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PERSPECTIVE

Rubber's inclusion in zero-deforestation legislation is necessary but not sufficient to reduce impacts on biodiversity

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Abstract

Agricultural commodity production is a major driver of tropical deforestation and biodiversity loss. Natural rubber from *Hevea brasiliensis*, a valuable commodity without viable substitutes, has recently been included in the European Union (EU) deforestation regulation that aims to halt imports of goods containing embedded deforestation. Sustained growth in demand for rubber is driven by increasing tire production, caused by rising transport flows and personal car ownership. We show that average natural rubber yields remain static, meaning 2.7–5.3 million ha of additional plantations could be needed by 2030 to meet demand. A systematic literature search identified 106 case studies concerning transitions to and from rubber, revealing that substantial rubber plantation area expansion since 2010 has occurred at the expense of natural forest. Eliminating deforestation from rubber supply chains requires support for millions of smallholder growers to maintain or increase production from existing plantations, without land or water degradation. Supply chain traceability efforts offer opportunities to deliver such support. While the inclusion of rubber in EU legislation is a positive step, it is critical to ensure that smallholders are not marginalized to avoid exacerbating poverty, and that other markets follow suit to avoid displacement of rubber-driven deforestation to unregulated markets.

KEYWORDS
biodiversity, climate change, disease, smallholder, supply chain, sustainability, swidden, tropical forest

Avoiding tropical deforestation is critical to protect biodiversity, address climate change, protect ecosystem service delivery, and support indigenous peoples (IPBES, 2019). As conversion to agricultural land is a key driver of forest loss (Pendrill, Gardner, et al., 2022), there are increasing initiatives to eliminate deforestation from agricultural commodity supply chains (Lyons-White et al., 2020; Seymour & Harris, 2019). Legislative proposals to regulate the import of deforestation-linked commodities have recently been approved in the European Union (EU) (European Commission, 2021a; Council of the EU, 2023; European Parliament, 2023), are currently under consideration in the United States (S.2950—117th Congress [2021–2022]: FOREST Act of 2021 [https://www.congress.gov/bill/117th-congress/senate-bill/2950]), and the United Kingdom has introduced legislation through section 116 of the UK Environment Act 2021, with secondary implementing legislation forthcoming (DEFRA, 2021).

Natural rubber (*Hevea brasiliensis*) is essential for the manufacture of vehicle and airplane tires (comprising 70% of global natural rubber consumption), medical equipment, prophylactics, and sportswear (Laroche et al., 2022). A voluntary rubber sustainability initiative, the Global Platform for Sustainable Natural Rubber (GPSNR), works to address deforestation alongside other sustainability concerns (https://sustainablenaturalrubber.org). Sustainability guidelines for Chinese businesses investing in rubber plantations and processing overseas include a zero-deforestation principle (CCCMC, 2017), although these have not been widely adopted (Jiang, 2022). Meanwhile, 62% of 30 key large-scale rubber growers or processors have made voluntary zero-deforestation commitments, although only 14% provide evidence of monitoring deforestation within their operations or supply chains (ZSL/SPOTT, 2022).

Rubber is among seven commodities named in the EU Regulation on deforestation-free products, which will require businesses placing goods on the EU market to show they were not produced on land deforested or degraded after 31 December 2020 (European Commission, 2021a). Rubber (alongside soy, cattle, palm oil, cocoa, coffee, and timber) was selected based on analysis of deforestation risk (European Commission, 2021b, 2021c; European Commission & Directorate General for the Environment, 2018; Persson et al., 2021). Although the estimated area of deforestation linked to rubber is lower than that for pasture, soy, or oil palm, the quality of data on rubber deforestation is also relatively poorer than that for other commodities, meaning uncertainty is higher (Pendrill, Gardner, et al., 2022). The similar legislative proposals under earlier stages of consideration in the United States and the implementing legislation under construction in the United Kingdom may or may not include rubber.

Rubber is chiefly grown by smallholder farmers (Laroche et al., 2022; Warren-Thomas et al., 2015), and there are substantial challenges in equitably meeting sustainability standards and eliminating deforestation from smallholder-dominated supply chains (Grabs et al., 2021; Lyons-White et al., 2020). Here, we outline the importance of meeting this challenge by showing that, based on current trajectories, demand for rubber in the coming decade will likely lead to further expansion of plantations in new frontiers, that recent expansion has been linked to deforestation (and biodiversity loss) in most producing regions, and that rubber is linked to other deforestation-risk commodities through indirect land-use change. We discuss how traceability requirements of new deforestation laws offer an opportunity to support smallholder rubber farmers to maintain and improve yields in existing plantations, improving livelihoods and maintaining rubber supply without increasing the global plantation footprint. We also suggest that without expanding the proportion of the world rubber market covered by zero-deforestation regulations, impact will remain limited.

1 | INCREASING RUBBER DEMAND HAS BEEN MET BY EXPANSION OF PLANTATION AREA FROM 2010 TO 2020

Global rubber production has increased steadily over the past decade, and as annual yields per hectare have been mostly stable, this has been achieved through increased plantation area (Figures 1 & S1). Global harvested area increased by 3.3 million ha between 2010 and 2020, bringing the total to 12.8 million ha (these data represent mature plantations, not total planted area). This falls at the higher end of previous predictions based on expected demand increase between 2010 and 2018: predicted expansion under multiple assumptions of intensification, yields, and displacement of rubber area with oil palm was 0.9–4.2 million ha (Warren-Thomas et al., 2015). Most rubber-producing countries increased their harvested rubber area between 2010 and 2020 (Figure 1). The greatest increases were in Thailand (1.4 million ha) and Cote D'Ivoire (0.41 million ha), followed by Vietnam, Cambodia, and Indonesia with increases of more than 0.2 million ha each (Table S1). Only four countries reduced their rubber area (greatest reduction was −0.019 million ha in India).

2 | RECENT RUBBER EXPANSION HAS BEEN LINKED TO DEFORESTATION AND BIODIVERSITY LOSS

The conversion of natural forests (old-growth or secondary), and of complex agroforestry systems, to monocultural rubber has well-documented negative effects on biodiversity (synthesized in Clough et al., 2016; He Pia & Martin, 2015; Mang & Brodie, 2015). Declines in species richness and changes to species composition have been documented across multiple taxa, from soil invertebrates to birds, mammals, and plants, while increases in invasive earthworms and plants have been reported in multiple

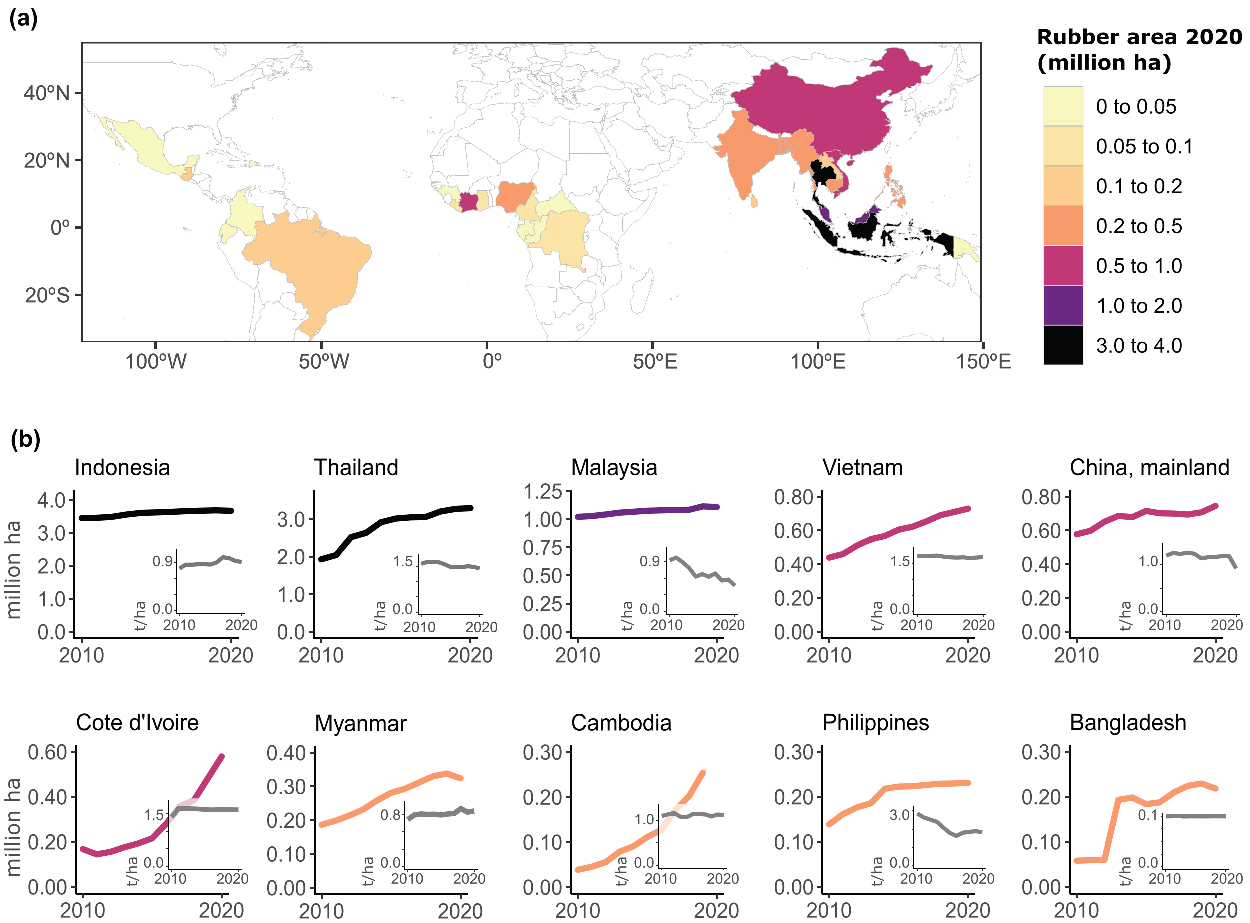

FIGURE 1 (a) Harvested area of natural rubber per country in 2020. (b) Harvested area of natural rubber from 2010 to 2020 for the top 10 countries for absolute rubber area increase over the same period (color of the main graph line reflects the 2020 total shown on the map; subplots per country show annual yields in metric tons per hectare; countries sorted by rubber area in 2020). All data from FAOSTAT, except for government estimates reported for Lao PDR (Supporting Information, Table S1).

countries (narrative review of 53 studies in Supporting Information).

No analysis has yet quantified deforestation for rubber at the global scale, at least partly due to the technical challenges of detecting such transitions. Classification of rubber plantations from earth observation satellites is more challenging than for other tree plantations (Hoang & Kanemoto, 2021; Ye et al., 2018). In addition, patterns of land-cover change to rubber are often more complex than for some other plantation crops, such as oil palm that tends to be established in larger contiguous blocks, as 80% of rubber is grown by smallholders (Laroche et al., 2022). However, multiple sources of evidence show that a substantial proportion of recent rubber area expansion has involved deforestation.

We conducted a systematic search for published evidence of land-use and land-cover change to and from rubber since 2010, which returned 106 distinct case studies (Data S1); 75 studies reported land-use or land-cover change to rubber, covering 140 transitions (Figure 2a; Data S1). The majority of transitions were reported at a scale of thousands of hectares ($n = 80$), but smaller scale transitions were also captured: hundreds of hectares ($n = 14$), tens of hectares ($n = 4$), or individual farms or fields ($n = 24$; Figure S2).

Transitions from natural forest to rubber were reported in 52 studies covering all regions except South America, while 21 studies reported transitions from swidden agriculture systems (shifting cultivation systems that often include patches of forest that are reservoirs of biodiversity in a landscape; Padoch & Pinedo-Vasquez, 2010). Transitions from agriculture (34 studies) and other plantations (20 studies) were also common. The simplified land-use and land-cover definitions reported here are provided in full in Data S1.

Only 32 studies reported the areas of land converted to rubber; the vast majority of this area was transition from forest to rubber (1.8 million ha, compared to 0.31 million ha converted from nonforest to rubber), while the area of rubber converted back to other land uses was

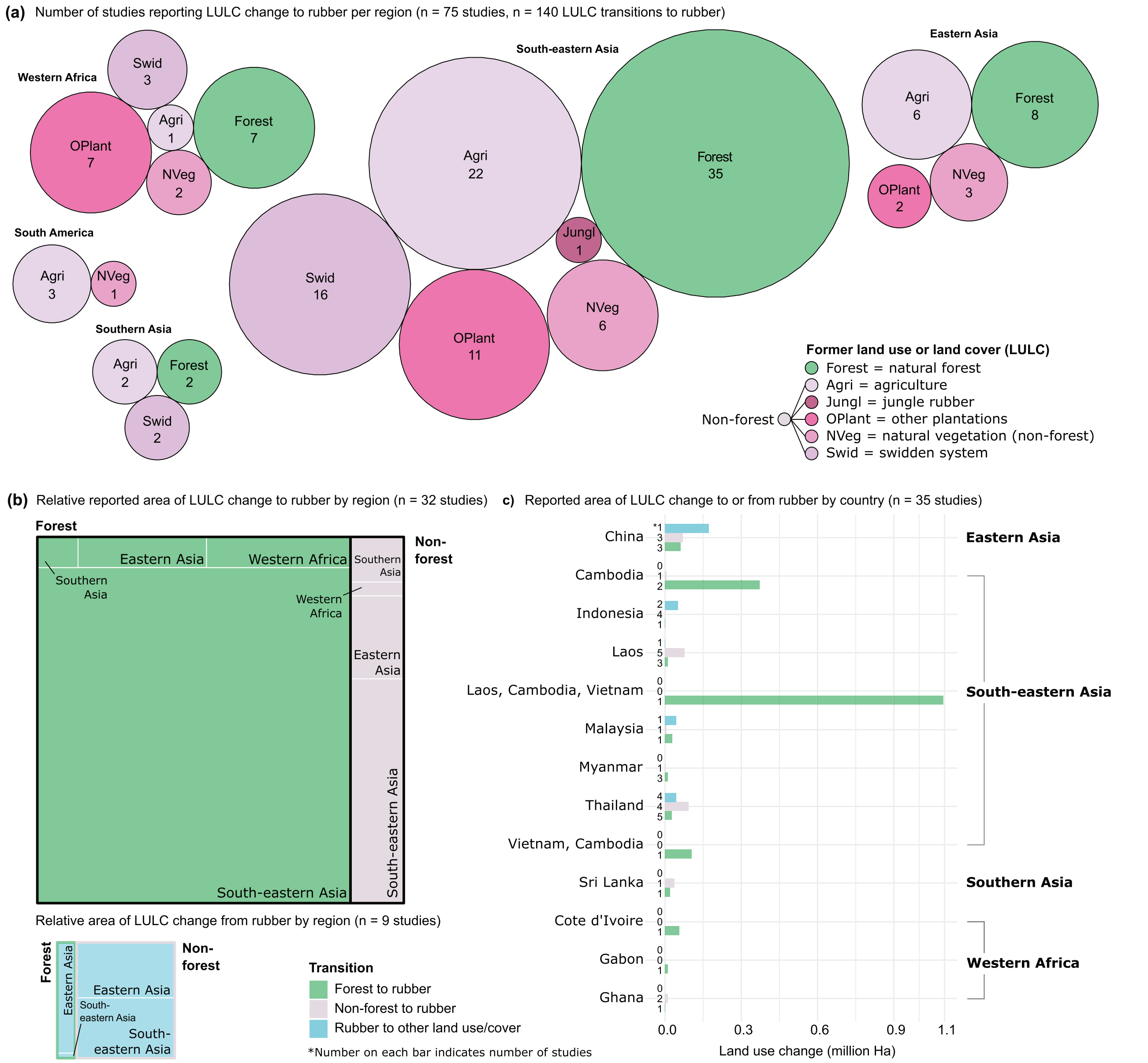

FIGURE 2 Panel (a) Number of published case studies reporting land-use and land-cover conversion to rubber plantations from 2010 onward, grouped by UN region (Data S1), with circle areas proportional to number of studies (total number of unique studies = 75, some studies reported more than one transition so total transitions shown on figure = 140); for the subset of studies that report the area converted, panel (b) shows the reported area of land converted to rubber per UN region from forest or nonforest (sum of land area reported as converted to rubber across 32 studies, of which 1.8 mHa was converted from forest, and 0.31 mHa from nonforest) and from rubber to forest or nonforest (sum of land area reported as converted from rubber across nine studies, 0.30 mHa total, of which 0.05 mHa reverted to forest) with area of rectangles proportional to area reported; panel (c) shows the sum of reported land area of rubber reported per country from forest and nonforest to rubber, and from rubber to other land uses/covers; study detail provided in Data S1; version with panels (a) and (b) results per country in Figure S3.

much smaller (nine studies, 0.30 mHa total; only 0.05 mHa reverted to forest; Figure 2b; Data S1). While there may be a publication bias toward reporting deforestation as opposed to other land-use and land-cover transitions, this indicates that deforestation in rubber supply chains is widespread. One particularly clear example is Cambodia, where large tracts of old-growth forests were converted at industrial scale (Figure 3; 20,000–100,000 ha of forest were converted to rubber each year from 2010 to 2015; Grogan et al., 2019).

Evidence for deforestation linked indirectly to rubber expansion was reported from five studies (references in Table S2). In Laos and Indonesia, rubber planting onto former swidden rice systems has displaced demand for swidden agriculture to the forest frontier. In Cambodia, increased demand for farmland to support workers at

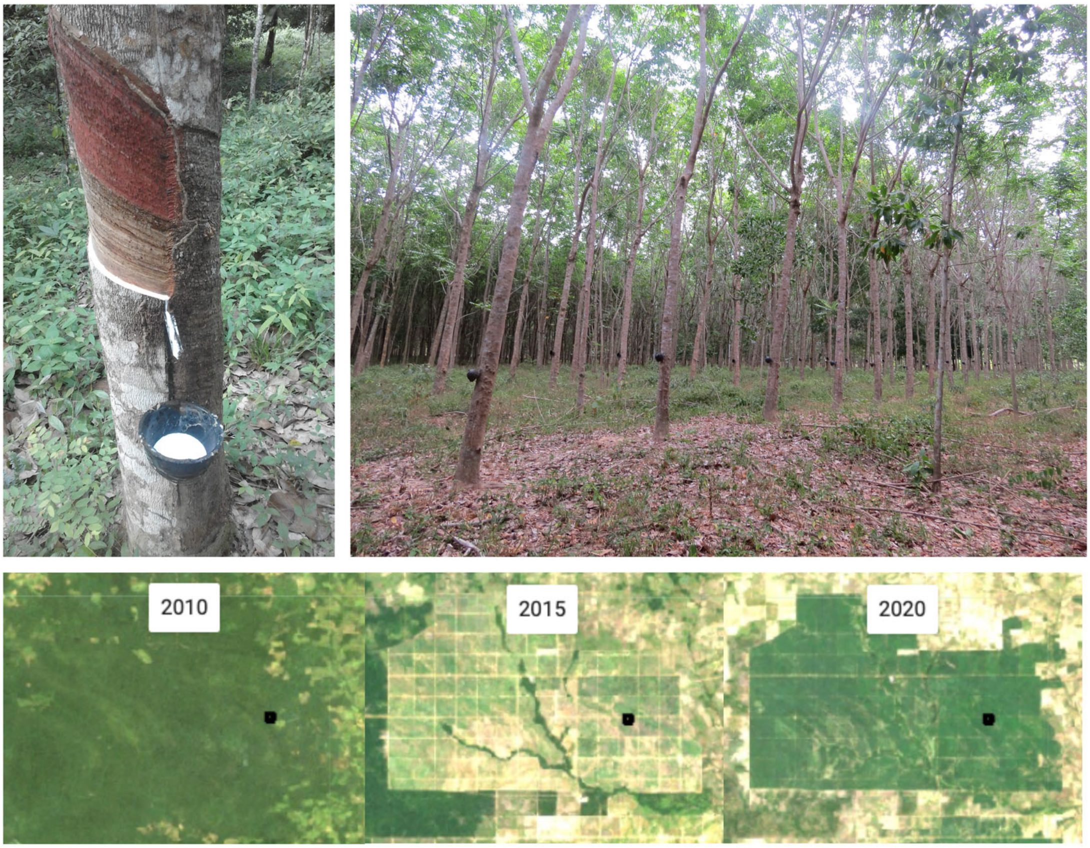

FIGURE 3 Top left: Tapping a rubber tree in Southern Thailand. Top right: Smallholder rubber plantation in Thailand (photos: E Warren-Thomas). Bottom: Example of industrial-scale forest conversion to rubber in Northern Cambodia (Oddar Meanchey Province); Landsat true color annual composite images (courtesy of the U.S. Geological Survey) of intact forest (in 2010, R/G/B = Landsat-5 Band 3/2/1), forest clearance (by 2015, R/G/B = Landsat-8 Band 4/3/2), and rubber plantations (by 2020, R/G/B = Landsat-8 Band 4/3/2).

industrial-scale rubber plantations is expected in currently forested landscapes. Recent replacement of rice and fruit orchards with rubber in Thailand may also be expected to have indirect land-use change effects elsewhere, but notably, here rubber was itself displaced by oil palm. Lastly, replacement of old cocoa plantations with rubber in Cote D'Ivoire is linked to forest clearance for new cocoa farms, and replacing traditional agroforestry practices post-cocoa cultivation. Land-cover and land-use change for rubber in West and Central Africa warrants particular attention, given that many nations still have high forest cover (Lyons-White et al., 2020), and the EU sources much rubber from this region (Laroche et al., 2022; Supporting Information).

In addition to our systematic literature search, we also collated subnational government statistics on forest cover loss and rubber plantation gain for the top two rubber-producing countries (Supporting Information). Co-occurrence of rubber gain and forest loss between 2014 and 2022 at the province level is shown for Indonesia (mostly on the islands of Sumatra and Borneo; see also data from Pendrill, Persson, et al. [2022] in Data S2), and between 2012 and 2018 for Thailand (mostly in the northeastern region; Data S3). These data indicate further locations, beyond the case studies shown above, where deforestation for rubber plantation expansion may have occurred since 2010.

3 | THE GROWTH IN RUBBER DEMAND WILL CONTINUE

Globally, demand for natural rubber is likely to continue rising. Recent contractions in demand during the COVID-19 pandemic are likely to be short term (World Bank Group, 2021). Global freight and passenger flows are predicted to triple by 2050 (International Transport Forum, 2019). In addition, somewhat ironically given the links between natural rubber and deforestation, industry efforts to increase the proportion of natural rubber relative to synthetic compounds in tire manufacturing for sustainability reasons will contribute to increased demand for natural rubber (Laroche et al., 2022). Given static yields per unit area (Figure 1), increased demand is likely to be met with expansion.

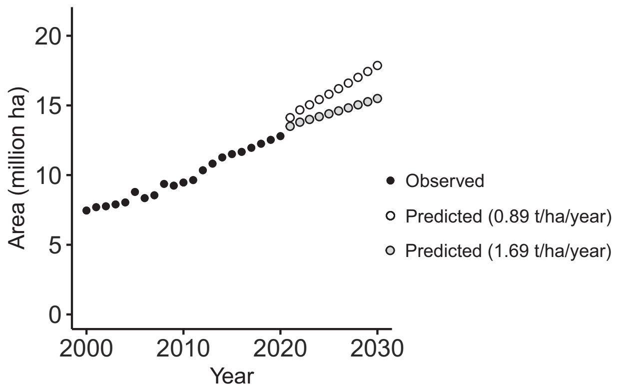

FIGURE 4 Historical rubber global rubber area from 2000 to 2020, with projections of demand by 2030 converted to predicted area increases, estimated using average yields for 2010–2020 from the highest yielding (Vietnam 1.69 metric tons/ha/year) or lowest yielding (Indonesia 0.89 metric tons/ha/year) of the top 10 producing countries. Observed data from FAOSTAT; data sources in Supporting Information; data in Table S3.

Estimates from rubber industry analysts (Table S3) indicate natural rubber demand could reach 17.2 million metric tons by 2030 (an increase of 4.6 million metric tons from 2020). The additional harvested rubber area required to meet the projected 2030 demand can be estimated using average national yields for 2010–2020 from the highest yielding (Vietnam, 1.69 metric tons/ha/year) or the lowest yielding (Indonesia, 0.89 metric tons/ha/year), of the top 10 producing countries. This shows meeting projected 2030 demand could require 2.7–5.3 million ha of additional harvested rubber area relative to 2020 (Table S3; Figure 4).

Rubber prices tend to be volatile and are currently relatively low (Figure S4), but this has not prevented the sustained expansion of rubber in the recent past (Figures 4 and S1). Changes in the cost of oil (used to produce synthetic alternatives), fluctuating currency exchange rates, climate and disease impacts on production, and stockpiling behavior can result in price bubbles and uncertainty for producers (Su et al., 2019). Although high prices drive rubber planting (e.g., Grogan et al., 2019), high establishment costs mean farmers retain their trees but reduce or crease tapping when prices fall in the hope of future recovery. In other countries, rubber remains more profitable than other land uses even when global prices are low (further detail in Supporting Information), while land concession contracts may require companies to plant irrespective of rubber prices (Hurni & Fox, 2018). Alternative crops may also be established by smallholders on additional areas of land while waiting for rubber prices to rise, adding to pressure on remaining forests (Zhang et al., 2019). Together these factors can generate a ratchet effect of ever-increasing area.

Disease and climate change risk may further add to land demand for rubber by reducing productivity of existing plantations. Pathogens have always presented a challenge in rubber production, but they may be on the rise: *Pestalotiopsis* leaf-blight fungi are currently reducing yields by 25% across ~0.4 million ha of rubber in Indonesia, and multiple leaf-fall diseases are affecting China, Indonesia, Thailand, Malaysia, Sri Lanka, and India (Pinizzotto et al., 2021). Changing weather patterns are already impacting plantations across South and Southeast Asia: prolonged dry seasons can reduce the risk of fungal disease but reduce rubber tree growth and latex flow, warmer winters in China are linked to increased fungal damage, while intensified rainfall reduces available tapping days and causes flooding that prevents harvest (further detail in Supporting Information). Moreover, many existing plantations are in locations likely to become increasingly marginal as climate change progresses, further limiting productivity (Ahrends et al., 2015).

4 | NEXT STEPS FOR REDUCING THE CONTRIBUTION OF RUBBER PRODUCTION TO DEFORESTATION AND BIODIVERSITY LOSS

Reducing deforestation driven by internationally traded commodities will require both demand- and supply-side initiatives (Bager et al., 2021). Demand-side measures mean tackling unsustainable levels of consumption, requiring transformative social, economic, political, and technological change (IPBES, 2019). In the context of rubber, sustainable public transport policies that reduce reliance on personal cars for transport could substantially reduce demand for rubber tires as cars use much more rubber per person-kilometer than buses or trams/rail (Laroche et al., 2022). Technological advances in recycling are also urgently needed as tires can currently only be recycled into a limited set of alternative products (Abbas-Abadi et al., 2022).

On the supply side, sustainable intensification in the right place could increase yields for rubber within the existing plantation footprint without degrading land or water, thus meeting demand without area expansion and associated deforestation risks. We are not advocating for intensification of low-yielding but high-complexity jungle rubber systems, such as in Indonesia, which are critically important habitats for forest-dependent species and provide multiple ecosystem services (e.g., Clough et al., 2016). However, low yields are also reported from some monocultural systems (see Supporting Information on GPSNR work to tackle this), which already have much lower biodiversity value (narrative review of 53 studies in Supporting Information). Although existing monocultural rubber farms support only a small subset of biodiversity, adopting agroforestry or less-intensive weed management practices can enhance species diversity, benefit soils, and improve livelihoods while maintaining high yields (Wang et al., 2021; Warren-Thomas et al., 2019).

Yield increases could result directly from zero-deforestation laws if the need for traceability from grower to product is used to simultaneously deliver support to smallholders to sustainably intensify production. Smallholder growers need help to improve agricultural practices by accessing high-yielding, disease-tolerant, and climate-adapted seedlings for planting, improving tapping practices, and applying appropriate latex stimulation (Pinizzotto et al., 2021). Joint traceability work and smallholder support have been demonstrated in pilot work in Indonesia (Butcher, 2020; Southwell, 2022) and by the GPSNR (Supporting Information). Further development of intercropping and agroforestry practices could also improve water and soil management that could boost or at least sustain yields in the long term (Wang et al., 2021).

Indirect yield increases may also arise if zero-deforestation laws limit opportunities for plantation expansion, as there is evidence that constraining agricultural land availability can drive endogenous intensification (Garrett et al., 2018). Expansion of rubber within countries has also been associated with increased yields, possibly due to increased availability of skilled labor and policy support (García et al., 2020). This offers hope that in countries with large existing rubber areas, the inclusion of rubber in zero-deforestation laws could synergize with zero-deforestation commitments in the private sector to constrain land availability for rubber, and thus indirectly drive yield improvements. However, given that rubber demand is relatively elastic to prices, intensification (i.e., increasing yields) would only prevent further plantation expansion if strong land-use governance and planning policies are in place to protect natural forests, which requires support from producer country governments (García et al., 2020).

A further challenge for the successful implementation of zero-deforestation laws in the rubber supply chain is avoiding unintended consequences for the livelihoods of smallholder growers, as suppliers could simply switch to larger-scale producers to ease traceability (Bager et al., 2021). The limited capacity of smallholders to meet standards due to resource constraints means that state or private sector support will be needed to ensure continued market access and avoid poverty being exacerbated (Grabs et al., 2021).

Displacement of deforestation risk among commodities is another challenge that needs addressing to ensure policies and initiatives result in real reductions in deforestation. For example, rubber planted on former cocoa farms (where soil nutrient depletion makes cocoa unviable; see Data S1) in Cote D'Ivoire could be considered deforestation free, but masks linked deforestation for cocoa and abandonment of post-cocoa agroforestry practices. Inclusion of both commodities, as is the case in the current EU legislation, may stimulate joint efforts across crops to improve long-term viability of plantation area. This could avoid the need for expansion onto forested land, thus driving real change that could not be achieved through commodity-specific initiatives.

An important remaining issue is that deforestation-risk rubber may simply be displaced to unregulated markets outside the remit of zero-deforestation laws (Bager et al., 2021). Implementation of China's existing national rubber sustainability guidelines (CCCMC, 2017) in the context of imported rubber would be a key step in preventing such displacement between markets. Therefore, policy efforts to increase the proportion of the market covered by such laws, and to encourage the market coverage of voluntary commitments, will be important. For example, the United Kingdom and the United States are currently considering legislation for deforestation from imports. The inclusion of rubber into these laws is an important next step.

AUTHOR CONTRIBUTIONS

Conceptualization: Eleanor Warren-Thomas. *Data curation*: Eleanor Warren-Thomas. *Formal analysis*: Eleanor Warren-Thomas. *Methodology*: Eleanor Warren-Thomas. *Investigation*: Eleanor Warren-Thomas, Julia P. G. Jones, Maria M. H. Wang, Antje Ahrends, and Yunxia Wang. *Visualization*: Eleanor Warren-Thomas, Antje Ahrends, and Yunxia Wang. *Project administration*: Eleanor Warren-Thomas. *Writing—original draft*: Eleanor Warren-Thomas. *Writing—review and editing*: Eleanor Warren-Thomas, Julia P. G. Jones, Maria M. H. Wang, Antje Ahrends, and Yunxia Wang.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data are available in the Supporting Information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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