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REVIEWS

Increasing Demand for Natural Rubber Necessitates a Robust Sustainability Initiative to Mitigate Impacts on Tropical Biodiversity

Eleanor Warren-Thomas[1], Paul M. Dolman[1], & David P. Edwards[2]

[1] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK
[2] Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK

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Correspondence
Eleanor Warren-Thomas, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK.
Tel: 01603 593175.
E-mail: e.warren-thomas@uea.ac.uk

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Abstract

Strong international demand for natural rubber is driving expansion of industrial-scale and smallholder monoculture plantations, with >2 million ha established during the last decade. Mainland Southeast Asia and Southwest China represent the epicenter of rapid rubber expansion; here we review impacts on forest ecosystems and biodiversity. We estimate that 4.3–8.5 million ha of additional rubber plantations are required to meet projected demand by 2024, threatening significant areas of Asian forest, including many protected areas. Uncertainties concern the potential for yield intensification of existing cultivation to mitigate demand for new rubber area, versus potential displacement of rubber by more profitable oil palm. Our review of available studies indicates that conversion of forests or swidden agriculture to monoculture rubber negatively impacts bird, bat and invertebrate biodiversity. However, rubber agroforests in some areas of Southeast Asia support a subset of forest biodiversity in landscapes that retain little natural forest. Work is urgently needed to: improve understanding of whether land-sparing or land-sharing rubber cultivation will best serve biodiversity conservation, investigate the potential to accommodate biodiversity within existing rubber-dominated landscapes while maintaining yields, and ensure rigorous biodiversity and social standards via the development of a sustainability initiative.

Introduction

Tropical forest loss is increasing (Hansen *et al*. 2013), primarily due to agricultural expansion (Gibbs *et al*. 2010; Foley *et al*. 2011). Continued agricultural expansion and intensification are predicted, driven by rising demand (Laurance *et al*. 2013). Concern over expansion of agro-industrial tree plantations in the tropics, including oil palm (Fitzherbert *et al*. 2008; Koh & Wilcove 2008) and paper-pulp (Wilcove *et al*. 2013), led to a series of sustainability labels developed to reduce negative biodiversity, ecosystem service and social outcomes (Edwards & Laurance 2012; Edwards *et al*. 2012). Here, we focus on another rapidly expanding plantation crop: natural rubber, *Hevea brasiliensis*. There is growing concern that rubber cultivation is negatively impacting livelihoods, soils and ecosystem services (Ziegler *et al*. 2009b; Fox & Castella 2013; Xu *et al*. 2013). Here, we estimate potential future rubber extent, and collate evidence for biodiversity impacts of rubber cultivation from across Southeast Asia, to inform emerging sustainability labeling efforts by the rubber industry and focus further research on this rapidly expanding crop.

The distribution of rubber across Southeast Asia (Figure 1) coincides with four biodiversity hotspots: Sundaland (Malay Peninsula, Borneo, Sumatra, Java, and Bali), Indo-Burma (Laos, Cambodia, Vietnam, most of Myanmar and Thailand, and parts of Southwest China, including Xishuangbanna and Hainan Island), Wallacea (Indonesian islands east of Bali and Borneo but west of New Guinea, plus Timor Leste), and the Philippines (Myers *et al*. 2000), supporting large numbers of endemic

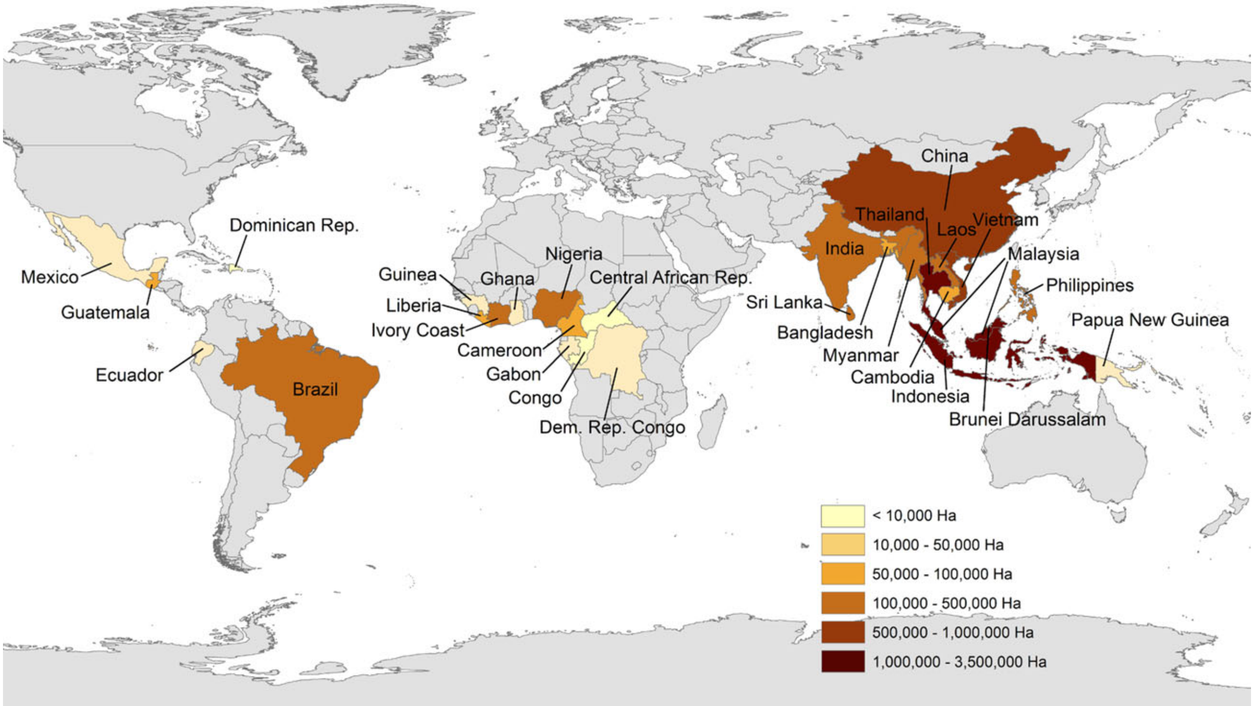

Figure 1 Rubber extent in all rubber producing countries, excluding Bolivia for which data were unavailable. Data sources listed in Table S2.

and highly threatened species (Sodhi *et al.* 2004). Rubber cultivation occurs within multiple biogeographic realms and ecoregions, including subtropical montane rainforests and coniferous forests in Southwest China, moist and dry evergreen and deciduous forests in Indo-Burma, and tropical and subtropical moist lowland forests in Sundaland, Wallacea and the Philippines (Olson *et al.* 2001). Cultivation practices vary from large-industrial or smallholder monocultural plantations, to various methods of rubber agroforestry (Fox & Castella 2013).

Global demand for natural rubber has increased rapidly in the past decade, driven particularly by China's economic emergence (Figure S1; FAO 2013). Natural rubber is preferred for many products, with 70% of global consumption used in tyres (Clay 2004). Rising demand, partly driven by the increased cost of crude oil used for synthetic alternatives, has caused price volatility, peaking in 2011 at US\$6.26 kg^{-1} on the Singapore Commodity Exchange and with a longer-term increase from US\$1.1 kg^{-1} in 2003 to US\$2.8 kg^{-1} in 2013 (Figure 2). By 2012, rubber covered an area equivalent to 71% of oil palm extent within Southeast Asia (including Southwest China) and 57% of oil palm globally (FAO 2013). It is the most rapidly expanding tree crop within mainland Southeast Asia (Cambodia, Laos, Myanmar, Thailand, Vietnam, and Yunnan, Southwest China; Fox *et al.* 2012).

Concern over rubber expansion has been building, initially focusing on rapid planting in Xishuangbanna, since the early 2000s (Guo *et al.* 2002; Fox & Vogler 2005; Ziegler *et al.* 2009b; Xu *et al.* 2013), then widening to mainland Southeast Asia (Li & Fox 2012; Fox & Castella 2013). In montane regions of mainland Southeast Asia (MMSEA; defined as areas >300 m asl), plantations on steep slopes detrimentally affect soil erosion, landslide risk and water quality (Li *et al.* 2007; Ziegler *et al.* 2009a), with ecosystem service provision across 35,000 ha of Xishuangbanna (Menglun township) reduced by an estimated 28% over 18 years following rubber establishment; a loss valued at US\$11.4 million (Hu *et al.* 2008). Conversion of swidden (or shifting) agriculture and forest to rubber can result in substantial carbon emissions (Li *et al.* 2008), although carbon outcomes can be highly variable (Ziegler *et al.* 2012; Yuen *et al.* 2013).

Conversion to rubber can increase evapo-transpiration by 15–18% relative to native vegetation (Tan *et al.* 2011). While native vegetation takes up subsurface water after rainfall, rubber depletes deep-soil moisture during the dry season, with potential to reduce groundwater and streamflow (Guardiola-Claramonte

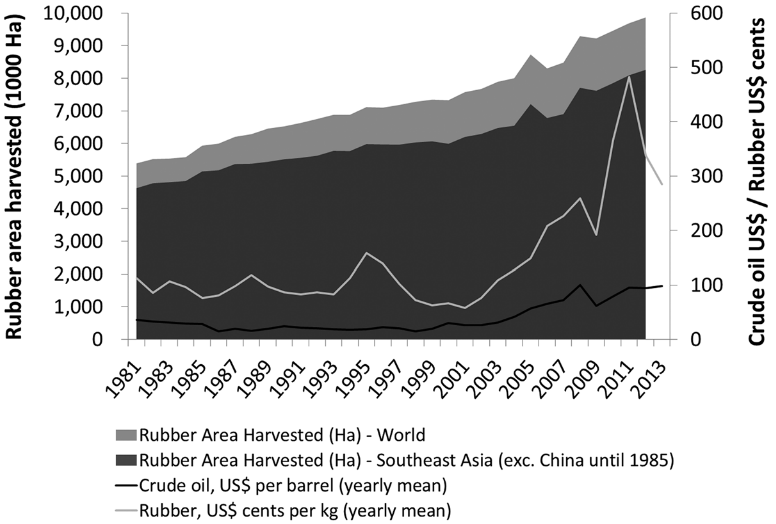

Figure 2 Trends in harvested area of rubber and price of rubber and crude oil, 1981–2013. Rubber area data sourced from FAOSTAT Online Statistical Service (FAO 2013). Data do not include Laos (no data available) and data for China are only included from 1985 onwards. Price data for crude oil in US$ per barrel sourced from IMF Primary Commodity Prices database (IMF 2013) and for natural rubber in US$ per kg from the World Bank Global Economic Monitor Databank on commodities, defined as "Rubber (Asia), RSS3 grade, Singapore Commodity Exchange Ltd (SICOM) nearby contract beginning 2004; during 2000 to 2003, Singapore RSS1; previously Malaysia RSS1" (The World Bank 2013).

et al. 2008; Kobayashi *et al*. 2014). These impacts may be compounded by reduced fog interception relative to complex natural canopies, which provides a major dry season water input in Xishuangbanna (Xu *et al*. 2013). Basin-scale modeling showed conversion to rubber could reduce annual water discharge by 29% (Guardiola-Claramonte *et al*. 2010) and, although unproven, low stream flow and well desiccation have been attributed to rubber plantations in Xishuangbanna (Qiu 2009).

Although establishment of rubber plantations has substantially increased smallholder income in Southwest China and Northern Thailand (Liu *et al*. 2006; Fox *et al*. 2013) there are concerns that replacing swidden agriculture with industrial-scale rubber plantations in mainland Southeast Asia could disadvantage rural communities (Baird 2010; Ziegler *et al*. 2011; Fox & Castella 2013). Reports of evictions, coercion, increased poverty, decreased food security and poor labor conditions associated with rubber plantations have recently emerged from Laos, Cambodia and Myanmar (OHCHR 2007; Baird 2010; Woods 2011; Global Witness 2013). Despite concern over possible biodiversity declines following conversion to rubber (e.g., Ziegler *et al*. 2009b), emerging evidence of biodiversity impacts has not been collated and synthesized previously, despite a rubber extent comparable to that of oil palm.

In this article, we summarize the history of rubber expansion and land-use change, contrasting the contexts across Southeast Asia, particularly between insular (Sabah, Sarawak, and Indonesia) and mainland areas. We project the likely scale of expansion required for expected future rubber demand, and quantitatively review evidence on the responses of biodiversity to rubber cultivation in differing bio-geographic contexts. We finish by highlighting research needed to help meet demand at minimum environmental cost, and to build a robust rubber sustainability initiative.

Land use change for rubber cultivation—a brief history

Southeast Asia (including parts of Southwest China) is the epicenter of rubber cultivation, containing 84% of total global area in 2012 (Figure 1, Table S1). Rubber was first planted in state-run plantations in Malaysia, Indonesia, and southern areas of Thailand, Vietnam, Cambodia and Myanmar, and subsequently adopted into smallholder agroforestry systems 10° either side of the equator (Clay 2004). "Traditional" rubber varieties required ≈2000 sunshine hours year^{-1}, mean annual temperatures of 28 ± 2°C, and annual rainfall of 2000–4000 mm (Priyadarshan *et al*. 2005). From the 1950s, development of high-yielding clonal varieties in China, which tolerate long dry seasons, less sunshine and temperatures as low as −1°C (Priyadarshan *et al*. 2005), facilitated a wave of rubber monoculture expansion to 22°N (Clay 2004; Li & Fox 2012) and to higher altitudes (Nguyen 2013; >900 m asl, returns are minimal or nonexistent, Yi *et al*. 2013). Expansion was compounded by replacement of rubber with oil palm across Malaysia and Indonesia (Gunarso *et al*. 2013), coupled with the ability of rubber to grow on a wide range of soil types (Priyadarshan *et al*. 2005; Usha Nair *et al*. 2010; Priyadarshan 2011; Li *et al*. 2012), including low-fertility areas unsuitable for more profitable crops such as cacao, coffee, or oil palm.

Subsequent expansion has been rapid: globally, land area under rubber has grown 1.8-fold over the past three decades, from 5.5 to 9.9 million ha from 1983 to 2012

(Figure 2). The mean expansion rate of 107,608 (±21,269 SE) ha year^{-1} in harvested area during the first two decades more than doubled to 219,188 (±111,440 SE) ha year^{-1} in the last decade (Figure 2). Official data on rubber area at the national level (FAO 2013) can be unreliable (Table S1) resulting in attempts to directly assess rubber area using remote sensing. In mainland Southeast Asia, 2.1 million ha of rubber has been detected, with around 550,000 ha established within four years preceding Li and Fox's study (2012). In Bungo District, Jambi, and Indonesia, where primary forests are almost nonexistent, analysis of land-use change showed a net increase in rubber despite expansion of oil palm onto former rubber plantations (Feintrenie & Levang 2009; Ekadinata & Vincent 2011). In contrast, rubber area in Peninsula Malaysia declined with conversion to oil palm (Abdullah & Hezri 2008).

Smallholders tend 85–93% of the rubber area in Thailand and Malaysia (in plantations, Figure 3a), and in Indonesia (in agroforests, Figure 3b), but elsewhere in mainland Southeast Asia, agribusiness dominates production (50–77%; Fox & Castella 2013) with heavy investment in monocultural plantations (Li & Fox 2012). Rubber is also cultivated in the Philippines, mostly on the island of Mindanao (BAS 2013), and commonly in monocultures, with a small amount of agroforestry (Mercado *et al.* 2010).

Growing demand and future expansion

Demand for natural rubber is strong: global consumption in 2010 was 10,700,000 t, centered on the Asia-Pacific region (70%; IRSG 2013). Predictions suggest strong near-term demand, underpinned by growth in global rubber consumption (3.5% per annum) and the tyre market (5.3% per annum; Pakiam 2013). Li and Fox (2012) report data from a 2009 study by the International Rubber Study Group (IRSG) predicting annual consumption of 13,000,000 t by 2018, an increase of 3,100,000 t from 2010. More recently, IRSG estimated annual consumption of 17,000,000 t by 2023 (Rubberworld 2014), or 19,100,000 t by 2025 (Rusmana 2013); the mean (18,050,000 t by 2024) represents an increase of 7,350,000 t (≈40%) from 2010. The governments of Laos (Baird 2010), Cambodia (Vannarin & Lewis 2013), Malaysia (ETP 2013), Myanmar (Woods 2011), and Vietnam (Li & Fox 2012) intend to increase the area under cultivation, while there is also potential to intensify low yielding rubber, chiefly managed by smallholders, across Malaysia and Indonesia (Table S2 and Figure S2).

How much land is required to meet demand by 2018 and 2024?

From these estimates of rubber demand by 2018 and 2024, we quantify potential expansion in plantation area. We explore four scenarios for Southeast Asia:

1a, Basic: retention of existing rubber cultivation at current yields without intensification or further displacement, with future demand met by expansion at yields of modern plantations in mainland Southeast Asia (0.915–1.452 t ha^{-1} year^{-1}, Appendix S1).

1b, Basic + displacement: as 1a but with displacement of existing rubber cultivation by oil palm in Sabah, Sarawak and Indonesia, considering two scenarios of oil palm expansion from the Roundtable on Sustainable Palm Oil (RSPO): business-as-usual (BAU: 3,350,000 ha additional oil palm for 2010–2018), or a moratorium on peat and high biomass forest conversion (2,600,000 ha; Harris *et al.* 2013), with 34% of oil palm expansion predicted to displace rubber (Appendix S1). Rubber demand not met by remaining production (Appendix S1, Table S7) is met by expansion in mainland Southeast Asia, as in 1a.

2a, Intensified: some future demand is met by intensification of existing smallholder rubber cultivation in peninsula Malaysia, Sabah, Sarawak and Indonesia (plus a small 38,000 ha area of low-yielding estate cultivation on peninsula Malaysia), under scenarios derived from: likely maximum achievable yields, existing rubber area, and existing yields (Appendix S1, Tables S4–S6). Due to uncertainty in likely uptake of intensified production, we consider intensification of 75% by area as an upper bound, but 25–50% more plausible (Appendix S1). Residual future demand is met by expansion, as in 1a.

2b Intensified + displacement: as 2a, but also with displacement of some existing rubber production in Sabah, Sarawak and Indonesia by oil palm as in 1b. Residual future demand is met by expansion, as in 1a.

Anticipating intensification of 25–50% of low-yielding area in Indonesia and Malaysia, with no displacement by oil palm, we estimate that 1,394,707–3,017,838 ha of rubber expansion would be required to meet predicted 2018 demand (Table 1). Under the BAU scenario of oil palm expansion, this increases to 1,919,123–3,850,027 ha, making the threat from rubber expansion similar to that predicted for oil palm (2,600,000–3,350,000 ha) over the same period (Table S7). By 2024, with 25–50% intensification, we estimate 4,321,704–7,662,647 ha of expansion without oil palm displacement, and 4,846,

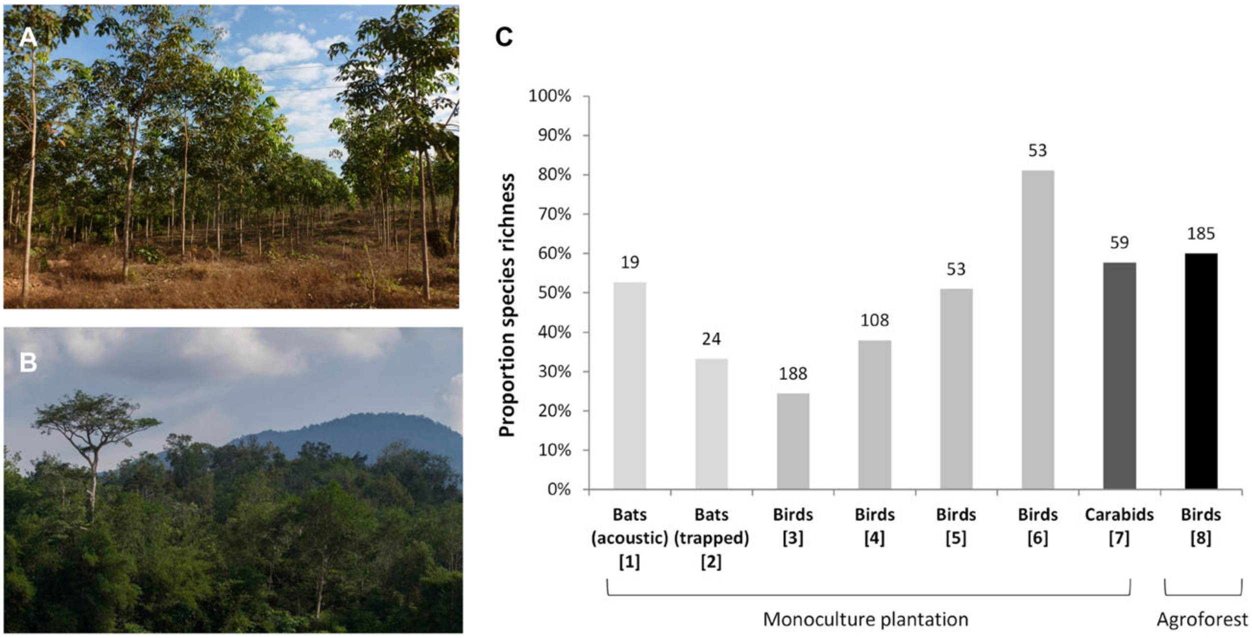

Figure 3 (A) Newly established immature rubber plantation, Kratie, Cambodia. Intensively managed monoculture rubber has a simple structure comprising a closed canopy kept clear of understorey growth. (B) Rubber agroforestry, Lubuk Beringin village, Jambi, Indonesia. Smallholder rubber agroforests are low-intensity multicropping systems that contain natural colonizing vegetation, making them more structurally complex. (C) Species richness of mature monoculture rubber plantations as a percentage of that found in natural forests (lowland primary rainforest [1–5], semi-deciduous monsoon forest [6] or primary and secondary forest [7]) and of rubber agroforest compared to primary lowland rainforest [8]. Study locations: [1,2] southern Thailand (Phommexay *et al*. 2011), [3] peninsular Malaysia (Peh *et al*. 2006), [4] southern Thailand (Aratrakorn *et al*. 2006), [5] Sumatra, Indonesia (Danielsen & Heegaard 1995), [6] Hainan Island, China (Li *et al*. 2013), [7] Yunnan, China (Meng *et al*. 2011), and [8] Sumatra, Indonesia (Thiollay 1995). Numbers at top of bars represent species richness of natural forest for each study. Photo credits: (A) Eleanor Warren-Thomas; and (B) Tri Saputro for Center for International Forestry Research (CIFOR), photograph licensed under a Creative Commons Attribution-NonCommercial-NoDerivs License 2.0.

120–8,494,836 ha under BAU oil palm expansion. Under a moratorium on peat/high biomass forest conversion, expansion estimates for oil palm lie between these figures (Table 1).

Biodiversity and rubber cultivation

Natural forest has been recently converted to rubber plantations in mainland Southeast Asia (Li *et al*. 2007; Li & Fox 2012; Appendix S2), and to rubber agroforests and plantations in Indonesia (Ekadinata & Vincent 2011). In Vietnam, 79% of rubber plantations established in the Central Highlands by 2012 were on former natural forest (92,000 ha; Phuc & Nghi 2014), and in Xishuangbanna, low-altitude areas highest in plant biodiversity are most profitable for rubber (Yi *et al*., 2013). Within MMSEA, 14% of young and mature rubber plantations were established onto Global Land Cover classes representing natural tree cover (Li & Fox 2012, Appendix S2). This has included de-gazettement of protected areas in China (Guo *et al*. 2002), Laos (Baird 2010) and Cambodia (Open Development Cambodia 2014). For example, more than 70% of the 75,000 ha Snoul Wildlife Sanctuary, Cambodia, mostly comprising lowland evergreen forest, was cleared for rubber during 2009–2013 (Boyle & Titthara 2013).

Natural habitat conversion to rubber is set to continue: regional scale simulations for MMSEA predict conversion of 4.25 million ha to rubber and other deciduous broadleaved plantations by 2050, mostly replacing evergreen broadleaf forest and forest-field mosaics (Fox *et al*. 2012). In Cambodia, the majority of areas allocated to rubber are forested (Dararath *et al*. 2011; Open Development Cambodia 2014), including within the largest contiguous lowland dry evergreen and semi-evergreen forest remaining in mainland Southeast Asia (McKenney *et al*. 2004) and globally significant dry deciduous forests (Tordoff *et al*. 2005). Such areas support an assemblage of Critically Endangered and Endangered waterbirds, ungulates and primates, likely to decline on clearance and fragmentation of currently contiguous forests (Tordoff *et al*. 2005).

Table 1 Estimated area of new monocultural rubber plantations required on mainland Southeast Asia to meet demand predicted for 2018 and 2024, considering (a) upper and lower bounds of potential rubber yield achieved in new monocultural rubber plantations, (b) extent of intensification of existing rubber production by smallholders in Malaysia and Indonesia (including a small 38,000 ha area of low-yielding estate rubber on peninsula Malaysia), and (c) displacement of smallholder rubber production by oil palm in Sabah, Sarawak, and Indonesia. Scenario numbers follow those in main text. Shaded cells represent most likely intensification scenarios

Scenarios	Scenario of new oil palm expansion	Area existing rubber in Sabah, Sarawak and Indonesia displaced by oil palm by 2018	Scenario of intensification in Indonesia/ Malaysia*	Area of monocultural plantation required to meet predicted demand[†] (ha), under scenarios of upper and lower monoculture yields in mainland Southeast Asia[‡]			
				Demand: 13,800,000 t year^{-1} by 2018 (3.1 million t increase from 2010)		Demand: 18,050,000 t year^{-1} by 2024 (7.35 million t increase from 2010)	
				Yield: 0.915 t ha^{-1} year^{-1}	Yield: 1.452 t ha^{-1} year^{-1}	Yield: 0.915 t ha^{-1} year^{-1}	Yield: 1.452 t ha^{-1} year^{-1}
1a	**Not considered**	0 ha	**0%**	3,387,978	2,134,986	8,032,787	5,061,983
2a			**25%**	3,017,838	1,764,846	7,662,647	4,691,844
2a			**50%**	2,647,699	1,394,707	7,292,507	4,321,704
2a			**75%**	2,148,339	895,347	6,793,148	3,822,345
1b	**Peat/high biomass moratorium**	884,000 ha[§]	**0%**	4,057,405	2,556,836	8,702,213	5,483,833
2b			**25%**	3,687,265	2,186,696	8,332,074	5,113,693
2b			**50%**	3,317,125	1,816,556	7,961,934	4,743,553
2b			**75%**	2,817,766	1,317,197	7,462,575	4,244,194
1b	**Business-as-usual**[¶]	1,139,000 ha	**0%**	4,220,167	2,659,403	8,864,975	5,586,400
2b			**25%**	3,850,027	2,289,263	8,494,836	5,216,260
2b			**50%**	3,479,887	1,919,123	8,124,696	4,846,120
2b			**75%**	2,980,528	1,419,764	7,625,337	4,346,761

[*] Intensifying to a yield of 1.494 t ha^{-1} year^{-1} in Malaysia, or to 1.310 t ha^{-1} year^{-1} in Indonesia (Table S6)

[†] Minimum and maximum yields of current plantations on mainland Southeast Asia, based on tapped area adjusted for initial unproductive years during the 25 year planation cycle (Appendix S1, Table S3)

[‡] Demand estimates from IRSG as reported in Li & Fox (2012), Rusmana (2013) and Rubberworld (2014)

[§] Area and production estimates from Table S7; area here is area of displaced rubber cultivation, which is converted to production and then to area of new plantations, and added to total predicted rubber area for each intensification and demand scenario.

[¶] Harris *et al*. (2013) predict a greater area of oil palm expansion in this scenario, where plantations continue to be established using business-as-usual practices

Although no studies have quantified the loss of large ungulates, primates, apex predators or waterbirds following forest conversion to rubber in Southeast Asia, population persistence is unlikely within highly managed, active rubber landscapes. Danielsen and Heegaard (1995) reported lower primate richness and abundance in plantations relative to primary forest, with macaques and gibbons absent, and a substantial reduction in the abundance of tree shrews and squirrels. We found eight studies assessing impacts on smaller taxa in Southeast Asia. Synthesizing across these, we find that conversion of primary or secondary forest to rubber monoculture decreases the species richness of birds, bats and carabid beetles by 19–76% (Figure 3c, 1–7; Danielsen & Heegaard 1995; Aratrakorn *et al.* 2006; Peh *et al.* 2006; Meng *et al.* 2011; Phommexay *et al.* 2011; Li *et al.* 2013). Conversion also changes species composition, with forest specialists replaced by disturbance-tolerant, widespread species (Nájera & Simonetti 2010). In lowland Thailand, 15 of 16 threatened bird species were restricted to forest, whereas species composition in rubber was similar to oil palm, representing a replacement of forest specialists (particularly frugivores and insectivores) with widespread generalists, usually of smaller body size (Aratrakorn *et al.* 2006).

Similarly, on Hainan Island, 29 of 53 bird species in secondary semi-deciduous forest were absent from mature monoculture rubber, especially obligate frugivores, whereas 19 of 43 species in rubber were absent from forest (Li *et al.* 2013). This pattern is similar for carabid beetles in China (Meng *et al.* 2011), and bats in Indonesia (Danielsen & Heegaard 1995) and Thailand (Phommexay *et al.* 2011), where 13 species were restricted to forest, and insectivorous bats showed 20-fold lower activity in rubber (355 individuals from 24 species in forest, versus 16 individuals from eight species in plantations) attributed to lower insect biomass.

While assessing impacts of primary forest conversion to rubber is relatively straightforward, more complex patterns of land-use change present a challenge in assessing biodiversity impacts. In mainland Southeast Asia, over half the current rubber plantation extent was established on mosaics of natural vegetation (grassland, shrubland and forest) and cropland, including former swidden (Appendix S2; Li *et al.* 2007; Li & Fox 2012), while in Indonesia conversion of low-intensity rubber agroforest (Figure 3b) to monocultural plantations is an emerging trend (Feintrenie & Levang 2009; Ekadinata & Vincent 2011). Moreover, rubber plantation establishment on swidden or agroforest may displace them into frontier forests, particularly where migrants or outside companies establish plantations (e.g., China; Li *et al.* 2007), representing leakage of biodiversity impacts beyond plantation boundaries.

The biodiversity value of swidden in Southeast Asia is poorly known, and no direct comparisons between swidden and rubber have been made (but see Rerkasem *et al.* (2009) for loss of exceptional agrobiodiversity after swidden conversion to rubber). The reduction in species richness of 19% following conversion of secondary forest to rubber monoculture on Hainan (Li *et al.* 2013), suggests secondary forest fallows in swidden landscapes might also retain higher biodiversity value than rubber monocultures.

Although there are negatives for species richness and composition of creating rubber agroforest on primary or secondary forest (Figure 3c, [8]; Thiollay 1995), agroforest harbors greater biological value than monoculture rubber, supporting more forest specialist bird and plant species (Beukema *et al.* 2007), with increased bird diversity in plantations that have greater complexity in habitat structure (Aratrakorn *et al.* 2006; Nájera & Simonetti 2010). In some lowland areas of Indonesia, rubber agroforests are the only remaining forest-like habitats, supporting a subset of forest species not found in expanding monocultures (Beukema *et al.* 2007; Feintrenie & Levang 2009; Ekadinata & Vincent 2011).

There are also indications of substantial impacts on freshwater taxa. In Laos, local people reported dramatic declines in fish, crabs, shrimps, shellfish, turtles and streambank vegetation, attributed to run-off from rubber plantations (pesticide, herbicide and sediment), with fishermen reporting skin reactions from standing in streams (Baird 2010). In Xishuangbanna, fertilizer run-off from rubber plantations has caused waterway eutrophication, declines in filtering services by aquatic vegetation, and contamination of well water (Xu *et al.*, 2013), while benthic macroinvertebrate diversity declines with increased intensity of rubber cultivation (Zhao *et al* 2014). Together, these findings show that rubber expansion could substantially exacerbate the extinction crisis in Southeast Asia.

Critical directions

The recent rubber boom has been compared to that of oil palm (Fox *et al.* 2012) with potentially catastrophic biodiversity impacts. Net area under rubber is increasing in Borneo and Sumatra, despite oil palm replacing some rubber area, alongside the novel expansion of monocultures in mainland Southeast Asia. Some have suggested policies to support and promote monoculture cultivation by smallholders in this novel expansion (Fox & Castella 2013). Others promote low-intensity agroforestry (Yi *et al.* 2013), which could provide farmers with diverse income sources while reducing ecological impacts within cultivated areas; although this could reduce yield and thus increase hunger for land. We therefore highlight two critical areas for further work:

(1) **Research to support meeting rubber demand while minimizing biodiversity loss**

Meeting global rubber demand while minimizing biodiversity and ecosystem service losses requires understanding contrasts in species assemblage among production systems of differing yield (agroforests, monocultures) and when replacing different land uses (e.g., swidden, natural forest).

Research is needed to:

(a) Quantify biodiversity value of swidden landscapes relative to rubber; considering monocultural rubber plantations in mainland Southeast Asia, and both agroforests and monocultures in Sabah, Sarawak, Indonesia and the Philippines. Knowledge about impacts on aquatic ecosystems is scarce, and also necessitates urgent research, particularly where local populations depend upon freshwater fisheries (Baird 2010).

(b) Evaluate relative benefits for forest biodiversity (Phalan *et al.* 2011) and carbon storage (Gilroy *et al.*

2014) of low-intensity agroforest rubber (possibly including high-yielding varieties) over a wider area of mainland Southeast Asia (land-sharing), and intensive high-yielding monocultures combined with protected natural habitats (land-sparing). Within monocultures, assess whether retention of connected and protected forest patches on a fine scale offers greater resilience for biodiversity, versus intensified plantations with protection of larger forest blocks elsewhere in a landscape. In Brazil, forest species utilize rubber monocultures up to 2 km from the edge of large forest fragments (140–625 ha; Flesher & Laufer 2013), but in Bornean oil palm plantations, smaller forest patches (0.7–87 ha) are species-poor, and protecting larger forest blocks would protect more bird biodiversity (Edwards *et al.* 2010).

(c) Use spatially explicit conservation planning to investigate least damaging locations for rubber development, as conducted for oil palm (Venter *et al.* 2013). Modeling predicted yields of agroforests, smallholder plantations and large-scale commercial plantations, the costs of expansion onto different land-use types, and a range of conservation scenarios (land-sharing vs. sparing, carbon protection, biodiversity conservation; e.g., Koh & Ghazoul 2010) will inform trade-offs between production, profit, and wildlife conservation.

(d) Investigate whether biodiversity value within plantations can be improved without negatively affecting yield (e.g., as for coffee and cacao; Tscharntke *et al.* 2011). Although there has been little success in enhancing the biodiversity value of oil palm (Fitzherbert *et al.* 2008), given the apparently higher biodiversity value of agroforests with dense semi-natural understorey vegetation (Figure 3b), compared with rubber monoculture (Figure 3a; Beukema *et al.* 2007; Nájera & Simonetti 2010), we need to understand whether structural complexity can be improved within monoculture rubber without reducing yield. Similarly, we need to identify and quantify any pest control benefits of wildlife within plantations, and investigate whether landscape configuration of forest and cultivation impacts yield (Edwards *et al.* 2014).

(2) The urgent need for a robust sustainability initiative

A sustainability standard for rubber cultivation, the Sustainable Natural Rubber Initiative (SNR-i; IRSG 2014) is only just emerging, leaving rubber expansion to be driven by market forces, farmer choice, and governmental policy. Negative environmental consequences of rubber cultivation are known within MMSEA, but whether expansion-focused policies will be modified is unclear; although in Xishuangbanna there are recent plans to revert relatively unproductive rubber areas to forest (Ives 2013). While RSPO certification encourages oil palm expansion onto nonforest lands, including rubber (Koh & Wilcove 2008), rubber can currently expand without limitations to market access on recently deforested land or steep slopes, including those originally intended for oil palm, but which cannot be RSPO certified (Lim 2011).

There are many criticisms of current certification schemes: certified products are not fully sold, there are issues with compliance and integrating smallholders, and assessments of biologically important locations are questionable and potentially corruptible (e.g., Schouten & Glasbergen 2011; Edwards & Laurance 2012). Notwithstanding the complexities of developing an effective certification label, there are reasons to be optimistic that certification requirements may strengthen to prevent conservation losses and gain market traction. In the cases of oil palm, paper-pulp, and cattle, consumer pressure has resulted in major corporations only purchasing certified products; further, 400 of the world’s largest corporations have stated that by 2020 their supply chains will be deforestation free (Preston 2010).

A potential concern may be the contribution of China, as the world’s largest consumer of rubber, to driving sustainable rubber cultivation, given low interest in RSPO-certified oil palm thus far (Laurance *et al.* 2010). However, where large international companies or distributors commit to sourcing sustainable commodities, strong pressure can be exerted on producers (e.g., Nestlé and Unilever actions on oil palm). Major tyre producers, for instance, Bridgestone (Japan), Michelin (France), Goodyear Tire and Rubber Company (USA), and Continental AG (Germany) are based in economies with a stronger interest in sustainable sourcing, but supply tyres to the Chinese market (e.g., Bridgestone 2013). Moreover, without such a standard, there is little hope for change.

The SNR-i launched its pilot phase in January 2015, with participating entities (small/large growers, processors, traders, and downstream rubber users) offering compliance with Voluntary Guidelines and Criteria (IRSG 2014). Criterion 3 refers to forest sustainability, requiring establishment of plantations only on land “officially identified as suitable for rubber plantations or agricultural purposes” and “respect for legally protected areas and protected species habitats”, ensuring that “new natural rubber plantations are not established within protected areas”. We assert that environmental impact assessments must be compulsory for new plantations under this criterion, and high conservation value and high carbon stock forests identified during the assessment process must be directly protected from conversion to rubber cultivation. Although Criterion 5 addresses respect of human and labor rights through avoidance of child and forced labor, the standard must also place strong emphasis on free prior and informed consent for local people involved in plantation establishment. The standard should also contain measures to support existing agroforestry producers in accessing sustainability-focused rubber markets.

In conclusion, the speed and scale of the new rubber boom means environmental and social considerations have so far been sidelined, with a spate of protected area de-gazettement and evictions of marginalized local peoples. The current focal regions for rubber production in Sundaland, and its rapid expansion in Indo-Burma, make this an urgent issue of global conservation importance. We urge that scientists fully engage with the development of the SNR-i to ensure relevance to biodiversity conservation, with prevention of further rubber development in key natural forests the minimum prerequisite for continued access to lucrative western and brand-label markets. Business-as-usual practice carries with it a significant danger that rubber development could destroy Indo-Burma's remaining wildernesses, and with it, the last hopes of regaining mammal populations that just a century ago were only rivaled by those in East Africa (Tordoff *et al*. 2005).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Figure S1. Top five importers of rubber 2000–2011.

Figure S2. Yield (tonnes ha^{-1}) of rubber producing countries relative to mean global yield.

Table S1. Data sources on rubber extent in Southeast Asia.

Table S2. Harvested area, annual production and yield of rubber producing countries in 2011.

Table S3. Yield of rubber producing countries in mainland Southeast Asia; data from ANRPC (2014) for 2011. No data are available for Laos.

Table S4. Yield estimates of existing smallholder and estate rubber production in Malaysia and Indonesia, from governmental statistics and on-farm studies.

Table S5. Smallholder and plantation production figures used in subsequent analysis for Malaysia and Indonesia—selected figures from Table S4.

Table S6. Intensification scenarios: we explore intensification of both smallholder and estate rubber area in Malaysia (insular and peninsula) and smallholder rubber area in Indonesia, by estimating the production increase generated by intensifying of 25%, 50%, or 75% of existing rubber area to the maximum likely yields for each location.

Table S7. Oil palm expansion and displacement of rubber agroforest and plantations in insular Malaysia and Indonesia.

Table S8. (*Also Table 1 in Main Text*) Predicted area of new monocultural rubber plantations required on mainland Southeast Asia to meet predicted demand by 2018 and 2024, considering (1) upper and lower bounds of potential rubber yield achieved in new monocultural rubber plantations, (2) extent of intensification of existing rubber production by smallholders in Malaysia and Indonesia, and (3) displacement of smallholder rubber production by oil palm in insular Malaysia and Indonesia.

Appendix S1. Predicted expansion of rubber cultivation area in response to increased demand, smallholder intensification and conversion of rubber plantations to oil palm.

Appendix S2. Rubber expansion in Montane Mainland Southeast Asia (MMSEA).

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