



RESEARCH ARTICLE

# Drivers of deforestation and degradation for 28 tropical conservation landscapes

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Received: 20 February 2019 / Revised: 25 September 2019 / Accepted: 5 February 2020 / Published online: 9 March 2020

**Abstract** Analysing the drivers of deforestation and forest degradation in conservation landscapes can provide crucial information for conservation management. While rates of forest loss can be measured through remote sensing, on the ground information is needed to confirm the commodities and actors behind deforestation. We administered a questionnaire to Wildlife Conservation Society's landscape managers to assess the deforestation drivers in 28 tropical conservation landscapes. Commercial and subsistence agriculture were the main drivers of deforestation, followed by settlement expansion and infrastructure development. Rice, rubber, cassava and maize were the crops most frequently cited as drivers of deforestation in these emblematic conservation landscapes. Landscape managers expected deforestation trends to continue at similar or greater magnitude in the future, calling for urgent measures to mitigate these trends.

**Keywords** Agricultural commodities · Drivers of deforestation · Protected landscapes · Wildlife conservation

## INTRODUCTION

Tropical forests are increasingly threatened by deforestation, which poses a large threat to global biodiversity (Gibson et al. 2011; Houghton 2012; Laurance 2012; Barlow et al. 2016). These various threats can only be averted if they are well characterised. Extensive evidence suggests that agricultural expansion (Laurance et al. 2014;

Lewis et al. 2015) and infrastructure development (Geist and Lambin 2002; Armenteras et al. 2017) are the key direct drivers of deforestation. Mining and oil exploration have also put pressure on terrestrial nature areas in some countries (Watson et al. 2014). Although natural fires are not common in moist tropical forests, anthropogenic fires have become increasingly common (Lewis et al. 2015). Furthermore, fuelwood and charcoal production in both commercial and subsistence forms are recognized as important drivers of forest degradation, mainly in the African region (Lawrence and Vandecar 2015; Tegegne et al. 2016).

Although the definition of the term 'deforestation' is constantly evolving, it is generally referred to as the conversion of a forest into different land-use types or permanent reduction of the tree canopy cover below the 10% threshold (FAO 2015; Carter et al. 2018). Degradation in contrast refers to a progressive decline of forest structure and composition resulting in a loss of functions on which the resilience of the forest is based. This typically leads to severe alteration of species composition and productivity of that ecosystem (Vásquez-Grandón et al. 2018).

Substantial variation exists in the regional and site-specific realities of deforestation and forest degradation. Key details such as the pace and extent of deforestation, the crops and commodities driving deforestation, and key actors involved all shape the kind of policy responses needed to avert the loss of biodiversity. Variables such as population densities (Tritsch and Le Tourneau 2016), agricultural rents (Carrasco et al. 2017) and accessibility through road networks (Barber et al. 2014) also interact in deforestation and degradation occurrences. Governance factors, including land tenure systems, are also indirectly involved in deforestation (MacUra et al. 2015; Tritsch and Le Tourneau 2016). These indirect drivers, including

**Electronic supplementary material** The online version of this article (<https://doi.org/10.1007/s13280-020-01325-9>) contains supplementary material, which is available to authorized users.

principal actors and market destinations of commodities, receive comparatively less attention. Detailed information required to inform effective interventions tailored to local realities is thus often difficult to obtain.

Remote-sensing advances have enabled forest loss to be mapped at increasingly high spatial and temporal resolutions (Hansen et al. 2013; Margono et al. 2014; Stibig et al. 2014) but these maps generally lack information on the specific crops and actors that drive forest loss. In addition, ground-truthing of data is often required and utilised to improve the accurate classification of land cover types in remote-sensing approaches (De Alban et al. 2018). While commodity-specific studies of land-use change are increasingly available (Gunarso et al. 2013; Ruf et al. 2015; Warren-Thomas et al. 2015; Miettinen et al. 2018) an understanding of whether deforestation is largely driven by thousands of individual smallholders or a few large companies can have substantial impacts on required conservation policies.

Recent studies have filled these gaps to some extent, for example using high-resolution census data to show that large land holdings contributed more to the slowdown of deforestation in the Brazilian Amazon than smallholders between 2004 and 2011 (Godar et al. 2015). In addition, maps of oil palm concession boundaries show that big companies caused more deforestation through oil palm expansion than smallholders in Indonesia (Lee et al. 2014). However, high-resolution census data, ground-truthing data and agricultural concession boundaries are time consuming to collect and not widely available. In addition, it is important to understand the extent of forest degradation and the underlying reasons, which is often difficult to achieve through remote-sensing methods. Further, the loss of non-forest habitats (e.g. savannah, grasslands) is also being regarded as a severe environmental issue (Overbeck et al. 2015) and should be urgently assessed.

The use of expert opinion on the ground can serve as a complement to previous remote-sensing analyses. For instance, expert opinion is useful in understanding whether deforestation has occurred due to commercial or subsistence agriculture, which is hard to capture using satellite images (Ravikumar et al. 2017). Experts, e.g. researchers or conservation practitioners with decades of experience in particular landscapes, have access to the most recent information regarding ongoing activities in their landscapes. Their opinions can be useful in the event that long-term monitoring data are unavailable, as demonstrated in studies of long-term biodiversity declines in protected areas (Laurance 2012). Although country-level data are available through organizations such as Food and Agriculture Organization and USAID, it is not spatially explicit and cannot be used to assess individual landscapes. Global information is also available through selected datasets (Hansen et al. 2013; Venter et al. 2016) but these do not

include all drivers of deforestation and forest degradation at a landscape level.

Furthermore, expert opinion can be gathered quickly through surveys, while fieldwork and remote sensing require substantial inputs of time, money, and expertise. The Wildlife Conservation Society's (WCS) conservation landscapes offer a unique opportunity to attain a comprehensive picture of these deforestation drivers in emblematic conservation landscapes pan-tropically by leveraging the expertise of landscape managers immersed in the realities of their study sites.

We used a network of conservation priority landscapes across three continents where the WCS is active. With the general aim to recognize deforestation trends and drivers across different emblematic tropical conservation landscapes in Asia, Africa and the Neotropics, we:

- (i) identify the current major drivers and patterns of deforestation in 28 landscapes among different regions;
- (ii) identify the presence and reasons for forest degradation within the landscapes;
- (iii) identify specific crops (commercial and subsistence) and other commodities that are causing deforestation;
- (iv) identify associations between commodities and their market destination, principal actors and their land tenure regimes; and
- (v) summarise conservation recommendations made for the landscapes assessed.

## MATERIALS AND METHODS

### Overview

We assessed the presence and drivers of deforestation and degradation across 28 tropical landscapes by administering a questionnaire to WCS landscape managers. In addition, we extracted data for forest cover loss, population density, accessibility (travel time to cities) and agricultural rent for each landscape using Geographical Information Systems (GIS). We used quantitative and qualitative approaches to analyse the data.

### Landscapes

The survey respondents were landscape managers of the WCS tropical landscapes. WCS defines these landscapes according to the presence of six criteria: an explicit goal that targets conservation of ecosystems and native species, specific objectives that ensure conservation, sufficient management conditions to achieve objectives, defined geographical extent, monitoring of threats and mitigation,

and perceived necessity of WCS engagement to achieve conservation goals. We refer to these areas in this paper as ‘WCS landscapes’ for brevity, but in doing so do not mean to imply that WCS owns, manages, or has political authority over these landscapes. These are landscapes in which WCS has ongoing conservation, monitoring and intervention projects.

The 28 WCS tropical landscapes (out of 75 global landscapes) we assessed spread across 18 countries in tropical Asia, Africa and the Neotropics (referred to as America hereafter) (Fig. 1, Fig. S1). We primarily focused on terrestrial landscapes (for landscapes, ‘Bangladesh coast’ and ‘MaMaBay’, which had terrestrial and marine components, we only assessed the terrestrial component). The landscapes ranged from 0.15 to 13 million hectares in size, and had between 7.27% and 100% of their land protected (Table S1; WDPA 2018). The average values of land protected in the considered landscapes of Asian, African and American regions were 64%, 24% and 65%, respectively.

### Data collection

Our questionnaire, which included both open-ended and closed questions, asked WCS landscape managers about the presence and severity of deforestation within their landscapes, major drivers of deforestation and degradation, agricultural commodities responsible for deforestation, actors behind agricultural drivers and conservation recommendations (Table 1, Supplementary methods and Appendix 1).

We gathered data on both proximate (direct) and underlying (indirect) drivers of deforestation. Direct drivers, identified as human activities that directly affect forest cover, results in the reduction of carbon stocks as well (Kissinger et al. 2012). Indirect drivers—complex, socio-economic, cultural, political and technological processes—have an impact on the proximate drivers causing deforestation and forest degradation (Kissinger et al. 2012). For instance, in our survey, we elicited information on direct drivers of deforestation and forest degradation (e.g. agriculture, infrastructure development, charcoal production) and indirect drivers (e.g. market destination, principal actors, and land tenure).

To complement our data and to identify additional underlying drivers at the landscape level, we gathered data on forest loss (Hansen et al. 2013), population density (CIESEN 2016), agricultural rents (Carrasco et al. 2017) and travel time to cities (Weiss et al. 2018). Further, we calculated mean and standard deviation for these variables for tropical Asia, tropical Africa and tropical America to identify if our landscapes deviated from regional characteristics (see supplementary methods).

### Data analysis

We used R version 3.4.3 (R Core Team 2017) to analyse and visualise our data.

For objective (i), we used descriptive statistics and non-metric multi-dimensional scaling (NMDS). For objectives (ii) and (iii), we used descriptive statistics. We used canonical correspondence analysis (CCA) for the analysis of objective (iv) including the commercial and subsistence commodities that showed highest frequencies of occurrence within the considered landscapes. We specified the market destination, principal actors and the percentage of land under different land tenure regimes as explanatory variables in the CCA models. For objective (v), we qualitatively analysed the survey responses.

## RESULTS

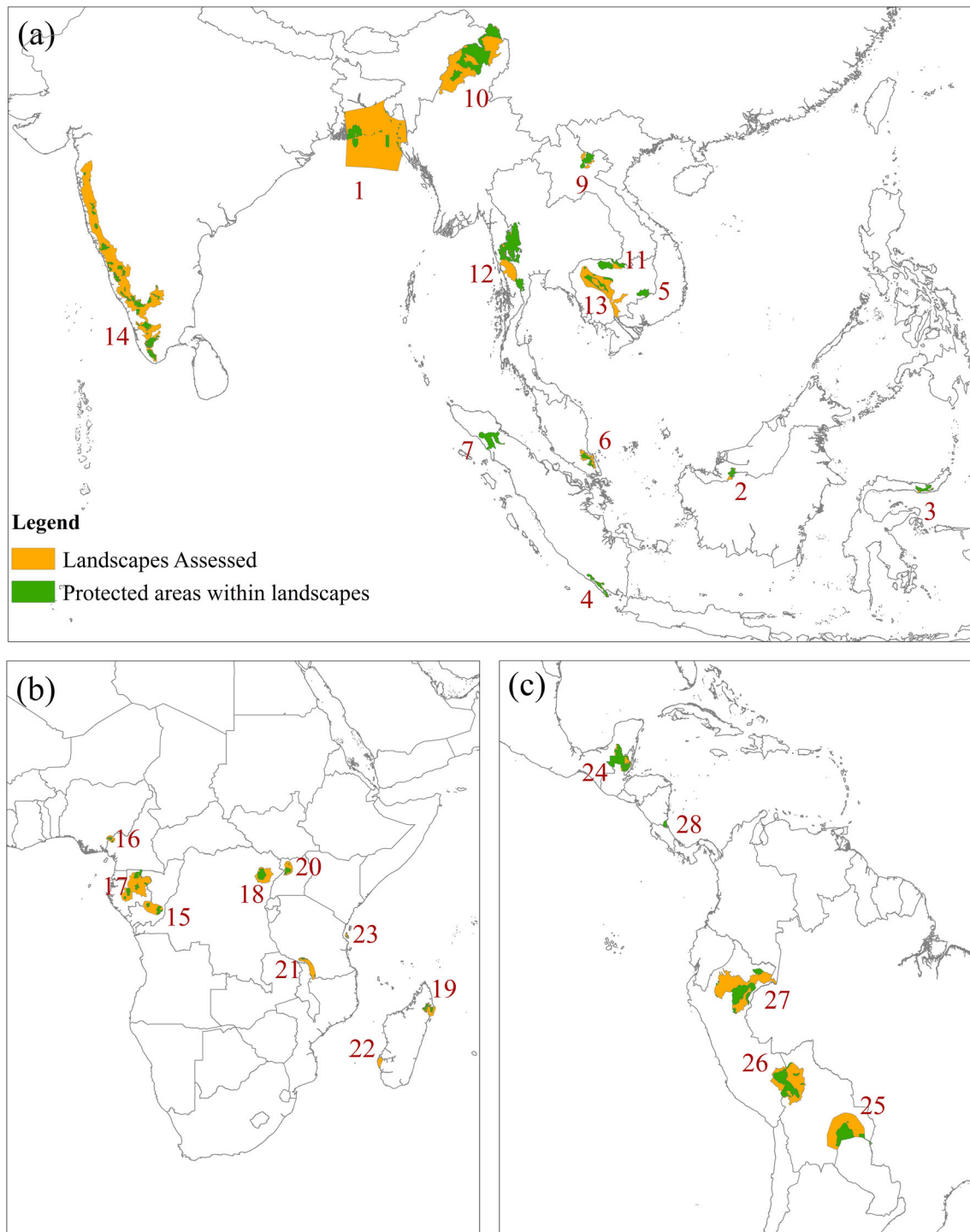
### Deforestation and forest cover loss

According to our respondents, 93% (26 out of 28 responses; Table S2) of the assessed tropical landscapes faced ongoing deforestation (Fig. S2-a). Only two landscapes, Bateke and Gabon forest in Gabon, appeared to have avoided forest loss (Fig. S2-b). The reported percentage of land affected by deforestation in each landscape varied while data were unavailable for some landscapes (Fig. S2-b). The highest reported percentages were observed in Southern Highlands in Tanzania and Batang-Ai/Lanjak-Entimau in Malaysia (Fig. S2-b).

Forest cover loss (calculated using Hansen et al. 2013) has continued to increase in these landscapes although the trend has slowed down post 2010 (Fig. S3-a). The highest forest loss (in km<sup>2</sup>) seem to have occurred in the American landscapes (Gran Chaco-Bolivia, Maya forest, Greater Madidi-Tambopata and Greater Samiria-Yavari) compared to African and Asian landscapes (Fig. S3-a, Table S1). The five landscapes with highest percentage forest loss were Endau Rompin in Malaysia, Zanzibar forest in Tanzania, Eastern Mondulkiri forests in Cambodia, Northern Plains in Cambodia and Maya forest in Guatemala (Fig. S3-b). The protected area forest loss was highest in the Maya forest in America (Table S1, Fig. S4-a). American and Asian landscapes had a higher protected area forest loss compared to African landscapes (Fig. S4-a).

### Drivers of deforestation

Among the nine drivers of deforestation considered (Table 1), agriculture showed the highest severity, followed by settlement expansion, infrastructure



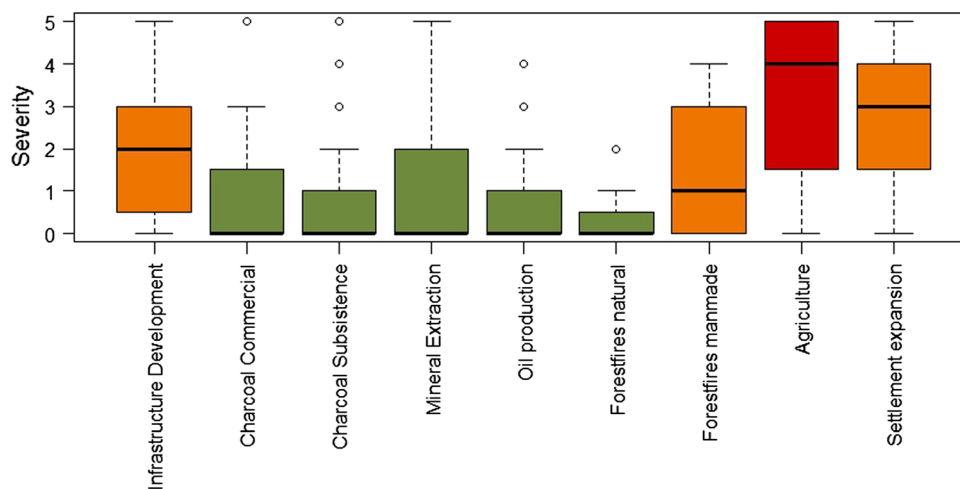
**Fig. 1** Landscapes assessed for the study. **a** Tropical Asian landscapes, **b** Tropical African landscapes, **c** Tropical American landscapes. The numbers indicate the “Landscape Number”. Names of the landscapes are given in Table S1 of supplementary information

development, and forest fires (anthropogenic) (Fig. 2). The percentage of land affected by each driver showed a similar pattern where agriculture, the main driver, affected 20% of land considered (Fig. S6). The potential impact for the next decade differed between different drivers, as predicted by

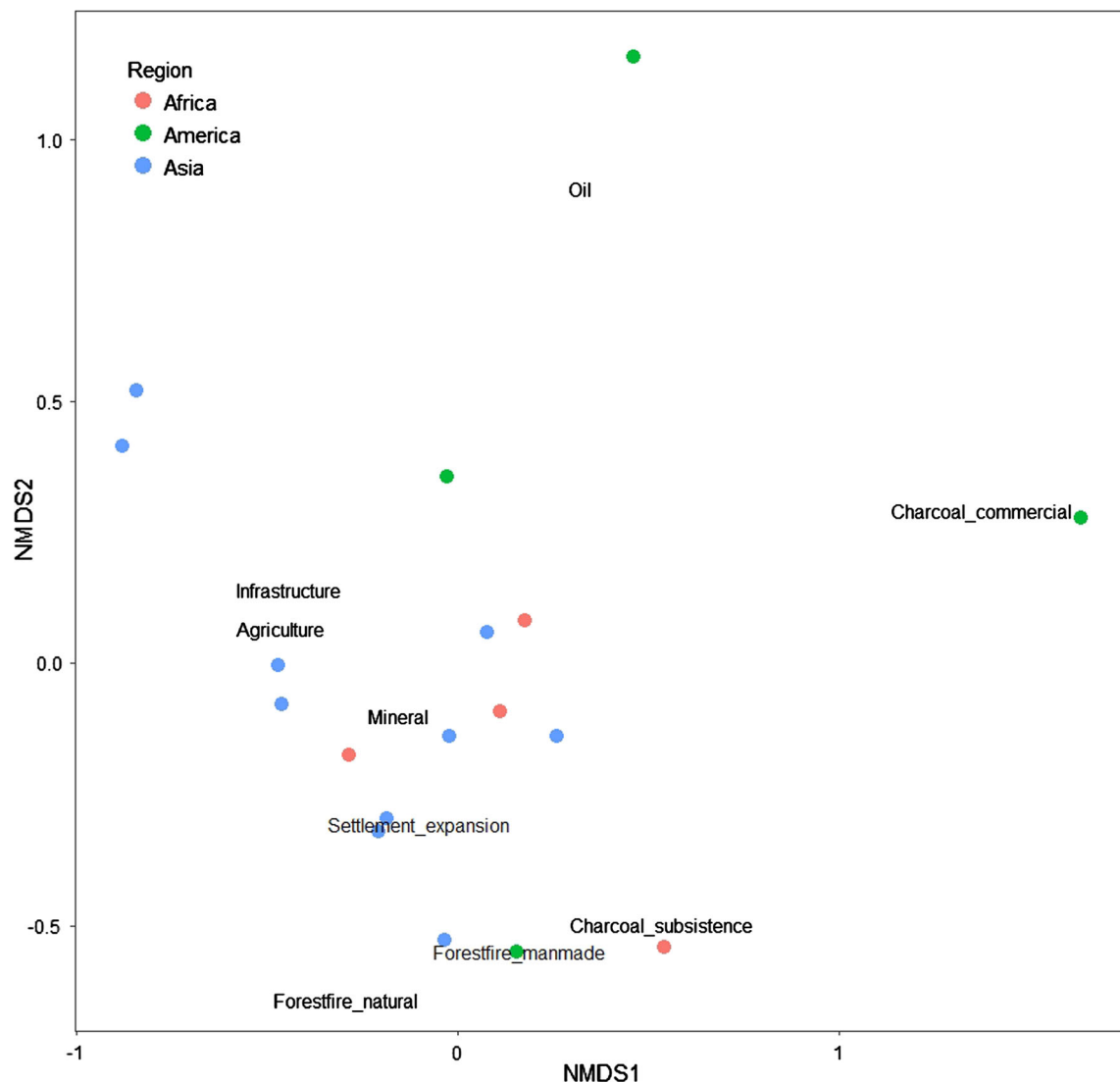
the respondents. The drivers of deforestation predicted to increase most were infrastructure development and settlement expansion followed by agriculture and mineral extraction (Table 2). Agricultural encroachment was expected to increase in 65% of the landscapes and to stay

**Table 1** Summary of question categories of the survey questionnaire used for the study (Please refer to Appendix 1 in SI for the complete questionnaire)

| Category   | Variables   | Additional information   |
|--|---|--|
| Deforestation  | Presence, percentage, Severity, future trends   | Deforestation within the landscape (10 year time scale)  |
| Forest degradation                                   | Presence, causes  |  |
| Agricultural encroachment                            | Presence  | Encroachment through commercial or/and subsistence agriculture   |
| Commercial agriculture as a driver of deforestation  | Top 3 commercial commodities, severity, percentage, future trends, market destination, principal actors | Market destination (domestic, international etc.), principal actors (small holders, medium-sized enterprise, large-scale or industrial), severity (scale of 1–5)   |
| Subsistence agriculture as a driver of deforestation | Top 3 subsistence commodities, severity, percentage, future trends                                      |  |
| Drivers of deforestation                             | Severity, percentage, future trends   | Drivers include infrastructure development, charcoal making (commercial), charcoal making (subsistence), mineral extraction, oil exploration/production, forest fires (natural), forest fires (manmade), agriculture, settlement expansion |
| Land tenure  | Percentage, security of tenure  | Tenures include public land (government administered), public land (designated for community use), private land (community owned), private land (individuals or firms), disputed land  |
| Conservation actions                                 | Past and present actions, potential recommendations   | Conservation actions include site/area protection, resource and habitat protection, site/area management etc.  |

**Fig. 2** Severity of different drivers of deforestation in the landscapes considered. High, medium and low severity is indicated by the colours red, orange and green, respectively**Table 2** The potential impact of different drivers of deforestation as predicted by respondents (percentage of responses for each category of impacts)

| Potential impact over the next decade (predictions) | Infrastructure development | Charcoal making (Commercial) | Charcoal making (Subsistence) | Mineral extraction | Oil exploration/production | Forest fire (natural) | Forest fire (manmade) | Agriculture | Settlement expansion |
|---|----------------------------|------------------------------|-------------------------------|--------------------|----------------------------|-----------------------|-----------------------|-------------|----------------------|
| Increasing  | 73.7                       | 41.7                         | 36.4                          | 61.5               | 54.6                       | 0                     | 40                    | 65          | 73.7                 |
| Stay the same                                       | 15.8                       | 33.3                         | 27.3                          | 23.1               | 18.2                       | 88.9                  | 33.3                  | 30          | 15.8                 |
| Decreasing  | 0                          | 8.3                          | 9.1                           | 7.7                | 9.1                        | 0                     | 13.3                  | 0           | 5.3                  |
| Unknown   | 10.5                       | 16.7                         | 27.3                          | 7.7                | 18.2                       | 11                    | 13.3                  | 5           | 5.3                  |



**Fig. 3** NMDS plot for the reported percentage of landscapes affected by different drivers of deforestation. The drivers are Infrastructure development, Charcoal making (commercial), Charcoal making (subsistence), Mineral extraction, Oil exploration/production, Forest fire (natural), Forest fire (manmade), Agriculture and Settlement expansion

the same in 30% of the landscapes according to respondents (Table 2).

According to our NMDS analysis, agriculture, infrastructure development, mineral production, charcoal making (subsistence), settlement expansion and forest fires (anthropogenic) were more associated with the Asian region (Fig. 3). Oil production and charcoal making (commercial) were associated mostly with America (Fig. 3).

Population densities were highest in the landscapes of the Bangladesh coast, Western Ghats and Zanzibar forest (Table S1, Fig. S4-b). Although larger in size, the population densities in the American landscapes seemed to be much lower (Fig. S4-b). All our landscapes fell within one standard deviation from the mean population density of the region (Table S1). Agricultural rent greatly varied between

the landscapes (Fig. S4-c). With respect to travel time to cities, the majority of our landscapes were within one standard deviation from the mean (Table S1 and Fig. S4-d). We did not identify any significant patterns between forest loss and these additional variables (Fig. S5). These results suggest the landscapes are not unusually different from other areas in their respective continents.

### Forest degradation

According to respondents, forest degradation was present in 90% of the landscapes assessed (Table S2). Respondents identified illegal logging and selective timber extraction activities within protected boundaries as the main causes. Asian landscapes faced issues of household fuelwood

extraction and small-scale agriculture, while small-scale charcoal production was associated with forest degradation in African landscapes.

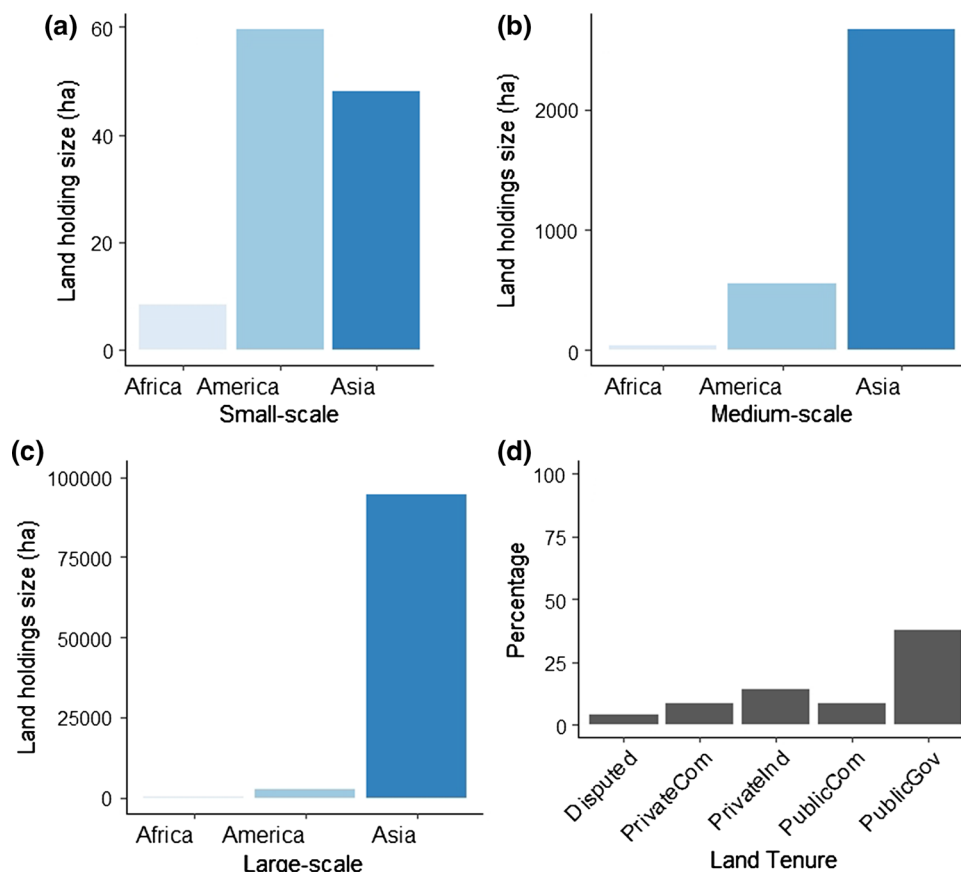
The loss of non-forest habitats created serious environmental issues in 43% of the landscapes (Table S2). According to the managers, the loss of grasslands and wetlands was endangering wildlife and ecosystems in all three regions. The main reasons, as reported, were attributed to small-scale agricultural activities, ranching and poorly managed irrigation.

### Agricultural land holdings and commodities

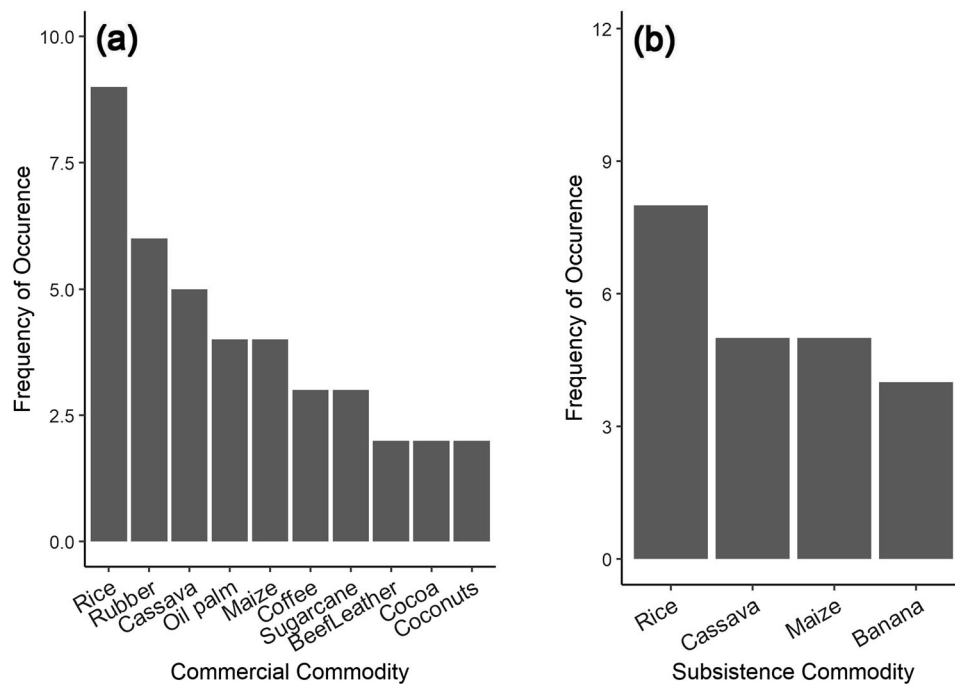
Agricultural encroachment occurred in 92.3% of the landscapes assessed (Table S2). In 61.5% of the landscapes, both commercial and subsistence agriculture drove deforestation. Small-scale holdings ranged from 0.5 to 50 ha (mean  $5.8 \pm 2.6$ ) in size (Fig. 4a). Medium-scale holdings were around 200 ha (mean  $171.9 \pm 90.2$ ) (Fig. 4b) while large-scale holdings were expanding up to

80 000 ha (mean  $5399.1 \pm 3602$ ) (Fig. 4c). The main type of land tenure in the majority of surveyed landscapes was government-owned land tenure followed by private and individual/firm-owned land tenure (Fig. 4d).

Rice, rubber, and cassava appeared more frequently as the top three commercial commodity drivers of deforestation in the study landscapes (Fig. 5a). Rice, cassava, and maize were the most frequently cited subsistence commodities (Fig. 5b). Rice was the most frequently cited commercial and subsistence crop driving deforestation (rated as commodity 1 in the survey) (Figs. S7-a, S7b). Landscapes including Northern Plains, Tonle Sap (Asia), and Southwest Dry Forest (Africa) reported rice to be the top commercial crop while it was frequently cited within the commercial crops in other Asian landscapes (Table S1). At the subsistence level, in Asian landscapes such as Bukit Barisan, Eastern Mondulkiri, Nam Et-Phou Louey and Northern Forest Complex rice was the top crop driving deforestation. The situation was similar in MaMaBay, Murchison and Southwest Dry Forest in Africa (Table S1).



**Fig. 4** a–c Reported area sizes of small, medium and large-scale agricultural land holdings, respectively; d Percentages of land under different land tenures as reported by the managers (PublicGov- Government-owned land tenure, PrivateInd- Private or individual-owned, PrivateCom- Private community used, Publiccom- Government-owned, community used and Disputed land)



**Fig. 5** Frequency of occurrence of different commodities in the considered landscapes: **a** Top ten commercial commodities listed as commodity 1, 2 or 3, **b** Top four subsistence commodities listed as commodity 1, 2 or 3. Please note that the sample sizes were different and that the data availability was lower for ‘America’

### Associations between crops and actors

Out of the CCA models tested (Table S3), the best CCA model yielded an inertia of 4.96 out of which 95% was explained by the constraints specified (Fig. 6). According to this analysis, commercial crops such as rice, rubber, coffee and sugarcane were more associated with international markets and the Asian region. In contrast, subsistence cultivation of maize, cassava, and bananas was more associated with the African region. Commercial beef and leather production were more associated with the American landscapes (Fig. 6).

### Conservation recommendations by survey respondents

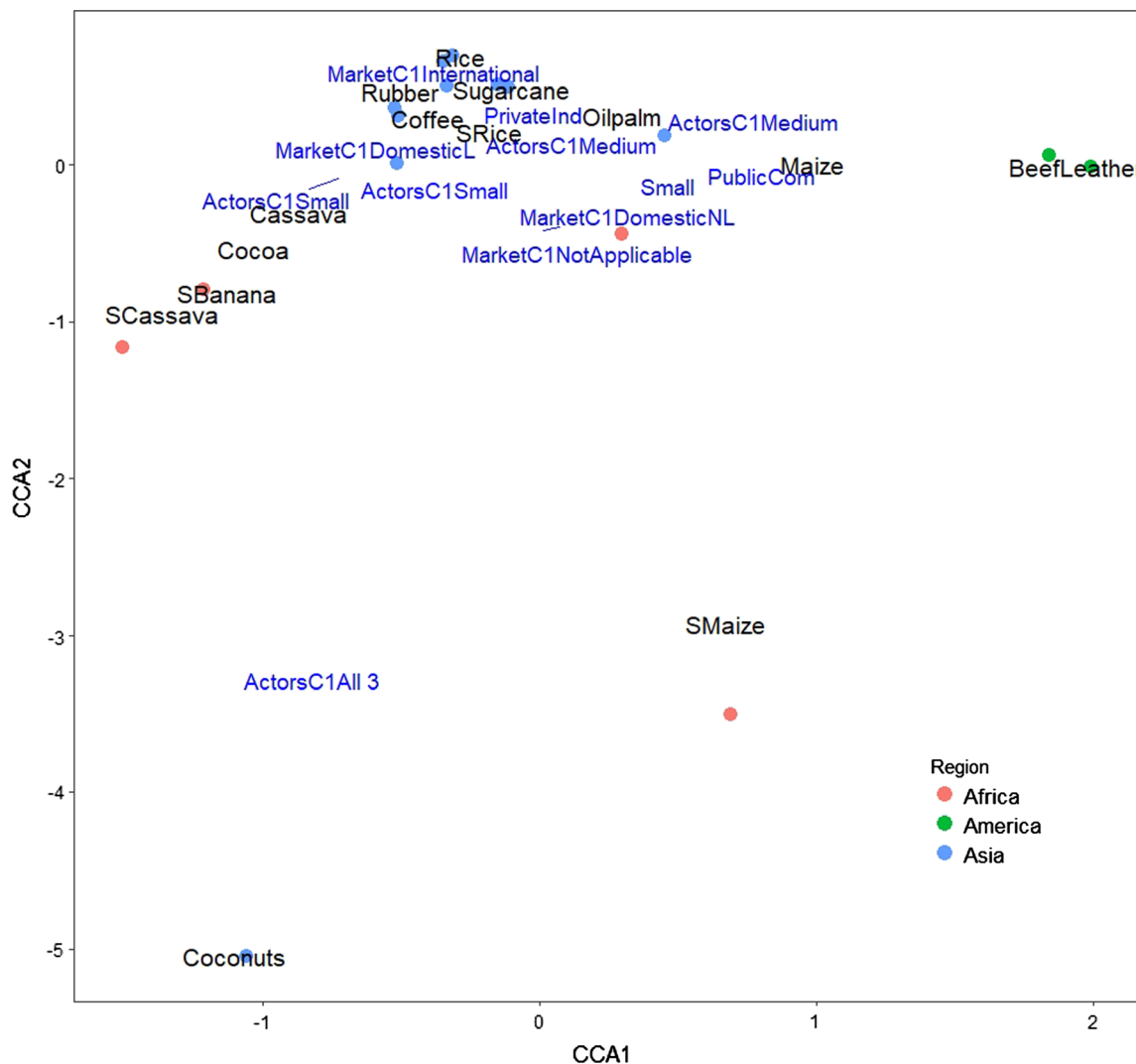
The current conservation actions being taken and recommendations for the future varied between landscapes of the three regions (Table S4 and Fig. S8). The most common actions for Asian landscapes were resource & habitat protection, site/area management and awareness & communications. The landscape managers of Asian landscapes commonly recommended policies and regulations, compliance and enforcement, conservation payments and linked enterprises for the future among many others. Resource and habitat protection, site/area management and protection, and training were commonly observed and recommended for our African landscapes together with awareness, policies and conservation payments. Overall,

the conservation action most commonly recommended for all landscapes was “policies and regulations” while ex situ conservation and invasive species control were not given much importance (Table S4). Actions recommended varied greatly between individual landscapes (Fig. S8).

## DISCUSSION

Deforestation continues to occur in varying severities across the tropics, due to a variety of direct and indirect drivers of deforestation. Our study portrays that deforestation and degradation is currently happening in the majority of the WCS conservation landscapes assessed irrespective of the area under legal protection, as found in previous studies on the tropics (Nelson and Chomitz 2011; Jones et al. 2018). The results show that agricultural expansion is the greatest driver of deforestation within these emblematic conservation landscapes with the most frequently identified commodities being rice, rubber, cassava and maize. Large-scale commercial agriculture and international market destinations were more commonly observed in the studied landscapes in Asia in contrast to subsistence agriculture being commonly observed in the African landscapes. Agricultural land holdings also differed in size between the three regions.

The total forest cover loss was highest in the American landscapes we studied (above 16900 km<sup>2</sup>), compared to Asia (5500 km<sup>2</sup>) and Africa (4300 km<sup>2</sup>). However, the



**Fig. 6** CCA analysis conducted for top commercial and subsistence (referred to by letter ‘S’) commodities (black text) and their explanatory variables (size of land holdings (Small), market destination, principal actors and land tenure (blue text)). Market destination of commodity 1 (MarketC1) includes domestic local (Domestic L), domestic non-local (DomesticNL), international, all or unknown markets. Responses that indicated ‘not applicable’ also existed. Principal actors of commodity 1 (ActorsC1) include smallholders (Small), medium-sized enterprises (Medium), large-scale/industrial agriculture (Industrial), small and medium (SmallMed), medium and large (MedLarge) and all actors (All). Land tenure include public land/government-owned (PublicGov), public land/community use (PublicCom), private land/community use (PrivateCom), private land/individual use (PrivateInd) and disputed land (Disputed)

percentage forest loss was higher in some Asian landscapes. Previous studies also find that area-weighted forest loss is higher in Asia compared to other regions for protected areas (Spracklen et al. 2015). Maya forest in Guatemala seem to have suffered a significant loss of protected lands compared to other landscapes. The protected area loss was lower in the African landscapes, but this could be because they had lower percentages of protected areas compared to Asian and American landscapes. The reported deforestation by landscape managers was generally higher for most of our landscapes than the calculated forest loss (Hansen et al. 2013). This could be because global forest cover data (Hansen et al. 2013) does not differentiate

between tree crops and natural forests. Therefore, the calculated forest loss would probably be an underestimation for most of the landscapes. However, there could also be instances where remote sensing captures natural changes in forests such as wild fires and tree falls which landscape managers may not classify as deforestation.

The findings on agricultural drivers are corroborated by previous studies which estimated that the majority of global deforestation was caused by agricultural expansion (Laurance 2012; Carter et al. 2018). The 28 landscapes we assessed revealed that agricultural encroachment is the most pressing concern in these regions leading to deforestation. Human settlement expansion, was the second-

most serious threat to tropical forests, supporting previous findings, especially in Neotropical and African countries (Kissinger et al. 2012). Our findings and available evidence suggests that Asian forests too, face pressures due to human settlements (Phumee et al. 2018).

Research suggests that infrastructure development is also a major cause of deforestation in developing countries (Laurance et al. 2015). For example, previous studies have found that in African countries this is a serious problem (Tegegne et al. 2016). Giving similar observations, some African landscapes that we assessed were located in such developing countries (e.g. Congo, Camaroon, Madagascar). In addition, we found that anthropogenic forest fires (Nelson and Chomitz 2011) were also an important driver of deforestation in all three regions. Commercial charcoal production, more associated with the American landscapes, continue to worsen the situation leading to forest degradation. This has been observed in countries such as Peru in South America (Bennett-Curry et al. 2013). Logging and timber extraction activities seem to drive degradation in Asia while charcoal and fuelwood drive degradation in Africa as identified by previous research as well (Kissinger et al. 2012).

Underlying (indirect) drivers such as population density, agricultural rent and travel time to cities did not show any clear relationships with forest loss. One reason could be because our landscapes were politically and ecologically very diverse. The conventional forest transition theory could be used to gain a better understanding about these occurrences (Barbier et al. 2010). In our landscapes where forest loss was highest (Gran Chaco-Bolivia, Maya forest and Greater Madidi-Tambopata in America), travel time to cities were at a medium level and agricultural rents were not very high. The population densities were low. It could be inferred that these landscapes are at an earlier phase of the forest transition curve. The landscapes that had the lowest forest loss (Batang Ai, Indio-Maiz and Bogani-Nani Wartabone) had low agricultural rents and medium to high travel time to cities (low accessibility). However, these landscapes were largely protected which may be the reason for low forest loss. In our study, an equal number of landscapes reported commercial or subsistence agriculture as drivers of deforestation. Available evidence from Africa and Asia suggests that subsistence agriculture too, drives a considerable amount of deforestation (Kissinger et al. 2012). Further, studies conducted in Congo and Cameroon, in the African region, have established that subsistence agriculture is the most important driver of deforestation in those countries at present (Tegegne et al. 2016). Although subsistence agriculture is suggested to be a main driver in countries such as Peru based on remote sensing and the size of deforestation patches, this assertion is not well

substantiated without complementary fieldwork studies (Ravikumar et al. 2017).

One of our main findings is that the frequency of reporting rice as a main driver exceeds all other crops in the tropical landscapes we studied. Rice was reported to be a top commercial crop mainly in Asian and African landscapes. It was reported as a top subsistence crop too driving deforestation in landscapes from both regions. Rice appears thus to be underestimated as a driver of deforestation. Although research had identified rice as a rapidly expanding crop and deforestation driver in tropical regions (Gibbs 2010), it remains relatively unstudied. Further research is required to identify the extent of deforestation caused by this staple food crop important to billions of people.

The second crop identified to be a deforestation driver in the considered landscapes was rubber. The demand for rubber continues to expand at a significant rate leading to expansion of plantations at both industrial and smallholder scales (Warren-Thomas et al. 2015). As an industrial crop, it has gained wide attention as a driver of deforestation and continues to be scrutinized (Ahrends et al. 2015; Warren-Thomas et al. 2015). Cassava has also been identified as an important crop in tropical countries (Gibbs 2010) but does not currently receive enough attention as a driver of deforestation. It should be noted, however, that our data does not estimate the extent of deforestation these crops cause and refers only to the frequency of their presence in our landscapes. Agricultural commodity production in the tropics is increasingly destined for export. International demand for agricultural commodities has increased the role of agriculture in driving tropical forest conversion (Henders et al. 2018). We found that certain commodities such as rice, rubber and coffee were more strongly associated with international market destinations. The landscapes in which these crops were prominent in were mostly located in Asia. Countries such as Thailand, India, Myanmar and Cambodia exported large quantities of rice to international markets in 2015 alone (UN Comtrade 2018). Thailand, Indonesia, Malaysia, Cambodia and Myanmar also exported rubber similarly within the same period of time (UN Comtrade 2018). This information is consistent with our findings regarding international markets.

Weak land tenure may contribute to the deforestation through agricultural expansion (Woods 2012; Robinson et al. 2018). The landscapes we studied were mainly under government-owned land tenure and individual/firm-owned land tenure. Tenure regularization can help to control deforestation (Godar et al. 2015) and is an important avenue of future research. Studies suggest that recognizing individual land tenure could help restrict deforestation and that the future land use that have not been registered is uncertain (Tritsch and Le Tourneau 2016).

The relative contribution of different actors to deforestation may vary over space and time. Agriculture in the American landscapes we studied was largely characterized by small and medium-scale land holdings, in contrast to the medium and large holdings more common in Asia. The trends in our data only represent the period between the years 2005–2015. According to other studies, in South America, deforestation caused by commercial crops was much higher compared to subsistence crops from 1990 to 2005 (De Sy et al. 2015). There is also evidence for large field sizes in deforested land to be common in Latin America and East Asia before year 2005 (Dang et al. 2019). In the Amazon region, the annual deforestation caused by large-scale holdings decreased due to policy interventions and regulations from 2005 to 2011 but small-scale activities continued to occur (Godar et al. 2015). However, large clearings of primary forest for crops like oil palm and cacao have also continued in the American region (Finer and Novoa 2015). Larger forest clearings driven by industrial-scale actors (Austin et al. 2017) may reflect our results for Asia where most landholdings were medium-large scale. It is possible that small-scale actors could encroach into protected lands without repercussions from government regulations more easily than large-scale actors (Dang et al. 2019). This could be due to land scarcity or the displacement of smallholders by large-scale companies (Dang et al. 2019). Proactive programmes such as the TRASE project (Global Canopy 2018) could intervene by increasing the transparency of agricultural commodity supply chains.

That rice, rubber and cassava—often linked to smallholders—appeared as the main crops behind deforestation in the studied landscapes could seem at odds with previous research that has identified large agribusinesses actors linked to oil palm and soybean as the main drivers of deforestation. Research has for instance shown that the share of deforestation due to large-scale agribusinesses has increased substantially since 2001 (Finer and Novoa 2015). This contradiction could respond to the idiosyncrasies of our landscapes, in their majority of high emblematic value for conservation. Conservation importance is linked to protection and institutional measures that keep large agricultural concessions outside the landscapes. This could explain our unusual results. Thus, our results should not be interpreted to indicate that deforestation by commodities such as oil palm and soybean are declining but rather that diverse drivers are at play, specifically in the conservation landscapes studied. Similarly, our results should not be interpreted as putting the blame on smallholders, especially when the role of global corporations and their capacity to change the paths of development globally are clearer than ever (Folke et al. 2019). This warning is linked to the main caveats of our study: our results are not entirely

representative of tropical landscapes. Further, these landscapes are disproportionately protected. Response rates and confidence estimates also varied between the three regions assessed. Therefore, our study depicts landscape level trends rather than regional or global trends. We report the responses given and predictions made by on-the-ground experts working on these landscapes. Another critical caveat is that our study corresponds to a snapshot in time and does not account for the prevailing temporal trends by which, e.g. large agribusinesses have been shown to increasingly occupy a larger fraction of the deforestation footprint (Finer and Novoa 2015).

## CONCLUSIONS

The most frequently cited agricultural commodity driver of forest change in the tropical landscapes we surveyed was rice, followed by rubber and cassava. Rice and cassava have previously been relatively overlooked in conservation research. After agriculture, settlement expansion and infrastructure development are also significant drivers of deforestation in the landscapes we studied and are likely to increase their relevance in the future. There were identifiable patterns in actors, crops and recommended conservation interventions between the studied landscapes in the three tropical regions, Asia, Africa and America (the Neotropics). Asian landscapes were characterized by large-scale commercial agriculture destined for international markets which also relate to medium-large-scale land holdings within the landscapes considered. In contrast, African landscapes were characterized by subsistence agriculture and domestic markets. American landscapes had greater association with the beef and leather industries and small-medium-scale land holdings. While these results do not indicate that large-scale commercial agriculture is declining in these regions, they do suggest, however, that habitat loss is pervasive across landscapes of conservation importance, describing complex and varied direct and indirect drivers of deforestation that seem to have marked typologies by continent.

**Acknowledgements** We would like to acknowledge the support received from the Wildlife Conservation Society for the surveys conducted. We would also like to thank the Department of Biological Sciences of the National University of Singapore and the Government of Singapore for providing the NUS-IRP scholarship.

## REFERENCES

- Ahrends, A., P.M. Hollingsworth, A.D. Ziegler, J.M. Fox, H. Chen, Y. Su, and J. Xu. 2015. Current trends of rubber plantation

- expansion may threaten biodiversity and livelihoods. *Global Environmental Change* 34: 48–58. <https://doi.org/10.1016/j.gloenvcha.2015.06.002>.
- Armenteras, D., J.M. Espelta, N. Rodríguez, and J. Retana. 2017. Deforestation dynamics and drivers in different forest types in Latin America: Three decades of studies (1980–2010). *Global Environmental Change* 46: 139–147. <https://doi.org/10.1016/j.gloenvcha.2017.09.002>.
- Austin, K.G., A. Mosnier, J. Pirker, I. McCallum, S. Fritz, and P.S. Kasibhatla. 2017. Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments. *Land Use Policy* 69: 41–48. <https://doi.org/10.1016/j.landusepol.2017.08.036>.
- Barber, C.P., M.A. Cochrane, C.M. Souza, and W.F. Laurance. 2014. Roads, deforestation, and the mitigating effect of protected areas in the Amazon. *Biological Conservation* 177: 203–209. <https://doi.org/10.1016/j.biocon.2014.07.004>.
- Barbier, E.B., J.C. Burgess, and A. Grainger. 2010. The forest transition: Towards a more comprehensive theoretical framework. *Land Use Policy* 27: 98–107. <https://doi.org/10.1016/j.landusepol.2009.02.001>.
- Barlow, J., G.D. Lennox, J. Ferreira, E. Berenguer, A.C. Lees, R. Mac Nally, J.R. Thomson, S.F.D.B. Ferraz, et al. 2016. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. *Nature* 535: 144–147. <https://doi.org/10.1038/nature18326>.
- Bennett-Curry, A., Y. Malhi, and M. Menton. 2013. Leakage effects in natural resource supply chains: A case study from the Peruvian commercial charcoal market. *International Journal of Sustainable Development and World Ecology* 20: 336–348. <https://doi.org/10.1080/13504509.2013.804892>.
- Carrasco, L.R., E.L. Webb, W.S. Symes, L.P. Koh, and N.S. Sodhi. 2017. Global economic trade-offs between wild nature and tropical agriculture. *PLoS Biology* 15: 1–23. <https://doi.org/10.1371/journal.pbio.2001657>.
- Carter, S., M. Herold, V. Avitabile, S. De Bruin, V. De Sy, L. Kooistra, and M.C. Rufino. 2018. Agriculture-driven deforestation in the tropics from 1990–2015: Emissions, trends and uncertainties. *Environmental Research Letters* 13: 1–13. <https://doi.org/10.1088/1748-9326/aa9ea4>.
- Dang, D.K.D., A.C. Patterson, and L.R. Carrasco. 2019. An analysis of the spatial association between deforestation and agricultural field sizes in the tropics and subtropics. *PLoS ONE* 14: 1–14. <https://doi.org/10.1371/journal.pone.0209918>.
- De Alban, J.D.T., G.M. Connette, P. Oswald, and E.L. Webb. 2018. Combined Landsat and L-band SAR data improves land cover classification and change detection in dynamic tropical landscapes. *Remote Sensing* 10: 306. <https://doi.org/10.3390/rs10020306>.
- De Sy, V., M. Herold, F. Achard, R. Beuchle, J.G.P.W. Clevers, E.L. And, and L. Verchot. 2015. Land use patterns and related carbon losses following deforestation in South America. *Environmental Research Letters* 10: 124004. <https://doi.org/10.1088/1748-9326/10/12/124004>.
- FAO. 2015. *Global forest resources assessment 2015 desk reference*. Food and Agriculture Organization of the United Nations.
- Finer, M., and S. Novoa. 2015. MAAP Synthesis # 1: Patterns and Drivers of Deforestation in the Peruvian Amazon We present a preliminary analysis of current patterns and drivers of deforestation in the Peruvian Amazon. This analysis is.
- Folke, C., H. Österblom, J. Jouffray, E.F. Lambin, W.N. Adger, M. Scheffer, B.I. Crona, M. Nyström, et al. 2019. Transnational corporations and the challenge of biosphere stewardship. *Nature Ecology and Evolution*. 3: 1396–1403. <https://doi.org/10.1038/s41559-019-0978-z>.
- Geist, H.J., and E.F. Lambin. 2002. Proximate causes and underlying driving forces of tropical deforestation. *BioScience* 52: 143–150. [https://doi.org/10.1641/0006-3568\(2002\)052%5b0143:pcaudf%5d2.0.co;2](https://doi.org/10.1641/0006-3568(2002)052%5b0143:pcaudf%5d2.0.co;2).
- Gibbs, H.K. 2010. Gesundheitliche beeinträchtigung durch häusliche schimmelpilzbelastungen. *PNAS* 107: 16732–16737. <https://doi.org/10.1073/pnas.0910275107>.
- Gibson, L., T.M. Lee, L.P. Koh, B.W. Brook, T.A. Gardner, J. Barlow, C.A. Peres, C.J.A. Bradshaw, et al. 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature* 478: 378–381. <https://doi.org/10.1038/nature10425>.
- Global Canopy. 2018. Retrieved 20 September, 2018 from <https://www.globalcanopy.org/what-we-do/supply-chains/trase>.
- Godar, J., T.A. Gardner, E.J. Tizado, and P. Pacheco. 2015. Correction for Godar et al., Actor-specific contributions to the deforestation slowdown in the Brazilian Amazon. *Proceedings of the National Academy of Sciences* 112: E3089–E3089. <https://doi.org/10.1073/pnas.1508418112>.
- Gunarso, P., F. Agus, B. H. Sahardjo, N. Harris, M. Van Noordwijk, and T. J. Killeen. 2013. Historical Co2 emissions from land use and land use change from the oil palm industry in Indonesia, Malaysia and Papua New Guinea. *Reports from the Technical Panels of the 2 nd Greenhouse Gas Working Group of the Roundtable on Sustainable Palm Oil (RSPO)*, 65–88 pp. <https://doi.org/10.1111/ijpo.12051>.
- Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S.A. Turubanova, A. Tyukavina, D. Thau, S.V. Stehman, et al. 2013. High-resolution global maps of 21st-century forest cover change. *Science* 342: 850–853. <https://doi.org/10.1126/science.1244693>.
- Henders, S., M. Ostwald, V. Verendel, and P. Ibisch. 2018. Do national strategies under the UN biodiversity and climate conventions address agricultural commodity consumption as deforestation driver? *Land Use Policy* 70: 580–590. <https://doi.org/10.1016/j.landusepol.2017.10.043>.
- Houghton, R.A. 2012. Carbon emissions and the drivers of deforestation and forest degradation in the tropics. *Current Opinion in Environmental Sustainability* 4: 597–603. <https://doi.org/10.1016/j.cosust.2012.06.006>.
- Jones, K.R., O. Venter, R.A. Fuller, J.R. Allan, S.L. Maxwell, P.J. Negret, and J.E.M. Watson. 2018. One-third of global protected land is under intense human pressure. *Science* 360: 788–791. <https://doi.org/10.1126/science.aap9565>.
- Kissinger, G., M. Herold, and V. De Sy. 2012. Drivers of Deforestation and Forest Degradation. *A synthesis report for REDD + Policymakers*. 48. <https://doi.org/10.1016/j.rse.2010.01.001>.
- Laurance, W.F. 2012. Condición física, adiposidad y autoconcepto en adolescentes. Estudio piloto. *Revista de Psicología del Deporte* 22: 453–461. <https://doi.org/10.1038/nature11318>.
- Laurance, W.F., A. Peletier-Jellema, B. Geenen, H. Koster, P. Verweij, P. Van Dijck, T.E. Lovejoy, J. Schleicher, et al. 2015. Reducing the global environmental impacts of rapid infrastructure expansion. *Current Biology* 25: R259–R262. <https://doi.org/10.1016/j.cub.2015.02.050>.
- Laurance, W.F., J. Sayer, and K.G. Cassman. 2014. Agricultural expansion and its impacts on tropical nature. *Trends in Ecology & Evolution* 29: 107–116. <https://doi.org/10.1016/j.tree.2013.12.001>.
- Lawrence, D., and K. Vandecar. 2015. Effects of tropical deforestation on climate and agriculture. *Nature Climate Change* 5: 27–36. <https://doi.org/10.1038/nclimate2430>.
- Lee, J.S.H., S. Abood, J. Ghazoul, B. Barus, K. Obidzinski, and L.P. Koh. 2014. Environmental impacts of large-scale oil palm enterprises exceed that of smallholdings in Indonesia. *Conservation Letters* 7: 25–33. <https://doi.org/10.1111/conl.12039>.

- Lewis, S.L., D.P. Edwards, and D. Galbraith. 2015. Increasing human dominance of tropical forests. *Science* 349: 827–832. <https://doi.org/10.1126/science.aaa9932>.
- MacUra, B., L. Secco, and A.S. Pullin. 2015. What evidence exists on the impact of governance type on the conservation effectiveness of forest protected areas? Knowledge base and evidence gaps. *Environmental Evidence* 4: 24. <https://doi.org/10.1186/s13750-015-0051-6>.
- Margono, B.A., P.V. Potapov, S. Turubanova, F. Stolle, and M.C. Hansen. 2014. Primary forest cover loss in Indonesia over 2000–2012. *Nature Climate Change* 4: 730–735. <https://doi.org/10.1038/nclimate2277>.
- Miettinen, J., D.L.A. Gaveau, and S.C. Liew. 2018. Comparison of visual and automated oil palm mapping in Borneo. *International Journal of Remote Sensing* 40: 8174–8185. <https://doi.org/10.1080/01431161.2018.1479799>.
- Nelson, A., and K.M. Chomitz. 2011. Effectiveness of strict vs multiple use protected areas in reducing tropical forest fires: A global analysis using matching methods. *PLoS ONE* 6: e22722. <https://doi.org/10.1371/journal.pone.0022722>.
- Overbeck, G.E., E. Vélez-Martin, F.R. Scarano, T.M. Lewinsohn, C.R. Fonseca, S.T. Meyer, S.C. Müller, P. Ceotto, et al. 2015. Conservation in Brazil needs to include non-forest ecosystems. *Diversity and Distributions* 21: 1455–1460. <https://doi.org/10.1111/ddi.12380>.
- Phumee, P., A. Pagdee, and J. Kawasaki. 2018. Energy crops, livelihoods, and legal deforestation: A case study at Phu Wiang National Park, Thailand. *Journal of Sustainable Forestry* 37: 120–138. <https://doi.org/10.1080/10549811.2017.1318292>.
- R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from <https://www.R-project.org/>.
- Ravikumar, A., R.R. Sears, P. Cronkleton, M. Menton, and M. Pérez-Ojeda del Arco. 2017. Is small-scale agriculture really the main driver of deforestation in the Peruvian Amazon? Moving beyond the prevailing narrative. *Conservation Letters* 10: 170–177. <https://doi.org/10.1111/conl.12264>.
- Robinson, B.E., Y.J. Masuda, A. Kelly, M.B. Holland, C. Bedford, M. Childress, D. Fletschner, E.T. Game, et al. 2018. Incorporating land tenure security into conservation. *Conservation Letters* 11: 1–12. <https://doi.org/10.1111/conl.12383>.
- Ruf, F., G. Schroth, and K. Doffangui. 2015. Climate change, cocoa migrations and deforestation in West Africa: What does the past tell us about the future? *Sustainability Science* 10: 101–111. <https://doi.org/10.1007/s11625-014-0282-4>.
- Spracklen, B.D., M. Kalamandeen, D. Galbraith, E. Gloor, and D.V. Spracklen. 2015. A global analysis of deforestation in moist tropical forest protected areas. *PLoS ONE* 10: 1–17. <https://doi.org/10.1371/journal.pone.0143886>.
- Stibig, H.J., F. Achard, S. Carboni, R. Raši, and J. Miettinen. 2014. Change in tropical forest cover of Southeast Asia from 1990 to 2010. *Biogeosciences* 11: 247–258. <https://doi.org/10.5194/bg-11-247-2014>.
- Tegegne, Y.T., M. Lindner, K. Fobissie, and M. Kanninen. 2016. Evolution of drivers of deforestation and forest degradation in the Congo Basin forests: Exploring possible policy options to address forest loss. *Land Use Policy* 51: 312–324. <https://doi.org/10.1016/j.landusepol.2015.11.024>.
- Tritsch, I., and F.M. Le Tourneau. 2016. Population densities and deforestation in the Brazilian Amazon: New insights on the current human settlement patterns. *Applied Geography* 76: 163–172. <https://doi.org/10.1016/j.apgeog.2016.09.022>.
- UN Comtrade (United Nations) database, 2014–2017. 2018. Retrieved from <https://comtrade.un.org/>.
- Vásquez-Grandón, A., P.J. Donoso, and V. Gerding. 2018. Forest degradation: When is a forest degraded? *Forests* 9: 1–13. <https://doi.org/10.3390/f9110726>.
- Venter, O., E.W. Sanderson, A. Magrath, J.R. Allan, J. Beher, K.R. Jones, H.P. Possingham, W.F. Laurance, et al. 2016. Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nature Communications* 7: 1–11. <https://doi.org/10.1038/ncomms12558>.
- Warren-Thomas, E., P.M. Dolman, and D.P. Edwards. 2015. Increasing demand for natural rubber necessitates a robust sustainability initiative to mitigate impacts on tropical biodiversity. *Conservation Letters* 8: 230–241. <https://doi.org/10.1111/conl.12170>.
- Watson, J.E.M., N. Dudley, D.B. Segan, and M. Hockings. 2014. The performance and potential of protected areas. *Nature* 515: 67–73. <https://doi.org/10.1038/nature13947>.
- Weiss, D.J., A. Nelson, H.S. Gibson, W. Temperley, S. Peedell, A. Lieber, M. Hancher, E. Poyart, et al. 2018. A global map of travel time to cities to assess inequalities in accessibility in 2015. *Nature* 553: 333–336. <https://doi.org/10.1038/nature25181>.
- Woods, K. 2012. The political ecology of rubber production in Myanmar: An overview: 1–66.
- World Database on Protected Areas (WDPA). 2018. Retrieved 20 June, 2018, from <https://www.protectedplanet.net/c/world-database-on-protected-areas>.

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