues, USD 2000 for international CSOs with revenues exceeding USD 5 million, USD 500 for all other CSOs, USD 500 for Affiliate Member organisations, USD 100 for Affiliate Member individuals, and no fees for smallholder producers (GPSNR, 2021l).

Every Ordinary Member has one vote in the General Assembly, meaning that each member company, CSO, or individual smallholder will have one vote (GPSNR, 2021m). The General Assembly will first aim for consensus, defined by the GPSNR statutes as 'decision-making that achieves balance among participants, allows dissent, and leads to common and lasting agreements', otherwise a weighted voting system will be used (GPSNR, 2021m, p. 6). Voting power is divided equally among stakeholder categories, so each stakeholder category has 20% voting power (GPSNR, 2021m).

The Executive Committee consists of three seats for every stakeholder category, elected by members of that category (GPSNR, 2021m). The Executive Committee's role includes providing strategic direction and establishing Working Groups, approving and implementing recommendations, reviewing budgets, and overseeing the Secretariat (GPSNR, 2021m). The Statutes mandate that the Executive Committee ‘represents a diverse group of Members in terms of geography, size and nature of businesses/organizations within each of the membership categories’ (GPSNR, 2021m, p. 8). The Executive Committee meets quarterly (GPSNR, 2021m).

Working Groups can be created by the Executive Committee as necessary for specific tasks and issues to fulfil GPSNR objectives, such as developing standards, capacity building, and ‘training (for smallholders)’ (GPSNR, 2021m, p. 10). Similar to the directive for the Executive Committee, the Statutes mandate that Working Groups should aim for **‘**a balanced representation of each of the platform categories and a balance of different views within Members’ categories’ (GPSNR, 2021m, p. 12). While the Executive Committee decides on the overall priorities and strategic direction of GPSNR, Working Groups are the driving force behind GPSNR’s activities as they meet more frequently and are responsible for providing recommendations to the Executive Committee on various priorities (GPSNR, 2022e, 2022i, 2022j). Therefore, participation in Working Groups is an important way for GPSNR members not elected to the Executive Committee to be able to influence GPSNR’s priorities and activities.

While GPSNR has not presented itself as a certification body, perhaps because the implementation of standards and monitoring are still being developed, the MSI has set rules around the use of its logo and sustainability claims that its members can make (GPSNR, 2022h). Since the 3rd General Assembly, GPSNR has adopted sustainability reporting requirements for its industry members (GPSNR, 2021i). Companies must demonstrate compliance with these requirements via a detailed questionnaire, which is audited by the Secretariat (GPSNR, 2022b). GPSNR is also developing an assurance model for further compliance monitoring (GPSNR, 2022c). Currently, there are no reporting requirements for smallholder members, but GPSNR is holding consultations with smallholders about developing an equivalent policy for smallholders (GPSNR, 2022c).

4.6.2 *Evolution of inclusiveness in GPSNR*

The membership structure, voting system, and governance structure of GPSNR as described in the previous section appear to be broadly equitable on paper. Nevertheless, not all of the current stakeholder categories were always present throughout GPSNR's history. The voting and executive rights for smallholders and CSOs had to be negotiated for by CSOs, as will be explored in greater detail in this section. Table 1 summarises the changes relating to each component of MSI inclusiveness at different phases of GPSNR's evolution in its first three years of operation. The chronological narrative follows, describing the details and events surrounding the changes described in Table 1.

4.6.2.1 Soft launch and CSO dispute (October 2018 – February 2019)

Before the soft-launch of GPSNR, the Tire Industry Project reportedly spent a year conducting 'stakeholder collaboration' in designing the platform (GPSNR, 2018b), which included stakeholder consultations to discuss membership criteria, core principles, and governance structure of the proposed MSI (Mighty Earth, 2018a). The first news article published on the GPSNR website lists stakeholders in the supply chain as including manufacturers of tyres and other rubber products, rubber latex suppliers and processors, non-governmental organizations, and 'representatives of individual smallholder producers' (GPSNR, 2018b). However, neither smallholders nor representatives of smallholders were included among the stakeholders who 'contributed to the development' of GPSNR (WBCSD, 2018), whereas automakers were included in the list[4]. In terms of civil society stakeholders, several NGOs were consulted, but all were large international NGOs with headquarters in the United States, United Kingdom, or Europe[5] (ERJ, 2018).

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[4] "Stakeholders including tire manufacturers, other rubber users, suppliers and processors, vehicle makers and NGOs, contributed to the development of the Global Platform for Sustainable Natural Rubber (GPSNR). This included alignment on a wide-reaching set of priorities for the natural rubber supply chain." (WBCSD, 2018, para. 2)

[5] (ERJ, 2018) states that Mighty Earth, WWF, Global Witness, Birdlife, Rainforest Alliance, FSC and ProForest were the NGOs consulted before the soft launch of GPSNR.

Table 1. Summary of changes in the components of MSI inclusiveness across different phases of GPSNR's development.

Component of MSI inclusiveness	Soft launch (Oct 2018 – Feb 2019)	1st General Assembly (Mar 2019)	Smallholder recruitment and onboarding (Apr 2019 – Sep 2020)	2nd General Assembly and after (Oct 2020 – Nov 2021)	3rd General Assembly (Dec 2021)
Stakeholder composition of membership	Only industry actors in membership	Stakeholder categories with voting rights created for CSOs and smallholders			
	CSOs consulted but not included in membership	CSOs become members			
	Smallholders neither consulted nor included in membership	No smallholder members yet	27 smallholders become members	28 smallholder members at 2nd General Assembly	67 smallholder members at 3rd General Assembly
Geographical representation	Rubber producer countries comprise 11% of voting membership	Rubber producer countries comprise 17% of voting membership		Rubber producer countries comprise 55% of voting membership	Rubber producer countries comprise 55% of voting membership
	Only two rubber producer countries represented (Thailand, Indonesia)	Two more rubber producer countries represented (Cote d'Ivoire, Malaysia)		Five more rubber producer countries represented (Vietnam, India, Myanmar, Brazil, Guatemala)	Four more rubber producer countries represented (China, Philippines, Cambodia, Colombia)

(Table 1 continues on next page)

Component of MSI inclusiveness	Soft launch (Oct 2018 – Feb 2019)	1st General Assembly (Mar 2019)	Smallholder recruitment and onboarding (Apr 2019 – Sep 2020)	2nd General Assembly and after (Oct 2020 – Nov 2021)	3rd General Assembly (Dec 2021)
Governance of decision-making (stakeholder composition of the Executive Committee; voting rights)	Only 'value-chain stakeholders' on Executive Committee	Equal number of seats on Executive Committee for every stakeholder category			
	CSOs as advisory only; unclear whether smallholders have seat in Executive Committee	Smallholder seats assured but vacant		Three smallholders elected to Executive Committee	Indonesian smallholder replaces outgoing Vietnamese smallholder on Executive Committee
		Voting weight of 30% each for the categories of producers/processors/traders, tyre-makers/rubber-buyers, and CSOs; 10% for car-makers/ downstream users		Equal voting weight (20% each) for the five stakeholder categories, including smallholders' category	
Quality of smallholder participation			Smallholders give input during recruitment workshops	Smallholders able to vote at General Assembly	Smallholders able to vote at General Assembly
			One smallholder joins working group	Additional smallholders join working groups	
			Consultation held with smallholders about capacity building priorities	GPNSR holds smallholders' satisfaction survey	

In October 2018, GPSNR was ‘soft-launched’ by the Tire Industry Project (GPSNR, 2018b). At the launch ceremony, the GPSNR Members Statement was signed by the Founding Members, consisting of only industry members[6] (WBCSD, 2018). Thus, GPSNR’s membership at the time consisted of only industry members – eleven tyre companies from the Tire Industry Project, six companies in the producers/processors/ traders category, and one car-maker (Table 2). Only 11% (two out of 18) of the Founding Member companies were from rubber producer countries, one from Thailand and one from Indonesia (Table 3).

Table 2. Changes in the number of GPSNR Ordinary Members with voting rights across different stakeholder categories over time. Data compiled from: (WBCSD, 2018; GPSNR, 2019a, 2020h, 2020l, 2021c, 2022d).

Stakeholder categories	Soft launch (2018)	1st General Assembly (2019)	2nd General Assembly (2020)	3rd General Assembly (2021)
Smallholders	0	0	28	67
CSOs	0	11	13	16
Producers, processors, and traders	6	10	13	16
Tyre-makers and other rubber makers/buyers	11	12	14	19
Car-makers, other downstream users, and financial institutions	1	3	5	9
Total	18	36	71	127

[6] GPSNR Founding Members: Tire Industry Project (Bridgestone, Continental, Cooper Tires, Goodyear, Hankook, Kumho, Michelin, Pirelli, Sumitomo, Yokohama, and Toyo Tires), Ford Motor Company, Halcyon Agri Corporation Limited, ITOCHU Corporation, Kirana Megatara, SIPEF, The Socfin Group, and Southland Global PTE Ltd. (WBCSD, 2018)

Table 3. Geographical representation of GPSNR membership by country, compared to their percentage shares of global production and consumption of rubber in 2020. Global production data was from FAO (2022). Global consumption data was from ETRMA (2021). Abbreviations: EU27 = European Union excluding the United Kingdom; USA = United States of America. Data on membership compiled from: (WBCSD, 2018; GPSNR, 2019a, 2020e, 2020h, 2020l, 2020t, 2021c, 2022d).

Country	% global production in 2020	% global consumption in 2020	% share of voting membership (number of members in parentheses)			
			Soft launch	1st GA	2nd GA	3rd GA
			Producer countries			
Thailand	34	6	6% (1)	6% (2)	10% (7)	6% (7)
Indonesia	22	no data	6% (1)	6% (2)	10% (7)	29% (36)
Vietnam	9	no data	0% (0)	0% (0)	10% (7)	6% (7)
Cote d'Ivoire	7	no data	0% (0)	3% (1)	10% (7)	7% (8)
China	5	43	0% (0)	0% (0)	0% (0)	1% (1)
India	5	8	0% (0)	0% (0)	2% (1)	2% (2)
Malaysia	4	no data	0% (0)	3% (1)	2% (1)	1% (1)
Philippines	3	no data	0% (0)	0% (0)	0% (0)	1% (1)
Cambodia	3	no data	0% (0)	0% (0)	0% (0)	9% (11)
Myanmar	2	no data	0% (0)	0% (0)	6% (4)	4% (4)
Brazil	2	no data	0% (0)	0% (0)	3% (2)	1% (1)
Guatemala	0.8	no data	0% (0)	0% (0)	2% (1)	1% (1)
Colombia	0.1	no data	0% (0)	0% (0)	0% (0)	1% (1)
			Non-producer countries			
EU27	0	8	28% (5)	34% (12)	21% (15)	17% (21)
USA	0	6	17% (3)	23% (8)	11% (8)	8% (9)
Japan	0	5	28% (5)	14% (5)	9% (6)	5% (6)
Other non-producer countries	0	no data	17% (3)	14% (5)	10% (7)	8% (10)

Within the Members Statement, GPSNR pledged to 'establish standards, methods and tools', according to twelve principles covering ecosystem protection, water management, land rights, labour rights, human rights, equity, traceability, transparency, anti-corruption, grievance mechanisms, auditing, and capacity building (GPSNR, 2018a, p. 1). It was unclear, from the Members Statement, if smallholders would be invited as equal collaborators and partners in GPSNR. Within the twelve principles, smallholders seemed to be relegated to the role of passive, target beneficiaries of GPSNR's planned activities – the two mentions of 'smallholder' were to promote poverty alleviation programmes and a vague note regarding traceability[7]. The principles also included 'support [for] training and educational efforts to raise awareness and build capacity for the implementation of these principles'[8]. The target audience for training and education efforts were not explicitly mentioned in this document, but later communications by GPSNR would confirm that smallholders formed the primary target group for capacity building projects (GPSNR, 2020c).

The Members Statement also lacked a commitment to a governance model that would allow non-industry stakeholders to have an equal or substantive voice in the key decision-making and implementation body of GPSNR. In the month prior to the soft launch, the CSOs that were engaged by the stakeholder consultation had written a joint letter to the Tire Industry Project to express their concerns (Mighty Earth, 2018a). The proposed governance model at the time of the soft launch consisted of a 'Value Chain Committee' with executive power, and a separate 'Advisory and Monitoring Committee' for non-industry stakeholders, whose role was limited to providing guidance (Mighty Earth, 2018a). The CSOs argued that the tyre industry would have 'too much control' in this model, since civil society and smallholder

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[7] "To recognize and promote human rights within the natural rubber value chain, including alleviating poverty by promoting programs that improve smallholders' livelihoods.
To establish and implement protocols for rubber traceability from farm to end-user, working towards full traceability for industrial plantations and applying a risk-based approach for smallholder farms." (GPSNR, 2018a, p. 4)

[8] "To support training and educational efforts to raise awareness and build capacity for the implementation of these principles, including improvement of production practices by focusing on vertical (improved yield and quality) rather than horizontal (increased planted area) expansion." (GPSNR, 2018a, p. 5)

representatives would be excluded from the highest decision-making roles (Mighty Earth, 2018a; ERJ, 2019, para. 9). The CSOs were negotiating for a system where value-chain industry stakeholders would have 50% of the vote, with the other 50% for smallholder representatives, NGOs, academia, and other non-value-chain stakeholders (ERJ, 2019). Mighty Earth also claimed that the Tire Industry Project had been excluding CSOs from certain discussions and rejecting requests for an independent professional mediator to facilitate meetings in an impartial way (Mighty Earth, 2018a).

Despite at least seven CSOs[9] being engaged in discussions for eight months leading up to the soft launch (ERJ, 2018), the Founding Members statement received zero signatures from CSOs (WBCSD, 2018). There was also a lack of CSO presence at the ceremonial soft launch (WBCSD, 2019b). As a protest strategy, Mighty Earth publicised their lack of support for GPSNR, turned down the Tire Industry Project's invitation to attend the soft launch ceremony, and published an open letter on their website (Mighty Earth, 2018a, 2018b).

Following the lack of reception by CSOs at the soft launch, the Tire Industry Project agreed to have an independent conflict mediator arbitrate the next set of stakeholder discussions in late November in Geneva (ERJ, 2018, 2019). The November meeting was described as a 'breakthrough in the dispute' between the Tire Industry Project and CSOs, where a new, more equitable governance model was drafted (ERJ, 2019). This new governance model reportedly would give CSOs equal seats in the Executive Committee and have more balanced representation in votes in the General Assembly (ERJ, 2019). Another stakeholder workshop was held in Singapore in January 2019, which saw GPSNR Founding Members and invited stakeholders 'unanimously' agreeing to prioritise 'smallholder inclusivity within the platform' (GPSNR, 2019d, para. 1) and that 'this critically important stakeholder group should be part of the GPSNR decision making structure' (WBCSD, 2019c, para. 4). To this end, the

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[9] See footnote 2.

Smallholders Representation Working Group was formed to 'identify and secure adequate smallholder representation within the GPSNR governance' (GPSNR, 2019d, para. 1).

4.6.2.2 1st General Assembly (March 2019)

The 1st General Assembly was held in Singapore in March 2019, in conjunction with a rubber industry conference called the World Rubber Summit (GPSNR, 2019a). The 1st General Assembly saw a widening of stakeholder inclusion in membership and participation in decision-making in GPSNR. While smallholder representation was not yet present in GSPNR, CSOs were, at that point, included in the voting membership (Ordinary Members) and have seats in the Executive Committee.

In terms of changes in stakeholder membership composition, eleven CSOs joined, along with four more companies in the producers/processors/traders category, and two more car-makers; thus increasing the range of interests represented in membership (GPSNR, 2019a). In terms of geographical representation, membership was still skewed towards non-producer countries. There were four new members from rubber producer countries compared to 14 new members from non-producer countries (Table 3). Out of the eleven CSOs that joined at the 1st GA, only one was headquartered in a rubber producer country (ResourceTrust Network, Ghana), the rest were headquartered in the United States (4), United Kingdom (2), and Europe (4) (GPSNR, 2019a). At this point, rubber producer countries comprised only 17% of the total voting membership (six out of 36 members; Table 3). The rubber producer countries represented were Thailand, Indonesia, Cote d'Ivoire, and Malaysia (Table 3). Europe had the largest share (34%) of members (Table 3).

With the approval of the new governance model, CSO representatives were elected alongside industry representatives to the Executive Committee (GPSNR, 2019a). At the time of the 1st General Assembly, there were no smallholder members yet so the voting weight was divided as follows: 30% each for the categories of producers/processors/traders, tyre-makers/rubber-buyers, and CSOs; and 10% for car-makers/downstream users (GPSNR, 2019f). These voting weights roughly correspond to the share of membership from each category: 27% producers/processors/traders (10 members), 33% tyre-makers/rubber-buyers (12 members), 30% CSOs (11 members), and 8% car-makers (3 members).

4.6.2.3 Smallholder recruitment (March – December 2019)

Following the 1st General Assembly, the Smallholder Representation Working Group took steps to recruit smallholders, demonstrating commitment to their mandate of 'facilitat[ing] smallholder representation with an equal role in decision-making within GPSNR' (GPSNR, 2022i, p. 1). Their main strategy was to work through 'Country Champions', i.e. eleven selected GPSNR members with deep knowledge of working in selected rubber producer countries and ties with local organisations and government authorities (GPSNR, 2019d, para. 2). The Country Champions conducted interviews with smallholder associations and organisations in their allocated countries, as well as helped to promote interest in GPSNR with local stakeholders in those countries (GPSNR, 2019d).

From October to December 2019, the Smallholder Representation Working Group organised smallholder recruitment workshops in Indonesia, Thailand, Brazil, Côte d'Ivoire and Vietnam (GPSNR, 2019e). These workshops were facilitated by an external consultant and funded by Partnerships for Forests, a grant programme for public-private-community partnerships financed by the United Kingdom Foreign Commonwealth and Development Office (Partnerships for Forests, 2022). The workshops were attended by independent smallholders, representatives of smallholder organizations, industry, and CSO representatives from the Smallholder Representation Working Group, the Secretariat, and observers (such as local CSOs and researchers) (CIFOR and CIRAD, 2019).

During the workshop, smallholders were introduced to GPSNR, participated in a stakeholder mapping exercise, and asked about their views on the future of rubber, their constraints, vision for sustainable rubber, how to structure smallholder representation in GPSNR, expectations for GPSNR, and contributions to GPSNR (CIFOR and CIRAD, 2019). In addition to the group discussions, the workshop included a field visit to a rubber-processing factory and a presentation on global and country-specific rubber markets by an industry member. Having smallholders, rubber processors, and GPSNR industry representatives in the same room provided opportunities for face-to-face interactions between smallholders and downstream players in the rubber value chain who may otherwise never meet.

One common challenge highlighted by smallholders attending the workshops was the issue of low and/or fluctuating rubber prices (CIFOR and CIRAD, 2019; Feng, 2020; GPSNR, 2020b). For example, in a video interview with GPSNR, an Indonesian smallholder shared his views (GPSNR, 2020m):

> There are several obstacles faced to promote sustainable natural rubber. The first is to manage the plantation economy, or economies of scale. Then there is the problem of fluctuating prices, so that the costs for managing the plantation are quite difficult to deal with.

Smallholders asserted that, at low rubber prices, they could barely earn a living, much less afford to invest in sustainability improvements (Feng, 2020). As a female Vietnamese smallholder noted in another GPSNR interview (GPSNR, 2020n), they are lacking access to market information and are concerned about meeting household needs:

> Because agents and middlemen often force prices, there is no standard to follow for price calculation. The biggest expectation, which almost everyone wishes is to improve pricing, how to meet the needs of the farmers’ life.

An article by Eco-Business quotes a Thai smallholder (Feng, 2020, para. 7):

> The price of sustainable rubber must cover our costs for producing it. You must pay us at a price that enables us to survive. It's not right if you want to save the world but do not care about rubber farmers[.]

In contrast, the issue of rubber prices hardly featured in GPSNR news – the term 'price' only occurred once – in the preamble to introducing an e-trading platform as an innovative funding mechanism for GPSNR, it was recognised that 'low and unpredictable rubber prices are a constraint to smallholders who produce the bulk of global rubber output' (GPSNR, 2020r, para. 2). The lack of emphasis on rubber pricing may be due to the constraints imposed by anti-trust/anti-competition laws, as enshrined in the Code of Conduct, which prohibit GPSNR members from exchanging 'commercially sensitive' information such as 'previous, current or future prices' and 'purchasing prices or trading terms with suppliers' (GPSNR, 2020d, p. 3). There is a tension between industry's interests in avoiding legalistic troubles and smallholders' desire to talk about rubber pricing.

Other than pricing, smallholders interviewed by GPSNR brought up a range of issues, ideas, and hopes (GPSNR, 2020b). In parsing different statements by smallholders from different countries ranging from Ghana to Vietnam, it became evident that smallholders are not a monolithic group. Whereas Indonesian smallholders spoke about the lack of government support, the complex supply chain, and the need for better farming knowledge and skills, Vietnamese smallholders spoke about the lack of access to updated technology, climate change, and urban development affecting land and labour (GPSNR, 2020b). Brazilian smallholders were concerned about clarity in sustainability standards for rubber (Feng, 2020; GPSNR, 2020b). Smallholders were equally not monolithic in their understanding of what the future of rubber is to look like. Thai smallholders spoke about greater access to niche markets and increasing value of rubber products via globally-accepted standards (GPSNR, 2020b). In contrast, Ghanaian smallholders talked about building capacity, technology, and farmer organisations. Only one smallholder spoke about the ecological dimension of sustainable rubber production, as follows (GPSNR, 2020o):

> The sustainable rubber development is to have a right and effective way, on how we can protect the environment, not only will we ensure the family economy but also return what we have taken from Mother Nature.

4.6.2.4 Onboarding smallholders into GPSNR (January – September 2020)

After almost a year of discussion, in December 2019 the Smallholder Representation Working Group presented the finalised definition of rubber smallholders for GPSNR, as covered in 4.6.1 Overview of GPSNR membership and governance structure (GPSNR, 2019c). According to GPSNR, the working group considered input from smallholder workshops and the International Rubber Study Group while formulating the smallholder definition, which aims to be ‘pragmatic and standardized’ whilst acknowledging heterogeneity among countries (GPSNR, 2019c). It was unclear how much influence smallholders actually had in deciding the smallholder definition. Based on a report by an affiliate observer, smallholders participating in the workshops were consulted about how they would like to be represented in GPSNR (CIFOR and CIRAD, 2019).

By the end of April 2020, GPSNR had recruited 27 new smallholder members from seven rubber-producer countries (GPSNR, 2020j, 2020t). With their mandate of recruiting smallholders into GPSNR fulfilled, the Smallholder Representation Working Group shifted its focus to ensuring smallholder members’ robust inclusion and participation in GPSNR, as reflected by the change in the Working Group Terms of Reference (GPSNR, 2022i). To prepare smallholders for the 2nd General Assembly, the Smallholder Representation Working Group discussed matters such as hiring translators and facilitators as well as additional orientation sessions to help smallholders participate in GPSNR’s processes (GPSNR, 2020s). However, the in-person General Assembly was postponed and ultimately cancelled due to the COVID-19 pandemic (GPSNR, 2020q).

After the 2nd General Assembly was switched to a completely virtual format and postponed to September 2020, the Smallholder Representation Working Group started preparing smallholders to participate in the virtual General Assembly (GPSNR, 2020u). They first held video-teleconferencing calls at the national level with smallholders, facilitated by Country Champions, to allow smallholders within each country to get acquainted with the video conferencing software, get updates on GPSNR, and an overview of the activities leading up to the General Assembly which would include another two national calls and three international calls (GPSNR, 2020p). The international calls with smallholders were facilitated by an external consultant, with simultaneous interpretation in multiple languages (GPSNR, 2020f). The calls were met with reportedly very active participation from smallholders (GPSNR, 2020f). However, the four Myanmar smallholders were not able to participate because their access to internet was cut off by flooding (GPSNR, 2020f).

4.6.2.5 2nd General Assembly and after (October 2020 – November 2021)

The 2nd General Assembly again marked a formal widening of stakeholder inclusion in membership and participation in governance and decision-making in GPSNR, with the creation of the Smallholders' stakeholder category with equal voting rights as the four other existing categories, and the election of three smallholders to the Executive Committee (GPSNR, 2020h).

In terms of changes in membership composition, the smallholders' category had the biggest increase in number with 28 new members (Table 2). All other categories had only the addition of 2-3 new members respectively (Table 2). In terms of geographical representation, the coverage of rubber producer countries increased. This was mostly due to the inclusion of new smallholder members from seven countries across three continents, namely Brazil, Côte d'Ivoire, Ghana, Indonesia, Thailand, Vietnam, and Myanmar (GPSNR, 2020t, 2020j). There was also a tyre-maker from India and a rubber processor from Guatemala (GPSNR, 2020l), bringing the number of rubber producer countries represented to nine (Table 5). At this point, rubber producer countries comprised 55% of the total voting membership, signifying a balanced ratio between producer and non-producer countries for the first time (Table 3). The countries of origin of the smallholder representatives on the Executive

Committee, namely Thailand, Indonesia, and Cote d'Ivoire, are also among the top rubber producer countries (Table 3).

After the 2nd GA, the smallholders held a fourth International Call, which aimed to reflect on smallholder participation so far and in the future, to hear from the newly elected Executive Committee representatives, to introduce smallholders to the various Working Groups, and to have a discussion about smallholder participation in the future (GPSNR, 2020k). Some of the issues brought up were: language barriers faced by the smallholder Executive Committee representatives, questions about GPSNR's expectations for policy and traceability requirements for smallholders, and conversations around maintaining group communication among smallholders across cultural and language barriers (GPSNR, 2020k).

Following this meeting, smallholders started joining Working Groups and increasing their participation in GPSNR's input-gathering, prioritising, and decision-making processes. Efforts were made to invite smallholders to collaborate in creating GPSNR outputs; for example, the Capacity Building Working Group was recruiting for 'smallholder members who have experience in Good Agricultural Practices to join the Task Force. They will have the opportunity to collaborate and create the GAPs together with other Task Force members.' (GPSNR, 2020i, para. 7). By March 2021, the Smallholder Representation Working Group had recruited smallholders from Indonesia and Vietnam (GPSNR, 2021d). Around the same time, the Smallholder Representation Working Group divided into two subgroups, one focused on increasing geographical representation of smallholders (recruiting smallholders from countries without smallholder representation in GPSNR), and the other focused on enhancing participation of existing smallholder members, including improving representation by minority groups (GPSNR, 2021d).

Prior to the 2nd General Assembly, only one smallholder had been participating in a Working Group – namely, a rubber smallholder who was also the current President of the Association of Natural Rubber Producers of Côte d'Ivoire (GPSNR, 2020e). The same smallholder was also one of the three smallholders who had been elected to the Executive Committee at the 2nd General Assembly (GPSNR, 2020a).

Given that the Capacity Building Working Group did not initially include smallholders from different countries, how were the capacity building goals and priorities determined? The procedure taken by the Working Group was to first conduct 'stakeholder interviews' to identify priorities, then conduct separate stakeholder consultations with smallholders, after they were recruited into GPSNR, to gather feedback on proposed capacity building initiatives (GPSNR, 2020u). As a result, sometimes smallholders came up with completely different ideas which better reflected their experiences, such as in the case of Thai smallholders who proposed a focus on smallholder income diversification through agroforestry (GPSNR, 2020u, 2022a). After smallholders were recruited into the Capacity Building and other working groups, they then had the opportunity to feedback directly into working group discussions. The resulting capacity building projects foci were: training on Good Agricultural Practices, distribution of high-yielding clonal rubber planting material, disease management training, development of market for rubberwood, establishing tapper cooperatives, and agroforestry training (GPSNR, 2022a).

In May 2021, GPSNR conducted a satisfaction survey amongst its smallholder members, receiving a response rate of 57% (GPSNR, 2021e). According to GPSNR, smallholders gave suggestions on how to improve communications, information-sharing, and the participation of smallholders within GPSNR. Many smallholders were confused about membership rules (i.e. what are the sustainability requirements for smallholder and company members) and the purpose of the Smallholder Representation Working Group (GPSNR, 2021e). Regarding barriers to participation, the summary by GPSNR mentioned challenges around access and usage of technology as well as language barriers. It should be noted that GPSNR reporting of the smallholders' international calls and survey did not highlight any concerns about pricing and financial support for smallholder to adopt sustainable practices. This is surprising given that these issues were top smallholder priorities, as evidenced by their interviews with GPSNR, workshop reports, and other media (CIFOR and CIRAD, 2019; Feng, 2020; GPSNR, 2020b).

Another key issue where the quality of participation was in question is agroforestry, a topic of interest for smallholders. Smallholder members had specifically asked GPSNR to investigate the issue of agroforestry (Nature4Climate, 2021; GPSNR, 2022g). The conversations around rubber agroforestry had not occurred in a vacuum. In May 2021, Mighty Earth had organised a webinar and launched a report on rubber agroforestry, which was attended by GPSNR members and interested smallholders (Mighty Earth, 2021c). In August 2021, the Capacity Building Working Group created a new task force on agroforestry to develop GPSNR's position on agroforestry (GPSNR, 2021b). GPSNR announced its Agroforestry Position in conjunction with the United Nations (UN) Conference on Climate Change (COP26) in November 2021, which included a commitment to 'piloting, studying and furthering the practice of agroforestry in natural rubber production as a potential climate mitigation and adaptation strategy', as well as call for governments, rubber companies, and companies dealing in other commodity crops to help finance agroforestry projects in the top rubber producer countries (ERJ, 2021; GPSNR, 2021g, p. 1). This was a significant event because it indicates how agroforestry, which had not been a major part of GPSNR priorities before, rose in importance to become a publicised commitment and call for funding by GPSNR, because of its importance to smallholder members in GPSNR.

There was also a gradual shift in the language used by GPSNR to describe the role of smallholders, from depicting smallholders as targets of assistance (e.g. 'Strong, sustainable supply chains can only be achieved if the most fragile player, smallholders, are empowered.' (GPSNR, 2019e, para. 1)), to recognising the agency of smallholders, e.g. 'While COVID-19 exposes the vulnerabilities of smallholders, it also reveals the potential they have to be agents of change and drivers of transformation.' (GPSNR, 2020j, para. 3). It was likely not a coincidence that this change in language came after GPSNR's direct interactions with smallholders via the smallholder workshops, and the increase in smallholder participation such as the first smallholder joining a working group following their inclusion in the platform (GPSNR, 2020e). Several smallholders were leaders in their communities or farmer associations who were confident in speaking about issues that mattered to them, as captured by GPSNR video interviews (GPSNR, 2020b).

4.6.2.6 3rd General Assembly (December 2021)

The 3rd General Assembly saw further widening of stakeholder inclusion in GPSNR, in terms of smallholder membership numbers, geographical scope of membership, and continued participation of all stakeholder categories in the Executive Committee.

As of the 3rd General Assembly, there were 39 new smallholder members, bringing the total number of smallholders to 67 (GPSNR, 2021c). All other categories had only the addition of 3-5 new members (Table 2). In terms of numbers, smallholders formed the biggest stakeholder category, comprising more than half the total Ordinary Members in GPSNR at the 3rd GA. While members of the smallholders' category are individual smallholders, members of other stakeholder categories consist of companies or organisations. It is important to note that the number of members per stakeholder category do not necessarily mean greater influence over decision-making, as voting is weighted by category, as explained in 4.6.1 Overview of GPSNR membership and governance structure.

In terms of geographical representation, GPSNR welcomed companies from Mainland China, Taiwan, Philippines, and Colombia, as well as smallholders from Cambodia, countries which had not yet been covered by GPSNR (GPSNR, 2022d). This brought the number of rubber producer countries represented to thirteen. The outgoing Vietnamese smallholder Executive Committee representative was replaced by an Indonesian smallholder (GPSNR, 2022d). The countries of origin of the smallholder representatives on the Executive Committee were Thailand, Indonesia, and Cote d'Ivoire, again all top rubber producers (Table 3). At this point, rubber producer countries comprised 64% of the total voting membership (Table 3). This shift was largely due to the influx of 28 new smallholder members from Indonesia

(GPSNR, 2021f), such that Indonesia now has the largest share of voting members (29%) in GPSNR. Despite China and India being major consumers and producers of rubber, they comprised only 1% of membership each (Table 3). Thailand also had a smaller share of membership (6%) despite being the largest rubber producer and a major consumer (Table 3). Nevertheless, GPSNR is actively seeking to recruit smallholder members from countries lacking smallholder representation in GPSNR (GPSNR, 2022d).

4.6.3 Components of inclusiveness and other themes

4.6.3.1 Membership composition and geographical representation

On paper, the membership composition and geographical representation in GPSNR seem to meet the criteria set by Fransen and Kolk (2007) and Schouten, Leroy and Glasbergen (2012) to be considered inclusive. By recognising smallholders as a separate stakeholder category, GPSNR acknowledged that smallholders should not be lumped into the same category as industrial producers. This was a clear departure from GPSNR's initial proposed governance structure at the soft launch, which did not have a smallholders' category separate from industrial producers, as in the RTRS. The change in stakeholder structure was likely in large part due to the negotiations by CSOs after the soft launch, as discussed earlier in 4.6.2.1 Soft launch and CSO dispute (October 2018 – February 2019). In addition, the tiered or differentiated fee system recognises the differential financial capacities of different stakeholders, and makes membership in GPSNR more financially accessible for smallholders and smaller, local NGOs. This approach to smallholder inclusion can be linked to contextual equity or equity in access (Brown and Corbera, 2003; McDermott, Mahanty and Schreckenberg, 2013), as smallholders have vastly different needs, interests, and access to market information from industrial producers.

Geographical representation, while initially skewed towards non-producer countries, became more balanced and covered an increasing number of rubber producer countries represented over time. To compare with other MSIs, Schouten, Leroy and Glasbergen (2012) found that RTRS did not adequately represent the largest soy producing country (United States) nor the largest soy importer (China) – although this may have changed in recent years. Schouten, Leroy and Glasbergen (2012) also reported that the RTRS was working with smallholders in Indian and Latin American producers' organisations, but had no members from either Africa or Oceania. The Forest Stewardship Council and Roundtable on Sustainable Biomaterials are said to have a balance between northern and southern organisations (Pinto and McDermott, 2013; Schleifer, 2019).

In some ways, stakeholder inclusion precedes participation, as (1) the stakeholder must first be included in membership to be able to formally participate in the MSI; and (2) the stakeholder must first be included in governance roles to be able to formally participate in institutional decision-making (Fransen and Kolk, 2007). Nevertheless, stakeholders can still influence MSI activities and decision-making without being formally included, for example via self-mobilisation and activism (Adeyeye, Hagerman and Pelai, 2019). This was demonstrated by the NGOs that were excluded from decision-making roles and some negotiations by the Tire Industry Project before the soft launch of GPSNR, but mobilised themselves in protest, which eventually resulted in them claiming equal voting membership and decision-making rights for themselves and for smallholders. NGOs have often effectively advocated for land rights and stronger sustainability standards on behalf of the marginalised, partly by raising public awareness (Byerlee and Rueda, 2015). NGOs continue to perform a watchdog role in reporting environmental and social grievances caused by the rubber industry (Bernath, 2020; Mighty Earth, 2021a; Global Witness, 2022), and have not hesitated to hold GPSNR member companies accountable when they appear to be disregarding environmental and societal interests (Mighty Earth, 2020, 2021b; Wijeratna, 2020). For example, Mighty Earth called out GPSNR tyre-makers for lobbying against including rubber in the European Union's (EU) list of forest risk commodities, which would require greater due diligence requirements for rubber products imported into the EU (Mighty Earth, 2021b).

Nevertheless, one NGO has cautioned that GPSNR needs to avoid the common challenge faced by commodity MSIs of 'favouring corporations and international

NGOs' which possess 'greater resources of time and money to stay involved during the long process' (Hines, 2019, para. 16). It is typical for large international NGOs to represent the interests of stakeholders who are unable to participate in MSIs and other forms of partnerships (Bitzer and Marazzi, 2021), which may inadvertently exclude local NGOs who are under-resourced relative to international NGOs (Boström and Hallström, 2010; Moog, Spicer and Böhm, 2015). Nevertheless, local NGOs are key intermediaries between local communities or smallholders and international stakeholders (whether multi-national corporations or international NGOs) (Brown and Corbera, 2003; Cheyns, 2014). Local NGOs who have built close relationships with smallholders and local communities are able to offer localised support for smallholders to articulate their issues of concern in ways that are more readily accepted in international forums (Cheyns, 2014). In GPSNR, this key intermediary role is played by 'Country Champions', but it is unclear who these country champions are and whether they are appropriately resourced (GPSNR, 2019d). A future study could consider focusing on the role of intermediary organisations or individuals in linking smallholders to GPSNR and the challenges they may face while in this role.

4.6.3.2 Inclusive governance of decision-making

While smallholders were not present at the 1st General Assembly in 2019, by the 2nd General Assembly in 2020, three smallholders were elected to the Executive Committee, occupying the same number of seats as the three industry stakeholder categories (industrial producers/processors/traders, tyre-makers, and car-makers) and CSOs (GPSNR, 2020h). Thus, GPSNR's governing board appears to be more inclusive of non-commercial interests and smallholders, in comparison with that of the Roundtable on Sustainable Palm Oil (RSPO). For many years, oil palm smallholders had no direct representation on the RSPO Board of Governors, nor in key Working Groups (Ponte and Cheyns, 2013; Cheyns, 2014). Only one seat (out of sixteen) is allocated for smallholders on the Board of Governors, compared to eleven allocated to commercial interests (growers, processors/traders, consumer goods manufacturers, retailers, banks/investors), and four to environmental and social

NGOs (RSPO, 2023b). This suggests that commercial interests dominate the governance board. In terms of the voting system in the General Assembly, every member has one vote so the stakeholder category with the most members can skew decision-making (Schouten, Leroy and Glasbergen, 2012). In comparison, voting power in GPSNR's General Assembly is equally split between five stakeholder categories, preventing any one stakeholder category from dominating (GPSNR, 2021m).

The Round Table on Responsible Soy (RTRS) is divided into three constituencies: Producers; Industry, Trade and Finance; and CSOs, which have the same voting rights and an equal number of seats on their Executive Board (RTRS, 2023). Each constituency has a veto right to prevent any single interest group from dominating the process (Schleifer, 2019). While there is no separate category for smallholders, smallholders or smallholder organisations can join as Producer members (Schouten, Leroy and Glasbergen, 2012). Schouten, Leroy and Glasbergen (2012) and García-López and Arizpe (2010) noted that the RTRS faced challenges in the inclusion of smallholders, local groups and development NGOs. No smallholders or smallholder organisations were included in the Organising Committee or Executive Board even after five years since the MSI's establishment (Schouten, Leroy and Glasbergen, 2012). In comparison, GPSNR was able to include three smallholders on the Executive Committee within two years since the soft launch.

While the structure of GPSNR's Executive Committee and General Assembly voting system appears to have an inclusive design based on Fransen and Kolk's (2007) and Schouten, Leroy and Glasbergen's (2012) operationalisations, other researchers are less optimistic that equal access to decision-making equates to equitable decision-making. For example, Edmunds and Wollenberg (2001) argue that multi-stakeholder negotiations that claim to be neutral often mask historical or structural inequities faced by disadvantaged groups. From this view, consensus may not be legitimate when stakeholders have vastly different access to resources and power (Edmunds and Wollenberg, 2001). Hence, even when decision-making structures in MSIs are designed to favour non-commercial interests – such as in the case of the Forest

Stewardship Council, where social and environmental stakeholders make up two-thirds of all governance bodies – the pressure to maintain economic competitiveness can end up excluding minority voices of dissent and jeopardise legitimacy (Moog, Spicer and Böhm, 2015). Thus, in addition to inclusive design of governance structures, the quality of participation of less powerful stakeholders in various decision-making processes in MSIs is also key to evaluate inclusiveness in decision-making.

4.6.3.3 Quality of participation

As noted by Bitzer and Marazzi (2021), while procedurally there may not be many obstacles for smallholders to join MSIs, actual participation is dependent on their capabilities and access to resources. For example, although GPSNR does not charge membership fees for smallholder members, smallholders may still face disadvantages compared to other stakeholder categories. For one, struggles with what Cheyns (2011) calls the dominant, technocratic communication style in MSIs, remain. The main language of communication is English, and organisational documents are written using technical jargon familiar to businesses and CSOs. While translations are provided, it may still be difficult for smallholders to understand the content or nuances in documents. Further challenges for smallholders may include poor access to internet (GPSNR, 2020f) and uncompensated time spent participating in GPSNR meetings. These factors may have contributed to GPSNR struggling to get responses to written surveys (e.g. 57% response rate on the smallholders' satisfaction survey), necessitating direct calls or individual outreach via locally based GPSNR members.

These difficulties resonate with similar challenges to smallholder inclusiveness reported by other MSIs (Ponte and Cheyns, 2013; Ponte, 2014; de Bakker, Rasche and Ponte, 2019). Smallholders in the RSPO were systematically shut down from speaking about 'political' issues like justice and land rights, or being 'militant' about local peoples' struggles (Cheyns, 2011, pp. 14–16). Bitzer and Marazzi (2021, p. 391) found that in Trustea, an MSI for sustainable tea production, smallholders were perceived by founders to be 'unable to discuss sustainability in a structured way' or ‘not able to think of the common good’ and thus excluded from contributing to the development of the MSI. Crucially, these struggles are most acute for the most disadvantaged smallholders (those who do not speak English at all, who lack internet access, or who cannot afford to take time off work), i.e. those whose voices most needed to be heard. To address this, it is important to heed smallholders’ differential needs and recognise that full procedural equity involves more than equal seats on the Executive Committee, but an attention to contextual equity (McDermott, Mahanty and Schreckenberg, 2013).

By the 3rd General Assembly, a number of smallholders had joined working groups and were invited to give feedback on GPSNR activities and procedures. Their comments appeared to have influenced some capacity building projects (see 4.6.2.5 2nd General Assembly and after (October 2020 – November 2021)). Pricing was a key concern among smallholders (see 4.6.2.3 Smallholder recruitment (March – December 2019)), yet open discussions of pricing were constrained by anti-trust/anti-competition laws, which prohibit GPSNR members from exchanging ‘commercially sensitive’ information such as prices (GPSNR, 2020d, p. 3). Industry’s tendency to brush off any discussion of rubber pricing has been prevalent since before the 1st General Assembly, as reported by Fair Rubber (2019, paras 1, 4):

> At the recent World Rubber Summit in Singapore . . . representatives from Thailand (rubber producer No. 1 globally), Indonesia (No. 2), India, Sri Lanka, Malaysia… in a plenary emphasised one after the other that there was an urgent need to discuss pricing: The present level is causing small farmers to stop tapping, as they cannot even cover their production costs, the tappers move to the cities, or the rubber trees are cut down and replaced with oil palms. The comment of the session moderator: “Pricing is a multidimensional issue. Anything else?”

The reluctance of downstream industry actors to talk about the unsustainability of low prices of raw material is not confined to the rubber sector either. In the same article, Fair Rubber (2019, para. 3) reports on the experience of a speaker from Cote d'Ivoire negotiating with cocoa buyers on sustainability:

> . . . the buyers put forward detailed lists of issues like deforestation, pesticide (mis)use, forced and child labour …but when the discussion touches on the (unsustainably) low price, the answer is that "this is a function of the market forces."

As emphasised by Reinecke's (2010, p. 567) study of Fairtrade minimum price setting, this 'free market' idea ignores that 'trade relationships are characterised by inequalities in information and bargaining power'. This means that the free-market defence may be construed as an attempt to absolve GPSNR of the responsibility to pay a fair price to smallholders.

Nevertheless, GPSNR failing to do anything about pricing concerns would risk them losing legitimacy with smallholders as it would appear that their voices are not being listened to. Thus, it appears that GPSNR has made some efforts to indirectly address smallholders' concerns, such as creating mechanisms to channel funds from companies into capacity-building activities rather than changing pricing. For example, GPSNR has focused on developing Good Agricultural Practices to help smallholders improve incomes by increasing productivity or reducing yield losses (GPSNR, 2021a), but without facilitating smallholders' ability to negotiate pricing. GPSNR had also commissioned a consultant study on 'Living Income Gaps in Natural Rubber', and the resulting report did discuss rubber prices and their links to the living income gap faced by rubber smallholders (Loos and Langenberger, 2021). However, it is as yet unclear how the consultant report has informed GPSNR's strategies.

One other, more recent development in GPSNR is the adoption of a 'Shared Responsibility Framework' that 'charts out a mechanism where the costs and benefits of the platform's sustainability initiatives will be equitably distributed across all actors within the supply chain' (GPSNR, 2022f, para. 1). This framework is based around three pillars of 'Shared Investments, Value Transfer and Target setting, and Knowledge and Data sharing' (GPSNR, 2022f, para. 2). Yet, this ambitious-sounding strategy seems like a roundabout way of addressing inequitable pricing issues, as compared to paying a fair price premium for sustainably produced rubber (Fair Rubber, 2019). Hence, a further study that critically evaluates GPSNR's Shared Responsibility Framework is needed to clarify whether it is genuinely designed to address inequities in pricing and smallholders' access to market information, or merely greenwash.

Since the inclusion of smallholders as members in GPSNR, at least some industry actors in GPSNR have acknowledged the importance of addressing rubber pricing issues to ensure the security of rubber supply and smallholder incomes. For example, the head of natural rubber purchasing at Pirelli, a GPSNR founding member and tyre-maker, was quoted as counting low rubber prices as 'a major concern', which impacts smallholder livelihoods (Small, 2020, para. 13). The CEO of Halcyon Agri – also a founding member – has written and spoken about the problem with rubber prices (Meyer, 2018), quoted as proposing 'a new pricing paradigm, allowing producers to determine prices in relation to sustainability and other qualitative criteria that enables them to produce a product the world needs, in quantities that are sufficient, at prices which are workable for the farmer and the consumer' (Small, 2020, para. 15). To achieve this ambition, Halcyon Agri – the 'world's largest rubber processing company' – is promoting their digital marketplace named HeveaConnect, which has 'traded in excess of 28,000 tonnes of rubber, or $38m worth' in less than a year since it was launched (Small, 2020, paras 2, 17).

Fair Rubber, which was invited to join GPSNR but chose not to join, expressed scepticism that downstream actors in commodity value chains like tyre-makers would actually take the priorities of Global South producers and smallholders seriously (Fair Rubber, 2019). Their scepticism has been echoed by researchers, who found that smallholder priorities did not fit with MSI standards (Nelson and Tallontire, 2014; Krauss and Krishnan, 2021). More broadly, some researchers even question whether businesses are willing to sacrifice profit for sustainability (see discussion by Milne and Gray (2013)). Case studies of private sustainability standards from other commodities have shown that the priorities of producers and smallholders in developing countries tend to be overshadowed by demands from downstream purchasers (Krauss and Krishnan, 2021). Nevertheless, perhaps direct representation from smallholders in working groups and the Executive Committee in GPSNR can bring about changes in priorities, as reflected by the adoption of agroforestry as a priority issue. Smallholders were reportedly the 'catalyst' for GPSNR's public commitment to agroforestry (GPSNR, 2022g, p. 2). As Andriesse and Tanwattana (2018) noted, companies in global value chains are not typically interested in supporting farmers to adopt diversification strategies such as agroforestry, as doing so may divert resources away from the commodity of interest and go against corporate strategies of specialisation and economies of scale. Thus, for GPSNR and its member companies to publicly commit to supporting agroforestry, can be seen as evidence of smallholders' growing influence and a step towards becoming 'co-creators of issues and priorities' in GPSNR. That said, GPSNR's public commitment to agroforestry could be seen as lacking substance, as it does not require any extra effort or funding on the part of member companies. Further analysis of GPSNR member companies' financial contributions to capacity building projects, compared to their annual profits, for instance, could provide deeper insights into the extent of industry actors' commitment to an 'equitable rubber value chain'.

4.6.3.4 Equal partnership and co-creation of issues and priorities

One of the interesting findings was the change in GPSNR's portrayal of smallholders, from describing smallholders as 'fragile' (GPSNR, 2019e, para. 1) to 'agents of change and drivers of transformation' (GPSNR, 2020e, para. 3). The initial perception or depiction of smallholders as 'objects of assistance' has been observed by other researchers (Cheyns, 2011; Dove, 2011). Companies tend to use that tactic to justify decisions made as being in smallholders' interests, despite smallholders not being consulted or included in decision-making (Cheyns, 2011; Dove, 2011). Inclusiveness in MSIs may provide a way to remedy this narrow perception of smallholders, as demonstrated by the change in GPSNR after the inclusion of smallholders into GPSNR and working groups. Boström (2006, p. 361) suggests that MSIs make actors accountable to each other, as it 'forces actors to engage in a dialogue and repeated interaction over time, which in turn can result in mutual learning and mutual trust among actors and mutual respect for each other's intentions and competence'. It would seem that the inclusion and participation of smallholders increased accountability and mutual respect within GPSNR, as company representatives and the Secretariat now have to repeatedly come face-to-face with smallholders as fellow members in the Executive Committee and in Working Group meetings.

Nevertheless, other NGOs who did not join GPSNR expressed some scepticism towards the potential of GPSNR to be truly inclusive (Fair Rubber, 2019; Hines, 2019). One of the criticisms was that smallholders, indigenous communities, and local NGOs were not included in the development of GPSNR's founding principles, vision, and mission (Hines, 2019). GPSNR was called to extend the scope of stakeholder inclusion and quality of participation by involving indigenous farmers and communities as 'equal partners in the process' (Hines, 2019, para. 14). The idea of 'equal partnership' is expressed in the definition of stakeholder inclusion by Wenzel *et al.* (2020, p. 3), i.e. 'giving voice to stakeholders through co-creation of an organisation's issues, priorities, and procedures'. 'Co-creation' involves active participation and substantial input provided by stakeholders from the very early stages of developing an MSI. 'Co-creation of issues and priorities' means that all stakeholders have a hand in framing what will or will not be issues that are discussed, while 'co-creation of procedures' means that all stakeholders have a hand in deciding how decision-making should be structured. This also harkens back to the idea of 'degrees of participation' (Reed, 2008, p. 2419) as well as procedural equity in terms of setting the overarching objectives of projects (McDermott, Mahanty and Schreckenberg, 2013). 'Co-creation' has not been the case for the initiation and early development of GPSNR, echoing the findings by Bitzer and Marazzi (2021) who found that small tea growers were not included in the development stage but only later in the MSI process.

Another challenge to inclusiveness of smallholders concerns the heterogeneity of smallholders and their lack of structures or organization. It took GPSNR almost a year to agree on a definition for smallholders and how to structure their representation in GPSNR (GPSNR, 2019c). The struggle to define equitable representation of millions of smallholders from different countries and contexts was likely one of the factors that hindered GPSNR from including smallholders from the very beginning of the multi-stakeholder process. As the range of opinions found in GPSNR's interviews of 12 smallholders from five countries showed, regional and cultural contexts influence smallholders' views of what is needed for sustainable rubber production (GPSNR, 2020b) (see 4.6.2.3 Smallholder recruitment (March – December 2019)). While GPSNR had registered 67 smallholder members from nine rubber producer countries by the end of 2021 (Table 3), there were still many countries without smallholder representation (Table S1). Moreover, there are minority groups whose voices may not yet be represented in GPSNR such as landless tappers, female farmers, and indigenous and ethnic minorities.

Enabling all smallholders be a substantive part of the conversation cannot be achieved easily and takes time. GPSNR's strategies towards realising greater and more equitable participation by smallholders should include moving smallholder members towards self-mobilisation or self-organisation such that they can advocate for their own interests without assistance from the GPSNR Secretariat or other stakeholder members. Self-mobilisation can be considered the most active and autonomous form of participation (Adeyeye, Hagerman and Pelai, 2019). As Bendell (2005) has found, it is not uncommon for agendas in MSIs to be based on demands from international NGOs, large companies' opinions of what is practical to implement, and the recommendations of consultants and accountants. Bendell (2005) argues that stakeholders organising themselves is key to an equitable system of governance of multi-stakeholder organisations or activities. Nelson and Tallontire (2014) further posit that transformation of value chains requires the promotion of smallholder agency and smallholders' self-organisation to promote their own interests. Thus, smallholders can only be considered equal partners and co-owners in GPSNR if they can organise themselves sufficiently at national and global levels, and if they are able to substantially influence GPSNR's priorities and have an equal hand in setting agendas.

4.6.3.5 Degree to which inclusiveness in GPSNR contributes to distributional equity

One open question is the extent to which inclusiveness in GPSNR contributes to equitable outcomes for smallholders (i.e. distributional equity as in McDermott, Mahanty and Schreckenberg (2013)). In a case study of Forest Stewardship Council certification in Brazil, local stakeholders requested distributive benefits that were not covered by the certification's scope (Pinto and McDermott, 2013). To address the mismatch in stakeholder expectations, Pinto and McDermott (2013) suggested setting clear goals that relate to local stakeholders' requests for distributional equity.

In GPSNR's case, the most direct route to distributional benefits would appear to be fair pricing and living incomes for smallholders. It remains to be seen the extent to which GPSNR's Shared Responsibility Framework and Sustainability Reporting Requirements can bring about equitable outcomes for smallholders in the rubber value chain. GPSNR Capacity Building programmes do aim to reach smallholders who are not members of GPSNR, thus extending the scope of those who benefit from these activities (GPSNR, 2021j). GPSNR has also put out a tender for a consultant to evaluate options for developing a digital 'Knowledge Sharing Platform' (GPSNR, 2021k). This digital platform is envisioned to facilitate smallholder access to Good Agricultural Practices, live market information (e.g. natural rubber prices, supply and demand trends), and global financial market information (GPSNR, 2021k). To ensure progress towards its equity goals, GPSNR should consider evaluating the different dimensions of equity targeted and affected by their various capacity buildings initiatives.

Wider questions of GPSNR's impact remain to be assessed in further research, such as whether dialogues in the rubber industry have indeed reduced its socio-environmental damage. There are abiding negative civil-society reports about serious social and environmental transgressions due to rubber industry actors including one linked to a GPSNR-affiliated tyre-maker (Wijeratna, 2020; Mighty Earth, 2021a; Global Witness, 2022). Ecological concerns appeared to be only a minor concern among smallholders (GPSNR, 2020b) (see 4.6.2.3 Smallholder recruitment (March – December 2019)). The limitations of GPSNR are tied to the limitations of private sustainability initiatives more generally, as they are voluntary commitments with no legal repercussions (Cheyns and Riisgaard, 2014; Lambin *et al.*, 2018). While MSIs have been developed in response to government failures to address agro-commodity sustainability issues (Cheyns and Riisgaard, 2014; Lambin *et al.*, 2018), governments still play essential roles in creating and enforcing social and environmental regulations, as well as providing support systems for smallholders (Fox and Castella, 2013; Lambin *et al.*, 2018). One of the Indonesian smallholders interviewed by GPSNR mentioned how the lack of local and central government involvement was a key challenge to sustainable rubber production (GPSNR, 2020m). Further research could study how GPSNR's activities might complement (or possibly detract from) the inclusiveness and/or effectiveness of government policies, in order to create more widespread and long term impacts (Lambin *et al.*, 2014).

4.6.4 Limitations of this study

This study is limited by the availability of public data sources and the sole use of document analysis. For one, while GPSNR's reporting of the General Assemblies and regular working group updates on its website provide important information to assess inclusiveness, some important data are obscured or not provided at all. For example, the membership page does not clearly state the stakeholder categories and country of origin of GPSNR companies and organisations (GPSNR, 2022d). In particular, there is hardly any information about GPSNR's smallholder members on the membership page, even basic information such as the number of smallholders from each country. Including more information would allow GPSNR to demonstrate the extent of smallholder inclusion and participation in various processes, for example: the number of smallholder members who actually attended and voted in General Assemblies, the number of smallholders and countries represented in various working groups, the members responsible for chairing working groups, and the profile of smallholders running for Executive Committee. To increase transparency and enable greater public scrutiny of inclusiveness in its processes, GPSNR should consider making meeting minutes publicly available, as have been done by the RSPO, RTRS and other MSIs (Schleifer, Fiorini and Fransen, 2019; RSPO, 2023a). In addition, GPSNR should also provide a clear list of members and their countries of origin, such that grievances and assessments of inclusiveness can be more easily made by stakeholders inside and outside of GPSNR. As transparency is one of GPSNR's founding principles (GPSNR, 2018a), this move would allow GPSNR to come closer to achieving its mission and vision, as well as achieve greater legitimacy (Mena and Palazzo, 2012; Schleifer, 2019; Schönherr, 2022; Schouten, Toonen and Leeuwerik, 2022).

In addition, while care has been taken to obtain data from alternative sources where available, the majority of documents analysed were produced by GPSNR. Thus, the data may reflect self-reporting bias. For instance, there was a noticeable lack of GPSNR documents showcasing smallholders' perspectives or voices (Table S2). While NGOs have produced their own texts, there were no texts published independently by smallholders. Even though smallholders' made their own speeches, their answers could have been influenced by what was covered during the workshop, or by the way the questions were posed (GPSNR, 2020b, 2021h). It is unclear how much influence smallholders had on the video creation process or the final product, or if the editing process may have excluded any important points that smallholders could have made. Thus, this study has attempted to obtain smallholder perspectives from additional (but still limited) sources (e.g. CIFOR and CIRAD (2019), Feng (2020)) – this is a commonly used method of reducing bias referred to as triangulation (Mikkelsen, 2005; Maxwell, 2012).

While the chronological narrative does its best to provide contextual detail, the case study would benefit from the richness of other qualitative research methods such as participation observation and stakeholder interviews. Participant observation and interviews would be useful to directly analyse the actual 'voices' of various stakeholders and provide deeper insights into the quality of smallholder participation in GPSNR. That said, these methods are subject to participant reactivity and researcher bias and should be combined with document analysis in triangulation (Mikkelsen, 2005; Maxwell, 2012). In any case, case studies of MSIs based on document analysis can and do still provide useful insights on inclusiveness and other aspects of equity (McDermott, 2013; Pinto and McDermott, 2013; Ituarte-Lima, McDermott and Mulyani, 2014).

There are several aspects of inclusiveness that have not been covered by this study. For one, this study is lacking the perspective of inclusiveness in relation to other marginalised stakeholder groups, such as landless tappers or hired labourers, female farmers, and indigenous or ethnic minorities. There may also be deeper, unacknowledged historical and political tensions between smallholders and other stakeholders (Eriksen *et al.*, 2021); for example, in Indonesia there had been a history of oppression (and sometimes violent) conflicts between smallholders and government agencies, rubber companies, and local breeders (Utama, 2021). In addition, this study has not looked at the inclusiveness of standards monitoring and grievance mechanisms in GPSNR, which is important for ensuring equitable access to justice processes (Afrizal *et al.*, 2022), increasing legitimacy (Schouten, Toonen and Leeuwerik, 2022), and enabling effective public scrutiny (Schleifer, 2019). Fransen and Kolk (2007) found that few MSIs included stakeholders in monitoring of standards implementation in MSIs, perhaps due to the reluctance of companies to be transparent about their business practices. To counter this, Fransen and Kolk (2007) proposed more inclusive alternatives to the typical practice of auditing by professional firms, such as participatory social audits (Hausmann-Muela, 2011). Participatory monitoring and equitable grievance mechanisms thus provide promising avenues for further research into improving inclusiveness in GPSNR and other MSIs.

4.7 Conclusion

While MSIs are developed with great expectations as industry's new governance mechanism to address sustainability challenges, little is known about the ability of MSIs to be truly inclusive and participatory (Cheyns and Riisgaard, 2014). This analysis of inclusiveness towards smallholders by GPSNR, one of the most recent MSIs in the rubber industry, is important because of the paucity of academic research on rubber sustainability initiatives and particularly smallholder inclusiveness within them. By examining changes over time in key components of inclusiveness (Fransen and Kolk, 2007; Schouten, Leroy and Glasbergen, 2012; Schönherr, 2022; Schouten, Toonen and Leeuwerik, 2022), I showed how GPSNR has evolved to become more inclusive in membership, geographical representation, governance of decision-making, and has seen smallholder participation grow over time. Through an in-depth empirical description based on document analysis, I found that GPSNR adjusted their membership and governance structures in response to negotiations with CSOs and made efforts to recruit smallholders from rubber producer countries. In turn, when smallholders were included as members with equal decision-making rights as industry stakeholders, their participation in GPSNR grew and they were able to influence discussions in GPSNR to some extent. That said, challenges still remain for the full inclusion of smallholders' interests and full participation of smallholders. In particular, pricing is a key concern for smallholders, but an issue with which industry stakeholders are hesitant to engage. Constraints imposed by anti-trust laws, which are intended to promote fair competition among businesses but ironically perpetuate the marginalization of smallholders, will need to be carefully examined through the lens of equity. By working towards greater co-ownership with smallholders through higher quality of participation and equal partnership, GPSNR can truly begin to realise its vision of a 'fair, equitable and environmentally sound natural rubber value chain' (GPSNR, 2018a, p. 3).

4.8 Supplementary information

Table S1. Natural rubber production in tonnes and percentage of total production in 2020, by country, sorted from highest to lowest production. Data from FAO (2022).

Country	Production (tonnes)	% Total
Thailand	4703171.00	33.57
Indonesia	3037348.00	21.68
Vietnam	1226096.16	8.75
Côte d'Ivoire	936061.00	6.68
China	687600.00	4.91
India	687600.00	4.91
Malaysia	514702.00	3.67
Philippines	422407.10	3.02
Cambodia	358700.00	2.56
Myanmar	274265.00	1.96
Brazil	225622.00	1.61
Laos	201600.00	1.44
Nigeria	149540.21	1.07
Guatemala	108700.00	0.78
Mexico	92710.52	0.66
Liberia	86500.00	0.62
Sri Lanka	78204.00	0.56
Ghana	50400.00	0.36
Cameroon	47100.00	0.34
Gabon	23700.00	0.17
Bangladesh	21900.00	0.16
Ecuador	19300.06	0.14
Democratic Republic of the Congo	15214.00	0.11
Guinea	14878.32	0.11
Colombia	13400.00	0.1
Papua New Guinea	5500.00	0.04
Bolivia	3700.00	0.03
Congo	2317.66	0.02
Central African Republic	1207.79	0.01
Brunei Darussalam	263.17	0
Dominican Republic	63.16	0
Total	14009771.15	100

Table S2. Data sources for document (content) analysis, categorised by type of document, number of documents, and reason for selection. Not all documents collected and read were used in the final version of this chapter.

Source	Type of document	Number of documents	Reason for document selection
GPSNR	News (from October 2018 through February 2022, with a few later articles sourced as relevant to later analysis)	86	For constructing the chronological narrative; for analysing GPSNR perspectives of inclusiveness, activities, and priority issues; for analysing stakeholder inclusion and participation over time
	Organisational documents	44	For constructing the chronological narrative; for analysing membership and governance structure
	Webpages	16	For constructing the chronological narrative; for analysing membership and governance structure; for analysing GPSNR perspectives of inclusiveness, activities, and priority issues
	Tenders for consultant studies	18	For constructing the chronological narrative; for analysing GPSNR activities and priority issues
	Consultant reports	8	For constructing the chronological narrative; for analysing GPSNR priority issues
	YouTube videos (English subtitles were provided for interviews conducted in other languages)	11 smallholder interviews, one communications video featuring three smallholders	For constructing the chronological narrative; for understanding smallholders' perspectives
World Business Council for Sustainable Development	News and webpages	15	For constructing the chronological narrative; for background information on Tire Industry Project (the founders of GPSNR)
Companies in GPSNR	News, webpages, sustainability policies	31	For constructing the chronological narrative; for examining industry perspectives
NGOs in GPSNR	News and reports from various NGOs (Mighty Earth, World Wide Fund for Nature (WWF), BirdLife International, Zoological Society of London (ZSL), Programme for the Endorsement of Forest Certification (PEFC), Global Witness)	60	For constructing the chronological narrative; for analysing NGOs' perspectives

Source	Type of document	Number of documents	Reason for document selection
Other rubber sustainability initiatives	News, webpages, standards from other rubber sustainability initiatives	24	For constructing the initial chronological narrative (this information was later moved to 4.4 Research context: Rubber and rubber sustainability initiatives after refining research questions); for examining non-GPSNR perspectives
Other	Other news sources (The Guardian, EU Monitor, Tyrepress, Rubber News, European Rubber Journal, Mongabay, Supply Management Magazine, Eco Business, Business Unusual, Tire Technology International, LinkedIn, World Rubber Summit, Partnerships for Forests)	21	For constructing and corroborating the chronological narrative; for examining non-GPSNR perspectives
	YouTube videos	Two interviews with GPSNR Secretariat on agroforestry	For constructing the chronological narrative; for analysing GPSNR perspectives of inclusiveness, activities and priority issues

4.9 References

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5 Discussion

This thesis sets out to explore how to address the ecological, economic, and social dimensions of sustainable agriculture, using rubber as a case study. Although I focus on rubber, a highly important tropical commodity crop, my findings apply to varying degrees to other commodity crops and natural resource extractive industries that similarly result in tropical deforestation. In Chapters 2-4, utilising quantitative and qualitative methods and multiple disciplinary lenses spanning ecology, geography, economics, management, and political sciences, I discussed the insights that were obtained with each disciplinary approach. In this chapter, I will bring together the broad empirical and conceptual insights from the three interrelated but independent data chapters in relation to general themes and the wider literature, as well as in relation to each other. I argue that the ability to use various approaches from different disciplines to analyse complex issues such as commodity value chain sustainability will greatly enrich insights from individual studies, better avoid pitfalls, and accelerate progress towards genuine sustainability. Limitations and suggestions for future avenues of research, as well as lessons for other crops or sustainability initiatives are weaved throughout.

A common theme among my thesis chapters, and as observed by many others in various fields, are the inherent tensions and trade-offs between the three dimensions of sustainability (see reviews of trade-offs in corporate sustainability, protected areas, and agricultural sustainability, e.g. Van der Byl and Slawinski (2015); Oldekop *et al.* (2016); Kanter *et al.* (2018)). Trade-offs apply as well to my methodological choices across this thesis. I recognise that my choice to explore a breadth of methodologies and topics was at the cost of depth and focus, which is a departure from the traditional approach for doctoral studies. However, what this thesis lacks in depth, I believe, is compensated by the multidisciplinary angles I have brought in to obtain new insights for an under-researched crop, through adapting existing methodologies and frameworks. The challenge for future research will be to identify the most impactful research questions, and design rigorous studies not just for academic impact, but with wider, real and practical socio-ecological impacts in mind (Pullin *et al.*, 2013; Burke *et al.*, 2021).

5.1 Seeing linkages between ecological, economic, and social sustainability

The rubber case study provides a rich ecosystem to study complex linkages between economic, ecological, and social dimensions of commodity crop sustainability. Demand for oil palm is competing with rubber for land in the humid tropical lowlands as oil palm is perceived to be more lucrative than rubber, especially considering the higher labour requirements for rubber (Fox and Castella, 2013; Warren-Thomas, Dolman and Edwards, 2015). Due to the lower profitability of rubber, rubber plantations in traditional production areas, such as Malaysia and Indonesia, and jungle rubber systems representing the last vestiges of tropical forest in Indonesia (Ekadinata and Vincent, 2011) are being converted to oil palm (Jayathilake *et al.*, 2023). The conversion of rubber to oil palm is resulting in yet further demand for new land for rubber expansion in non-traditional, marginal environments, further north and upland. In Southwest China and mainland Southeast Asia, rubber plantations have been established in areas that were marginal for rubber productivity, such as higher elevation slopes and frost-prone areas (Ahrends *et al.*, 2015; Chen *et al.*, 2016). Yet, these marginal areas were important for biodiversity as they included nature reserves and protected areas, leading to a lose-lose situation for economic and ecological sustainability (Ahrends *et al.*, 2015; Chen *et al.*, 2016). Low rubber prices and income insecurity, along with challenges around securing labour, are also driving smallholders and estates in both traditional and non-traditional production areas to abandon rubber for other crops or other jobs, thus threatening the security of the rubber supply for the manufacturers of rubber products (Meyer, 2019). These observations provide a dynamic background for studying the linkages between economic, ecological, and social equity priorities in the context of rubber expansion (Chapter 2; Chapter 3) and stakeholder interactions in the context of a multi-stakeholder sustainability initiative for the rubber industry.

I considered 'economic interests' broadly to be factors that contribute to greater profits in the short/medium term, and meeting market demand for rubber and rubber products. In Chapter 2, I found that prioritising economic interests would lead to the most suitable lands being converted for rubber, but with the greatest losses for biodiversity. My analysis found no areas for rubber expansion that produced synergistic outcomes for both production and conservation goals, but compromising moderately on production could substantially reduce impacts on the most threatened species (Chapter 2). It opens up questions of how much compromise on either economic or conservation priorities can be acceptable to different parties with stakes in the issue of rubber expansion. In Chapter 3, I found that agricultural rents were important for explaining rubber expansion into forests, but not always in a predictable way. This finding suggests that other forms of less obvious economic interests, such as profits from timber harvest and granting of land concessions to foreign investors, can also create incentives for deforestation. Protected areas may have created legal and/or economic disincentives for deforestation compared to unprotected areas, but was insufficient to prevent conversion in areas most suitable for growing rubber and most easily accessible (Chapter 3). Given that deforestation tends to be more profitable in the short term than forest protection (Barbier, Burgess and Markandya, 1991; Andersen *et al.*, 2002), a stronger strategy for sustainable rubber is needed.

Considering conservation goals alone, without considering the economic trade-offs and implications, could also lead to political unfeasibility and undesirable outcomes for both. In Chapter 2, I found that prioritising ecological sustainability in rubber expansion (measured as minimising extinction threat to species and maximising aboveground carbon stocks) would lead to the most unsuitable lands being converted first. A recommendation to plant rubber on the most unsuitable lands in order to minimise biodiversity losses would likely be an unacceptable proposal for rubber growers, as growing rubber on unsuitable lands would lead to lower yields overall or crop losses from weather damage (Ahrends *et al.*, 2015). Lower yields would also have knock-on effects on social sustainability due to lower income insecurity, as well as ecological sustainability due to greater land area needed to meet yield targets (Balmford, Green and Scharlemann, 2005). Nevertheless, less suitable lands did end up being converted when the profits are expected to compensate for losses, especially at high rubber prices (Ahrends *et al.*, 2015), leading to suboptimal outcomes for both biodiversity and production goals.

Applying an equity lens to my first two chapters, which have focused more on ecological and economic dimensions, would invite the questions, ‘Whose interests are being considered?’ and ‘To whom do the benefits and costs (both ecological and economic) accrue?’ In Chapter 2, I identified ‘areas of compromise’ in New Guinea (West Papua in Indonesia and Papua New Guinea) and the country of Guinea in Africa, areas with relatively large tracts of unexploited land where rubber production could increase with relatively little loss to biodiversity. These, and most tropical producer countries, are considered low and low-middle income countries (World Bank Group, 2022), so it would appear that expanding rubber into those geographies would bring economic benefits to the development of those countries at relatively lower ecological costs. Yet, it is unclear how much local communities would actually benefit from agricultural expansion, or how much say they have in decisions regarding their land use and livelihoods choices (Vermeulen and Cotula, 2010). Applying an equity lens would encourage governmental decision-makers responsible for land-use policies to consider the socio-political implications of allowing or forbidding development of forests, and to consciously decide what kind of development is acceptable, ideally including local communities in decision-making and not merely on their behalf (Agrawal *et al.*, 2018). This is also applicable to Chapter 3, where one could ask, who profits (and loses) from rubber expansion in different areas? In Chapter 3, I touch upon some possible answers to this, such as the case of large-scale forest conversions to rubber plantations in Cambodia, where political elites and foreign investors likely profited the most at the expense of local communities (Byerlee, 2014; Oldenburg and Neef, 2014). Another equity angle for Chapter 3 is the issue of wage labour, which was included in my calculations of agricultural land rents. Higher wages mean lower net profits for the employer (who could be a large estate or land-owning smallholder), highlighting local inequalities between landowners and non-land owning wage labourers. Labour inequalities are not only a social concern, but an economic concern as insecure labour threatens rubber supply (Langenberger *et al.*, 2017; Hurni and Fox, 2018). Until a practical means of automation is secured (not without its own socioeconomic implications), a person has to do the menial job of tapping and collecting latex to keep the wheels of the rubber economy turning. Taking an equity-focused approach to sustainability, we have a collective social responsibility to ensure that rubber workers' rights are included in sustainability efforts, and this is what GPSNR members appear to commit to as well (GPSNR, 2018).

Considering the interface between ecological sustainability and equity, there are also synergies and trade-offs between inclusiveness and conservation effectiveness (Law *et al.*, 2018; Grabs *et al.*, 2021). In terms of synergies, the greater the participation of relevant stakeholders (both large-scale producers and smallholders) in voluntary sustainability initiatives, the more likely it is that they will accept and adopt the environmental requirements (Garrett *et al.*, 2018; Grabs *et al.*, 2021; Schouten, Toonen and Leeuwerik, 2022). Greater inclusiveness can also increase the range of issues of concern to be discussed and mutual accountability among stakeholders, thus encouraging greater acceptance and compliance to these voluntary standards (Fransen and Kolk, 2007; Mena and Palazzo, 2012).

On the other hand, interventions to increase equity, such as better access to markets and financing options for smallholders, may result in greater agricultural expansion at the expense of tropical forests (Carr *et al.*, 2021). Moreover, in the context of voluntary sustainability initiatives, practising inclusiveness often leads to a trade-off with efficiency (Vallejo and Hauselmann, 2004; Henry, Rasche and Möllering, 2022). Efficiency refers to the ability of sustainability initiatives' ability to deliver its objectives well (i.e. effectiveness) and speedily (Vallejo and Hauselmann, 2004). As collaboration, trust-building, and negotiation between stakeholders involved in the initiative take time and energy resources, striving for inclusiveness may conflict with the efficiency needs of businesses and overburden under-resourced stakeholders like smaller NGOs and smallholders (Henry, Rasche and Möllering, 2022). To counter the inefficiencies of being inclusive, sustainability initiatives may thus aim for less stringent environmental standards to allow greater numbers of smallholder producers to be included, or to target already close-to-compliant smallholders, which limits the additionality of environmental outcomes (Dietz and Grabs, 2022).

In Chapter 4, greater inclusion and participation of smallholders in GPSNR seemed to have led to greater coverage of issues, such as the adoption of agroforestry as a capacity-building funding priority for GPSNR. Smallholders in GPSNR were generally more concerned about socio-economic issues like pricing of rubber, compared to ecological sustainability (GPSNR, 2020) (Chapter 4). As such, my research suggests that achieving social inclusiveness in a rubber sustainability initiative may trade-off with ecological sustainability. Greater effort will need to be made to seek strategies that align conservation goals with smallholders' concerns in research, policy, and private sustainability initiatives on rubber and other forest-risk commodities in order to achieve aforementioned synergies between conservation effectiveness and equity.[10]

Lessons can be learned from the wider literature, such as the literature on payments for ecosystem services schemes, which attempt to reconcile local communities' socioeconomic interests with conservation interests. While conservation interventions may sometimes lead to costs for local communities such as foregone agricultural income and wildlife damage (Green *et al.*, 2018), such schemes can have 'win-win' outcomes if designed well for the specific context (Ola *et al.*, 2019). To increase the likelihood of successful and synergistic outcomes in payments for ecosystem services schemes, Ola *et al.* (2019) recommended monitoring the ecological outcomes of interventions, providing sufficient compensation, having prior engagement with local communities, and tailoring the scheme for local contexts. In Chapter 4, I found that GPSNR did improve representation of smallholders and rubber-producer countries in membership and governance of decision-making over time. However, these improvements in procedural equity are only the first step towards greater smallholder

[10] I remain regretful that I did not manage to carry out my proposed fieldwork in rubber smallholding communities, which would have formed an additional chapter, contributing new empirical data at the local-scale.

participation in co-producing synergistic solutions for ecological and equity dimensions of sustainability in rubber production. While my study did not focus on the conservation-equity synergies and trade-offs in GPSNR, it would be useful for GPSNR to monitor and evaluate its practices with, for instance, the design principles suggested by Grabs *et al.* (2021) for optimising environmental effectiveness and access equity in supply chain policies. In addition, Law *et al.* (2018) provide a set of recommendations for integrating ethics into conservation decisions that make explicit the trade-offs between equity and conservation objectives.

A perspective that sees long-term economic sustainability as synergistic with ecological and social sustainability, while not a new idea, is becoming increasingly apparent to many businesses and in the international policy arena (Savitz, 2013; IPCC, 2022). The IPCC warns that global aggregate net economic damages are projected to increase non-linearly with global warming, with equity considerations as developing countries are likely to experience higher economic damage per capita (IPCC, 2022). As ecosystem services valuation studies have demonstrated, forest ecosystems provide tremendous economic and social values to the public and are difficult to substitute or replace (de Groot *et al.*, 2012; Costanza *et al.*, 2014). Thus, it stands that promoting ecological conservation in equitable ways is crucial for promoting long-term prosperity and well-being of all (UN, 2008). Yet, even as GPSNR companies commit to ecosystem protection as one of GPSNR's core principles (GPSNR, 2018) (Chapter 4), reports of deforestation linked to GPSNR tyre-makers and non-GPSNR companies have continued to surface (Wijeratna, 2020) (Chapter 4). GPSNR tyre-makers have also lobbied for excluding rubber from the European Commission's forest-risk commodities due diligence requirements (Mighty Earth, 2021) (Chapter 4). Apart from the seeming lack of real commitment to ecosystem protection, there were tensions between smallholders' desire to discuss the equity of pricing and businesses' tendency to brush off this issue as something beyond their control (Chapter 4). It is hoped that the implementation of sustainability reporting and grievance mechanisms by GPSNR, as well as continued participation of civil society and smallholders in GPSNR's processes, will further increase the strength of the ecological and social sustainability interests as compared to short-term economic interests. Studies to assess the tangible impacts of GPSNR and producing recommendations for improving multi-stakeholder processes will be of practical value to GPSNR and for other crop sustainability initiatives.

A major limitation of this thesis was the lack of spatial data that differentiates smallholder versus estate rubber areas, making it difficult to attribute their respective impacts, and thus make potentially more equitable and targeted recommendations. The Land Matrix dataset used in Chapter 2 is one step towards documenting large scale land acquisitions for rubber, but the data is not granular (The Land Matrix, 2018). There are ongoing efforts in other fields that address this data gap empirically (e.g. oil palm in Indonesia (Lee *et al.*, 2014), slash-and-burn smallholder agriculture in the Amazon (Socolar, Valderrama Sandoval and Wilcove, 2019)). Traceability and transparency efforts by GPSNR could become an important source of data, but stakeholders must decide whether commercial interests overrule public interests in data sharing and access.

5.2 Managing trade-offs and optimising synergies: Challenges and opportunities in increasing sustainability of rubber production

Considering the complex trade-offs between economic, ecological, and equity goals, how can increased sustainability be achieved in the rubber industry? This section discusses some strategies that optimise for synergies between ecological, economic, and social sustainability of rubber production that have been mentioned and discussed in earlier chapters.

One of the more salient strategies is to increase yields on existing land (Chapter 2; Chapter 3) through development of high-yielding drought/cold-tolerant clones (Chapter 2) and through capacity-building for smallholders by increasing smallholder access to high-yielding clones and good agricultural practices (GPSNR, 2022) (Chapter 4). This, in theory, presents a ‘win-win-win’ situation by increasing productivity (economic), smallholder capacities (social), and spare tropical forests from further expansion (ecological). Other studies also suggest that investment into agricultural research and development may be one of the best ways to improve productivity, increase resilience to climate change, and reduce pressure on forests (Lobell, Baldos and Hertel, 2013; Byerlee, Stevenson and Villoria, 2014). However, as the ongoing debate on land-sparing approaches has noted, increased productivity does not necessarily reduce economic incentives of deforestation and cheaper production may perversely lead to increased supply and/or demand (Lim *et al.*, 2017) as well as increased costs for conservation (Phelps *et al.*, 2013). Thus, Byerlee, Stevenson and Villoria (2014) suggested that intensification strategies should be accompanied with strong land and forest protection policies such as regulations on forest clearing and land use zoning, increased uptake of private sustainability standards where regulations are lacking, and possibly payments for ecosystem services to provide incentives for forest preservation. Liao and Brown (2018) stressed the need to include smallholder wellbeing as an explicit goal of sustainable intensification, to attain synergies between equity, economic, and conservation goals.

The other strategy to optimise synergies that also came up in multiple chapters is agroforestry. Rubber-based agroforestry covers a broad range of practices or systems, ranging from low-yielding jungle rubber in Indonesia to simple short-term intercropping with annuals during the rubber immature phase (Langenberger *et al.*, 2017; Wang, Warren-Thomas and Wanger, 2020). Agroforestry and agroecological practices merit attention for their greater potential to increase environmental values on existing croplands and address equity issues as compared to conventional monocultures (Tscharntke *et al.*, 2011; Wilson and Lovell, 2016). As a strategy that rubber smallholders considered important for them (Chapter 4), diversifying income via agroforestry provides greater resilience against economic shocks like sudden rubber price drops (Chapter 3) while maintaining some income security under low rubber prices (Chapter 4). Adopting rubber agroforestry practices can enhance ecosystem functions (such as carbon storage, species diversity, and soil quality) in rubber plantations without reducing latex yields (Wang, Warren-Thomas and Wanger, 2020; Singh *et al.*, 2021), which is of interest to reconciling biodiversity with rubber production goals (Chapter 2). In theory, proponents of agroforestry present a ‘win-win-win’ situation in that it increases total productivity (economic), smallholder capacities (social), and improves the environmental quality of existing plantations (ecological). However, agroforestry researchers have also cautioned that there have been many documented failures with agroforestry crops if not designed well or without considering local biophysical and market contexts, which lead to social and economic downgrading (Langenberger *et al.*, 2017; Wang, Warren-Thomas and Wanger, 2020). Agroforestry has also been used as an excuse for deforestation, especially when agroforestry systems are incorrectly perceived as being of equivalent conservation value to primary forests (Wang, Warren-Thomas and Wanger, 2020).

The above strategies apply only to the production aspects of rubber. Nevertheless, end-of-life cycle or circular economy approaches may also provide synergistic outcomes for economic, ecological, and social sustainability (Araujo-Morera *et al.*, 2021; Formela, 2021). Circular economy approaches (e.g. recycling tyres, re-treading old tyres, and engineering tyres to extend their usable lifetime) aid in sustainability goals by reducing demand for latex and thus the need to expand rubber production, as well as reducing tyre waste and impacts to human health due to inappropriate disposal of tyres (Araujo-Morera *et al.*, 2021; Formela, 2021). The technology for recycling tyres to make new tyres is still nascent (Michelin, 2023). However, if the technology becomes available and cost-efficient, it may become an attractive strategy for tyre-makers as it can potentially reduce their ecological footprint without compromising their economic interests. At the same time, improved technology for end-of-life tyres carries the risk of equity trade-offs, as reduced demand for latex will further depress prices and affect the incomes of rubber smallholders (Gitz *et al.*, 2020). In the case of rubber production becoming a sunset industry due to technological advances, smallholders will need to be supported to transition to alternative crops (e.g. via rubber-based agroforestry) or alternative livelihood strategies (e.g. off-farm employment). Hence, there is a need for a combination of both production-side and end-of-life cycle approaches to effectively address relevant sustainability issues throughout the rubber production cycle.

More generally, to avoid deforestation and negative social impacts from rubber expansion, clearer guidelines or policies that integrate economic, social, and ecological sustainability risks should be given to any party seeking to establish new rubber plantations. Various rubber sustainability initiatives, including GPSNR, have developed voluntary guidelines or standards for the private sector (Chapter 1, Chapter 4). Instrumentally, increased sustainability in the industry could be achieved by increasing the voluntary uptake of robust sustainability criteria (Chapter 1: Table 3), as well as the careful implementation of synergistic strategies discussed above. While this thesis has not conducted a comparative, in-depth analysis of the robustness of different sustainability standards for rubber, I have discussed some key challenges and issues for consideration that should aid further investigation on different standards' abilities to mitigate trade-offs and optimise synergies between the different dimensions of sustainability. Both private and public sector policies should also plan for the dynamic effects of fluctuating commodity prices on land-use changes and prepare pre-emptive strategies to mitigate undesirable outcomes (Lim, 2019), such as the case of accelerated deforestation and financial losses due to the rubber price boom and bust in the 2000s (Chapter 3; Chapter 4).

As mentioned in the preceding paragraph and in the discussion on equity in rubber expansion in 5.1 Seeing linkages between ecological, economic, and social sustainability, the role of governments is a crucial element to manage trade-offs and achieve synergies across all three dimensions of sustainability in tropical agricultural commodity systems (ICSU, 2017; Agrawal *et al.*, 2018; Lambin *et al.*, 2018). Although private voluntary initiatives are often established to fill a gap in government regulations (Fransen and Kolk, 2007), governments are ultimately responsible for national and local land-use policies, agricultural policies, the granting of land concessions and land titles, providing support systems for smallholders and local communities, and enforcing environmental regulations within their jurisdictions (Fox and Castella, 2013; Tayleur *et al.*, 2017; Lambin *et al.*, 2018). Private voluntary initiatives and government efforts can have synergistic knock-on effects on each other; for instance, governments can facilitate monitoring of compliance with sustainability standards, whereas pressure and support from private actors can push governments to strengthen the enforcement of regulations or to broaden the scope of sustainable policies (Lambin *et al.*, 2018). For example, synergistic public policies and private supply chain policies have slowed down deforestation due to cattle ranching and soy expansion in Brazil (Nepstad *et al.*, 2014).

One public policy instrument that has been covered by this thesis (Chapter 3) is protected areas. Protected areas are one of the key international instruments for preventing deforestation, as evidenced by the recently concluded Kunming-Montreal Convention for Biological Diversity (CBD) in December 2022, which included a target to protect 30% of the world's land and ocean areas by 2030 (CBD, 2022). The pros and cons of protected areas have long been debated by NGOs and academics on both sides (e.g. see NRDC (2020) and Agrawal *et al.* (2020) for a recent exchange). Various systematic reviews have also been conducted on the evidence base and trade-offs for protected areas (e.g. Pullin *et al.*, 2013; Oldekop *et al.*, 2016; Ma *et al.*, 2020), all reporting positive and negative impacts of protected areas on conservation and social outcomes. Protected areas can and do have synergistic social and ecological impacts (Ma *et al.*, 2020), especially when designed with a social equity lens (e.g. co-management, empowerment, reducing economic inequalities, protecting cultures and livelihoods) (Oldekop *et al.*, 2016).

In trying to tackle an issue as broad as tropical commodity sustainability, which crosses multiple disciplinary boundaries, the solutions or paths towards achieving rubber sustainability are necessarily broad and require consideration of political feasibility. From a social sciences perspective, the degree to which sustainability solutions are readily accepted by businesses and policymakers (Chapter 4) may be related to how they present an optimistic view of green growth, which allows them to operate 'business-as-usual' to a certain degree (i.e. not having to radically change their practices) (Scrieciu, Rezai and Mechler, 2013). However, strategies to reduce growth (Kallis *et al.*, 2018) and manage supply and demand for sustainability (e.g. 'conservation-based agricultural trade' (Tilman *et al.*, 2017)) have not really come up in GPSNR or other voluntary sustainability initiatives for rubber. Thus, these strategies present a ripe avenue of inquiry by stakeholders and researchers, ideally conducted with truly multi-disciplinary and inclusive perspectives, with potentially far-reaching impacts across commodities.

5.3 Conclusion

In this thesis, I have used a range of methods in an attempt to explore the different and sometimes conflicting dimensions of social, economic, and environmental sustainability. Given the complexity of the problem, I have only been able to scratch the surface of many of the issues raised here. In short, I have shown how short-term economic interests of a few constitute a looming threat to the ecological and social well-being of local communities and the global population. Engaging and listening to stakeholders, especially those closest to the issues at hand, is the most direct way to ensure equitable and effective sustainability solutions.

As our planetary boundaries are being overshot and time is running out for us to prevent the worst impacts of climate change and biodiversity loss (IPBES, 2019; IPCC, 2022), it would be foolish to ignore the many imperatives to halt deforestation, merely to advance short-term economic interests for the already rich few. At the same time, it is no longer enough to blindly push for sustainability solutions without also considering social and equity implications – especially for the most disadvantaged stakeholders. Ultimately, there is no single easy solution to balance sustainability goals, but many partial solutions, all of which require us to think holistically and act in collaboration with one another. My thesis calls for academics from all disciplines, civil society, industry actors, and governments to use our collective expertise and privilege for the benefit of those most at risk of being marginalised by inequitable policies as well as to protect our planet, while recognising the under-tapped creativity and potential of smallholders and local communities to themselves be agents of sustained impact.

5.4 References

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‘This is your life and it's ending one minute at a time.’

~ Tyler Durden, Fight Club

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