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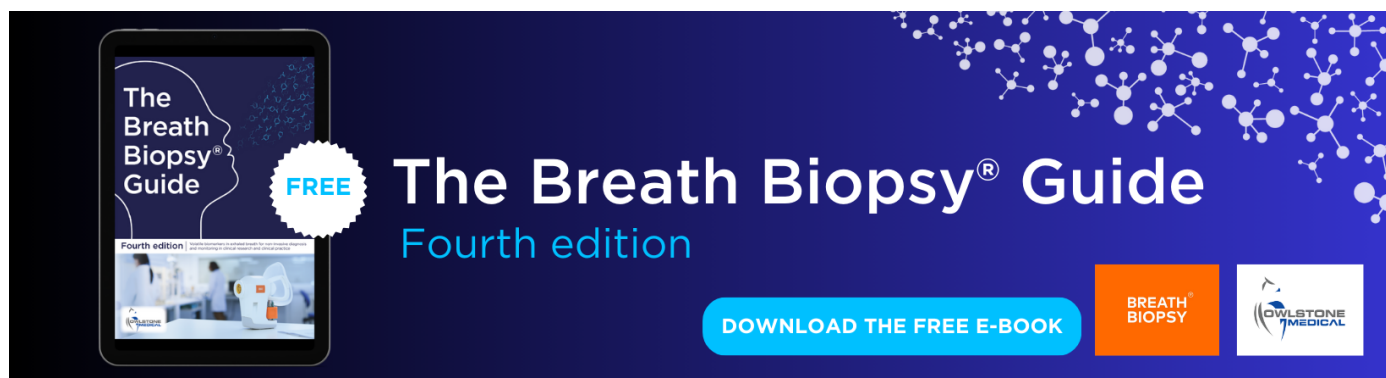
Foreign demand for agricultural commodities drives virtual carbon exports from Cambodia

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Foreign demand for agricultural commodities drives virtual carbon exports from Cambodia

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Supplementary material for this article is available [online](#)

Abstract

Rapid deforestation is a major sustainability challenge, partly as the loss of carbon sinks exacerbates global climate change. In Cambodia, more than 13% of the total land area has been contracted out to foreign and domestic agribusinesses in the form of economic land concessions, causing rapid large-scale land use change and deforestation. Additionally, the distant drivers of local and global environmental change often remain invisible. Here, we identify hotspots of carbon loss between 1987–2017 using the dynamic global vegetation model LPJ-GUESS and by comparing past and present land use and land cover. We also link global consumption and production patterns to their environmental effects in Cambodia by mapping the countries to which land-use embedded carbon are exported. We find that natural forests have decreased from 54%–21% between 1987 and 2017, mainly for the expansion of farmland and orchards, translating into 300 million tons of carbon lost, with loss rates over twice as high within economic land concessions. China is the largest importer of embedded carbon, mainly for rubber and sugarcane from Chinese agribusinesses. Cambodian investors have also negatively affected carbon pools through export-oriented products like rubber. The combined understanding of environmental change and trade flows makes it possible to identify distant drivers of deforestation, which is important for crafting more environmentally and socially responsible policies on national and transnational scales.

1. Introduction

Rapid deforestation is a major sustainability challenge, exacerbating environmental breakdown both at the local (e.g. biodiversity loss) and global level (e.g. climate change). Between year 2000 and 2012, about 2.3 million km² of forests were lost globally, with the highest loss rates in the tropics (2100 km² yr⁻¹) (Hansen *et al* 2013). Deforestation is a constraint for reaching the sustainable development goals (SDGs) by 2030 (United Nations 2015), particularly ‘Climate Action’ (goal 13) that aims to combat climate change and its impacts by reducing greenhouse gas emissions, and ‘Life on Land’ (goal 15) that aims to protect, restore and promote sustainable use of terrestrial ecosystems while halting and reversing land degradation and biodiversity loss. High deforestation rates can also be linked to the need for ‘Responsible consumption and production’ (goal 12), since current

deforestation rates are increasingly tied to globally rising demands for food and wood products.

Increased demand for food and other land-based commodities have major effects on CO₂-emissions, since land-use and land-cover changes either release or absorb atmospheric carbon (e.g. expansion of farmland on previously forested land). It is estimated that a complete deforestation of the tropics would result in a global warming equal to the burning of fossil fuels since 1850 (Lawrence and Vandecar 2014). Even though this scenario is unlikely, it shows the global importance of tropical forests as carbon sinks, and that their protection is crucial for limiting further global warming (Defries *et al* 2010).

The current speed of forest loss due to agricultural expansion is of great concern since these changes not only negatively affect carbon storage, but also biodiversity, and other ecosystem services (Foley *et al* 2005). Land use change and direct

exploitation are responsible for more than 50% of terrestrial biodiversity loss, which is declining faster than at any time in human history. Human actions are expected to push about 1 million species to extinction within a few decades unless drivers of biodiversity loss are reduced (Díaz *et al* 2019). Hydrological processes are also shifting due to land-use and land-cover change, leading, for example to desertification in areas of soil and ecosystem degradation, or tropical forest dieback associated with self-amplifying moisture and carbon feedbacks (Falkenmark *et al* 2019).

1.1. Natural resources embedded in trade

International trade caters to the growing demand for food and other products, but it is not only commodities that are being exported. A growing number of studies point to the natural resources that were lost or used during production *in situ* (i.e. embedded natural resources) that are ‘virtually’ exported. Virtual resource flows are commonly studied through footprint calculations, life cycle assessments, and modelling and mapping of trade flows (Henders *et al* 2015, da Silva *et al* 2016, Pendrill *et al* 2019, Seaquist and Johansson 2019). Water, land, and carbon are examples of natural resources that are embedded in production (Henders *et al* 2015, Johansson *et al* 2016) and virtually exported through trade. Their embeddedness is highly context-dependent and relates to modes of production, e.g. water-use efficiency of irrigation systems, water-use and pollution by factories, CO₂-emissions from tractors, or from direct and indirect land-use and land-cover change.

Such methods aim to visualize, analyse, and understand how international trade distances consumption from the socio-environmental impacts of production. It is estimated that between 21%–37% of global land use change associated with international trade of goods and services occur in locations other than where they are consumed (Wiedmann and Lenzen 2018), and that 29%–39% of deforestation-related carbon emissions are driven by international trade (Pendrill *et al* 2019). For example, top-consuming regions like the US, EU, and Japan together appropriate and consume over half of the embedded land in global trade, mainly from Africa, Russia, Brazil, China, and Australia. China, in turn, uses 75% of land embedded in domestic consumption within its own territory, and 25% in foreign countries (Yu *et al* 2013). These figures imply that over the past two decades, there has been a shift in the geography of global supply chains, from producing countries like China, towards other developing countries in the Global South (Wiedmann and Lenzen 2018). The allocation of production has also been accompanied by an overall increase in societal and environmental impacts with global to local effects, e.g. increased greenhouse gas emissions affecting global climate change, water use altering watershed hydrology, and pollution affecting local to regional

health (Yu *et al* 2013, Wiedmann and Lenzen 2018). Harmful social and environmental impacts tend to be higher in low-income countries, since the modes of production are more damaging due to a lack of environmental and social regulations (Moran *et al* 2013, Alsamawi *et al* 2017).

1.2. Economic land concessions and carbon loss in Cambodia

Cambodia is amongst the 15 countries with the largest deforestation rates, globally. Between year 2010 and 2015, the average loss rate was estimated to 1.3% per year (Macdicken *et al* 2016), with the highest forest loss (–22%) in the Mekong region between 1996 and 2015 (Ingalls *et al* 2018a). Even protected areas are under increased pressure from deforestation (Grogan *et al* 2018, Tabor *et al* 2018), and drivers of deforestation have become increasingly international in scope and are strongly tied to global commodity markets and investment flows (Ingalls *et al* 2018b). Political efforts are therefore needed in order to reduce deforestation caused by industrial-scale, export-oriented agricultural production (Defries *et al* 2010).

Cambodia is also one of the least developed countries of the world (rank 146/188 in Human Development Index (UNDP 2019)). Subsistence farming has long been the dominant livelihood, but over the past two decades Cambodian agriculture has experienced a rapid transition from small-scale farms to large-scale monocultures, and its agricultural sector has been increasingly integrated into the world economy (Mahanty and Milne 2016, Kramer 2017). Subsistence farming is currently estimated to support 40% of the population (compared to 80% in the 1990s) (Chan 2017). Similar shifts are also seen in neighbouring countries like Thailand, and is explained by a diversification to industry, tourism sectors, as well as mechanization and commercialization of agriculture.

While illegal logging and migration with expansion of small-scale farmland have caused deforestation in Cambodia over a long period of time (Davis *et al* 2015, Grogan *et al* 2018), economic land concessions (ELCs) have emerged as a major driver in recent decades, triggered by the increased demand for land and agricultural commodities by domestic and foreign actors. From the year 2001, the Cambodian Government granted up to 2.6 million hectares (ha) of land for ELCs, mainly for large-scale rubber, cassava, and sugarcane plantations (up to 10 000 ha in size) for export, but also for forest plantations (e.g. for pulp, and carbon sequestration) and tourism (Scurrah and Hirsch 2015, Hunsberger *et al* 2017, Ingalls *et al* 2018b). ELCs have caused extensive land-use and land-cover changes, and many researchers claim that cassava and rubber plantations currently drive Cambodia’s high local deforestation rates (Hansen *et al* 2013, Grogan *et al* 2018), triggering conflicts over natural resources use, while also

negatively affecting food security (personal communication, 2018).

In response to this, in 2012 the Cambodian government put a moratorium on new ELCs, as well as a partial revocation of poorly-performing ELCs (Mahanty and Milne 2016, Hunsberger *et al* 2017, Ingalls *et al* 2018b). This might have reduced the areal extent of ELCs to about 1.2 million ha (Ingalls *et al* 2018a). Revoked ELCs are currently in the process of re-distribution, but it is unclear to whom and for what purpose (personal communication, 2018).

1.3. Aim of study

Understanding the links between consumption and production is important for developing new conservation efforts and measures, both from the demand- and supply side of the production chain. Mapping and linking ELCs to deforestation in Cambodia have previously been studied by e.g. Davis *et al* (2015), Hurni and Fox (2018), Grogan *et al* (2019), but there is a limited understanding of how land-use and land-cover changes have affected carbon pools (i.e. carbon stored in above- and below-ground vegetation, soil, litter, and harvested products) on a national and sub-national scale, as well as how carbon loss rates have varied over the past three decades in different types of land-use areas in Cambodia (e.g. protected land, and land within and outside of ELCs). This highlights the need to link changes in carbon pools to transnational drivers of change, which requires quantification and mapping of virtual carbon exports.

In light of previous research and research gaps, we estimate how ELCs have affected terrestrial carbon budgets in Cambodia and map to which countries the embedded changes in carbon pools are exported. We reach these objectives by analyzing (1) land-use and land-cover changes in Cambodia from year 1987 to 2017, and (2) how carbon pools, and carbon pool change rates differ within and outside of ELCs, and in protected areas. Finally, (3) we map virtual carbon exports of commodities produced on ELCs.

We then discuss the effects of land-use and land-cover change in relation to three aspects: Hotspots of carbon loss within and outside of ELCs; virtual exports of carbon from domestic and non-domestic ELCs; as well as methodological limitations and assumptions.

2. Data and methods

2.1. Land-cover data

In order to model changes in carbon pools, we used annual land-cover products from 1987 to 2017 developed by SERVIR-Mekong (SERVIR Mekong 2019). These land-cover maps are based on Landsat and MODIS data, and classified through a variety of machine learning algorithms. The approach builds on primitive map layers (e.g. forest canopy cover,

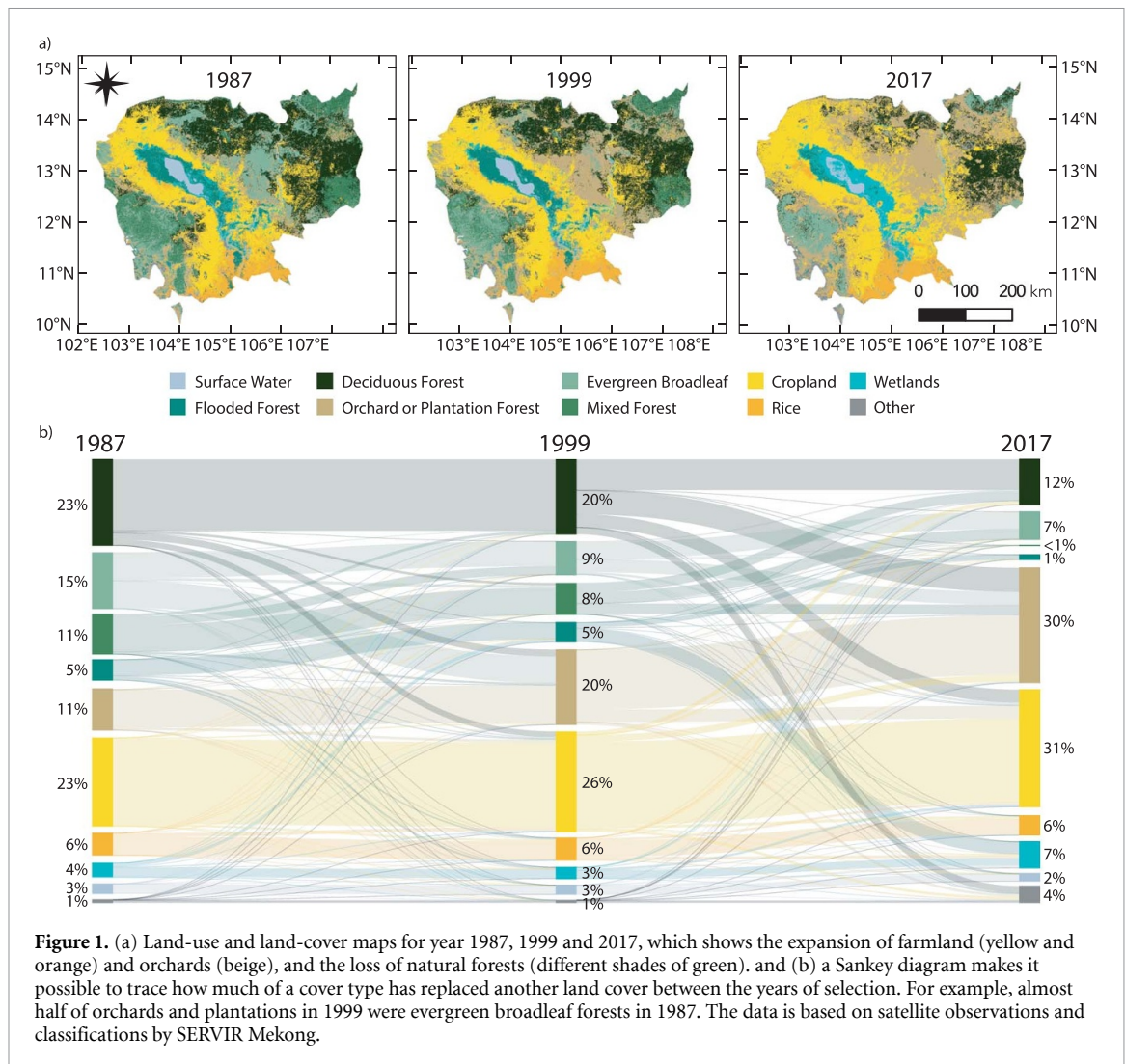
tree height), and decision tree logic for creating land cover classes defined by end users (Saah *et al* 2020). Forest classifications can distinguish between stable (i.e. primary, secondary and non-forested areas) and dynamic types of forests (i.e. loss, gain, rotation) (Potapov *et al* 2019), which is important in areas like Cambodia with high loss of primary forest for the establishments of plantation forests. Land cover maps were assessed with independent validation data (Saah *et al* 2020). SERVIR-Mekong provide two products (i.e. Version 1 and Version 2), and we chose to work with the Version 2 product because of its long-term duration (1987–2017), continuous temporal resolution (annual), high overall accuracy (95%), as well as the participatory and inclusive approach for defining land cover classes (Saah *et al* 2020).

In order to prepare the data for modelling with LPJ-GUESS, the land-cover maps were resampled from 30 m resolution to 6.7 km (approximately 1/16th of a degree). When resampling the data, zonal statistics were calculated for a grid with 6.7 km resolution. This means that each resampled pixel retains the information of the original 51 975 pixels, but as a fraction of land-cover classes of the high-resolution data. The land cover-categories were then recategorized and modelled as natural vegetation, cropland (later divided into fractions of rice and upland cereals based on initial pixel ratios), managed forest (represented by rubber), and grassland.

2.2. Modelling carbon emissions from land-use and land-cover change

Greenhouse gas emissions from agriculture, forestry and other land-use are best estimated by changes in carbon stocks, or CO₂-fluxes from biomass, dead organic matter, soils, and harvest (Aalde *et al* 2006). We used the global dynamic vegetation model LPJ-GUESS (Smith *et al* 2014, Olin *et al* 2015a) to simulate the effect of land-use change on carbon pools (supplementary information (stacks.iop.org/ERL/15/064034/mmedia)).

Climate forcings from CRU-NCEP (Wei *et al* 2014), mean air temperature, precipitation and radiation for the time period 1901–2015 were used in the simulations. Since there are no data for the period 2016–2017, we re-used the 2015 data for those years. Mean wet and dry nitrogen deposition were retrieved from Lamarque *et al* (2010). As soil input, data on mineral fractions (sand, silt and clay) for the dominant soil class in each grid cell from the global data set, WISE (Batjes 2014), was used. All input data sets are at 0.5 of a degree resolution, while the land use is on a finer resolution (see preceding section). There is no plant functional type (PFT) representing rubber trees in LPJ-GUESS, so for this study we developed a new PFT based on TrBE (Tropical Broadleaved Evergreen) to represent rubber trees. As rubber trees are very productive and consume more water than other evergreen tropical trees (Guardiola-Claramonte *et al*



2008), we modified them to reflect this by changing the maximum transpiration rate ($E_{\max}$) from 5 to 7.5 mm day^{-1} . We also implemented paddy rice as a cropland management alternative by allowing the paddies to be flooded during the growing season and by adopting a crop PFT with rice specific allocation parameters from de Vries (1989), see Olin *et al* (2015b).

2.3. Spatial data on economic land concessions and protected areas

ELC data were retrieved from the non-profit and non-governmental organization Cambodian League for the Promotion and Defence of Human Rights (LICADHO). The data include 275 land concessions covering 2.1 million ha, with information about company name, country of origin, start date, size of acquisition and crop production. LICADHO has collected and managed data on land concessions from concession documents as well as field surveys for over five years, but due to the government's lack of transparency it may be incomplete and contain some inaccuracies. This data was used in order to

link the crop production on ELCs with the modelled changes in carbon pools, and map virtual exports of carbon.

In order to see general trends of agricultural exports from Cambodia, we analyze agricultural trade data in terms of quantity (tonnes) and monetary value (US dollars) between 2000 and 2016. Monetary export values were acquired from United Nations Comtrade database, and we decided to focus on the four top agricultural products. These products include rubber, cassava, rice, and wood, and account for 68% of total trade (in monetary value) of land-based products. Export quantities were obtained for the same years from FAO-Stat.

Data about protected areas in Cambodia, with issuing dates between 1993 and 2019, were obtained from Open Development Cambodia. The shapefile includes different types of protected land and when the title was established, dominated by wildlife sanctuaries ($37\,711 \text{ km}^2$) and national parks ($17\,553 \text{ km}^2$), and minor ($<5000 \text{ km}^2$) protected areas like multiple use management areas, protected landscapes, Ramsar sites, and national heritage sites.

2.4. Data collection and interviews

Fieldwork was conducted in November 2018 in order to interview key actors about land-use and land-cover change in the context of ELCs and trade (See full list of interviewees in supplementary information). During fieldwork we also visited Snoul Wildlife Sanctuary and made field observations and measurements at rubber plantations.

3. Results

3.1. Changes in land use and land cover

We observe an accelerated trend of conversion of natural forests into farmland. Natural forests—dominated by deciduous-, evergreen-, mixed-, and flooded forests—decreased from 54%–21% of national coverage between 1987 and 2017, with more rapid changes occurring after 1999 (figure 1). Farmland—dominated by rice, cassava, and maize (Eliste 2015)—increased from 29%–36% with the increase occurring more gradually over time. Orchards and plantations—dominated by rubber and other fast-growing tree types—have increased from 11 to 30%. Annual changes between all types of land covers can be seen in figure S1.

We find that areas within ELCs have the largest fraction of forest loss, declining from 62%–16% between 1987 and 2017 while forests in protected areas have declined from 83 to 43%. In protected areas, the largest loss is seen in wildlife sanctuaries (47%) and less in National parks (23%).

3.2. Changes in carbon pools within and outside of economic land concessions

Our simulations show that 300 million tons carbon (MtC) have been lost from terrestrial ecosystems in Cambodia between 1987 and 2017 (figure 2; see figure S2 for high resolution map). This equals about one year of CO₂-emissions from 280 coal fire plants (EPA (United States Environmental Protection Agency) 2019). The total carbon loss in ELC areas equates to about 69 MtC (23% of total loss), and protected areas have lost about 68 MtC.

Areas within ELCs experienced higher carbon loss rates than other areas. Since ELCs and protected areas differ in spatial extent, covering 2.1 Mha and 6.2 Mha respectively (compared to Cambodia as a whole, 18.1 Mha), it is important to account for spatial extent when presenting carbon pool change rates. Carbon loss rates per ha (tCha⁻¹) between 1987 and 2017 show negative trends for all land use types (figure S3), but loss rates are twice as high within ELCs (−1.05 tCha⁻¹) compared to areas outside of ELCs (−0.55 tCha⁻¹), and lowest in protected areas (−0.45 tCha⁻¹). One-tailed z-tests show that carbon loss rates within ELCs are significantly higher ($Z_{\text{ELC,NoELC}} = -4.7$, $Z_{\text{ELC,PAs}} = -5.0$, $\alpha_{0.05} = -1.64$) than areas outside of ELCs and protected areas

($Z_{\text{NoELC,PAs}} = -1.0$, see calculations in supplementary Information).

Though there are long-term losses in carbon from terrestrial ecosystems, yearly change rates are highly variable (figure 3), and there are five periods of rapid carbon loss (376 MtC; 1990, 1997, 1999–2000, and 2011), and one period of carbon gain (73 MtC; 2005–2007).

3.3. Virtual carbon exports from land-based crop products

We find that domestic ELCs have caused the largest loss of terrestrial carbon pools, followed closely by Chinese and Vietnamese ELCs. In total, 41 MtC of terrestrial carbon have been lost from areas where ELCs have been established since 1999. Figure 4(a) shows that most carbon is exported to neighboring countries in South-East Asia and East Asia (25.7 MtC). Minor carbon importing regions (<1 MtC) are Europe, the Middle East, and North America.

Cambodian ELCs are responsible for the largest share of terrestrial carbon loss, with a total loss of 13 MtC dominated by plantations of rubber (table S1 for details), sugarcane, cassava, and palm oil. Chinese ELCs are estimated to have caused a net carbon loss of 11 MtC, mainly for sugarcane, trees, rubber, and cassava plantations. Vietnamese ELCs have also had large impacts on carbon pools, with 8 MtC embedded in rubber and palm oil plantations. Singapore, Malaysia, and Thailand have ELCs with net carbon losses <3 MtC, and France, Israel, South Korea, Russia, Sri Lanka, and USA <1 MtC. On the contrary, Belgian (rubber) and Japanese (trees) ELCs have had a positive impact on carbon pools with an increase of 0.1 and 0.05 MtC respectively.

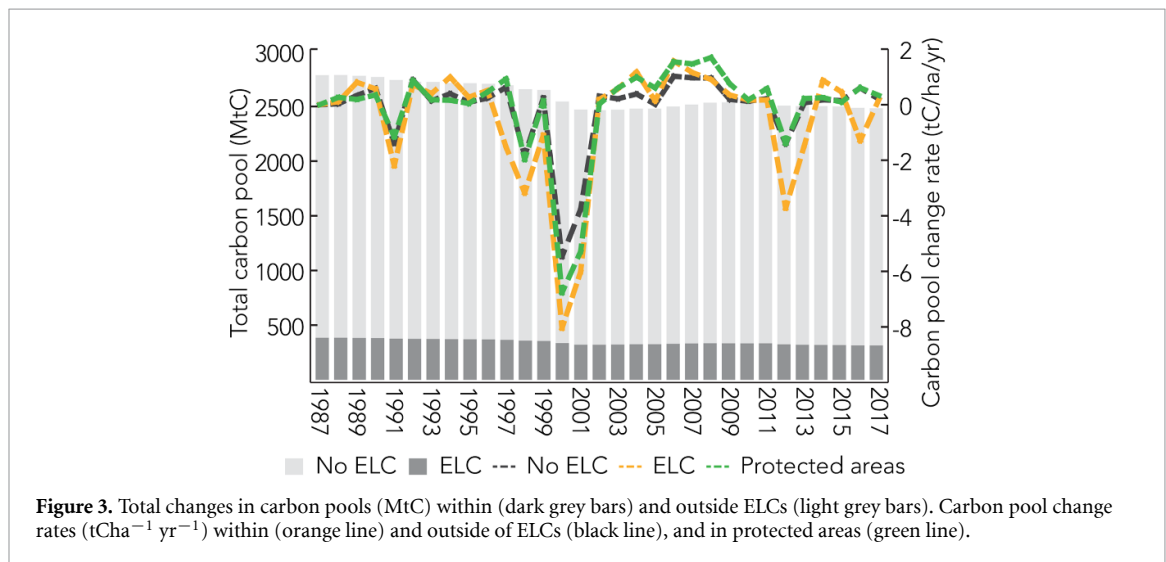
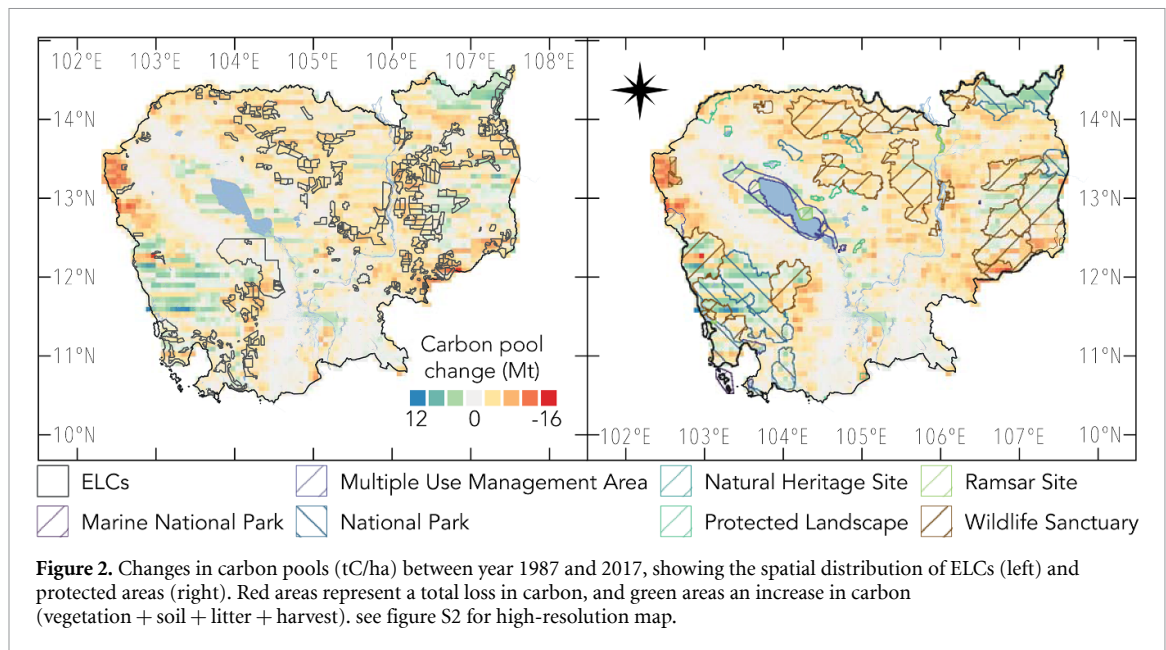
Rubber plantations have had the largest negative effect on terrestrial carbon pools, and between 1999 and in 2017 these plantations drove a total loss of 15 MtC. Sugarcane plantations have caused a loss of 6 MtC, and areas with tree plantations for carbon sequestration, pulp, and wood have had a net loss of 3.4 MtC. All export volumes have increased since year 2000, but export values for rubber and wood decreased after 2011 and 2014, respectively (figure 4(b)).

4. Discussion

4.1. Hotspots of carbon loss within and outside of economic land concessions

As carbon loss rates within ELCs are more than twice as high as in other areas, drivers of carbon loss can be strongly attributed to land-use and land-cover change for export-oriented commodity production.

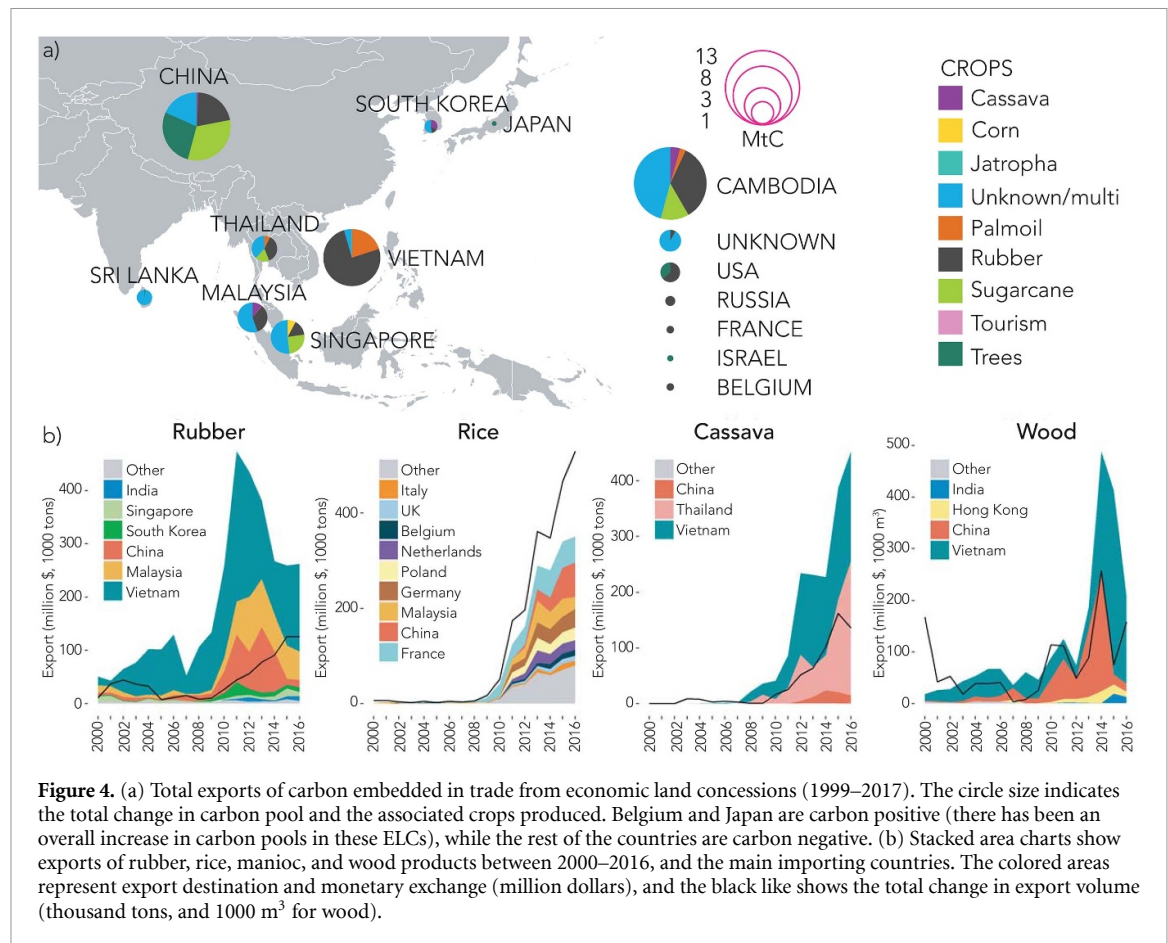
Among protected areas, wildlife sanctuaries have experienced the highest carbon loss due to the expansion of farmland and orchards in these areas. National parks have remained relatively untouched and experienced an overall increase in carbon pools with a net



gain of 9 Mt between 1987–2017 (345 to 354 Mt). About 25% of ELCs overlap with protected areas, and 10% of protected areas overlap with ELCs (table S2). Since most of this overlap is within wildlife sanctuaries (68%), and national parks (30%), ELCs are also likely to be a main driver of carbon loss also in protected areas.

There are areas outside of ELCs that also have high carbon loss rates, particularly along the Thai and Vietnamese border, and in areas around ELCs (figure 2). We hypothesize that this pattern can be explained by the opening of new frontiers, i.e. increasing accessibility to previously remote areas through roads and other infrastructure, which tend to cause rapid land degradation due to intensive resource extraction (Hall 2011). Rapid land use and land cover changes (with high carbon loss) along the Thai border are explained by the opening of a former conflict

zone, as this region was the last Khmer Rouge stronghold (Kong *et al* 2019). After peace agreements, this area experienced a rapid influx of land-poor farmers from lowland regions of Cambodia. Refugees also came searching for land to establish cash-crop farms for maize and cassava production, triggered by high market demands of these crops at the time (Kong *et al* 2019). Mahanty (2019) links more recent deforestation trends along the Vietnamese border to both direct and indirect effects of the of ELCs. Direct effects relate to the establishment of ELCs with cassava and timber production bound for Vietnam, while indirect effects seen around the ELCs, have their origin in increased illegal timber extraction, the search for new land by farmers previously displaced by ELCs, as well as increased rural population due to migrants looking for employment and farmland for themselves and their families (Fox *et al* 2018, Ingalls *et al* 2018b).



The high variability of annual carbon-loss rates shows that there have been periods of both carbon loss and gain in Cambodia between 1987–2017 (figure 2). The carbon gained does not, however, compensate for what was previously lost, since the loss for the whole country between 1987 and 2002 equates to about 321 MtC (180 MtC loss in 2000 and 2001 alone), while the gains were 73 MtC up to 2012, thereafter declining again by 55 MtC. The two years of highest carbon loss rates (2000 and 2012) can potentially be connected to the years when most land has been reported as ELCs (2000 and 2011; figure S4). As 2012 was a year of high carbon loss, it is uncertain as to whether the moratorium on new ELCs in 2012 effectively curbed the establishment of foreign agribusinesses in Cambodia (Fox *et al* 2018). After 2012, about a million passports have been sold to Chinese investors in turn for Cambodian citizenship, which might explain the further exploitation of land by foreign actors (personal communication, 2018).

4.2. Virtual carbon exports for domestic and non-domestic ELCs

Domestic ELCs have caused the largest loss in terrestrial carbon pools since 1999, followed closely by Chinese and Vietnamese ELCs. In this context it is important to consider that agricultural products grown on domestic ELCs are likely to be exported

to neighboring countries for refinement, since no refining plants are currently located in Cambodia (personal communication 2018; Mahanty (2019)). We hypothesize that rubber from Cambodian ELCs is mainly exported to Vietnam, Malaysia, and China, based on the export data presented in figure 3(b), which would increase these countries' virtual carbon imports.

Rubber plantations are responsible for a total loss of 15 MtC, and cassava another 1 MtC, but these numbers are likely to be higher considering that 'unknown' or mixed" crops are estimated to cause another 13 MtC of terrestrial carbon loss. Based on trade data from FAO and UN Comtrade, we hypothesize that the undefined crop categories should be represented by rubber, rice, cassava, and wood, since these exports have increased the most over the last two decades.

Although the export pattern only shows the first order of import destinations (i.e. not considering where rubber is exported after being converted to tires in China). The initial pattern of virtual carbon exports from Cambodia can be partly explained by current and historical geopolitical ties. For example, Chinese investment are currently welcome as a means of bringing economic development (Marks 2000). Cambodian ties to Vietnam go back to the invasion and occupation in 1978, when Vietnamese soldiers drove the Khmer Rouge regime from power.

4.3. Limitations and key assumptions

Tropical forest loss is difficult to observe through coarse or medium resolution satellite imagery, unless the deforestation is extensive and intense (Johansson and Abdi 2019). In order to assess how land-cover maps vary in terms of forest cover and forest loss, we compared existing land cover classifications of Cambodia on a national and sub-national scale. Even though the Version-2 land cover classifications by SERVIR-Mekong have high overall accuracy (94%; Saah *et al* (2020)), we compared the classification with SERVIR-Mekong Version 1 (from now on called Version 1), Kong *et al* (2019), and Venkatappa *et al* (2019). Version 1 was partly resampled by us to identify forest plantations (see supplementary information and figure S5–7). We found that estimates of natural forest loss are on average 29% larger for Version-2 data than other land-cover classifications (see full comparison in table S3). Hansen *et al* (2013) have estimated forest loss in Cambodia to –25% between 2001–2018, which is similar to the Version-2 estimates (21% decrease between 1999–2017; figure 1). Grogan *et al* (2019) obtained forest loss values for Cambodia that were 20% larger than those estimated by Hansen, and highlight that underestimates of forest loss are common in the subtropical biome (dominant in Cambodia). This finding suggests that even Version-2 data might underestimate forest loss in Cambodia, even though estimates are much higher than other classifications.

Due to the rather wide range of land cover estimates, we evaluated the influence of land cover input on simulated carbon pools by also modelling land-cover data from Kong, Venkatappa, and Version 1 (supplementary information, table S4, figure S8). Modelling Version-2 data estimates carbon pools in 2015 to equal 2502 MtC; which is on average 9% lower than model output based on Version-1 data (2726 MtC). The total carbon loss between 2000 and 2015 is however larger for Version 1 (159 MtC, compared to 44 MtC for version 2), because most changes occurred in 1999 in the Version-2 classification (see year-to-year variations in table S4). We did not investigate the uncertainty of the model implementation or parametrisation.

We also tested the influence of land cover for the simulation output by comparing our modelled results, with scenarios of less land cover change: one assuming that land-cover in Cambodia would have remained unchanged since 1999, and one for unchanged land cover since 1987. For the former, the total carbon pool in 2017 would have been 293 MtC larger than now (figure S9), and for the latter the total carbon pool in 2017 would have been 432 MtC larger than the current state (figure S10).

For modelling the land-cover data, we assumed that rubber was planted in all forest plantations, since rubber is the most common woody plant that is planted in Cambodia. The effect was that that

the simulated water use was increased, which led to increased productivity. Additionally, we did not modify the planting density in the rubber plantations which led to the simulation of denser plantations than what would have been the case, thereby overestimating the carbon gain in this land-use class. Finally, we did not distinguish between upland and lowland (flooded) rice, which potentially led to higher carbon storage in cropland soils since the soil below the lowland varieties is anoxic during the growing seasons. Therefore, there is a risk that we underestimated the carbon losses for simulations representing conversion from natural vegetation to rice production.

Several studies show that land-cover transitions from primary or secondary forests to rubber monocultures often result in a loss of above- and belowground carbon stocks and biodiversity (Guo and Gifford 2002, Bunker *et al* 2005, Guardiola-Claramonte *et al* 2010). Although LPJ-GUESS includes changes in soil carbon, these assumptions are currently underdeveloped, and the model is best at estimating above-ground carbon. There are therefore issues about soil carbon we cannot discuss since it would require further refinement and model development.

We have limited our study to focusing on environmental aspects of land use and land cover change in Cambodia over the past three decades, as many other studies focus on the social impacts. Few case-studies highlight positive social impacts, but rather report increasing challenges related to dispossession of agricultural lands, forests, and loss of livelihoods as well as increased conflicts over natural resources which is spurring resistance against the large-scale agribusinesses (Baird and Fox 2015, Neef and Touch 2015, Drbohlav and Hejkrlik 2018, Scheidel and Work 2018).

5. Conclusion

This study is the first to quantify changes in terrestrial carbon stocks for Cambodia between 1987 and 2017. We find that areas with ELC have twice the carbon loss rates compared to other areas in Cambodia, mainly due to the expansion of rubber plantations. We are also the first to map the destinations to which the carbon embedded in production is virtually exported. Virtual carbon is mainly exported to neighboring countries like China and Vietnam. Commercial crops grown on Cambodian ELCs are also likely to be exported to neighboring countries, but further research is needed to identify the destination of these crops. Finally, we account for the first order export destinations (e.g. rubber exported to China for refinement). Future studies could also identify higher order export destinations (e.g. locations of rubber products exported from China for consumption elsewhere). We suggest that the purpose, scale, as well as production location of ELCs should be considered in

order to help formulate effective policies for reducing deforestation rates.

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Data availability statement

The data that support the findings of this study are available upon request from the authors.

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