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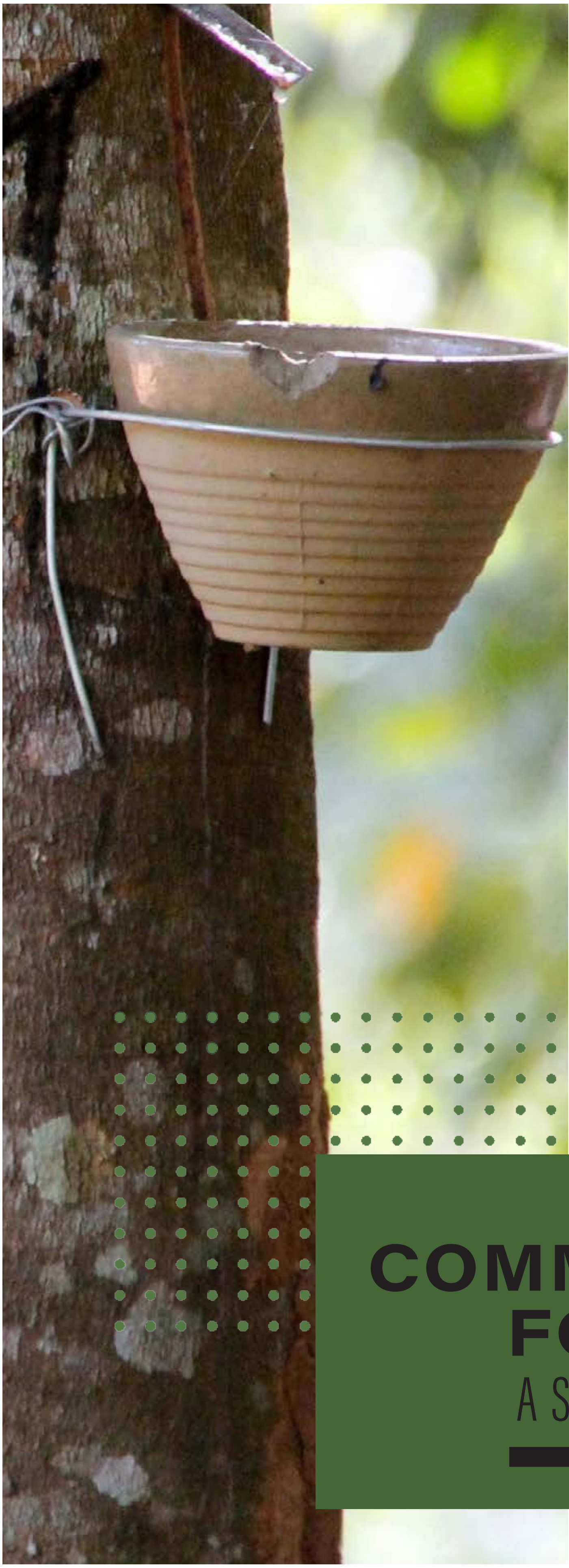

COMMODITY-DRIVEN FOREST LOSS

A STUDY OF SOUTHEAST ASIA

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TABLE OF CONTENTS

ABBREVIATIONS

AFOLU	Agriculture, Forestry and Other Land Use
AGB	Aboveground biomass
AWD	Alternate wetting and drying
BRG	Badan Restorasi Gambut
CARP	Comprehensive Agrarian Reform Program
CBFM	Community-based forest management
C	Carbon
CF	Community forest
ELC	Economic land concession
ES	Ecosystem services
FAO	Food and Agriculture Organization of the United Nations
FFC	Fine flavor cocoa
FLEGT	Forest law enforcement, governance and trade
FRA	Forest Resource Assessment
GDP	Gross domestic product
GHG	Greenhouse gas
GoP	The Government of the Philippines
HA	Hectares
ICC	Intraclass correlation coefficient
ICRAF	World Agroforestry Centre
IDP	Internally displaced person
IPCC	Intergovernmental Panel on Climate Change
JICA	Japan International Cooperation Agency
MG	Megagrams
Lao PDR	Lao People's Democratic Republic
MSS	Myanmar selection system
NDC	Nationally determined contributions
NGP	National Greening Program
NTFPs	Non-timber forest products
RDMA	Regional Development Mission for Asia
RECOFTC	Regional Community Forest Training Center
REDD	Reduced emissions from deforestation and degradation
RFD	Royal Forest Department
RSPO	Round Table on Sustainable Palm Oil
SDGs	Sustainable Development Goals
SEA	Southeast Asia
SIG	Spatial Informatics Group
UNDP	United Nations Development Program
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USFS	United States Forest Service
USFS IP	United States Forest Service International Programs

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EXECUTIVE SUMMARY

Southeast Asia's forests have experienced high levels of deforestation, which has important global and regional consequences given the exceptionally high biodiversity in Southeast Asian forest ecosystems and the immense amount of carbon stored in Indonesia's forested peatlands. Regionally, forest loss also leads to degraded water and air quality and availability. While the causes of deforestation are myriad, and have fluctuated in importance throughout the decades, one of the current drivers of deforestation in Southeast Asian is growth of the agricultural sector and demand for tropical food exports. Therefore, ways to reconcile development with environmental protection must be identified. Forest transitions to agriculture are a substantial cause of forest loss and subsequent carbon emissions. Finding ways to use natural lands more sustainably, while increasing the carbon stored in these lands, is an important challenge to address.

To address these challenges, the United States Agency for International Development's (USAID) Regional Development Mission for Asia (RDMA) supports work at the nexus of development and the environment, and is often tasked with helping countries identify ways to address development and environmental needs. In order to strengthen land use management, it is necessary to have detailed information on land use change and associated carbon stocks. To address this information gap, USAID RDMA is supporting an assessment of commodity crop development, forest loss and landscape carbon stocks in Southeast Asia, led by the US Department of Agriculture's Forest Service (USFS), Spatial Informatics Group (SIG), and World Agroforestry (ICRAF). Specifically, the assessment goals were to:

1) determine the primary commodity crops that have replaced natural forests in seven Southeast Asian (SEA) countries (Cambodia, Lao PDR, Indonesia, Myanmar, Thailand, Philippines and Vietnam,) from 2000-2015;

2) review literature up to 2019 to summarize what is known about the carbon budgets (emissions and storage) associated with the predominant regional commodity crops and conversion of forested land to these crops;

3) calculate the carbon losses or gains associated with these conversions using Tier 2 regionally-specific carbon stock factors; and,

4) identify regional and country-level policy recommendations that would help USAID prioritize investments into landscapes that maximize climate mitigation potential while allowing use for domestic and international agriculture needs.

The assessment used an approach that provided greater spatial and thematic resolution on deforestation and associated greenhouse gas emissions than previous studies. This approach employed point-sampling and photo-interpretation of high-resolution imagery to inventory land uses in areas experiencing forest loss, and then calculated carbon budgets for the forests and replacement land cover types using regional carbon stock factors. This led to spatially specific and regionally tailored results. The inventory focused on areas that exhibited a loss in tree canopy cover in a pre-existing global forest loss data set that was supplemented with additional regional data. Area estimates of converted land uses were produced, and where available, estimates of aboveground biomass (AGB) for forests and crops were included in carbon calculations. Common agroforestry practices, where both trees and ground cover crops are planted together, were also characterized in each landscape and their carbon benefits were quantified. This novel approach demonstrated where and to what extent greenhouse gas (GHG) emissions in the Agriculture, Forestry and Other Land Use (AFOLU) sector are highest throughout Southeast Asia.

Globally and regionally traded "boom crop" commodities have led to large scale conversion of primary and secondary forest into agricultural lands within the seven countries examined. While lowland population expansion and illegal and legal logging have also contributed to deforestation, commodity-crop expansion was by far the single largest driver of deforestation over the 2000-2015 period. Rubber has experienced substantial expansion in virtually every country in the region. Large areas of oil palm plantations have also been established in countries with appropriate climate, particularly Indonesia. Pulpwood (Acacia and Eucalyptus spp.) plantations were also common. Coffee and orchard (fruit and nut) crops have also played a role, but to a much lesser extent. Herbaceous and cereal crops appeared to be very common, and in over half the countries studied, were the dominant crop type on previously forested lands. In all countries, commodity crop exports had increased substantially between 2000 and 2015, and the growth in any particular export was roughly equivalent to the amount of land that had been converted from forest to that crop.

This study found that almost 1.5 billion MT of carbon has been lost from landscapes due to the conversion of forested lands to agriculture in Southeast Asia. However, contrary to prevailing beliefs, recent deforestation and related landscape carbon loss was not due to economic land concessions (ELCs) of crops like oil palm and rubber. While these crops were the prime driver of deforestation in Indonesia between 2000 and 2015, they were not the main driver across the whole region. At a regional level, the dominant driver actually appeared to be traditional herbaceous row crops, rice, or orchards, or some combination of these. This does not mean that the contribution of oil palm and rubber to deforestation should be minimized. They are indeed significant; however, when policymakers are looking for ways to minimize deforestation across Southeast Asia, the focus should be broadened to include a wider array of commodity crops.

Carbon stock factors for regional forest types and regional commodity crops were compiled from the literature. For all forest types, natural forest contained considerably more carbon – up to 10 times more – in its aboveground biomass than did an equivalent area of any type of crop grown in a monoculture. Natural forests also contain more carbon in their aboveground biomass than any crop grown in an agroforestry system. Some agroforestry systems, however, contained nearly as much carbon as early growth or degraded natural forest, and thus are a good practice to use when improving carbon storage in the landscape is the goal. The inventory showed that in most cases, commodity crops were grown in monocultures, though agroforestry practices were common in certain crops in certain countries. Establishing monoculture crops without an agroforestry component in previously forested lands results in the greatest possible loss of landscape carbon, aside from clearing forests and leaving the land completely barren.

Results of the study point to a number of practices that could be relatively quickly implemented. Below we summarize the six regional level recommendations for forest rehabilitation that simultaneously promote improved carbon storage in landscapes and better economic outcomes. An additional three recommendations are general best practices commonly discussed in the literature; these are included at the end of the report. Recommendations this study addressed included:

Recommendation 1: Fallow lands can be better used. Carbon storage can be improved by directing new agricultural expansion to occur on fallow or degraded lands that currently sequester relatively little carbon (Smith et al. 2007). In some locations, rubber trees grown in an agroforestry system may be the best use for many of these degraded lands, as they sequester a significant amount of carbon and produce relatively quick financial returns for growers. However, the suitability of the soil and microclimate for rubber must be assessed, along with community or national interests and capacity to develop a rubber sector.

Recommendation 2: Another practice that quickly improves landscape carbon would be to implement agroforestry practices, particularly those that conform to principles of conservation agriculture. The study found almost five million hectares of monoculture plantations throughout the region, most of it being either oil palm or herbaceous crop monoculture. If oil palm monocultures had low ground cover crops planted in the rows, and herbaceous crops were co-planted with trees, landscape carbon would be maximized, while also possibly improving soil nutrients, soil water retention and/or biodiversity.

Recommendation 3: Improving yields associated with agroforestry by providing technical and financial assistance may help preserve forests. Such livelihoods may include collection of forest products to support family consumption, or it might also include developing enterprises that generate income. However, evidence suggests that while improving farming within forests may help keep forests in place, improving farming efficiency in cleared lands may have the opposite effect and increase forest clearing, so assistance with yield improvements must be taken on a case-by-case basis, and must be combined with improvements in governance and enforcement of laws.

Recommendation 4: The ELC granting process and related resource rights issues need to be transparent so that decisions on land use are made with the full inclusion of all land users and potential stakeholders and people are fairly compensated for their lands. In most ELC granting processes, lands historically used by local communities are declared government property and granted or sold to concessions. This not only causes conflict (sometimes quite severe or deadly) between local communities and concessions, but may lead to severe forest degradation in the areas outside of the concession as communities set fires or otherwise exploit their limited remaining lands. Reforming the granting process, so that it is fair, inclusive, considers historic rights, and is transparent about ownership and management regimes would go a long way towards more efficiently using land.

Recommendation 5: Allowing some traditional shifting agriculture may improve the social standing of often marginalized upland people while still maintaining a moderate amount of carbon in the landscape. Limited shifting agriculture could be allowed, particularly in already degraded areas or where the other option is large scale ELCs. Results showed that upland shifting agriculture was not the major driver of deforestation that many assume it to be. Regardless, there has been a concerted effort by many Southeast Asian countries to end the practice of shifting agriculture. While this has produced improvements in the economic status and food security of some upland people, this is not consistently true. It has also not consistently led to higher-quality forested lands, as the fallows of shifting agriculture systems are typically more biodiverse and store more carbon than the ELCs or other permanent agricultural lands that replace them. Given these results, it may be wise for governments to continue to allow shifting agriculture for those communities that want to practice it, so long as it reuses fallows and does not lead to clearing of more virgin forest.

Recommendation 6: Continue to work with international agribusinesses to improve their supply chains, to meet consumer and policy-driven demand for deforestation-free products. Over the course of the study period, there has been a movement for change around consumption patterns. While supply-side interventions will help reduce deforestation and make supply chains greener, demand-side and larger structural change is needed as well. Smallholders, who are often part of these supply chains, may have a hard time complying with environmental rules without assistance. Smallholders and the stakeholders that represent them must therefore be brought into land use decision processes early on to help agribusinesses understand the on-the-ground realities of supply chains so they can design policies that are climate friendly and socially just.

Overall we conclude that identifying the primary drivers of deforestation and the carbon losses associated with different types of forest conversion will help policy makers and investors make climate-smart development decisions. While large-scale behavior change is needed to address deforestation in the long term, more immediate and easily implementable solutions are needed. As lower- and middle-income countries look to grow their economies, they should, where possible, be encouraged to expand service and technology sectors that minimally impact natural resources. When countries still need to rely on natural resources for economic growth, that growth must be as sustainable as possible. That means extracting resources from intact ecosystems no faster than replacement rates, sharing benefits from such extraction equitably between land users, and ensuring as much carbon as possible remains in landscapes. While achieving negative GHG emissions will take time, there are ways to strengthen land use management while mitigating environmental impacts from over-exploitation and short-sighted investments. To do so, it will be necessary to reconcile economic and environmental goals, allowing the region to follow a path of low emission development while still improving its economy and the livelihoods of its people.

Maximizing economic and environmental benefits are complex problems that involve changing, contradictory and difficult to identify needs. To address these needs, future research on tropical land management and carbon storage should focus on a number of areas where practical data is still insufficient. This would include trials of different types of agroforestry practices, improved understanding of how to minimize inefficiencies in commodity supply chains so as to reduce waste, and improved deforestation-free business models that can help small-scale harvesters and producers maximize economic gains while preserving their landscapes.

There is, however, no need to wait for future studies before taking action. Policymakers and practitioners across the region are already implementing all of the recommendations noted above. The issue is that the implementation is limited in scale and scope, and is not always locally adapted. The onus now is on national and local governments to trial and scale those best practices which are appropriate for their nations and the communities in them. There are ways to reconcile economic and environmental goals, but they require governments to break free of business-as-usual policies. Only through innovative, pro-people, pro-environmental policy change will the region begin to follow a path of climate-friendly development that preserves life on land while still helping its people realize a life without hunger or poverty.

INTRODUCTION

Tropical forests are a defining feature of the Southeast Asian landscape. Nearly 15 percent of the world's tropical forests are found there (Stibig et al. 2014), and the region also includes at least four of the twenty-five globally important biodiversity hotspots (Sodhi et al. 2010). Unfortunately, the region is also among the world's major deforestation hotspots, and accounts for, globally, most of the deforestation that occurs in tropical humid and lowland forests (Mietinnen et al. 2011; Hansen et al. 2013). Between 1990 and 2010, Southeast Asia lost an average of 1.6 million hectares (ha) of forest each year (0.6 percent per year), for a total loss of 32 million ha (Stibig et al. 2014). Its deforestation rate is comparable only to that of Brazil and Latin America (Hansen et al. 2013), and habitat and biodiversity loss (Sodhi et al. 2010) in the region is among the highest in the world.

Deforestation began in earnest in the post-World War Two period when conflicts and related governance issues bifurcated the growth of the region. From the second Indochina war between the United States and Vietnam, to the "communist purge" and subsequent 30+ year dictatorship in Indonesia, to the brutal Khmer Rouge regime that briefly held power in Cambodia, most of Southeast Asia was mired in turmoil. The outcomes of this turmoil were different in each nation, and seemed to depend both upon the extent and impacts of conflict, as well as the personalities and decisions of national leaders. In Thailand, Indonesia, Malaysia and the Philippines, strong leaders and/or limited violent conflict led to these countries opening their doors wide and joining the international marketplace. But Vietnam, Cambodia, Lao PDR, and Myanmar, which all experienced protracted internal and violent conflict, followed a different development trajectory and fell out of the international trade system to a large extent. Not only did this bifurcation substantially impact the speed of economic development, but it also dramatically shaped the status of forests in many of these countries (Kenney-Lazar 2018). This bifurcation also meant that extent of and rates of deforestation vary substantially throughout the region, from countries like Vietnam and Thailand (Yasmi et al. 2019) that are showing net forest gains, to countries like Indonesia and Malaysia, which have two of the top six highest rates of deforestation in the world (WRI 2019).

While a number of factors have driven deforestation in these countries over the years, including conflict, growing populations, shifting (also known as swidden or slash-and-burn) agriculture, and illegal and legal logging, natural resource exploitation in the name of economic development is currently the largest driver of deforestation (Curtis et al. 2018; Hurni and Fox 2018; Zeng et al. 2018). Granting concessions allowed Southeast

Asian countries to grow their economies through the rapid expansion of "boom crops." Boom crops are crops that result in fast increases in the amount of land that is devoted to a high-value crop through monoculture cultivation (Hall 2011). They have appeared repeatedly in many developing nations worldwide and are driven by the international market demand of land-based commodities, such as palm oil, rubber, banana, coffee, or hybrid maize (Van den Top 1995; Fox and Castella 2013; Cramb et al. 2017). Land changes brought about by boom crops may be ephemeral: oftentimes, within less than a decade, a particular crop expands rapidly and disappears again. Boom crops may bring economic growth on an aggregate level, but economic disparity tends to grow between early adopters and neighboring communities. Most governments cite local employment opportunities, infrastructure development and poverty alleviation as the official reasoning for why economic land concessions (ELCs) for boom crops are granted, although they are more often accompanied by unintended consequences which undermine local livelihoods and development (Barney 2017).

Hurni and Fox (2018) estimated that boom crops, especially rubber, occupy roughly 18 percent of continental SE Asia - excluding most of Myanmar and some of Thailand. They found that since 2003, an area of 7.5 million hectares (ha) has been planted with rubber and that 70 percent of this area had been forested land. Similarly, Zeng et al. (2018), found that between 2000 and 2014 cropland replaced 94 percent of cleared lowland forest and 88 percent of cleared highland forest; this amounted to an area of 27 million hectares (ha) of new cropland, largely planted with boom crops. Another study, by Curtis et al. (2018), attributed roughly 61 percent of forest loss to commodity crops, roughly 20 percent to shifting agriculture, and only about 14 percent to forestry activities. These estimates of agriculturally driven forest loss are supported by the changing role of the region in the production of cassava, maize, sugar cane, palm oil and rubber, all globally consumed boom crop commodities. Southeast Asia was the leading exporter of palm oil and rubber in both 2000 and 2016. During this same period, global demand for palm oil increased from less than 5 billion USD to more than 25 billion USD, while the demand for rubber had grown from 4 billion USD to more than 10 billion USD (Estrada et al. 2019).

The impacts of Southeast Asian deforestation, regardless of the driver, are felt at many scales: locally, nationally and globally. Nationally, at least in poor countries, economies grow, living standards improve, and the proportion of people living in poverty lowers. This effect, however, weakens as countries move up the income scale (Cuaresma et al. 2017). Locally, while poverty in some cases may be alleviated, health and livelihoods are often made more insecure as ecosystem services, and the landscapes upon which rural people depend, are degraded or eliminated (Yasuoka and Levins 2007; Garg 2015; Thompson et al. 2012). Many of the region's poorest, landscape-dependent people need the essential ecosystem services provided by tropical forests – like erosion control, retention of soil moisture, plant biodiversity, and wildlife habitats – to maintain the good health and stable livelihoods of their communities. Forests are also important for regulating climate and precipitation locally and regionally (Lean and Warrilow 1989; Lawrence and Vandecar 2015). The loss of forests often results in increased local temperatures, which in turn cause greater evapotranspiration, a loss of soil moisture, increasingly erratic precipitation, and ultimately, a decrease in productivity of agricultural and all nearby landscapes.

While the expansion of boom crops in SEA means consumers globally are able to access cheap, commercially important commodities, losing tropical forests means losing one of the major carbon stores of the planet and accelerating global climate change. Southeast Asia's forests cover only seven percent of the planet's surface but are estimated to store roughly 68 percent of the global carbon (C) stock of woody biomass, in addition to containing two-thirds of the world's biodiversity (Bebber and Butt 2017). Tropical peat soils, which underlie many tropical forests, contain large amounts of organic matter. When the forests are cleared and soils drained, this begins decaying, releasing methane and nitrous oxide (Oktarita et al. 2017; Winton et al. 2017; Isikura et al. 2019), which are both far more powerful greenhouse gases (GHGs) than carbon dioxide. Thus, as tropical forests are degraded and peatlands are drained for development, all of these GHGs are emitted into the atmosphere, contributing to a rise in average global temperatures. Conversely, as they are rehabilitated, they can help mitigate climate change – and can help countries attract REDD+ financing and carbon credit funds.

The quantity of carbon, or other GHG, that any area of tropical forest emits is dependent upon a number of factors, including current forest health or degree of degradation, amount of plant biomass, depth of soil (especially in peatlands), and ecozone. Ecozones are biogeographic realms where vegetation, hydrology and climatic characteristics are shared across a number of geographic areas which may not be physically linked. The United Nations' Food and Agriculture Organization

(FAO) classifies Southeast Asian landscapes into one of four different ecozones: rainforest, moist deciduous, dry and mountain. The tropical ecozone, the most prevalent, covers the coastal lowlands of Southeast Asia. This zone is marked by precipitation of more than 100 cm or even more than 200 cm per year, no dry season, constant heat and high biodiversity. The least common zone is tropical mountain systems. Tropical mountain systems are located in the Malaysian Peninsula, the Annamitic Range, the central mountain ranges of the islands of Indonesia and the Philippines, and the mountains in the southwestern Arabian Peninsula, with relatively high peaks (over 2,000 m) in India and Sri Lanka. Annual precipitation is more than 100 cm, sometimes more than 200 cm, and there may be a short dry season. These forests are found in Myanmar, Thailand, Lao PDR and Vietnam and have been affected by shifting cultivation. They still cover relatively large areas in Malaysia, Indonesia and the Philippines.

Knowing what ecozone a particular forest area or concession area that was formerly forest falls into is useful if one wants to calculate the amount of carbon stored or emitted by that particular area of land. This is because the Intergovernmental Panel on Climate Change (IPCC) has compiled and published carbon stock factors for broad ecozones across the planet, known as Tier I carbon factors. These factors are useful for making general estimates of carbon losses or gains due to land cover change; they lack, however, detail about specific land cover types and can over- or underestimate carbon changes depending on the carbon stock factors of crops or trees. To take into account these site-specific details, Tier II factors are being researched and available in many regions for different land cover types. Tier II factors are specific to land cover types within ecozones. These produce more precise estimates than Tier I carbon factors.

Carbon emissions from land use change, specifically from boom crop expansion, are often calculated globally and regionally, but few attempts have been made to estimate emissions at the country or landscape level. Such localized data is, however, needed so that land use decisions can be better tailored to meet national needs. In developing and middle-income economies like those in Southeast Asia, policy makers need to understand the relationship between development goals, land uses, and the conservation of carbon sinks, like forests, in order to plan their low-emission development paths. They also need to ensure that their development policies are in line with their Intended Nationally Determined Contributions (INDCs) to the United Nations Framework Convention on Climate Change (UNFCCC), and their Sustainable Development Goal (SDG) commitments. Additionally, they need to be able to provide information on the impacts of different development trajectories to investors who can help them reach their targets.

Carbon stock changes in landscapes are also of interest to the United States Agency for International Development's (USAID) Regional Development Mission for Asia (RDMA). USAID/RDMA facilitates investments in low-emission businesses in the agricultural, forestry, and other land use (AFOLU) sectors in Southeast Asian countries. USAID prioritizes AFOLU investments based on many factors, including sustainability beyond life of projects, impacts on other social outcomes, and potential for reducing GHG emissions. To prioritize the latter, USAID must have precise, locally based knowledge of how commodity crops (such as palm oil, rubber, rice, timber, cocoa, coffee, and acacia) have replaced natural forests in the region. Such knowledge can help them target investments into those lands and commodities that preserve the most carbon in the landscape while still helping nations realize their own path to economic development.


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The studies and results described in this report were designed to support Southeast Asian countries (Cambodia, Indonesia, Lao PDR, Myanmar, the Philippines, Thailand, and Vietnam) in making development decisions that minimize carbon emissions from the land use sector. The research can also help these countries better understand the relationship between development and forest conservation, specifically in line with their NDCs and SDGs commitments, including SDG 1 (No poverty) and SDG 15 (Life on Land). This study builds on previous research by disaggregating drivers of deforestation into more refined commodity crop categories; it also uses localized and more specific carbon factors — Tier II factors — to estimate carbon storage or losses in the landscape.

The results detailed in the following pages outline country-specific issues that supply chain actors can use to set priorities for natural resource conservation, estimate AFOLU-driven GHG emissions, and assess commodity-driven deforestation risks. The results also provide an analysis at national and local scales, which can help policy makers identify location-specific issues and develop nationally or locally tailored solutions. Finally, the results can help practitioners make decisions that strengthen land use management while mitigating environmental impacts from over-exploitation and short-sighted investments. Along with economic growth comes high demand for Asia's finite natural resources, leading to the danger of over-exploitation and irreversible land use change. It is part of USAID's mission to help Southeast Asia protect natural ecosystems, ecosystem services, food security, and environmental health, all while driving inclusive economic growth and stability. The information contained in this report helps them, as well as other development practitioners working in the region, make data-driven decisions that can guide Southeast Asia's environmental future.

METHODS

OVERVIEW

We used a map-assisted, sample-based area estimation approach to quantify the area of forest lost to other land uses, often referred to as activity data (Olofsson et al. 2014). This approach includes visual interpretation and labeling of land cover and land use at sample locations placed using a probabilistic sample strategy. Samples were located using a stratified random sample approach using map strata representing forest loss hotspots (Hansen et al. 2013; Stibig et al. 2003a, 2003b, 2004). At each sample, the interpretation team characterized forest loss dynamics by reviewing imagery and labeling the land cover in 2000 and 2015. No consistent historic coverage of high-resolution imagery (5 m or less) exists over the entire study region that dates back to the study baseline year of 2000; therefore interpreters examined the time series of the moderate resolution (30 m) Landsat archive when assigning the baseline land cover labels (Wulder et al. 2016). At each sample, they assigned one of three labels for the baseline, 2000, land cover assessment: natural forest, tree crops, or other land cover. For the land cover and use in 2015, we used a land cover classification with more class and sub-class options. This was possible because there was complete coverage of high-resolution imagery available, enabling interpreters to identify vegetation type at a finer level. These labels included common crop types, such as oil palm and coffee plantations. The presence of agroforestry practices was also classified at each sample after 2015.

After all plots were labeled, the area of forest lost by each crop type was analyzed. Estimates were generated using a clustered sample design estimator (Patterson 2012). Carbon dynamics were characterized using a gain/loss approach where carbon storage factors are multiplied by the area of land change activities (GFOI 2016). We applied published Tier 1 and Tier 2 carbon factors to the activity data to estimate loss of carbon pools and the current stock for each commodity crop class that had replaced natural forest since 2000 (Penman et al. 2003; IPCC 2006; GFOI 2016).

SAMPLE DESIGN

Plots were allocated using a stratified random sample in order to focus the collection of information in areas that experienced a permanent forest loss, specifically, clearing for agricultural production. Sample points were concentrated using map strata that represented hotspots of deforestation. Information from the annual Global Forest Change map collection (GFC) (version 1.5, in Google Earth Engine, Hansen et al. 2013) and a land cover map for the year 2000 (Stibig et al. 2003a, 2003b, 2004) were combined to create the hotspot maps. The land cover map for 2000 was used to differentiate forest loss hotspots that represent loss of primary and secondary forests from those that represent the harvest cycles of plantations (Stibig et al. 2003a, 2003b, 2004). Additional details are described in the Supplemental Methods Section A. The resulting strata in the hotspot map are depicted in the box at the bottom of page 7.

In each country, 1,000 plots were allocated across the three strata, with an additional 600 in Indonesia to take into account the size of the country and diversity of islands (Table 1). In the no loss strata, we only located 250 samples, with 400 in Indonesia. The remaining 750 were placed in the loss hotspot strata, based on their percent cover (Table 2). For Laos, Myanmar, Philippines, Thailand, and Vietnam the small proportion of land in stratum 1 meant that the number of plots of clustered samples was less than 200. Because stratum 1 represented forest loss hotspots of intact forest patches, we used a minimum sample size of 200.

RESPONSE DESIGN

At each plot location 24 clustered samples were systematically located, mimicking the design used by the USDA Forest Service's Image Based Change Estimation (ICE), a program to robustly estimate the amount of cover types in a landscape (Frescino et al. 2009). They have an associated set of unbiased estimators matching their sample design that are used to determine the proportion of cover types. Samples were clustered within plots with a 40 m diameter, covering an area of approximately 0.5 hectare (Figure 1). Each point represents 4.17 percent of the area of the plot. A circular plot was used to minimize edge effects from the different spatial alignment of each imagery source.

At each sample interpreters labeled the current land use activities by identifying commodity crops and land use practices using high (< 5 m^2) and moderate (30 m^2) resolution imagery. High resolution imagery is available with complete coverage starting in 2015, so these data streams were used to characterize more recent land cover and land use at each plot. Interpreters prioritized the use of Digital Globe and Bing high resolution imagery when labeling plot attributes and referred to the supplemental sources as needed (e.g., when the available imagery was not clear). One limitation of using Digital Globe and Bing imagery for classification is that these sources mosaic the best quality recent image together across the landscape to create a complete recent base layer, but the date of the image acquisition is not recorded for each pixel. Therefore, we can only assign a date of post-2015 to these labels.
Interpreting land cover for the baseline year posed some challenges because of the lack of historic imagery with an equivalent spatial resolution. These data limitations meant that different imagery sources were prioritized for determining the baseline labels of 2000 compared to more recent land cover interpretation. The Landsat data archive offers moderate resolution imagery at a 16-day frequency going back to 1984 (Wulder et al. 2016). Therefore, we visually interpreted Landsat images and time series plots to assign the baseline forest type label as either tree crop, natural forest, or other for the year 2000. Interpreters reviewed time series of the Landsat-derived indices, such as the normalized difference vegetation index and SWIR spectral curves for the years from 1990-2000. We also integrated a visually interpreted forest loss data set collected across the five Mekong basin countries using methods consistent with this effort (Potapov et al. 2019, full details in Supplemental Material Section A). All of these additional sample points were all located in strata 3. This allowed us to increase our sample size in order to reduce uncertainty in our area estimates of activity data.

Samples were labeled by a team of six interpreters with local knowledge of the land cover in southeast Asia and Asia Pacific. Interpretation and labeling were completed in the free and open source Open Foris application called Collect Earth Online (Saah et al. 2019). At each sample the interpreter answered three survey

SAMPLE DESIGN: STRATA IN HOTSPOT MAP

STRATUM 1	STRATUM 2	STRATUM 3
Intact forest loss: deforestation hotspots associated with larger, more intact forest patches.	**Canopy cover loss:** deforestation hotspots associated with tree cover in more fragmented, degraded landscapes, which may also include rotational tree crops.	**No loss:** areas not assigned as forest loss hotspots in stratum 1 or 2.

question cards. The first question in the questionnaire addressed the current (2015 or later) land cover at the plot, with detailed choices regarding the presence of a suite of commodity crop categories. The second question addressed the presence and composition of a commodity crop understory to describe the adoption of agroforestry systems. Finally, the presence and type of tree canopy cover was recorded for the baseline year of the study, 2000.

The classification system for both the crop types and agroforestry systems was developed through a literature review and based on the possibility of identifying land covers using spatial imagery. In line with the objective of identifying main agricultural commodities which possibly involved conversion of forest for their expansion, we used their total expansion area in the country as a selection criterion. The expansion area is most often proportional to the trading/export value. For example, Vietnam is one of main exporters for coffee and rice, and the cultivation of these two commodities are among the most expansive in the country. Indonesia is the biggest exporter of oil palm in the world, ranking higher than the next five, Malaysia, Guatemala, Colombia, Papua New Guinea, and Honduras, combined (indexmundi.com). The list of main commodities of the seven countries based on literature review were further refined based on the possibility of identifying with spatial imagery. Those having a specific pattern from aerial view were selected, and those with patterns that could not be recognized were classified into one group or excluded from the photo interpretation step with Collect Earth Online as further analysis.

During this event we also developed a supporting classification key. The key included a definition for each label, a description of what patterns to look for in the imagery, and example images from high resolution aerial imagery for each land cover or use and agroforestry class of interest. Definitions are summarized in the following sections, the full classification key is available in the Supplemental Materials Section B.

On the first survey card (top third, Figure 1), the interpreter documented the current land cover and the presence of understory. The 2015 land cover labels included 20 land cover categories. Agriculture land cover classes were selected by conducting a literature review on the economics of candidate commodities in each country in this study. Based on this review, we chose to focus on banana (*Musa* spp.), coconut (Cocos nucifera), coffee (Coffea arabica and *Coffea canephora*), rubber (Hevea brasiliensis), pulpwood trees (primarily Acacia spp. and Eucalyptus spp.), oil palm (Elaeis guineensis) and tea (Camellia sinensis). Crops were identified to the most specific level possible (such as pulpwood, nut/fruit orchards, oil palm, etc.). For example, some economically important crops, such as mango, cashew, jackfruit, and durian plantations, were not identifiable without site visits. However, they were identifiable as fruit and nut trees because of their spatial organization. As such, they were grouped together into one class—fruit/nut orchards. In all situations where the quality of imagery was insufficient to determine specific commodity types, crops were labeled based on their life form (other tree, other shrub, herbaceous, other crop, etc.). While the primary focus was to describe deforestation patterns from pressures to convert land to agricultural production, we still included high level land cover classes. These include non-commodity vegetation, built-up settlement, water, and other (for snow, bare soil, etc.). A follow-up question asks if there was crop understory present at any sample.

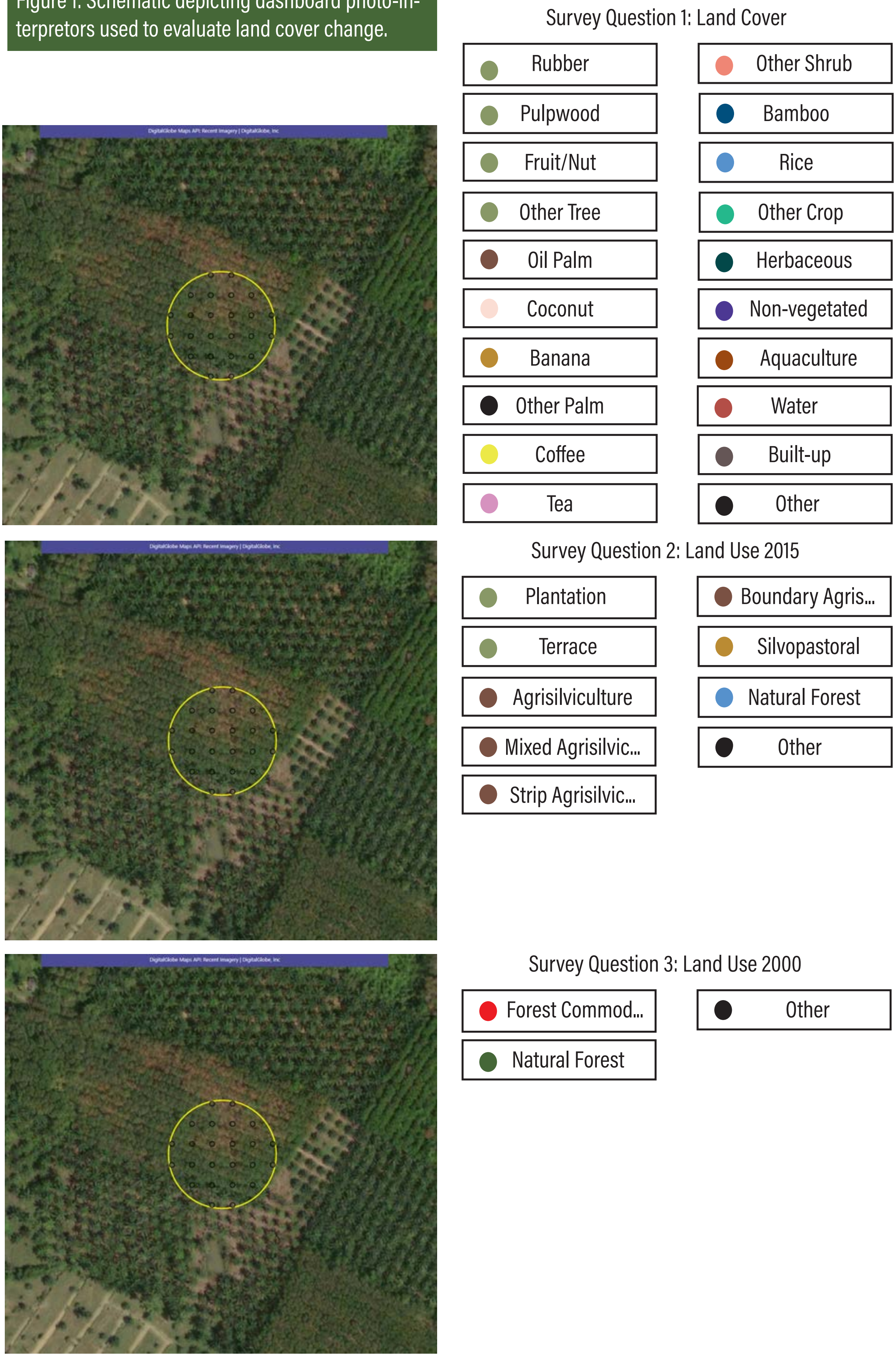
The second survey card (middle third, Figure 1) includes a question that captures the type of agricultural use associated with the land cover identified in question one. The interpreter assigned a plantation or agroforestry type label. Agroforestry describes a number of land-use systems and technologies that integrate trees (or other woody perennials such as bamboo) into agricultural systems (FAO 2010). A number of classification systems can be used to describe these different approaches (e.g. Schoeneberger 2009; Xu et al. 2013).

The third survey card (lower third, Figure 1) included a question that we used to determine if there was tree canopy cover loss and the type of tree canopy cover that was lost (e.g., conversion of natural forest or rotational tree commodity harvesting). Interpreters indicated if there was tree canopy cover in 2000, and labeled it as either a tree crop or natural forest.

Our target classes of interest are the samples that were crops in 2015 that were forest in 2000; however, to filter all samples with an agricultural land use in 2015 we needed to apply some rules that linked information from both the land cover and use labels. The approach to filter and assign the samples as target or not-target included two steps.

First, we filtered samples that were not natural forest in 2000. Then we assigned samples with a 2015 agriculture label. For this study, forest loss was defined as a stand-replacement loss of tree cover that results in a change in land use or cover. Further, only the loss of forest stands composed of primary or secondary native forests were included in our definition of forest loss;

Figure 1: Schematic depicting dashboard photo-interpretors used to evaluate land cover change.



stand clearing of activities of rotational tree plantations, orchards, and other anthropic tree-based land uses or covers were excluded.

After filtering for forest loss, samples were assigned an agricultural label if they met any of these five rules: 1) land cover label was coffee, tea, rubber, pulpwood, fruit and nut plantations, rice, or other crops; 2) samples labeled with a land cover label of bamboo that had any land use label except natural forest; 3) samples labeled with a land cover label of 'other trees' with a land use label of plantation; 4) samples labeled with a land cover label of 'other shrub' with either an agrisilviculture, boundary, mixed agrisilviculture, or terrace land use label; and 5) agriculture land use labels (plantation, mixed agrisilviculture, agrisilviculture, terrace, or boundary agrisilviculture) that had non-crop related land covers, these included non-vegetated, built-up, water, and other land cover. This fifth class was renamed crop support. It includes samples that were affiliated with agricultural land use but that did not intersect with the crop vegetation. Example situations of these sites include streams running through fields, barren ground in between rows of plants, or sheds and road pathways interspersed in the fields.

We also quantified the area of forest loss to broad level, non-crop land cover classes. These included development and three vegetation classes: non-crop herbaceous cover, grasslands, and shrub-lands.

QUALITY ASSURANCE

To ensure consistency of labels between interpreters, we held a training in February in Hanoi with our regional interpretation team. Discussions focused on working with Collect Earth Online, photo interpretation methods, and the co-development of the classification system and key. After the classification key was finalized, we completed a series of interpreter calibration projects to establish agreement within the photo-interpretation team prior to data collection. We also included a quality assessment process throughout the data collection efforts.

Following the workshop we completed a series of interpreter calibration projects to assess if plots were labeled consistently between interpreters, to ensure that the team was ready to begin data collection. As part of the assessment, all interpreters were assigned the same 200 plots. After the pilot data collection was completed, interpreter labels were assessed for agreement and measured with the iota and the intraclass correlation coefficient (ICC) (Bartko 1966; Conger 1980; Janson and Olsson 2001; Pengra et al. 2020). There was a significant improvement in interpreter agreement over the course of the calibration effort, with increasing ICC values, and with ICC values close to 1 for some classes and most common classes above 0.6. Improvements in iota appeared more modest (0.20 to 0.38), but this was complicated by the large number of variables considered (41) and high granularity of possible responses.

Once the data collection began, we assigned an additional 5 percent of plots as quality checks. Of these, 2.5 percent were self-checks where an interpreter reinterprets a plot they have already interpreted. The remaining 2.5 percent of these check plots were cross checks where an interpreter interprets a plot initially interpreted by another interpreter. These data were used to maintain consistency and identify and correct any problems in the photo interpretation process.

AREA ESTIMATION OF ACTIVITY DATA

The samples that experienced forest loss were then summarized using the approach presented in Patterson (2012) to produce a table of the area of crop commodity covers and their associated land uses that replaced forestlands since the year 2000. This approach treats the plot as the sampling unit, rather than the individual points; the point data are used to estimate the proportions of each cover and use type within the plots. The plots are a representative sample of the landscape since they are allocated in proportion to the strata and are randomly distributed within each stratum. Statistical estimators are then used to produce estimates of the proportion of land uses or cover types in the study area. Refer to the Supplemental Materials Section D for additional details and equations.

The data were aggregated by the type of change that took place and presented using Sankey flow diagrams. The width of each arrow is proportional to the quantity of carbon in each land cover type and illustrates the change in land cover/use between 2000 and 2015 (Riehmann et al. 2005).

CARBON STORAGE CAPACITY ANALYSIS

We assessed the current aboveground biomass carbon pool of commodity crops that replaced forests between 2000 and 2015, and also the difference compared to the carbon stock estimates of intact forestlands. Carbon dynamics were characterized using a gain/loss approach where carbon storage factors are multiplied by the area of land change activities (GFOI 2016). Carbon storage factors refer to the carbon content per unit area per land cover and land use type. Carbon storage factors were multiplied by the area of each land use group to generate estimates of current aboveground biomass carbon storage. They were also used to estimate loss of AGB carbon storage by comparing to the likely carbon AGB storage of the sampled area in 2000. The scarcity of carbon data for agriculture, forestry and other land uses has been acute (Kunreuther et al. 2014), and our review focused on AGC which are likely more available in the literature than those of belowground and soil part.

The international guidance documents for preparing greenhouse gas inventories from land use activities include three tiers of carbon factors (Penman et al. 2003; IPCC 2006; GFOI 2016). Tier 1 is the simplest, default method to estimate carbon factors using globally-available data. Carbon stock calculations using Tier 1 factors estimate carbon storage potential in a crop based on worldwide averages of carbon storage for that crop. Tier 2 factors use national-level averages of carbon stock factors for each crop; these factors are more spatially and climatically accurate. Tier 3 factors, not used in this research, are the most accurate of all and are based on estimates of carbon stocks in crops tied to specific geographical locations.

We compiled Tier 2 AGC factors for the list of main commodities of the seven countries. For Vietnam and Indonesia, the review considered international and national journal articles, and other publications such as project report, either published in English or national language (Vietnamese and Indonesian). For the other five countries, the review only considered publications in English, due to language constraints. All references of the compiled carbon data are provided in the Supplemental Methods Section E. The review mainly focused on Tier 2 AGC of the selected commodities, and when available, both in monoculture or mixed (agroforestry) type. The published AGC data from Cambodia, Laos, and Myanmar are likely very limited. Among main commodities of these countries, we only found a reference for cashew (Avtar et al. 2015) representing the category of fruit trees/nut, with a time-average AGC of 75 tons ha per year from systems ranging from 2 to 16 years-old. Most of the AGC data from these countries are for forest cover types. In these cases, carbon factors from neighboring countries, such as Vietnam, were used. Finally, the values for crops that were not identifiable using high resolution imagery alone—the other tree crop, other palm crop, other shrub crop, and other herbaceous crop categories—we used an average of all other crops with similar plant functional form. When region specific factors were not available, we used the most conservative approach for estimating carbon storage in agroforestry systems: we assumed that the trees provide the majority of biomass and thus the same carbon storage factors were used for both agroforestry systems and monocultures. A similarly conservative approach was taken for rice systems, where trees typically occur only as boundary plantings, but can contain nontrivial amounts of carbon (Feliciano et al. 2018). The values may underestimate some of the carbon in the landscape, though that is likely justified given it is a relatively small sum compared to the carbon emissions from the loss of forest cover. The final lists of commodities of the seven countries included in the analysis are given in Appendices 1-4 along with their corresponding AGC.

Annual emission factors associated with land cover transitions on peatland forests are compiled in Table 5. Carbon emissions between peatlands in the rainforest vs. mountain systems are not differentiated, so the same rate was applied to emissions in both systems.

The baseline data for the year 2000 only represents the presence of tree cover as a tree crop or more natural forest; the specific forest type and characteristics were identifiable (e.g., intact primary tropical rainforest vs. secondary forest). Therefore, forest types were assigned using the FAO ecofloristic zone data (Ruesch & Gibbs 2008) and IPCC Tier 1 factors (IPCC 2006). The ecofloristic zones characterize regions by their climate (tropical, subtropical, temperate, boreal, and polar) and vegetation type (humid forest, dry forest, moist deciduous forest, etc.).

CAMBODIA

KEY MESSAGES

A TOTAL OF 1.1 MILLION HECTARES (HA) OF FOREST WERE LOST BETWEEN 2000 AND 2015; JUST OVER 796 THOUSAND HA OF THAT LAND NOW SUPPORTS CROPS.

A TOTAL **0.425 MILLION HA OF FORESTLANDS WERE CONVERTED TO HERBACEOUS CROPS**, SUCH AS CASSAVA AND CEREAL GRAINS, **WHICH IS 53 PERCENT OF THE LOST FORESTLAND** NOW CURRENTLY IN AGRICULTURAL CULTIVATION. FORESTS WERE ALSO CONVERTED TO OTHER CROPS, BUT TO A LESSER EXTENT.

THE CARBON STORED WITHIN THE ABOVEGROUND BIOMASS OF THE CROPS REPLACING FORESTS IS 20.9 MILLION TONNES. **IF THESE LANDS WERE STILL FORESTED, THEY WOULD STORE 71.9 MILLION TONNES, A LOSS OF 71 PERCENT.**

Cambodia has a long history of forest management that may predate any other country in Southeast Asia. The first forestry administration in Cambodia dates back to before 634 BC, when the ancient Cambodians established the Klong Prey Chheu (DFW, 1985). The workings of this administration have been long lost to history, but records resurfaced documenting forestry practices adopted under a royal law in 1845. This law, which lasted until 1898, allowed newlywed couples to freely cut down trees to build their homes, and in fact anyone could fell trees if they paid a 10 percent royal tax. The result of this was that in those 50 years, nearly all of the most valuable trees, such as Afzelia and some species of Rosewood, were cut down to the point of local extinction. As that law was coming to a close, records in the Khmer language show that in early 1898, the first Cambodian Ministry of Forests was established with the support of the French (Kim et al. 2005). In 1963, the then all-Cambodian Ministry established a forest research institute that was well run and regulated forest use and removal that was, for the time, sustainable.

In the years since unsustainable practices prevailed, largely driven by the long-running civil conflict, deforestation took off when bombing and defoliants were dropped by the US during the Vietnam War. Fighting between the Lon Nol and the Khmer Rouge caused troupe movements and damage to forests, the mass dislocation of city and village populations during the Pol Pot regime into forest landscapes continued the trend, all capped off by the massive internal need for wood to rebuild homes after the conflict ended (Kim et al. 2005). Finally, the UN-backed democratic elections in 1993 brought one final conflict-related blow to forests: just prior to the elections, about 300,000 refugees returned from refugee camps in Thailand. These refugees found that they no longer had land, so more illegal clearing occurred as they resettled themselves (Kim et al. 2005).

1993 was also the year when the government instituted a concession policy in order to reduce illegal logging and increase government revenue. These concessions, unsurprisingly, led to greater levels of deforestation, but were not the only driver during this period. Illegal and

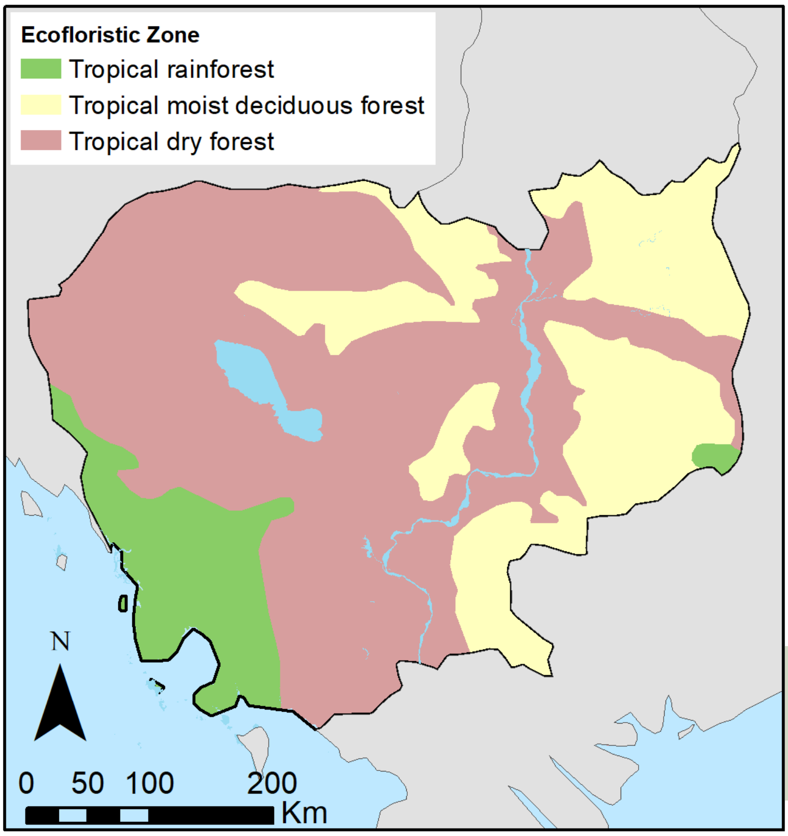


Figure 1: Ecozones in Cambodia, from Ruesch and Gibbs, 2008

Table 1: Volume (in millions of constant 2015 US dollars) of agricultural commodities traded in Cambodia in 2000 and 2015 (from www.bea.gov). Values derived from Chatham House, resourcetrade.earth (2018).

Commodity	USD value 2000	USD value 2015	% change
rice	1.4	309	22,000
rubber	70	174.8	149
palm oil	-	14.6	-
tree nuts	2.5	13.5	5,000
cereals	0.05	4.9	9,000
pulpwood	1.7	4.7	178
tree fruits	0.07	0.75	1,000
cocoa	-	0.6	-
coffee	0	0.02	41,000
banana	-	0.02	-
coconut	-	0.02	-
tea	-	0.01	-
tobacco	-	-	-

quasi-legal logging of protected areas had also been an important factor in the northwest along the border of Thailand and in the northeast along the border with Vietnam (EIA 2017; Ingalls et al. 2018; Kong et al. 2019). Although Cambodia has banned exports of roundwood, illegal logging for unprocessed exports has continued, even in protected areas. One of these unprocessed exports is likely charcoal (Pulitzer Center 2012); a 2012 FAO study found that 84 percent of the country was dependent upon it for their primary source of energy.

By the year 2000, Cambodia had lost substantial forest cover, but still was covered with a respectable 12 million hectare (ha), which was more than 66 percent of the land cover; this included 6.27 million ha of dense forest, and 5.85 million ha of mixed forests (ODC, 2019). A separate study with slightly different definitions of forestlands reported that 1990 forest cover totaled 12.9 million ha, but was reduced to 11.5 million ha in 2000—a reduction of 11 percent (FAO 2015). In 2005, 17 percent was lost compared to the 1990 baseline; 22 percent in 2010 and 27 percent in 2015 (ibid). By 2015, forest cover was down to 9.5 million ha (ibid), with a loss of 53 percent of its dense forest (ODC 2019). FAO estimated that in the period from 2005 to 2010, Cambodia had the third highest rate of deforestation in the world (FAO 2010).

Deforestation rates rose during this period and undoubtedly many of the above-mentioned drivers are still at work. If Cambodia is anything like the rest of the world's developing tropical nations, commodity crop plantations have been the major driver since the turn of the century (Curtis et al. 2018). Commodity crop agriculture is not the only driver—other land use demands are also a factor. Illegal logging still continues, and the increase in tourism in the country appears to be a driving factor, at least in areas frequented by tourists, such as Siem Reap. There, wood is harvested for charcoal, which is used to cook large amounts of the traditional foods preferred by tourists (Gaughan et al. 2009).

In terms of what type of commodity production system results in the most forest loss, economic land concessions (ELCs) for commodity plantations, as well as mining and other development account for, by far, most it. The total loss due to all ELCs occupies an area 2.35 million ha; of this area more than 500,000 ha are in protected forest areas, though the proportion of ELCs in forest has been reported to be as much as 50 percent (Davis et al. 2012; ODC 2019). ELCs tend to be associated with higher rates of deforestation—with rates as much as 105 percent higher, compared to other lands undergoing forest loss. In addition, leakage effects also tend to be present, with deforestation or degradation occurring outside the boundary of the ELC (Davis et al. 2012).

Traditional land uses that produce small clearings or other disturbances (such as collecting non-timber forest products) in forests are frequently described as producing forest degradation. ELCs often grant rights to forest clearing, for a variety of purposes, including forest restoration in these degraded systems; however, labelling traditional patterns of forest use as a form of degradation allows a mostly intact system with high carbon storage value to be converted to industrial monoculture, resulting in large losses of stored carbon and large emissions (Scheidel and Work 2016, 2018). ELCs may also be indirectly contributing to conversion in areas adjacent to concessions that lack good forest monitoring systems, or where there is no enforcement of forestry regulations preventing additional conversion (Work and Thuon 2017).

What to do about the expansion of these plantations is a topic that is hotly debated in policy circles. Such agriculture drives deforestation and releases enormous amounts of greenhouse gases (GHGs) into the atmosphere. However, such agriculture is necessary to support growing world populations. Many have suggested that until the underlying issues of population growth and unsustainable consumption can be addressed, the best solution to agriculture driven deforestation is to direct expansion onto the most appropriate lands, and devise ways of intensifying land use while keeping carbon in the ground. Our study, described below, estimates areas of land that have been converted for different agricultural crops, identifies the type of farming system used to grow those crops, and calculates carbon losses in land due to deforestation and conversion. Such information can help policy makers direct more environmentally sound and climate-friendly land use policies.

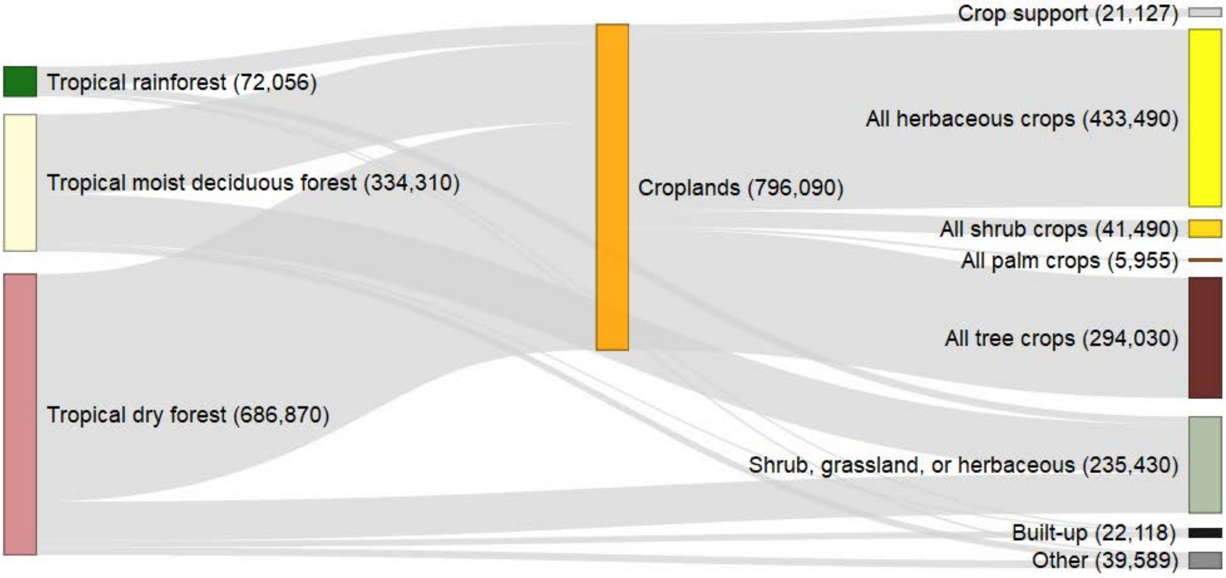


Figure 2: Composition of land use and crops in lands that underwent forest loss since 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in 2000, while the right side represents the land cover after 2015. The total area of all crops is represented by the croplands bar in the middle. Area estimates (ha) are adjacent to the labels.

AGRICULTURAL DEVELOPMENT TRENDS IN CAMBODIA

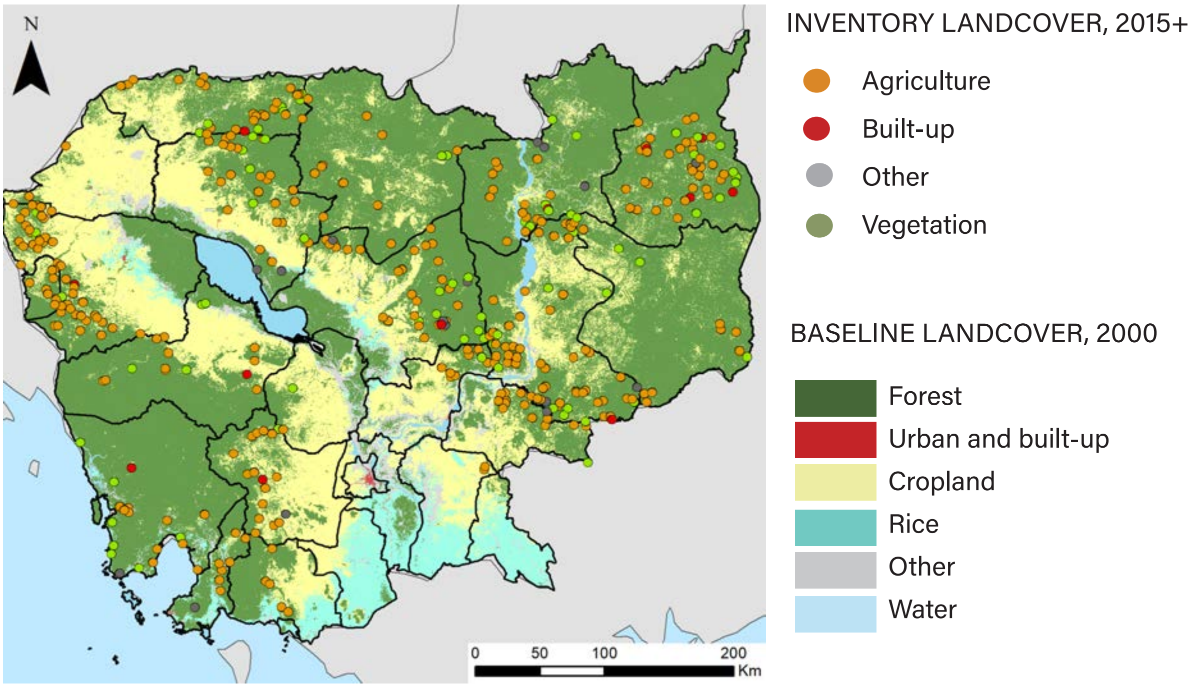
Cambodia has experienced significant growth in trade and exports of agricultural products since 2000. The growth was driven by increased yields, labor efficiency and mechanization, and agricultural land expansion (World Bank 2015). In particular: rice, rubber, palm oil, pulpwood (Acacia and eucalyptus), tree nuts (cashews), and cereals had large increases in traded volume and value between 2000 and 2015 (Table 1). Altogether these commodities accounted for more than USD 600 million in exports in 2015, compared to less than USD 100 million in 2000. There has also been growth in the value of cereal crops, coconuts and other tree fruits, cocoa, tea, and coffee; however, these crops are overall of relatively low economic importance in Cambodia. In terms of exported volume, the Census of Agriculture of Cambodia (2013), noted that rice and cereals dominate, with a record 180,3000 tons of exported cereal and 174,000 tons of exported rice in 2011.

Among perennial crops, rubber has the largest expansion area (75,400 ha), followed by cashew (60,000 ha), and mango (41,000 ha) (Census of Agriculture of Cambodia in 2013). Other commodities such as coconut and fruit trees, other than mango, had cultivation area below 10,000 ha (ibid). For example, citrus trees such as oranges, tangerines, pomelo, lime, lemon and kaffir lime occupied about 2,600 ha, accounting for about 0.7 percent of the total area of perennial crops. The total area of rubber plantation accounts for about 24 percent, managed by concession or households. The area increased by about 16 percent annually from 2002 to 2011 (World Bank 2015). Another crop with a large area of plantation coverage is banana, which constitutes about 24,000 ha or 7.6 percent of the total area of perennial crops in the country.

TREE CANOPY COVER LOSS IN CAMBODIA

Approximately 1.1 million ha in Cambodia have been converted to other land covers and uses since the baseline year of 2000, according to our photo-interpreted samples (Figure 5). When compared to baseline forest cover estimates from the global forest resource assessment, this is a loss of 9.5 percent of the forest since 2000, or 9.2 percent of the area of forest and woodland region (FAO 2015). The Cambodia contribution to the global forest resource assessment reported forest area for 2000 at 11.5 million ha, or 11.8 million ha of forest and woodlands (FAO 2015, Table 1A). However, while this comparison of loss to the Global Forest Resource Assessment (FRA) baseline estimate provides some context, caution needs to be taken when interpreting

Figure 3: Spatial distribution of plots in the sample that have been deforested over the study period, overlaid on a land cover map from 2000 (Saah et al. 2020).

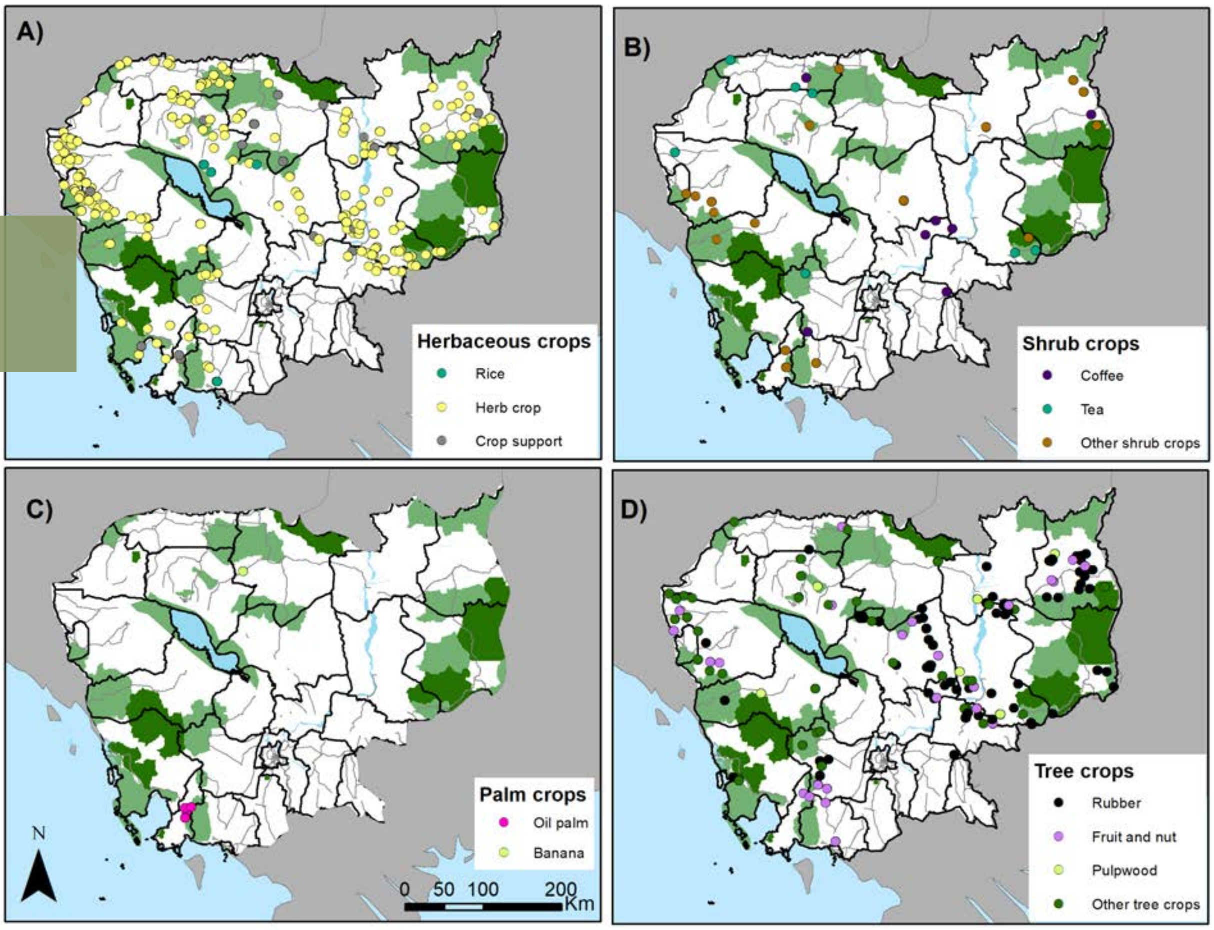


the percent loss estimates since both studies have a different definition of forestland. To some extent our definition aligns with the combined forest and woodland estimate from FAO (2015): forest is any half ha patch (or greater) with trees higher than 5 meters and a canopy cover of more than 10 percent that is not in predominantly agricultural or urban land use. Wooded land is nearly the same but the canopy cover is from 5 to 10 percent or has a combined cover of shrubs, bushes and trees above 10 percent (ibid). However, these do include rubber and other tree plantations, so it is not a direct comparison with definitions used in this study; our definition of forest cover excluded canopy cover and forest patch size thresholds.

Other agencies report forest cover estimates for our baseline year of 2000. Open Development Cambodia (ODC 2019) maps show 12 million ha of forest in 2000, 66 percent of the country area; 52 percent was dense forest and 48 percent was mixed forest. This means our estimates represent a loss of 9.1 percent of dense and mixed forests as mapped by Open Development Cambodia (ODC 2019). The variation in the estimates of total forested area for 2000 are partially attributed to differences in the operational definition of forest between reporting agencies and, to some extent, measurement uncertainties (Keenan et al. 2015, Tropek et al. 2014).

Regardless of the definition of forests, changes in tree cover are distributed across three ecozones: tropical rainforest, tropical moist deciduous forests, and tropical dry forest. The majority of forest loss is occurring in the tropical dry forest: 687,000 ha, roughly 63 percent of total forest loss. This is the dominant ecozone, running across central Cambodia (Figure 1) and covering 11.1 million ha, or 61 percent of the country. However, not all of this ecozone still supports forestlands, the same is true for the other ecozones. Thirty-one percent, approximately 334,000 ha, and 7 percent, 72,000 ha, of the forest clearing occurred in the tropical moist deciduous forests and tropical rainforest, respectively. The tropical moist deciduous forest zone is in the northeastern part of the country along the border with Vietnam and covers 28 percent of the nation (5 million ha). The tropical rainforest ecozone covers 11 percent, 2 million ha, and is located along the coastline and part of the southern border with Thailand.

Figure 4: Spatial distribution of crop types at plots within the sample where deforestation events were followed with crop cultivation (depicted by orange dots in Figure 4) overlaid on top of the road network. Dark green areas are protected forest boundaries, light green indicate boundaries of other protected areas such as national parks and wildlife sanctuaries (ODC 2020).



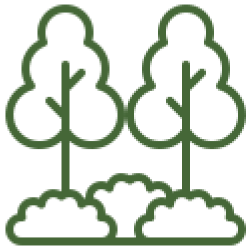
About 73 percent of the total forest loss, 796,090 ha out of 1.1 million ha of loss, is in cultivation (Figure 2). We also found that 18 percent, 235,430 ha, of the forest loss is now supporting non-crop vegetated landscapes, such as shrubland, grasses, or other herbaceous covers. This transition is observed primarily in the tropical moist deciduous ecozone in the north and eastern part of the country. These lands are likely temporary land use changes due to shifting agriculture as well as lands that have been more permanently degraded.

There may have been different drivers of deforestation and land uses in between the current state and 2000 that are not presented in these results. For example, in southeast Asia, deforestation is often initially driven by selective logging, then the land is subsequently converted to agriculture (Saunders et al. 2014). Because we have assessed land cover at just two points in time, not the full time-series of Landsat images, the results do not represent the potential intermediary land covers and uses or proximate driver of deforestation.

Forest conversion to crops is clustered along the forest and agricultural interface, adjacent to areas where there is already land in cultivation (Figure 3) or near primary road corridors (Figure 4). Figures 3 and 4 portray the spatial distribution of forest loss dynamics using the photo-interpreted points, including deforestation from conversion to crops, to other vegetation, and to built-up lands. Deforestation is largely occurring outside of protected forests, although some clearing activity is taking place within protected areas (Figure 4).

By itself, the available high-resolution imagery did not allow us to identify specific crop types on the vast majority (540,000 ha or 67.9 percent) of the deforested

TABLE 2: ABOVEGROUND BIOMASS CARBON STOCKS

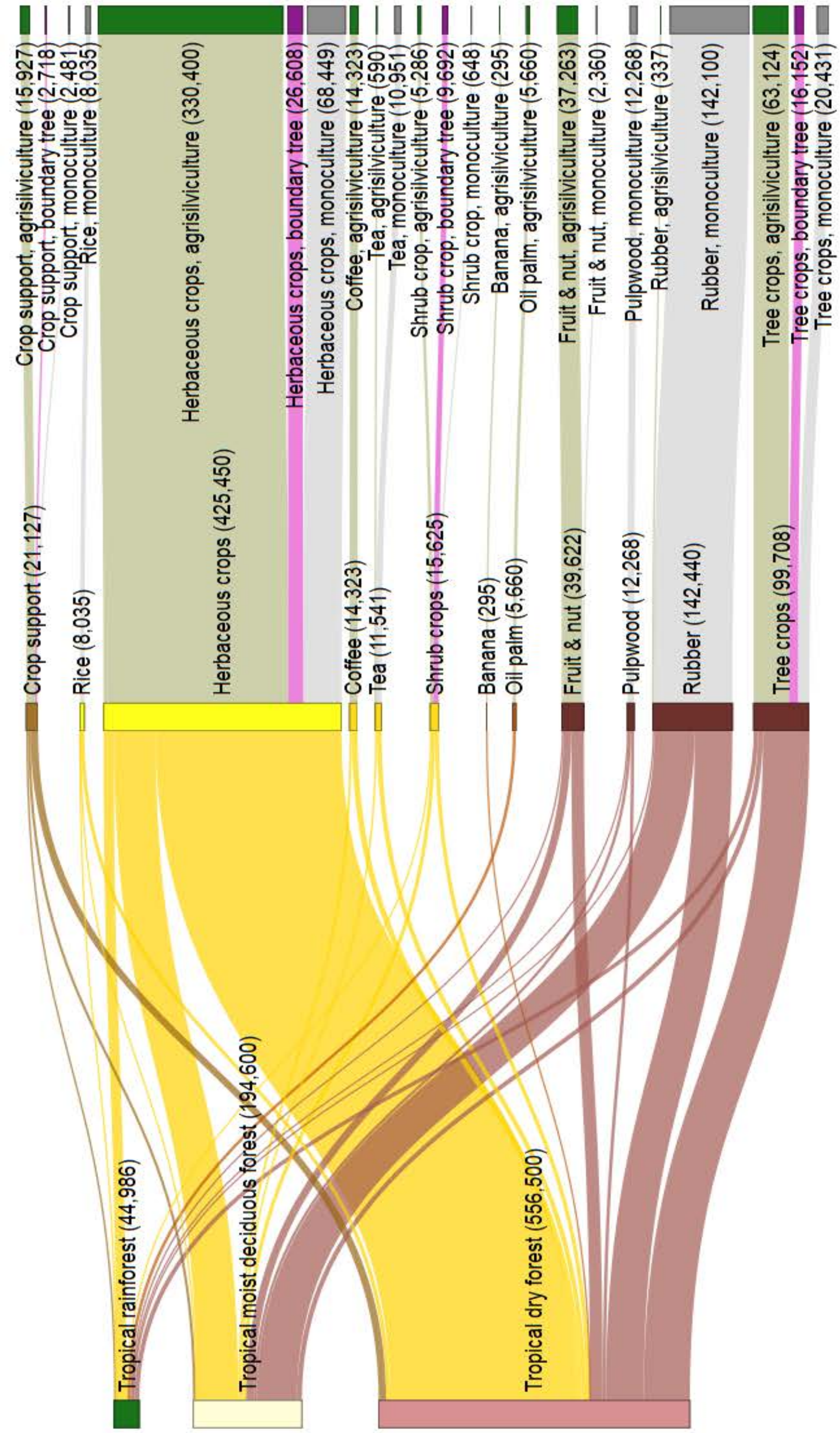


commodity	monoculture averaged (tonnes C/ha)	monoculture in Cambodia (tonnes C)	agroforestry averaged	agroforestry in Cambodia	total in Cambodia
banana	NA	NA	5.7	1,682	1,682
coffee	NA	NA	11.0	157,553	157,553
fruit and nut	75.0	177,000	75.0	2,794,650	2,971,650
oil palm	NA	NA	41.6	235,456	235,456
pulpwood	23.0	282,164	NA	NA	282,164
rubber	31.8	4,518,716	31.8	10,717	4,529,433
rice	1.1	8,838	NA	NA	8,838
tea	15.5	169,740	22.0	12,980	182,720
other herb crops	6.8	465,460	20	7,140,100	7,605,560
other tree crops	43.3	884,662	43.3	3,432,651	4,317,313
other shrub crops	10.5	6,804	16.5	247,120	253,924
crop support	6.8	16,871	20.0	372,920	389,791
TOTAL		**6,530,255**		**14,405,829**	**20,936,084**

	total tonnes C monoculture	total tonnes C agroforesty	total in Cambodia
herbaceous	474,298	7,140,100	7,614,398
shrub crops	176,544	417,653	594,197
palm crops	0	237,138	237,138
tree crops	5,862,542	6,238,018	12,100,560
crop support	16,871	372,920	389,791
TOTAL	**6,530,255**	**14,405,829**	**20,936,084**

Top: Aboveground time-averaged biomass carbon factors of commodity crops. Values for commodities were compiled from peer-reviewed and grey literature. Time-averaged values are used to estimate the carbon storage of rotational commodity crops because they average the carbon in freshly replanted and mature commodities. These values are then used to calculate aboveground biomass carbon contained in the total area of commodities in Cambodia. Calculations are restricted to those commodities in areas that lost natural canopy cover between 2000-2015. **Bottom**: total area of crops, grouped by life form, and total carbon contained in crops by life form.

Figure 5: The composition of crop commodities on land that had natural forest cover in the year 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in the year 2000; the middle section represents the crop type in 2015, with the agroforestry system indicated on the right. Area estimates, in hectares (ha), are included adjacent to the label.



lands. Most (approximately 425,000 ha) of these unidentifiable crops were low growing herbaceous plants other than rice, such as cassava, soybeans and maize (Figure 5). These herbaceous row crops are commonly grown along the edges of the cropland belt running from the northeast in Oddar Meanchey province and to the southwest (Figure 4A). Other crops not identified to a specific type include 99,708 ha of tree crops and 15,625 ha of shrub crops. The tree crops did not match the expected patterns of a monoculture plantation of rubber, coconut, oil palm, banana, or fruit and nut trees. Based on crop statistics, we infer that these trees could be teak, a mix of tree crops, or other species.

Of the identifiable crops, there were 142,440 ha of forest converted to rubber within the tropical moist deciduous and dry forest ecofloristic zones. Rubber and fruit and nut orchards also are in cultivation along this belt running southeast through the center of the country (Figure 4D). Two additional clusters of rubber plantings occur in the northeast in Ratana Kiri and in the south in Kampong Speu. There were 39,622 ha of fruit and nut and 12,268 ha of pulpwood tree plantations. There were also small amounts of oil palm (5,660 ha), banana (295 ha), coffee (14,323 ha), tea (11,541 ha) and rice (8,035 ha). Oil palm is clustered near the coast in Preah Sihanouk province. Many of the herbaceous and tree crops were interplanted following agroforestry practices. For example, only 26 percent of the broad herbaceous crop group are grown as monocultures. These trends appear to align well with previously published trends in forest loss, agriculture, and establishment of state-owned rubber plantations (Dararath et al. 2011; Kong et al. 2019).

The general pattern of commodity crops replacing forest roughly aligns with their export value (Table 1 and Figure 5); the largest exception to this is rice, as only 8.035 ha of rice was found on previously forested land. It should be noted that because this study only analyzes the area of a crop that has replaced forest, there may be crops that experienced growth in non-forest lands. Such growth would be reflected in the trade data shown in Table 1, but not reflected in the results of this study. Rubber and tree fruits/nuts both experienced large gains in export value over the study period and this is reflected in the large areas of previously forested lands that were converted to rubber and fruit/nut crops.

CARBON STORAGE IN CAMBODIA: IMPACTS AND OPPORTUNITIES

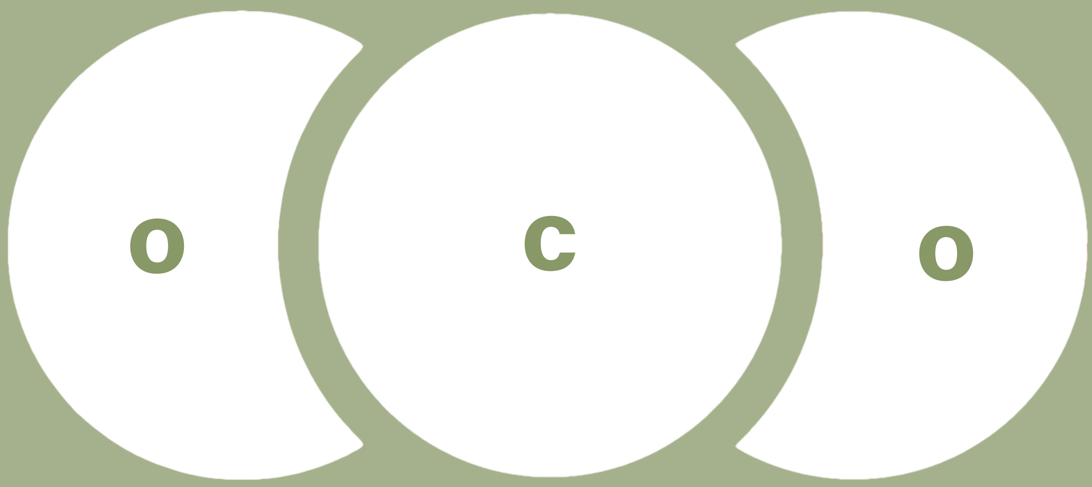
The estimated 20.9 million tonnes C stored in crops in 2015 is only a fraction—about 29 percent—of the carbon that would have been stored as aboveground plant biomass if the land was still in a state of natural tree cover (71.9 million tonnes C) (Table 3). We find that the greatest loss has happened via the tropical dry forest, with 14.2 million tonnes C lost, which is 68 percent of the total 20.9 million tonnes C lost from 2000 till 2015.

Certain types of land use change—for example from tropical rainforest to commodity crop agriculture—have significant negative consequences on carbon stocks, even if the commodity crops are grown in agroforestry systems. This is because tropical forests are among the most carbon-rich ecosystems on Earth. Estimates of carbon stored as aboveground biomass in native forests vary by region and forest type. For example, tier 1 values indicate tropical rainforests store 180 tonnes of aboveground carbon per ha (IPCC 2006, Table 2). Agricultural systems, by comparison, have tier 1 carbon storage values of only about 5 tonnes C/ha, and up to 50 tonnes C/ha if crops are grown in combination with trees (Cardinael et al. 2018; Ruesch and Gibbs 2008). Each crop system stores different amounts of carbon, which also can vary with regional climatic conditions. Tier 2 values take these differences into account; Table 2 contains the estimated Tier 2 aboveground carbon stock values for the crops that replaced forests in Cambodia. Fruit and nut plantations, such as cashews which are currently showing economic growth in Cambodia, had the greatest carbon storage factor at 75 tonnes C/ha. Rice had the lowest, at 1.1 tonnes C/ha.

We find that 4.3 million tonnes C is stored in tree crops that we were unable to identify to a specific crop type, or in agroforestry tree cover and boundary trees. The greatest stock of carbon is found in miscellaneous herbaceous crops in agroforestry systems. They store a total of 7.6 million tonnes C. Of the crop categories that were identifiable to a specific crop type, rubber plantations represent the largest carbon stock, at 4.5 million tonnes C, followed by the aggregate class of fruit and nut orchards with 3 million tonnes C. The carbon storage values of all other crop categories occupying lands that were forested in 2000 are located in Table 2.

Farmers in Cambodia are already using agroforestry practices widely. This is good news for those trying to preserve landscape carbon and may imply that more widespread scaling of agroforestry practices will be relatively simple due to existing national capacity. There appears to be significant room for adoption of these practices in the herbaceous crops category, where at least 0.474 million tonnes C are stored under monoculture cultivation (Table 2); however, this will depend largely on the needs of the specific crop types under

IN TOTAL,
51 MILLION TONNES OF CARBON WERE LOST DUE TO FOREST CONVERSION TO CROPLANDS BETWEEN 2000-2015 IN CAMBODIA.



cultivation here. Table 2 shows that agroforestry practices are used far more than monocultures across crop types in the country with the net carbon storage and land area showing better results. Table 2 shows that across all crop types, agroforestry has better carbon storage per hectare compared to monocultures.

Planting rubber or fruit and nut trees could also increase landscape carbon while building up the economic potential of two export crops of increasing economic value. Further population growth and income-related increases in per capita consumption of food and forestry products are likely to continue in Cambodia and will drive increases in domestic demand and export production. It will be important to increase the productivity of existing agricultural land and forests to reduce pressures on the remaining natural forest (Michinaka et al. 2013). Not only should agroforestry practices be extended to those places where monocultures still exist, but the productivity of existing agricultural land can and should be increased by other means, such as by encouraging farmer cooperatives, improved extension services, or access to credit for the vast majority of farmers in the country who are smallholders and farm less than 2 ha of land.

Of course, while development issues often trump landscape carbon stock concerns, the loss of Cambodia's forests should be a worry for the 77 percent of Cambodians who live in rural areas. This population is dependent upon natural resources, and as forests continue to degrade, those resources and the ecosystem services they provide will disappear or diminish. The 2008 Protected Areas (PAs) Law designated eight categories of protected areas in Cambodia; by late 2017, these areas covered 7.5 million ha, or nearly 41 percent of the country's total land area (ODC 2016). Protected areas provide health benefits compared to deforested and degraded landscapes, with lower rates of diarrhea, fever, and respiratory infections in PAs compared to areas of degraded forest (Pienkowski et al. 2017). While these areas should be both preserving ecosystem services and landscape carbon, there is evidence that this may not be the case. In Cambodia, PAs do not preclude many economic activities of local communities, such as resin-tapping (Clements et al. 2014; Beauchamp et al.

TABLE 3: CHANGES IN ABOVEGROUND BIOMASS (AGB) IN NATURAL FORESTS AND ALTERNATIVE CROPS BY ECOFLORISTIC ZONE (TONNES C/HA)

	average C/ha in AGB	C in forest (2000)	C in crops replacing forest (2015)	C lost due to conversion
TROPICAL RAINFOREST	180	8,097,660	1,352,972	**6,744,688**
TROPICAL MOIST DECIDUOUS FOREST	105	20,433,315	5,387,601	**15,045,714**
TROPICAL DRY FOREST	78	43,407,234	14,195,512	**29,211,722**
TOTAL		**71,938,209**	**20,936,085**	**51,002,124**

2018). In theory, this balance between community use and natural resource management is good; in practice, protected areas are not policed due to jurisdictional laws within concession areas, and deforestation rates are higher in these areas than they are anywhere else (David et al. 2015). Reversing the practice of allowing concessions in protected areas, or at least improving policing, should therefore be a primary concern for those who want to preserve landscape carbon.

CONCLUSIONS AND RECOMMENDATIONS FOR CAMBODIA

Despite challenges in setting historic baselines for tree cover and carbon sequestration, this analysis still provided better spatial resolution and thematic disaggregation than previous attempts (i.e., Curtis et al. 2018) due to the use of photo-interpretation of high-resolution imagery and Tier 2 carbon factors. Overall, we found that the main types of crops grown on formerly forested land in Cambodia are herbaceous row and tree crops. Available imagery is not sufficient to distinguish many of the specific herbaceous or tree crops present. The transition from natural forest to agriculture releases as much as 51 million tonnes C into the atmosphere, which is 71 percent of what the natural forest would have stored had it not been replaced. Protecting Cambodia's remaining forests, whether primary or secondary, is critical for reducing carbon emissions from land use change. It is also critical for the nation if it wants to meet pledges outlined in its NDC, be eligible for carbon credit funds, and improve local livelihoods and ecosystem services. Cambodia will struggle to preserve these forests in the face of growing populations and increasing consumption patterns unless effective policy decisions are made and enforced.

There are a number of options that Cambodia can implement in order to improve the carbon storage in its landscapes while still developing its agriculture sector. Many of these options are general and apply to all of Southeast Asia, and more generally, to all countries struggling to reconcile tropical forest protection with economic growth. These include: targeting agricultural expansion onto degraded or fallow lands; transitioning monoculture plantations into agroforests; giving farmers the knowledge and technology they need to more productively use their lands; paying attention to transportation networks and targeting agricultural development in those places which require less extensive transportation; securing land rights for local people and expanding the practice of community forestry; and exploring models for payments for ecosystem services to encourage people to leave forests standing.

However, a brief literature review illuminates a number of policy options which are specific to Cambodia. First, one study (Sasaki and Yoshimoto 2010) found that in Cambodia teak and rubber production could have positive net economic benefits, while oil palm and pulpwood would not. Rubber, teak, and fruit trees can sequester and store substantial amounts of carbon storage and also have a high economic value.

Cambodia has already been increasing investment into these (rubber and fruit/nut) crops over the study period, and continuing that investment seems worthy towards meeting economic and environmental goals. In areas where concessions exist on degraded lands, the government can target its support of landowners to plant rubber, teak and fruit/nut crops rather than other less profitable, less carbon-intense crops. Of course, reforestation to natural forest conditions would have better carbon and ecosystem payoffs but would not help Cambodia recognize the economic gains it wants to achieve. Although with the continuing development of carbon payment programs, eventually this may be a more profitable option.

As noted earlier, charcoal production and fuelwood harvesting are drivers of deforestation in Cambodia. The United Nations Development Program (UNDP) recently estimated that the annual consumption of fuelwood is about 6 million tons, which is equivalent to the annual loss of 71,600 ha of deciduous forests (Khmer Times 2019). As for fuelwood, in some areas, up to 96 percent of households depend on it as a primary source of energy for cooking, boiling water, preparing animal feed and protecting cattle against insects (San et al. 2012). The solution is unfortunately not as simple as putting quotas on fuelwood harvesting and charcoal production. For one, charcoal is a particularly lucrative livelihood for some of the most vulnerable members of the population (Geres 2015). Fuelwood is likewise the only energy option for most of the rural population. Various development initiatives over the years have attempted to tackle the problem of charcoal production and fuelwood harvesting, and these should be expanded. These initiatives included donating fuel-efficient cookstoves to communities (GNESD 2006), creating green charcoal out of coconut husks and other waste materials (KGC 2019), building bio-gas digesters more broadly (SNV 2019), installing solar power arrays (ADB 2016) and launching a new digital platform for sustainable charcoal production supported by UNDP, Geres and RECOFTC (Khmer Times 2019). Eliminating charcoal entirely will be difficult because it is important in cooking and flavoring many of Cambodia's traditional foods; however, consumption of both charcoal and other fuelwood can be minimized and made more sustainable through all of the above measures.

Cambodia is also in need of support with forest law enforcement. The illegal timber trade has been an issue at least since the times of the Khmer Rouge, when fighters traded timber illegally with Thailand in order to finance military operations (Alley 1997). A 2004 FAO study identified a faulty legal system, insufficient knowledge and poor knowledge management, excessive discretionary powers in the public and private sectors, poor implementation capacity of the public forest administration and enforcement agencies and lack of transparency in decision-making in the forestry sector at all levels as the root causes of forest crime (Amariei 2004). These factors are still underlying forest crime today.

Studies have identified a number of weak points and potential solutions in forest law enforcement policy and practice. First, corruption is still an issue among those responsible for policing forest and agriculture products, with shadow economies supported by state actors facilitating illegal trade (Mahanty 2019). Cambodia will need to make a true commitment to reducing corruption with the government ranks if it wants to protect its forests. Second, rangers need additional financing and training. The United States Forest Service began a training program for Cambodia forest rangers fairly recently (Phnom Penh Post 2018), and such training needs to be expanded to include all of the 1,200 plus rangers who protect Cambodia's forests. A related issue is the expansion of forest policing through community-based monitoring. At least one study has found that by providing communities with smartphones and basic training in using apps, 36 community members were able to record almost 11,000 entries on forest resources and illegal logging in just two years (Brofeldt 2018), which also saved money as compared to professional forest policing. Such simple, yet effective, programs can take advantage of the expansive rural populations, provide a cost-effective means of policing, and deliver technical training and thus improved technical capacity to Cambodia's most disadvantaged people.

Finally, laws concerning protected areas must be amended and enforced. As of 2017, approximately 41 percent of Cambodia's lands are encompassed by protected areas. However, this is a bit of a misnomer, as in some of these areas, deforestation is up to 105 percent higher than in non-protected areas as large-scale clearing and land conversions have continued (Scheidel and Work 2018; EIA, 2019). Part of the reason this continues is because a number of sub-decrees under the 2008 Protected Areas Law allow for parts of protected areas to be classified as sustainable use zones. These areas are, however, not sustainably used. Typically, these natural protected areas do not have zone management plans and, if they do, no geographical information is provided. As a result, any economic land concessions that are located in the protected areas cannot be monitored to see whether or not activities take place in a zone classified as high protection. Further, community rights in protected areas need to be clarified so that traditional and sustainable practices, such as resin tapping, are formally recognized. This may alleviate some of the tension and conflicts that occur in protected areas, particularly those that are also designated as concessions. Government rearrangements in the mandate of environmental agencies in recent years may improve the situation in protected areas, but it is yet too early to tell. Either way, the government support and adoption of laws that appropriately protect designated protected areas is vital to meeting forest conservation goals.

While designing and implementing effective environmental policies and practices is challenging in the best of situations, it is especially challenging in the most underdeveloped countries. Understandably, policies supporting economic growth and improved livelihoods are prioritized over environmental protection when the two are in conflict. However, such choices should not be necessary. There are ways to develop Cambodia's economy without exploiting further natural resources. Land use can be intensified in those areas where it is already degraded, new technology can be implemented to ensure further environmentally based growth is not exploiting new resources, and communities can be given land rights and the technical education that helps them understand, use and monitor their land effectively. Monitoring and penalizing investors (such as the Chinese) for unsavory development practices will also slow deforestation and support sustainable practices. Pilots that have demonstrated records of success—such as the sustainable charcoal initiatives—should be scaled up to avoid the of impacts subsiding after project closure. Such large-scale change and required coordination are no easy tasks, but it is achievable with thoughtful investment and a willing, well educated populace.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INDONESIA

KEY MESSAGES

A TOTAL OF 10.6 MILLION HA OF FOREST WERE LOST BETWEEN 2000 AND 2015; ABOUT 6 MILLION HA OF THAT LAND NOW SUPPORTS CROPS.

IN TOTAL **2.3 MILLION HA OF FORESTLANDS WERE CONVERTED TO OIL PALM PLANTATIONS, WHICH IS 19 PERCENT** OF THE LOST FORESTLAND THAT IS NOW CURRENTLY IN AGRICULTURAL CULTIVATION.

THE CARBON STORED WITHIN THE ABOVEGROUND BIOMASS OF THE CROPS REPLACING FORESTS IS **189 MILLION TONNES.** THIS REPRESENTS A LOSS OF **85.6 PERCENT OF THE CARBON STORED IN FORESTS** FROM 2000 TO 2015.

0.9 MILLION HA OF PEAT SWAMP HAVE DEGRADED SINCE 2000 and 693,000 HA ARE NOW UNDER CULTIVATION **RESULTING IN AN ADDITIONAL 10.8 MILLION TONNES C EMITTED** FROM PEAT DECOMPOSITION.

Global demand for agricultural and timber commodity crops has emerged as the primary driver behind tropical deforestation (Henders et al. 2015), and there is nowhere that this is more true than in Indonesia. Indonesia, once lushly forested and teeming with biological diversity, experienced rapid deforestation by 2014. The rise in deforestation rates occurred fairly rapidly, brought on by policies of economic liberalization under former President Suharto, who began granting economic land concessions in the 1970s. Previous to this government land grab, in 1950, nearly 159 million ha (87 percent of the total land area) in Indonesia was covered by forest. However, between 1950 and 1997, 59 million ha (37 percent) of the forest was removed and turned largely to support agricultural production. Between 1997 and 2015, an additional 9 million ha of forest was lost, leaving the country with a little over half of what it had in the middle of the previous century (Tsujino et al. 2015). This rate has slowed in the years since, although the forests are still under heavy conversion pressures brought on by explosive population growth and economic development.

Mining, energy, urbanization, and wildfires are other drivers of forest loss in Indonesia (Curtis et al. 2018), but commodity crop production and agriculture by far top the list. Indonesia is a major producer of commodities, particularly oil palm, rubber, and wood (both fiber and logging). Oil palm has been expanding particularly rapidly, with one recent analysis estimating that oil palm plantations took over 450,000 ha of forests per year between 1995-2015 (Austin et al. 2017). The cultivation of rubber has also been expanding. Between the years 2000 and 2010, approximately 2 million ha of new plantations were created, half of which were in montane areas (Blagodatsky et al. 2016). This trend of expansion is expected to continue, as rubber demand grew by 100 percent between 2000-2015 (International Rubber Study Group 2016) and will need to need to keep growing in order to meet the needs of auto industries in developing countries (Ahrends et al. 2015).

Finally, wood is another economically important commodity crop in Indonesia: exports of wood pulp, chips, and similar products exceeded USD 2.5 billion in 2015 (Table 1). Between 2000 and 2010, fiber plantations and logging concessions caused the greatest area of commodity crop forest loss: 1.9 million ha and 1.8 million ha, respectively (Abood et al. 2015). Kalimantan and Sumatra have been the islands experiencing the greatest impact of this spike in deforestation. As much as 5.4 million ha of the forests on these islands were

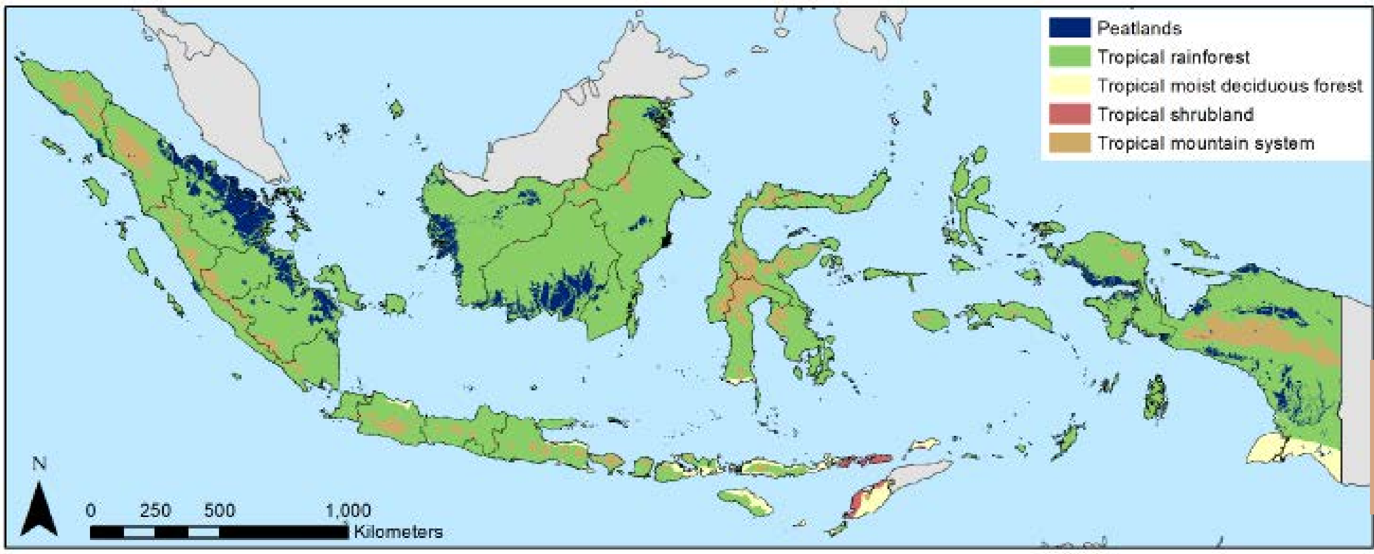


Figure 1: Ecozones in Indonesia, from Ruesch and Gibbs, 2008

Table 1: Volume (in millions of constant 2015 US dollars) of agricultural commodities traded in Indonesia in 2000 and 2015 (from www.bea.gov). Values derived from Chatham House, resourcetrade.earth (2018).

Commodity	USD value 2000	USD value 2015	% change
palm oil	1,990	17,892	798
rubber	1,416	4,367	208
pulpwood	1,466	2,532	72
cocoa	534	1365	256
coffee	508	1,289	154
coconut	640	1,184	85
tree nuts	104	478	461
tea	158	138	-13
tree fruits	43	101	236
rice	3	3	0
banana	-	-	-
cereals	-	-	-
tobacco	-	-	-

cleared between 2000 and 2010, 80 percent of which were on land concessions that allow for forest clearing (Broich et al. 2011).

In Indonesia, oil palm, rubber and pulpwood plantations are often found growing on former peat swamp forest that has been drained to convert it to dry land (Abood et al. 2015; Miettinen et al. 2010). Not only does such conversion result in deforestation, but it results in a profusion of negative and additive downstream impacts. Peat is normally covered with water much of the year, and the removal of this water via drainage canals leads to immediate oxidation of the peat and releases carbon dioxide into the atmosphere. Peat soils lack the structure of mineral soils, so once water is removed, the peat dome also begins to compress. Over the years, oxidization and land use causes further compression, and peat domes eventually collapse (Evans et al. 2019); one study on Acacia plantations found this rate to average 4.3 cm of subsidence per year (ibid). This collapse can be managed, but not reversed. It results in salt water intrusion in coastal areas, and an inability of peat soils to hold water properly (Thorburn and Kull 2015). If peat is not rehabilitated before collapse is complete, it will become perpetually flooded and both dryland commodity crop production and rehabilitation can become impossible (Sumarga et al. 2016).

Compounding peat drainage and oxidization issues are wildfires. Fires are frequently used to clear land by both small-holder shifting (slash-and-burn) agriculturalists as well as some commercial plantations. A frequent consequence is the unintended burning of peatlands (Page et al. 2002; Harrison et al. 2009; Turetsky et al. 2015). These fires are notoriously difficult to put out, because they burn not only at the surface, but deep into the carbon rich peat deposits that have accumulated over the years. Traditional knowledge suggests that only the onset of the rainy season can truly put them out; anecdotal accounts report that even short downpours (10 hours or less) are unable to put out these deep fires. As peatlands combust, their conversion from a carbon sink to a source is accelerated. Not only is carbon dioxide emission hastened, but hydrocarbons (e.g. methane, benzene and toluene), halocarbons (Page et al. 2002; Turetsky et al. 2015), and heavy metals and other noxious particulate matter are also released into the atmosphere.

Peat conversion therefore has significant implications on climate change mitigation and associated emissions reduction targets in Indonesia. Indonesia contains the largest total additive area and global volume of tropical peat soils of any country, at 20.7 million ha and 475 km^3, respectively. These peatlands are thought to contain 28.1 giga-tonnes (Gt) carbon (Warren et al. 2017). This accounts for, at a minimum, 56 percent of the global total tropical peat carbon stores, which are estimated to range from 50 to 105 Gt carbon (Hu et al. 2018; Page et al. 2011; Dargie et al. 2017; Yu et al. 2010). While peat depths can be up to 12 meters, a recent study found that 80 percent of Indonesian peatlands are over 3 m thick. The carbon contained in these shallow peatlands is estimated to be 10.6 Gt carbon, equivalent to about 12 years of global emissions from land use change at current rates (Warren et al. 2017). Understanding how much carbon lies in shallow deposits is especially important because Indonesia's current moratorium on development on peatlands only applies to peat deposits over 3 m deep. This means that the vast majority of Indonesia's peat, and carbon stored in it, are vulnerable to conversion under existing environmental regulations.

Because so many commodities are grown on carbon-rich peat, commodity-driven land use change in Indonesia has significant impacts on the greenhouse gas balance from the agriculture, forestry and other land use (AFOLU) sectors. Natural forests in Indonesia often have large carbon stocks, (over 250 tonnes C per ha) and the conversion of natural forest and peatlands to medium-scale cultivation and commodity plantations can generate large emissions and losses of carbon stocks (Miettinen et al. 2010; Guillaume et al. 2018). The AFOLU sector in Indonesia has traditionally been the country's biggest source of GHG emissions, and it will remain a large source if forest loss and commodity crop expansion both continue at a rapid pace and on carbon-rich soils. Further, commodity production itself can create emissions, which may or may not be significant: wetland rice production, as one example, creates soil conditions that generate methane (Hadi et al. 2005).

Because commodity crop production is likely to remain an important part of Indonesia's agriculture sector development, there is a need for future investments into the sector to assess possible impacts on forests and the climate system. To do this, knowledge of how and where natural forests are being converted to agricultural commodities and the associated greenhouse gas emissions are needed. The Curtis et al. (2018) study

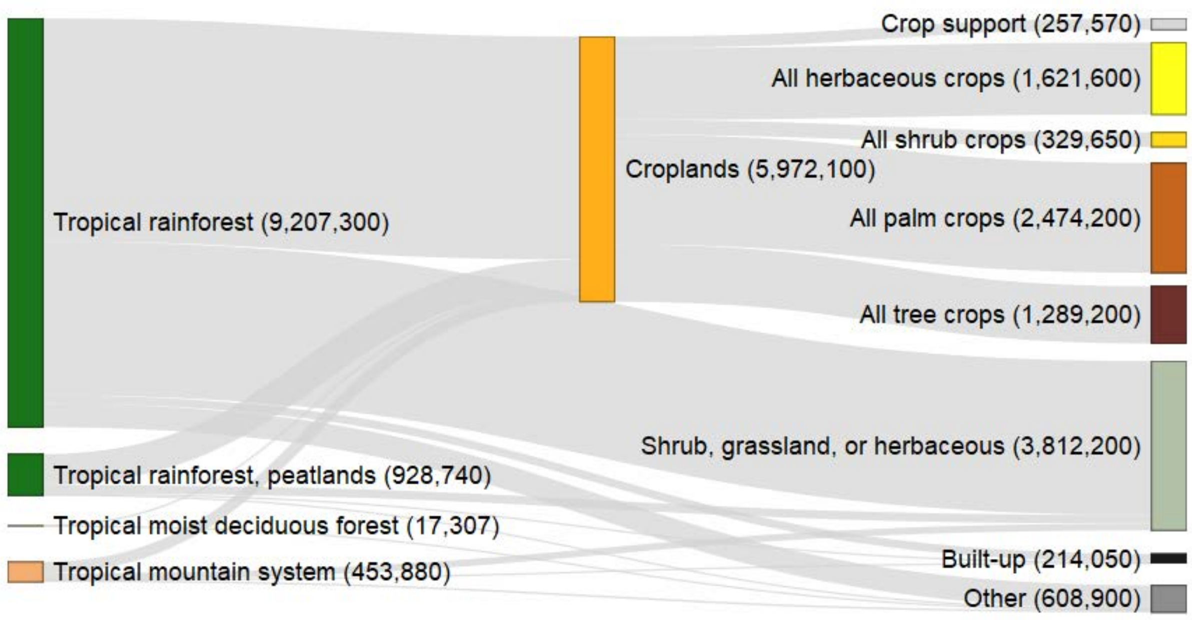


Figure 2: Composition of land use and crops in lands that underwent forest loss since 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in 2000, while the right side represents the land cover after 2015. The total area of all crops is represented by the croplands bar in the middle. Area estimates (ha) are adjacent to the labels.

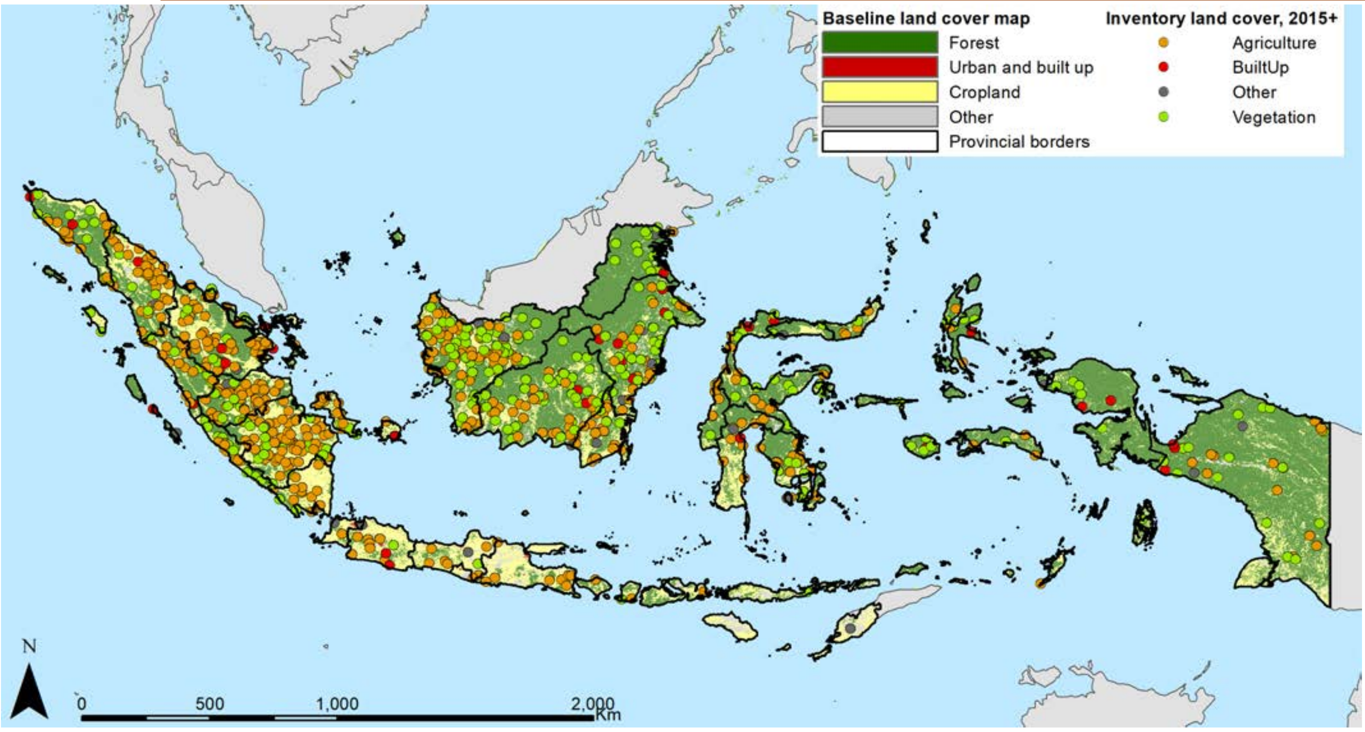
used as the baseline for this volume assessed high resolution imagery to identify the proximate causes of tree cover loss. They found that 53 percent of tree cover loss in Indonesia is commodity-driven while 45.7 percent is due to cycles of tree cover disturbance and regrowth—9 percent plantations and 36.7 percent shifting agriculture. We take this work a step farther by using photo-interpretation methods and regionally relevant carbon stock factors to estimate carbon loss as a result of the specific land use changes that are occurring in Indonesia. Determining emissions from peat fires, though important to Indonesia's overall GHG balance, was outside the scope of this study; estimates of peat decomposition are nonetheless presented in the results.

AGRICULTURAL DEVELOPMENT TRENDS IN INDONESIA

For over two decades (from 1970-1996) until the onset of the Asian Financial Crisis, economic growth (GDP) in Indonesia was strong, at roughly 7 percent yearly. The crisis slowed economic development, and in the post-crisis period the annual average GDP growth of 4.9 percent overall. Growth in the agriculture sector was even slower, topping out at 2.4 percent in the 2000-2006 period; this slowing has been attributed to a decline in production in non-food crops (Winoto & Siregar 2016). Estimates from recent years suggest that the rate has risen again, and as of 2019, growth in agricultural GDP was 4 percent. This means that agriculture is again one of the three biggest sectors of the economy, along with the processing sector and trade. This recent upsurge, according to the Government of Indonesia, is a result of new irrigation construction on dryland; a focus on cultivation of foods such as rice and corn, mango, banana, salacca zalacca, shallot, garlic and chili plants; increasing livestock, fish and shrimp cultivation; and, increasing plantation productivity through plantation revitalization. Overall, agriculture accounts for roughly 14 percent of the GDP (World Bank 2012).

Indonesia is the world's top producer of palm oil and a major global producer of rubber, copra, cocoa, coffee and spices, as well as the world's second largest marine fisheries producer. The country is a net importer of grains, horticulture and livestock products. Large

Figure 3: Spatial distribution of plots in the sample that have been deforested over the study period, overlaid on a land cover map from 2000 (Saah et al. 2020).



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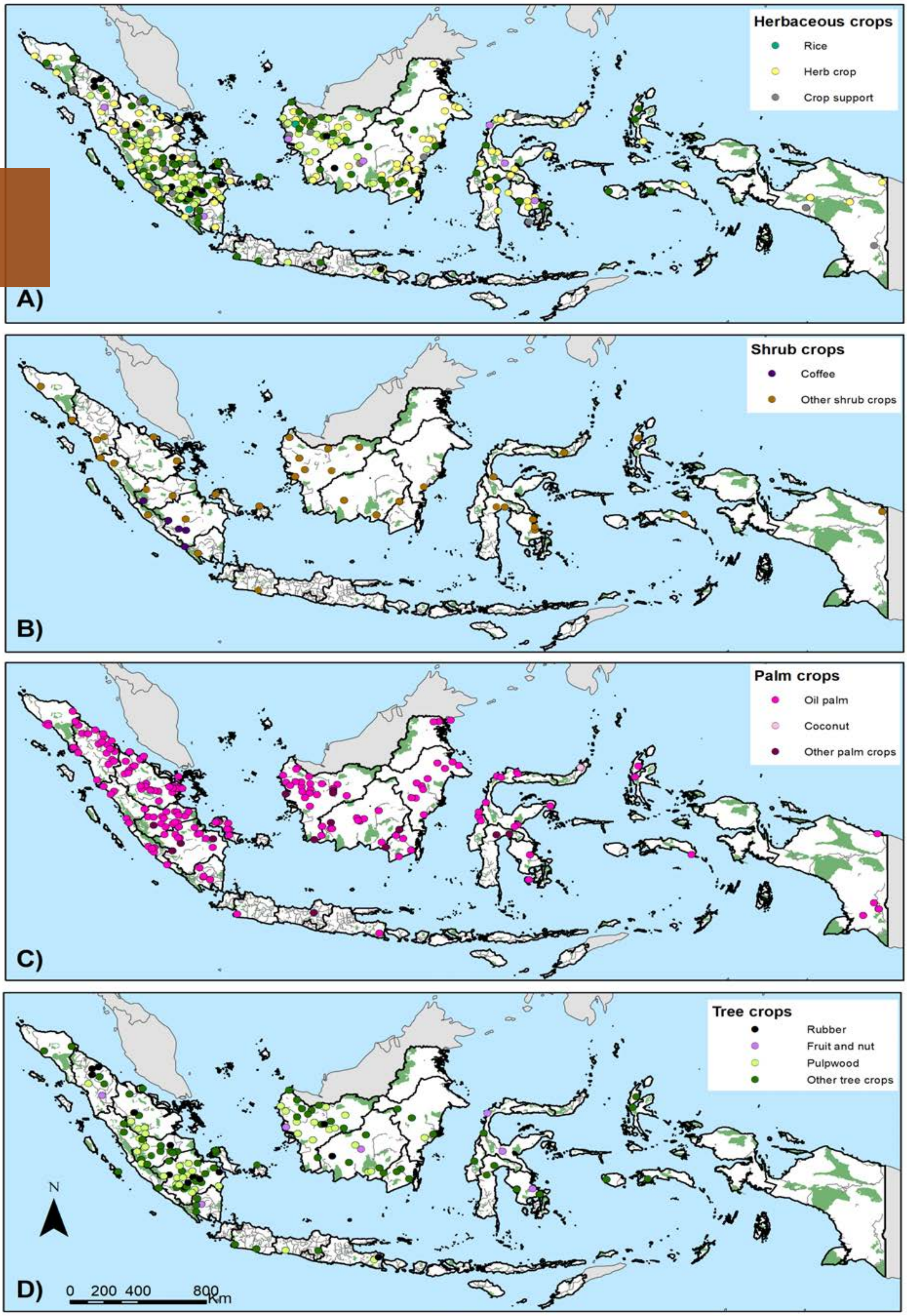
plantations grow export crops on about 15 percent of the total agricultural area, but most farmers—68 percent—are still smallholders who operate on less than one hectare of land, and 53 percent of farmers operate on less than 0.5 ha, making it quite difficult for them to attain the economic scale to profit from agricultural production. Despite this, agriculture is the main source of employment in rural areas, and in 2014, it employed 40.12 million people, or 33 percent of the total Indonesian workforce. Some estimates suggest that a 7 percent per annum increase in smallholder productivity could result in a USD 50 billion increase in agriculture revenues by 2030 (Quincieu 2015).

The export value of the country's crude oil palm reached USD 18.6 million in 2016, from the total cultivation area of 11.8 million ha (GAPKI and Ministry of Agriculture of Indonesia cited in Indonesian Investment 2017a). Of the total area, around 70% is in Sumatra island, and the rest is mainly in Kalimantan. Rubber was grown on 3.6 million ha in 2015, mainly located in North and South Sumatra province, Riau, Jambi, and West Kalimantan (Gapkindo cited in Indonesia Investment 2018). In 2017, coffee plantations in the country covered an area of approximately 1.24 million hectares (AEKI cited in Indonesia Investment 2017b). Tea is still one of main agricultural commodities in the country although its total expansion area has declined over the recent years to about 101,300 ha in 2016 (Mahesa 2017). Tea cultivation spread mainly in West Sumatra and across the provinces of Java, and the reduction of tea in other areas was driven by the conversion of tea into other more profitable crops such as oil palm or vegetables. Overall, tea production has remained relatively stable, due to higher productivity of remaining plantation (Indonesia Investment 2016).

While plantations are an important component of the agriculture economy, smallholder production still remains the dominant mode for the production of rubber, and accounts for practically all copra, coffee, rice and other secondary food crops. As an example of the extent of smallholder cropping: on Java approximately 5.4 million hectares are under smallholder cultivation, as opposed to 676,000 hectares under estate control, and in Sumatra 3.8 million hectares is under smallholder cultivation and with 1.3 million hectares are under estate control. In Sulawesi and Kalimantan the plantation sector accounts for less than 10 percent of total land under cultivation.

Figure 4: Spatial distribution of crop types at plots within the sample where deforestation events were followed with crop cultivation (depicted by orange dots in Figure 4) overlaid on top of the road network. Dark green areas are protected forest boundaries; light green indicate boundaries of other protected areas such as national parks and wildlife sanctuaries (ODC



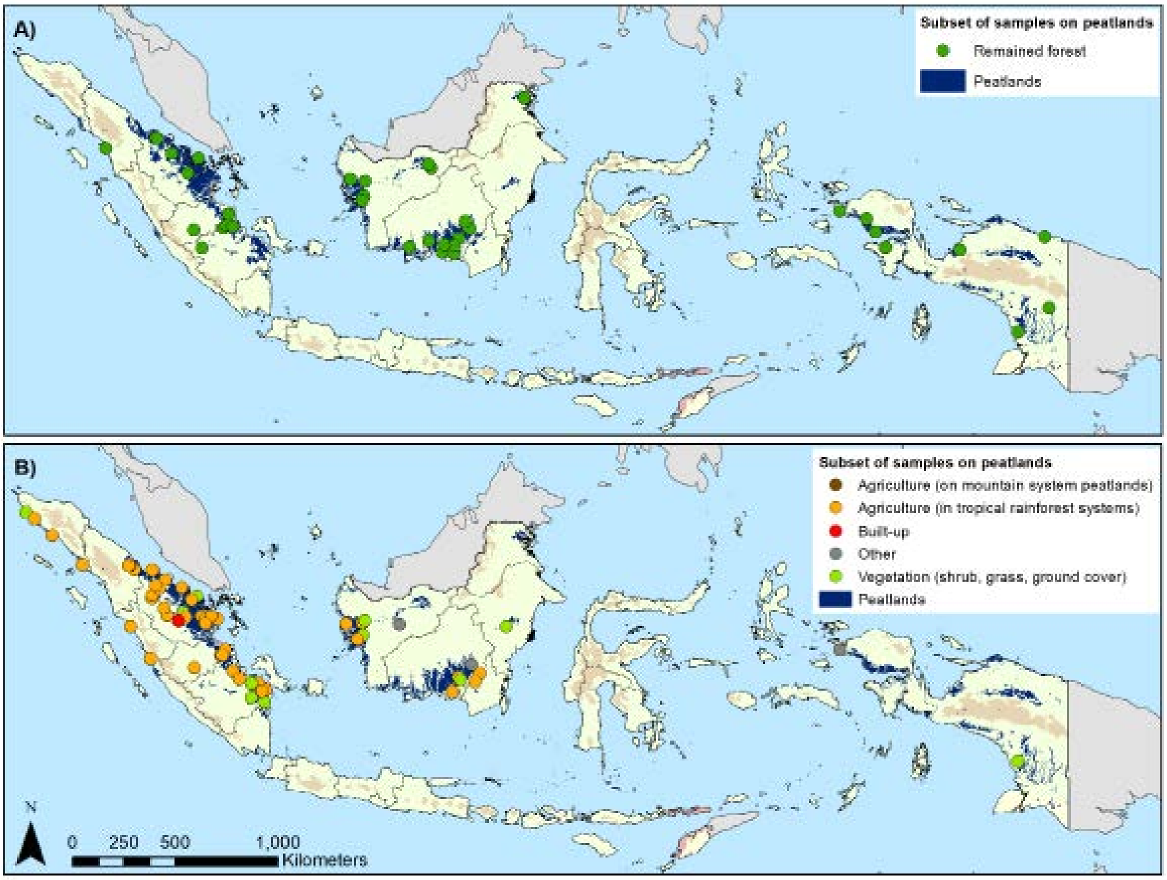


Figure 5: Spatial distribution of the subset of plots that were located on peatlands. Plots in a) remained forested between 2000-2015; in b) had forest clearing 2000-2015. The color of the dots represents the different types of land cover post-2015.

Further, the dynamics of smallholder production differ between different islands. Shifting agriculture dominates in the outer islands, while intensive double and triple cropping is the norm in Java. The typical Javanese farmer has access to only a few tiny plots of land, and must use them continuously. Many farmers have both irrigated "sawah" wet-rice land as well as unirrigated "tegalan" plots, and the smallholder cultivated land in Java is divided roughly in half by these two types. More than 40 percent of the total sawah land in Java is equipped with modern irrigation works which allow farmers to plant rice crops in both the wet and dry seasons; the remaining sawah is dependent upon basic village watering systems or rain, so there is only one wet season rice crop, followed by the planting of soybeans, maize, cassava, soybeans, groundnuts, and sweet potatoes. Java incidentally also accounts for the bulk of Indonesia's agriculture, with 44 percent of Indonesia's agricultural GDP coming from Java, primarily in the form of food crops. Sumatra, the third largest island, produces approximately 31 percent of Indonesia's agricultural GDP, mostly through estate crops (Quincieu 2015). The province of South Sulawesi produces the most food crops after three provinces in Java.

Palm oil is of course a major agricultural development concern for Indonesia. Domestic demand for palm oil to achieve biodiesel targets and meet food and industrial uses will be 20 million tonnes by 2025, which is equivalent to 61 percent of Indonesian palm oil production in 2014. This means it is possible for Indonesia to be self-sufficient without increasing plantation areas. However, to meet both domestic and international demand, estimates suggest 51 million tonnes of palm oil will be needed by 2025. This would require an additional 6 million hectares of land, assuming current yields. While the traditional method for expanding production has been to expand the area of production, this cannot continue if Indonesia wants to conserve landscape carbon. There is clear room for improvement on existing lands: the yields of Indonesian plantations have reached 3.8 tonnes palm oil per hectare, while Malaysia produces at least 4.5 tonne per ha (Khatiwada et al. 2018).

In 2013, Indonesia formulated its first long-term (2013-2045) agricultural development plan, which has a primary objective of promoting sustainable agro industries. The medium term 2015–2019 plan has an objective to achieve food sovereignty and enhance the welfare of farmers. The 2013 Law on Farmers' Protection and Empowerment aims to improve smallholder access to land, finance and markets; provide protection against climate events; and strengthen farmers' organizations. Indonesia's top agriculture priority in recent years has been rice self-sufficiency. To achieve this, the government provides farmers with significant market price support and fertilizer subsidies, the latter of which have been assessed as doing more harm than good. A rice drought insurance scheme is also being scaled up nationally, and to provide protein and diversified incomes, fisheries are expanding rapidly.
Climate change poses one of the most serious risks to food production and subsistence farming in the country. According to IFPRI, by 2050, the total rainfall in Indonesia is expected to increase, on average, by 10 percent from April through June, but decrease by 10 to 25 percent from July through September. The probability of experiencing a harmful delay in monsoon rains could more than double in some of the most important rice-growing regions in Indonesia. Clearly, adaptive strategies and appropriate water management will become increasingly necessary to ensure stable food production. Investments in water storage, drought tolerant crops, and crop diversification will be essential for climate-proofing agriculture production.

TREE CANOPY COVER LOSS IN INDONESIA

Our photo interpretation sample-based inventory results indicate that approximately 10.6 million ha of forests have been converted to other land uses or degraded land covers since 2000 (Figure 6). To get an estimate of the percent of forest loss, we can compare this to previously reported estimates of forest cover for 2000. We observe a range of percent forest loss—from 11.3 percent (Indrarto et al. 2012) to 8.7 percent of forests and woodland areas combined (FAO 2015). The variation is due to differences in the estimates of total forested area for 2000. Published estimates of forest cover for the baseline year of 2000 range from 108.6 million ha (Indonesian Ministry of Forestry 2000) to 93.9 million ha (Indrarto et al. 2012). The Indonesian contribution to the global forest resource assessment reported forest area for the same year was 99.4 million ha, with an additional 22.6 million ha of woodlands (FAO 2015, Table 1A). Differences are partially attributed to the operational definition of forest between reporting agencies and, to some extent, measurement uncertainties (Keenan et al. 2015, Tropek et al. 2014). For example, the map by Indrarto and colleagues (2012) should include a sample-based area adjustment to represent map uncertainty and adjust for map bias when it is used to report forested area.

Comparisons between our loss estimate and published forest cover baselines from 2000 do provide some important context; however, caution needs to be taken when interpreting the percent loss estimates. Each study has a different definition of what the researchers considered forestland. To some extent our definition aligns with the combined forest and woodland estimate from FAO (2015): forest is any half ha patch (or greater) with trees higher than 5 meters and a canopy cover of more than 10 percent that is not in predominantly agricultural or urban land use. Wooded land is nearly the same but the canopy cover is from 5 to 10 percent or has a combined cover of shrubs, bushes and trees above 10 percent (ibid). However, these do include rubber and other tree plantations, so it is not a direct comparison with definitions used in this study; while our definition of forest cover excluded canopy cover and forest patch size thresholds.

The tree cover and changes in tree cover are distributed across four different tropical ecozones: rainforest, mountain system, moist deciduous forest, and shrubland. The majority of forest loss occurred in the tropical rainforest ecozone; 10.1 million ha, roughly 95.6 percent of all clearing. This ecozone is also the most prevalent, covering roughly 90 percent of the archipelago, or 141.8 million ha (Figure 1). However, not all of this ecozone is still supporting forestlands; the same is true for the other ecozones. Less than one percent of the total deforestation activities were located in the tropical moist deciduous ecozone, a loss of 17,307 ha of forest. The tropical moist deciduous forest and tropical shrubland ecozones are located along the southern portion of Sumatra and Java, and in the interior of Sulawesi and Papua. Nearly 453,883 ha of forest in the tropical mountain system were cleared, 4.3 percent of the total observed forest clearing events. These higher altitude regions lie in the island interior and cover just 5 percent of the archipelago.

The country also contains a high percentage of peatlands. These are distributed along the northern coast of Sumatra Island, on the south and west coast of Kalimantan, and throughout Papua (WRI 2019, Figure 5). Nearly 929,000 ha of clearing occurred in swamp

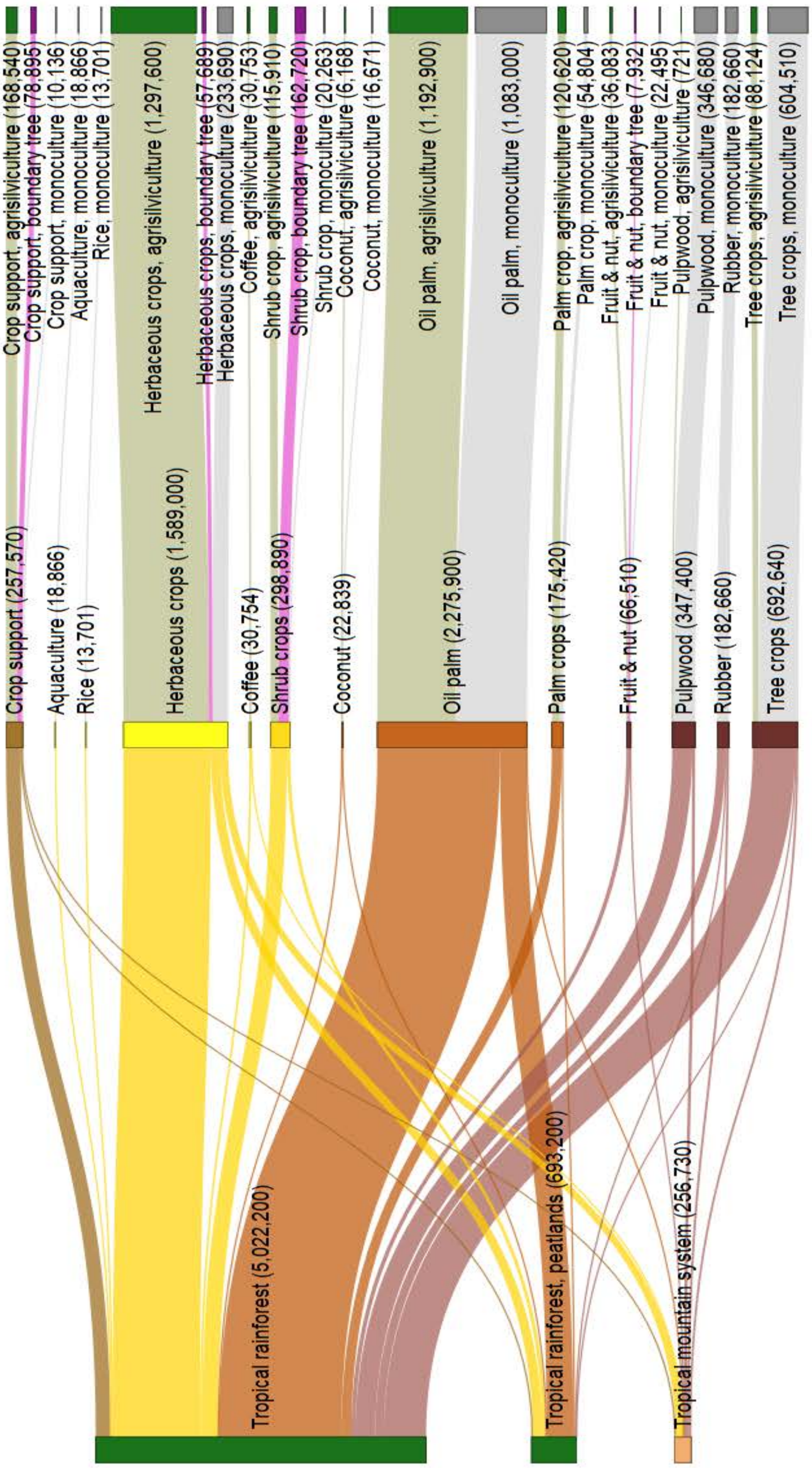
TABLE 2: ABOVEGROUND BIOMASS CARBON STOCKS

commodity	monoculture averaged (tonnes C/ha)	monoculture in Indonesia (tonnes C)	agroforestry averaged	agroforestry in Indonesia	total in Indonesia
aquaculture	5	94,330	NA	NA	94,330
coffee	NA	NA	32.8	1,008,731	1,008,731
coconut	32	533,472	32	197,376	730,848
fruit and nut	42.1	947,040	42.1	1,853,032	2,800,072
oil palm	39	42,238,521	39	46,521,384	88,759,905
pulpwood	38.2	13,242,947	38.2	27,542	13,270,489
rubber	38.2	6,977,536	NA	NA	6,977,536
rice	1	13,701	NA	NA	13,701
palm crops	32	1,753,760	32	3,859,680	5,613,440
other herb crops	5	1,168,450	20.0	27,105,900	28,274,350
other tree crops	39	23,576,046	43.3	21,200,286	26,102,669
other shrub crops	22.5	455,918	32.8	9,139,064	9,594,982
crop support	5	50,680	20.0	4,948,660	4,999,340
TOTAL		**91,052,401**		**98,098,205**	**189,150,606**

	total tonnes C monoculture	total tonnes C agroforesty	total in Indonesia
aquaculture	94,330	NA	94,330
herb crops	1,182,151	27,105,900	28,288,051
shrub crops	455,918	10,147,795	10,603,713
palm crops	44,525,753	50,578,440	95,104,193
tree crops	44,743,569	5,317,410	50,060,979
crop support	50,680	4,948,660	4,999,340
TOTAL	**91,052,401**	**98,098,205**	**189,150,606**

Top: Aboveground time-averaged biomass carbon factors of commodity crops. Values for commodities were compiled from peer-reviewed and grey literature. Time-averaged values are used to estimate the carbon storage of rotational commodity crops because they average the carbon in freshly replanted and mature commodities. These values are then used to calculate aboveground biomass carbon contained in the total area of commodities in Indonesia. Calculations are restricted to those commodities in areas that lost natural canopy cover between 2000-2015. **Bottom**: total area of crops, grouped by life form, and total carbon contained in crops by life form.

Figure 6: The composition of crop commodities on land that had natural forest cover in the year 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in the year 2000; the middle section represents the crop type in 2015, with the agroforestry system indicated on the right. Area estimates, in hectares (ha), are included adjacent to the label.



forestlands overlying peatlands, 8.8 percent of all deforestation.

All cleared tree canopy cover was labeled as either short-rotation tree commodities or natural forest in 2000, by interpreting Landsat time series to identify the forest land use. In total, we identified 10.6 million ha of land with changes in forest canopy that was attributed as a loss of natural tree cover. However, the forest types in Indonesia made it challenging to differentiate between forest and rotational commodity land use through photo-interpretation and time series analysis. Therefore, these estimates may be improved with verification with field data, to confirm an adequate differentiation has been conducted.

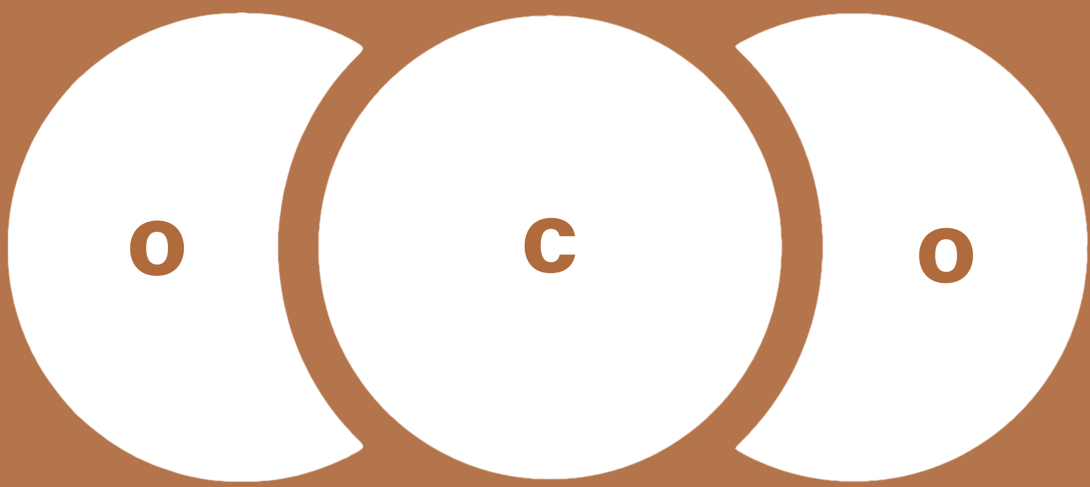
Of the 10.6 million ha of cleared forests, 56.3 percent was eventually converted to support 6 million ha of new croplands (Figure 5). Forest lands that were cleared and are under cultivation are located all along Sumatra, in western and coastal Kalimantan, and Sulawesi, with some in Java and smaller islands in the archipelago (Figure 3). The other prevalent conversion of forest was to other vegetated land covers. Over 3.8 million ha, or 35.9 percent, is supporting some other form of shrubby or herbaceous vegetation (Figure 1). Research on the land clearing activities in Indonesia suggest that regions where tree cover was converted to shrub, grass or ground vegetation is likely to be fallow land, either part of the shifting agriculture cycle (Dennis et al. 2005), or associated with speculative land clearing activities to claim tenure (McCarthy et al. 2012). The forest conversion to what appears to be fallow land—covered by shrublands, grasslands, and ground cover—is concentrated along the southern edge of the island of Sumatra and in the lowlands on Kalimantan islands; although there are examples of this conversion in the other islands as well (Figure 3). These patterns match other reports documenting patterns of deforestation. For example, Hansen and colleagues (2009) reported that 70 percent of total forest clearing in Indonesia occurred in the lowlands in Sumatra and Kalimantan from 1990 to 2005. A much smaller portion of forest was cleared and subsequently developed as part of urban or settlement regions—2 percent—while 5.7 percent was converted to other land covers, such as clearing for mining.

A related study of expansion of crop commodities in lands with concessions across five of the major islands in Indonesia found 6.6 million ha of forest were cleared between 2000 to 2010 for industrial concessions, including fiber plantations, logging, oil palm plantation, and mining (Abood et al. 2015). Direct comparisons between these estimates and our estimate is challenging for a couple different reasons. Abood and colleagues (2015) estimate changes in lands with concessions on the five major islands, but were not able to take into account impacts from small- and medium-scale land holdings. Further, their statistics are derived from a map to map comparison, on data with a spatial resolution of 250 m.

Some of the forest clearing occurred on peatlands; we found over 928,000 ha of forests standing on peatlands were cleared and converted to other land uses. Currently 693,200 ha of cleared peatland swamp forests are under cultivation (75 percent of cleared forests on peatlands). The northeast coast of Sumatra has a large concentration of peatland swamp forest clearing, and presumably draining, for crop cultivation (Figure 5). Abood et al. (2015) estimates that 1.4 million ha of peat swamp were cleared within lands allocated for logging and industrial development between 2000-2010, primarily for conversion to pulpwood and oil palm. Our slightly higher estimate is likely explained by the longer time period investigated in our study. Further, we document losses occurring both within and outside of concessions, capturing small- and medium-scale land holding activities, in addition to the large-scale concession activities monitored by Abood et al. (2015). The predominant land cover associated with the rest of the peatland forest loss, 191,000 ha, is vegetation such as shrublands, grasslands, or ground cover.

Herbaceous, palm, and tree crop commodities are cultivated in nearly equal amounts in areas that were forested in 2000: 1.6 million ha, 2.5 million ha, and 1.3 million ha, respectively (Figure 2). These commodities are concentrated on the islands of Sumatra, Kalimantan, and Sulawesi (Figure 4). Herbaceous crops such as cassava, soybeans, and maize were the most prevalent crop type associated with deforestation, impacting more than 1.6 million ha of forestland. The majority of the palm crops replacing forestlands are oil palm plantations; over 2.3 million ha have been converted since 2000 (Figure 6). Tree crops that were not able to be identified to species level replaced 692,640 ha. These tree crops did not have the classic signature or pattern that we expect with monoculture plantations of rubber, coconut, oil palm, banana, or a fruit or nut tree; however, the patterns present in the imagery alone are not clear enough to identify the composition. These tree crops could be teak, other stand trees, or a mix of tree commodities planted together. Rice, coconut, and pulpwood plantations are the following most prevalent commodities replacing forests, at 13,701, 22,839 and 347,400 ha, respectively. The spatial distribution

IN TOTAL, 1.1 BILLION TONNES OF CARBON WERE LOST DUE TO FOREST CONVERSION TO CROPLANDS BETWEEN 2000-2015 IN INDONESIA.



of specific crop commodity drivers reported here are similar to other studies in the region. Abood et al. (2015) reported that between 2000-2010, oil palm plantations were the largest driver of forest loss in Kalimantan, at 1.1 million ha. During the same period, pulpwood and fiber plantations were the predominant driver in Sumatra (1.2 million ha), followed by oil palm concessions (440,000 ha) (Abood et al., 2015). Fruit or nut orchards, fields with shrub commodities, rubber plantations, and coffee were also present in small amounts. In line with other reports, we observed most coffee fields in south Sumatra and Sulawesi (Figure 4B) (Gaveau et al. 2009).
On peatlands, oil palm plantations were the most prolific cultivated commodity, occupying 405,419 ha of previously forested land (Figure 6). Herbaceous crops were the second most prevalent commodity on peatlands, at 145,638 ha (Figure 6). Abood et al. (2015) estimated 26 percent of large-scale fiber concessions and 21 percent of large-scale oil palm concessions drove forest loss within peatlands.

CARBON STORAGE IN INDONESIA: IMPACTS AND OPPORTUNITIES

Commodity crop land uses that have replaced forestland are providing roughly 189 million tonnes C stock in aboveground biomass, which is only about 14 percent of the carbon that would have been stored as aboveground plant biomass if the land was still in a state of natural tree cover (1317million tonnes C) (Table 4). Much of this carbon (7 percent) is stored in oil palm plantations (89 million tonnes C). Replacement of natural forest with oil palm has been reported to produce losses of 174 tonnes C/ha in Indonesia (Guillaume et al. 2018). Assuming rates of forest clearing and conversion to oil palm found in this study (2.3 million ha), this suggests that these activities have resulted in the loss of 400 million tonnes C in aboveground biomass alone, roughly 33 percent of the total emissions due to commodity expansion. Much of the additional carbon found in commodities currently were classified as 'other trees.' This means that it was not possible to assign greater detail (i.e. crop type) through photo interpretation alone. These estimates, however, certainly underestimate emissions because they only take into account aboveground plant biomass. Forest loss in peatlands results in carbon dioxide emissions from soil as peat decomposes with changes in water table levels and peat combustion driven by the feedback between fire vulnerability and changes in hydrology (Miettinen and Liew 2010).

In regard to agricultural practices, overall, carbon storage is 29 tonnes C per hectare for agroforestry as compared to 28 tonnes C per hectare for monoculture sys-

TABLE 3: CHANGES IN ABOVEGROUND BIOMASS (AGB) IN NATURAL FORESTS AND ALTERNATIVE CROPS BY ECOFLORISTIC ZONE (TONNES C/HA)

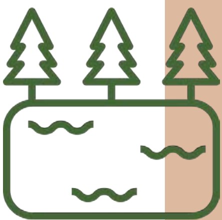
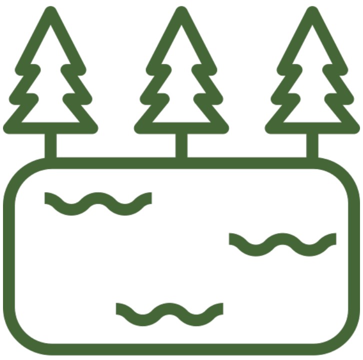
		average C/ha in AGB	C in forest (2000)	C in crops replacing forest (2015)	C lost due to conversion
	**TROPICAL RAINFOREST**	225	1,129,991,850	158,614,681	**971,377,169**
	**TROPICAL RAINFOREST, PEATLANDS**	225	155,970,675	23,187,350	**132,783,325**
	**TROPICAL MONTANE SYSTEM**	122	31,321,548	7,348,573	**23,972,975**
	TOTAL		**1,317,284,073**	**189,150,604**	**1,128,133,469**

TABLE 4: CARBON EMISSIONS FROM PEAT DECOMPOSITION ASSOCIATED WITH THE CONVERSION OF FORESTLAND, RESTRICTED TO THE AREA THAT HAD CANOPY COVER IN 2000. CARBON EMISSION FACTORS BASED ON DATA IN MIETTINEN AND LIEW (2010).



	area (ha) deforested	tonnes C/ha	Peat emissions (tonnes C)
rainforest to built-up	30,021	6.8	**204,143**
rainforest to crops	693,201	13.3	**9,219,573**
rainforest to shrub/grass	191,033	6.8	**1,299,024**
rainforest to other covers	14,481	6.8	**98,471**
TOTAL	**928,736**		**10,821,211**

tems, which indicates opportunities for improvement in such practices (Table 2). With each crop type, Table 2 shows that agroforestry practices are utilized more for herbaceous crops which results in a better carbon storage capacity of 20 tonnes C/ha as compared to 3 tonnes C/ha stored via the monoculture system. We find a similar trend for shrub crops with 33 tonnes C/ha via agroforestry as compared to 22 tonnes C/ha for monoculture crops. We also find that tree crops perform marginally better via agroforestry with 40 tonnes C/ha as compared to 39 tonnes C/ha via monoculture, and palm crops do marginally better as well, with about the same numbers for each system.

We estimate that 929,000 ha of peat swamp in Indonesia were degraded since 2000, with 693,000 ha being converted for cultivation (Table 4). This has resulted in an additional 10.8 million tonnes C of emissions per hectare from peat decomposition due to forest loss. The forest has been converted to both commodity crops and other land uses and land covers. Within the forestland that is now supporting commodities, the emissions from peat degradation is 9.2 million tonnes C, 85 percent of the total peatland emissions associated with land use changes. In addition to emissions from peat decomposition, emissions from peat fires are also significant (Page et al. 2002; Harrison et al. 2009; Turetsky et al. 2015); however, calculating these estimates is outside the scope of this study. Preservation of intact peat swamp forests and restoration of degraded ones is the most important carbon issue in the AFOLU sector in Indonesia.

CONCLUSIONS AND RECOMMENDATIONS FOR INDONESIA

To preserve carbon in the landscape and ensure that Indonesia can meet its ambitious commitments to reduce GHG emissions 41 percent by 2030, it is imperative that Indonesia protect its vast tracts of peat. Protection means, first and foremost, prevention of the repeat occurrence of devastating peat fires, such as in 2015 and 2019. Estimates of GHG emissions from peat fires during the record-breaking 2015 season suggested that Indonesia's peat fires were released more CO2 daily than did all of the European Union (EU) from combustion of fossil fuels (8.9 million tonnes CO^2 per day) (Hiujnen et al. 2017). Clearly, elimination of peat fires would have huge positive repercussions on Indonesia's efforts to reduce GHGs.

Prevention of peat fires is not a straightforward task; it likely will require a combination of policy, law enforcement, physical and market approaches to be successful. As for policy approaches, the present President Jokowi made a positive step by establishing the Badan Restorasi Gambut (BRG, or "Peat Restoration Agency") after the 2015 fires. This agency has pledged to restore over 2 million ha peat by 2020 (Reuters 2016); however, claims about the restored area of peat are variable and hard to confirm. The most recent reports in the media suggest that only 679,000 ha had been restored as of the end of 2018 (The Palm Scribe 2018). The fires of 2019 undoubtedly temporarily slowed restoration plans. BRG is receiving support from many international donors, but that support will have to be increased if the agency is to come close to meeting its stated goals. Besides peat restoration by BRG, Indonesia also needs to revisit its 2016 ban on development of peat over 3 meters deep. While this ban is useful in protecting deep peat, the vast majority of peat in Indonesia is under 3 m deep; this peat must also be preserved, as it includes the low-lying peatland along rivers and coasts. If this peat disappears, not only will GHGs be released, but any human settlements on or near peat will be subjected to constant flooding.

Finally, expanding paludiculture and supporting new and existing value chains for peat products and services is an option that would help people grow their local economies, while preserving the landscape. Paludiculture is agriculture that makes use of flooded peatlands. In Indonesia, crops and non-timber forest products (NTFPs) that can be grown on or collected from peat include (but are not limited to) jeletung rubber trees, sago, areca nut, coffee, rattan, betelnut, honey and coconut. Most of these products need to be linked to better and more demanding markets in order to be profitable for farmers. This can be done but may require changing consumer preferences and awareness about climate-friendly products. Sago is a good example of this: the high-energy starch is Indonesia's most important paludiculture crop. Sales of have tripled in the six years between 2013 and 2019 as a result of diversified products creating more consumer demand (The Christian Science Monitor 2019). Ecotourism is another development option that would keep the peat forest intact (Syamsu and Putrisari 2016).

While maintaining functional forested peatlands may be the best way to preserve carbon in the AFOLU sector, there are also many opportunities to preserve both peat and dryland forest within existing, yet unused concessions, particularly in those designated for fiber/pulpwood (Abood et al. 2015). There is a great deal of previously forested land that is not yet planted (10.4

million ha of "other vegetation" in Figure 3). Using degraded or vacant lands to support new agriculture is a recommended approach for improving landscape carbon storage throughout this volume. Indonesia is not different, and if or when new concessions for agriculture are granted, they should first make use of this 10.4 million ha that is available and waiting.

Another dryland option is to encourage extensive production systems that preserve a substantial amount of native tree canopy (and thus avoid carbon losses associated with forest clearing) such as jungle rubber. Jungle rubber flourishes within existing forest structures and, besides provision of various services, also holds a greater quantity of carbon than any of the tree crop commodity systems examined here. Such an approach might not be feasible for other tree commodities. That is because fragile fresh fruit bundles, including oil palm, typically must be extracted and processed quickly. This requires a highly centralized plantation system with a good transportation network and easy access to processing facilities. Overly bruised fruit bundles are rejected for processing. Rubber, on the other hand, can be collected in a much more distributed system without running into quality problems with product processing (Guillaume et al. 2018).

Finally, local people should be encouraged to protect their peat and dryland areas through better use of village funds (Dana Desa). The Dana Desa program (Law 6/2014), also started by President Jokowi, has given a portion of USD 18.36 million to each of the over 76,000 villages that dot the archipelago (Reuters 2019). Supporters of the law claim that it has allowed villages to invest thousands of dollars into new roads, schools and clinics. Detractors claim that while this is true, much of this infrastructure and other large purchases (such as cars for the village chief—J. Jadin, personal communication) are not necessary, nor are they designed to help villagers adapt to climate change. Investing into climate change awareness and vulnerability assessments for these villages has been suggested as a way to encourage villagers to use the funds for more sustainable purposes. Helping villages adapt to and mitigate climate change will also make them eligible to receive funds under the Climate Village Program (ProKlim, Minister of Environment Regulation No. P.84/MenLHK-Setjen/Kum.1/11/2016). On peat, such funds could be used to patrol for and quickly extinguish peat fires, as well as to block small canals to rewet peat. On drylands they could be used to implement climate-smart farming systems, invest in technology to improve water use, or replant forests and mangroves to restore ecosystem services.

Other general recommendations that apply to Indonesia as well as all of Southeast Asia include planting trees into existing herbaceous systems to create agroforests, improving farmers' access to the technology and information that would help them sustainably intensify cultivation, transition from traditional flooded, highly fertilized rice farming to alternate wet dry, low input rice farming, making use of indigenous and women's knowledge to improve cultivation and sustainably manage forests, securing land rights for people, particularly through the use of community forestry (called social forestry and various other names in Indonesia), introducing animals into plantations to diversify income and improve soil quality, and paying attention to the impacts roads have on patterns of forest regrowth.

Indonesia, like Thailand and Vietnam discussed later in this volume, is a middle-income country that is facing the so-called "middle-income trap." To emerge from this trap, Indonesia's people and policymakers must devise ways to transition from a natural resource-based economy to one that develops via technology and services. As a country with near complete cell phone penetration and the biggest user of several social media apps in the world, Indonesia is well on its way towards high-tech. However, as the fourth most populous nation in the world, it must also focus on climate-friendly production and consumption. The recommendation's listed above will help the production side, but the government, the private sector, and development partners must concertedly address the consumption side not only so they can weather future changes in the climate, but so they can be a role model for other countries on the path towards achieving Sustainable Development Goals.


©Jadin

LAO PDR

KEY MESSAGES

A TOTAL OF 945 THOUSAND HECTARES (HA) OF FOREST WERE LOST BETWEEN 2000 AND 2015; ABOUT 500,000 HA OF THAT LAND WERE CONVERTED TO AGRICULTURE.

FIFTY PERCENT OF FORESTLANDS CONVERTED TO AGRICULTURE (254,000 HA) WERE CONVERTED TO HERBACEOUS CROPS, SUCH AS MAIZE, CASSAVA, AND SUGAR CANE; THE REMAINDER WERE CONVERTED TO TREE CROPS INCLUDING PULPWOOD AND RUBBER.

THE TOTAL CARBON STORAGE WITHIN THE ABOVEGROUND PLANT BIOMASS OF THE CROPS REPLACING FORESTED LAND IS 9.1 MILLION TONNES C. **IF THESE LANDS WERE STILL FORESTED, THEY WOULD HOLD 56.9 MILLION TONNES C, WHICH EQUATES TO A LOSS OF 84 PERCENT OF THE ORIGINAL ABOVEGROUND CARBON STOCK.**

Small, landlocked Lao People's Democratic Republic (Lao PDR) is a country experiencing rapid economic and environmental change. One of the world's poorest countries at the turn of the 21st century, Lao PDR's economy is now one of the fastest growing in East Asia (WorldBank 2019), and as of 2019, its Gross Domestic Product (GDP) has climbed out of the lowest third of world economies (IMF April 2019). This rapid growth has been the result of Lao PDR's socialist-oriented market policies that combine a high-degree of state ownership of companies along with foreign direct investment (UNDP 2007). This growth also has, until recently, been largely dependent upon the exploitation of natural resources (UNDP 2007). This has resulted in widespread deforestation, air pollution, and degraded waterways.

While the past five years have seen a shift from such natural resource-dependent growth towards growth of the service, tourism and technical sectors, 70 percent of the 6.6 million people of Lao PDR still depend on forests and waterways for their livelihoods (World Bank 2019). Many of these people practice subsistence farming either in fixed plots or through shifting (slash-and-burn) agriculture (Thapa 1998; Sandewall et al. 2001). Shifting agriculture is characterized by periodic land clearing for growing food crops or managing the understory of forests. After several years of growing crops, nutrient-depleted land lies fallow in order to recover, and farmers move on to a new area of land. Shifting agriculture typically requires large areas of land due to the low productivity of any given parcel of land, and therefore has historically been viewed as an undesirable farming practice that leads to deforestation and land degradation (Geist and Lambin 2002; Li et al. 2014).

Lao PDR used to have some of the richest biodiversity in Southeast Asia. However, the country has undergone significant forest and land cover changes over the last few decades and deforestation has become a major issue. The deforestation rate has skyrocketed since 1982 (Robichaud et al. 2009) when forests covered almost 50 percent of the country. By 2002 the forest cover was only 41 percent and has gradually decreased since then (Forest Carbon Partnership Facility 2014; Vongsiharath

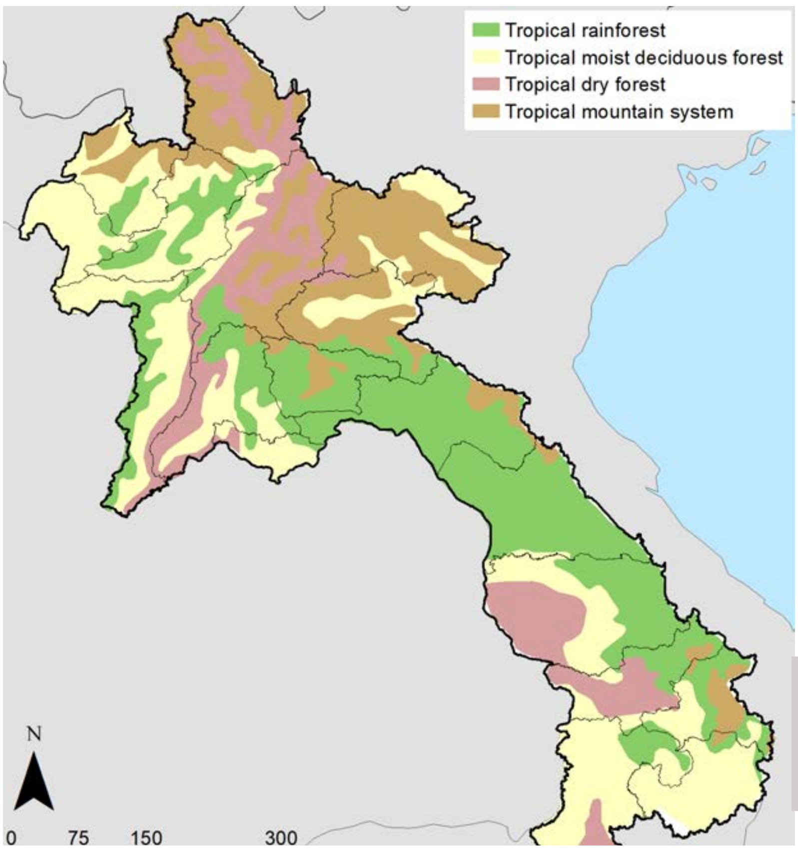


Figure 1: Ecozones in Laos PDR, from Ruesch and Gibbs, 2008

Table 1: Volume (in millions of constant 2015 US dollars) of agricultural commodities traded in Lao PDR in 2000 and 2015 (from www.bea.gov). Values derived from Chatham House, resourcetrade.earth (2018).

Commodity	USD value 2000	USD value 2015	% change
rubber	0.1	122.8	134,458
cereals	0.4	78.1	19,503
coffee	25.1	74.7	198
rice	0.04	40.3	103,839
tree fruits	2.1	18.8	805
tree nuts	0	14.8	29,807,381
tobacco	0	11.2	
banana	0	3.5	168,117
pulpwood	0.05	1.8	3,599
tea	0.01	1.2	8,417
cocoa	-	-	-
coconut	-	-	-
palm oil	-	-	-

2011). The remaining forest cover appears to be a mix of secondary forests, plantations and bamboo, and how much is primary forest is unclear (Forest Carbon Partnership Facility 2014). Estimates suggest 1.2 million of the total 18.7 million ha of forest was primary forest in 2015 (FAO 2015D). Lao PDR's government is addressing this forest loss and trying to increase forest cover up to 70 percent by 2020 through numerous efforts including afforestation, reforestation and stabilization/reduction of shifting cultivation (Ministry of Agriculture and Forestry 2005).

In Lao PDR, the government has been encouraging a move away from shifting agriculture through a series of land policy reforms. The 2003 Land Law stipulates that all land in Lao PDR is officially owned by the government. However, beginning in 2007, the Land Use Planning and Land Allocation Policy outlined the rights of local people to use and manage natural resources, and encouraged their participation in the management, planning and protection of the forest. The government introduced policies to encourage (or outright relocate) people living in the uplands to move to the lowlands, and transition from traditional shifting agriculture systems to permanent agriculture; these initiatives were meant to protect forests and raise the standard of living (Vandergeest 2003; Sandewall et al. 2001; Robichaud et al. 2009). Though guided by good intentions, these programs have often created hardships for displaced groups: when community access is restricted due to resettlement programs, steady conflicts among smallholders and government agencies has often been the result (Saunders et al. 2014).

Also, in 2007, the government reclassified all forests into three categories: production, protection and conservation forests. However, village or community forests are not included in any of these categories, making sustainable use and management of these areas difficult to administer. Forest use in Lao PDR is also complicated by widespread illegal logging, which is a result of poor enforcement of concession boundaries and related corruption (EIA 2017). One example of this corruption is evident if one looks at the land granting history: because the government owns forest lands, it can also grant forest concessions, and it often does so with little heed for sustainability principles. Government land granting to domestic and foreign investors has been profligate—as of 2012, conservative estimates suggest that approximately 2,642 land agreements, totaling 1.1 million ha (nearly 5 percent the country's area), were in place for agriculture and mining (Saunders et al. 2014). The majority of this allocated land was classified as primary forest, with as much as 23 percent of this area categorized as protected forest (Schönweger et al. 2012). Foreign investment firms from China, Thailand, and Vietnam held 53 percent of this concession area (Schönweger et al. 2012).

Adding to the complexities of forest management is the fact that all levels of government can grant concessions, without knowledge or permission from higher levels of government. This has created a situation in which the legal status of forests is often unknown or disputed. Such murky ownership rights mean that local people have little incentive to report or otherwise act against illegal logging, as it is unclear whose land they would be protecting or what benefits they would otherwise gain from the protected land (Thapa 1998; Saunders et al. 2014).

As a result of this unclear land ownership, poor monitoring and rampant corruption, good data on the drivers of forest loss in Lao PDR are scarce. Many believe that forest loss has primarily been driven by logging practices that have propagated through poor governance (Thapa 1998; Saunders et al. 2014; EIA 2017); however, trade volumes of agricultural commodities in Southeast Asia have also been correlated with patterns of deforestation and ecological degradation (Leblois, A. et al. 2017; Curtis et al. 2018; Hurni and Fox 2018; Taubert et al. 2018).

The degree and magnitude at which forests have been converted due to commodity expansion is largely unknown. Therefore, in order to understand and prevent further forest loss, commodity expansion must be characterized. In addition, land conversion contributes significantly to national greenhouse gas emissions from the land use sector. In Asia, 67 percent of carbon emissions due to deforestation between 1990 and 2015 were associated with clearance for agriculture (Carter et al. 2018). For countries such as Lao PDR, which are striving to meet greenhouse gas (GHG) emission pledges and continue down a trajectory of low emission development, understanding the extent of GHG emissions or reductions due to land use decisions will be key to achieving national targets.

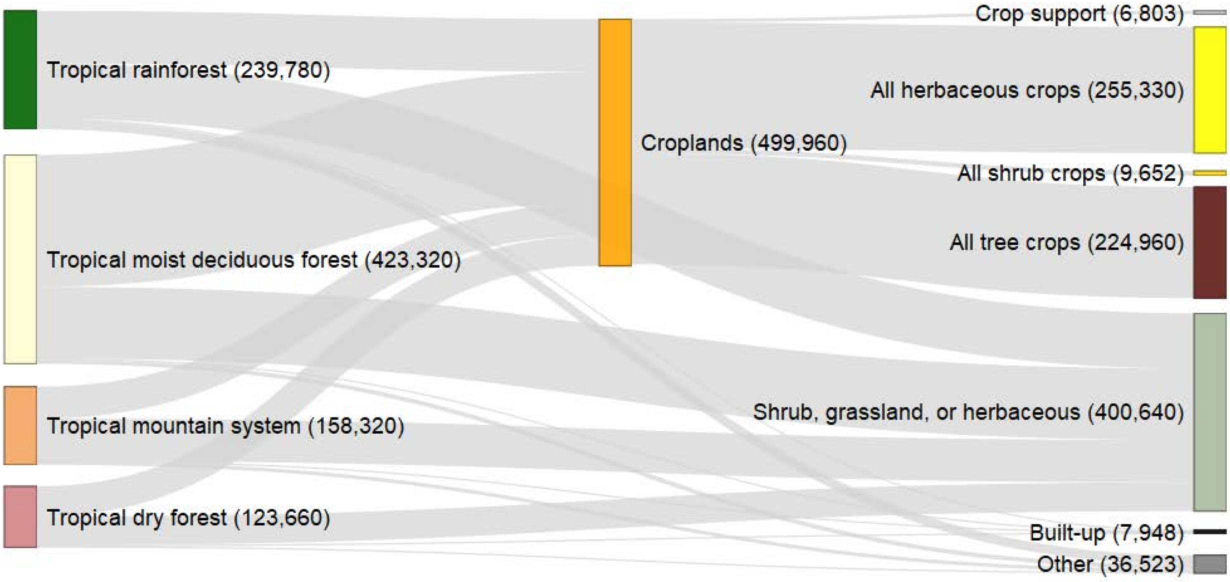


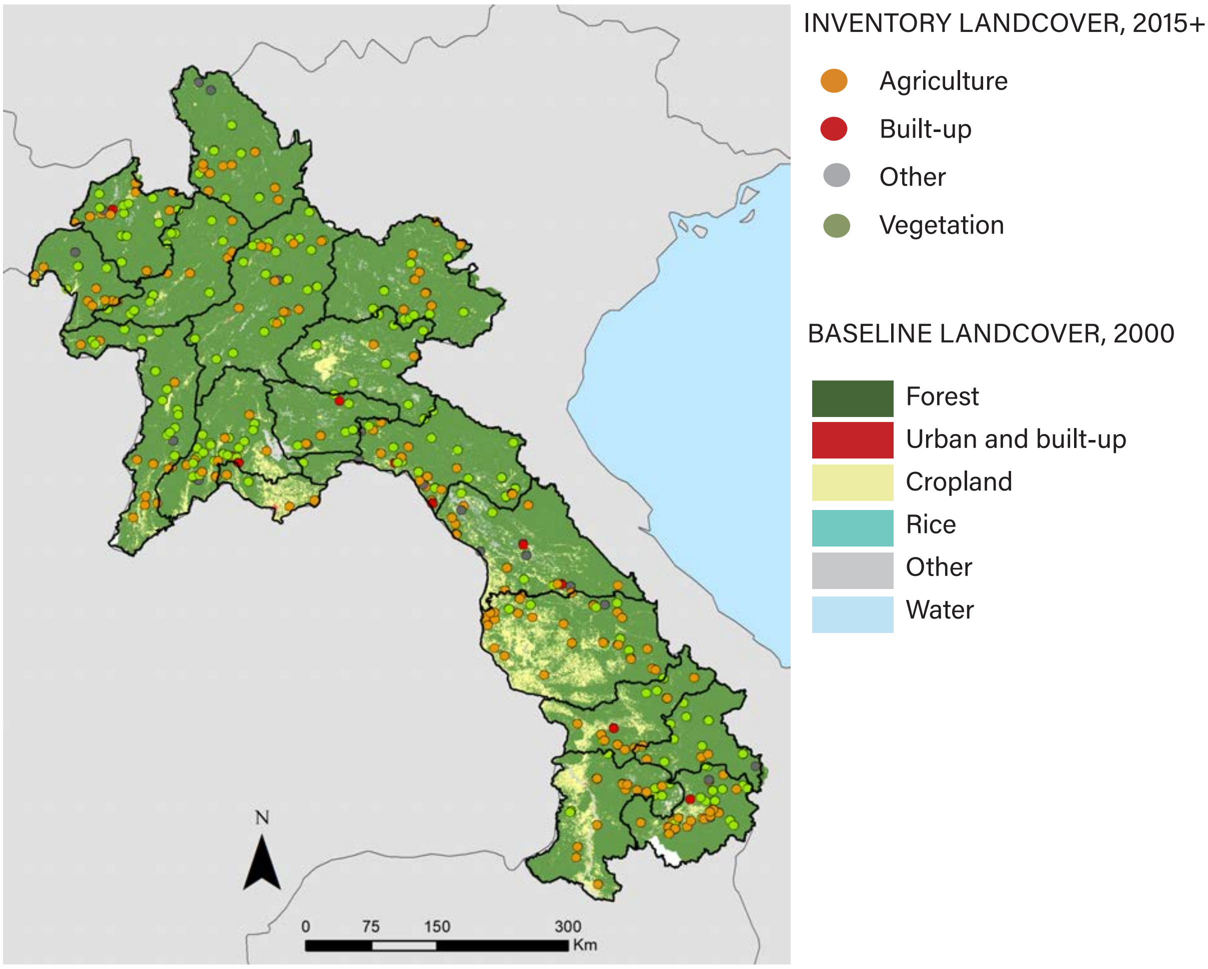
Figure 2: Composition of land use and crops in lands that underwent forest loss since 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in 2000, while the right side represents the land cover after 2015. The total area of all crops is represented by the croplands bar in the middle. Area estimates (ha) are adjacent to the labels.

AGRICULTURAL DEVELOPMENT TRENDS IN LAO PDR

Various estimates for the proportional extent of shifting agriculture are available for Lao PDR, ranging from 10 percent (Hansen 1998) to 20.5 percent (Chazee 1994) for the 1990s, to 28.2 percent for the 2000s (Messerli et al. 2009). In more recent years, a trend towards a decrease in shifting agriculture area has been observed and reported locally in Lao PDR (VanBlient 2012). Areas with shifting agriculture show a pattern of shorter fallow periods, with a decline from twelve to eight years in the average fallow period length (Chazee 1994; Schmidt-Vog 2009). This decline has largely been attributed to limited access to land, public policies, government-supported paddy rice cultivation, and expansion of commodity tree crops, such as rubber (Thongmanivong et al. 2005; Ziegler et al. 2009, Van-Blient 2012, Ingalls et al. 2018).

While shifting agriculture is considered to be a major driver of deforestation by land use decision-makers in Lao PDR (Curtis 2018), some also favor stabilizing this agriculture regime so that those who want to continue this practice area able to. There are many benefits to shifting agriculture, including hydrological regulation of landscapes, efficient nutrient cycling, higher degrees of agro-biodiversity, among others (Ingalls et al. 2018). Previous studies have found that the 6.5 million ha of shifting agriculture (28.2 percent of the country) show no sign of transition into permanent agriculture (Mes-serli et al. 2009), meaning that no permanent forest loss will be the result of such agricultural practices in the short term. Additionally, 77 percent of these areas can be found in environments coexisting with forests, meaning that shifting agriculture is already existing harmoniously with forests.

Figure 3: Spatial distribution of plots in the sample that have been deforested over the study period, overlaid on a land cover map from 2000 (Saah et al. 2020).

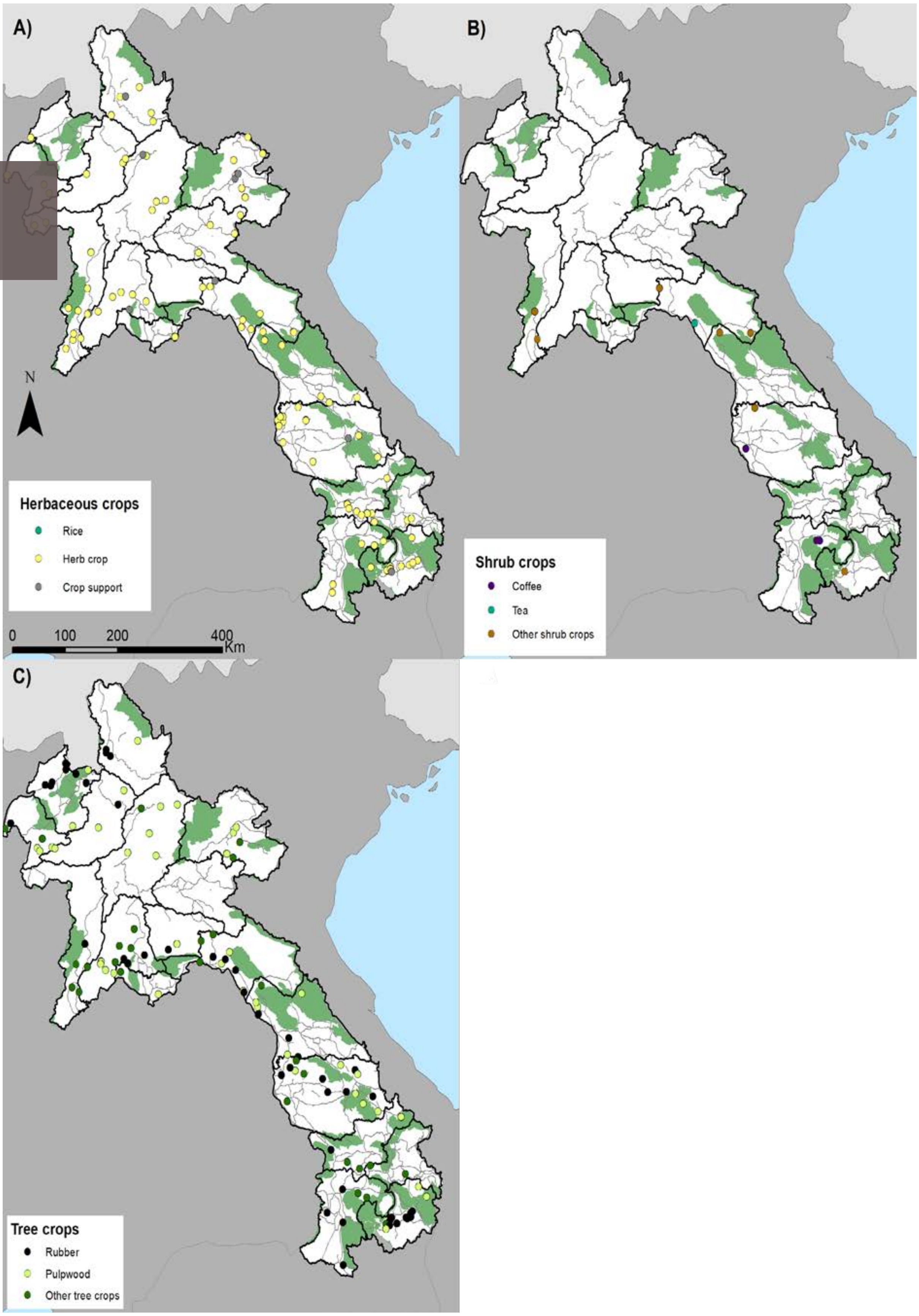


The population distribution in the country could also be used as an argument in favor of stabilizing shifting agriculture. While shifting and permanent agriculture occupy comparable proportions of the country (28.2 and 29 percent, respectively), there are enormous differences in population density associated with each type of system: 18.8 persons/km^2 for shifting agriculture areas and 152 persons/km^2 for settled agriculture (Messerli et al. 2009). This indicates that any given area of shifting agriculture puts much less population pressure on natural resources while providing benefits for local people and the environment.

There are no consistent maps depicting the location and growth of specific commodities available; however, aspatial statistics on the growth and volume of agricultural commodities traded provide some baseline information about which crops have experienced growth driven by agricultural markets. Lao PDR engaged in low levels of international trade in common regional commodities in the year 2000, when there was less than 28 million dollars of trade in commodities (other than raw timber: Table 1). While a large increase in the trade of commodities like rubber, cereal crops, coffee, cereals, and tree nut and fruits has taken place since then, total exports were still modest and amounted to less than half a billion dollars in 2015. The development of previously forested land has been driven by a handful of commodities traded regionally, particularly in response to Chinese market demand for rubber and crops such as bananas (Manivong and Cramb 2008; Friis and Nielsen 2016).

Coffee was formerly the dominant non-timber commodity export of Lao PDR, but it has had relatively slow growth compared to other commodities (Table 1, percent change column). It has now been overtaken by rubber and cereals in terms of dollar value of exports. While the tripling in export value over 15 years that coffee has experienced would be considered very good growth under normal circumstances, it appears that in Lao PDR, even faster growth in coffee exports may have been suppressed due to mining and hydropower competing for the same land (Delang et al. 2013).

Figure 4: Spatial distribution of crop types at plots within the sample where deforestation events were followed with crop cultivation (depicted by orange dots in Figure 4) overlaid on top of the road network. Dark green areas are protected forest boundaries, light green indicates boundaries of other protected areas such as national parks and wildlife sanctuaries (ODC



TREE CANOPY COVER LOSS IN LAO PDR

The area of forest and woodland in 2000 was estimated to total 20.4 million ha—16.5 million ha and 3.9 million ha, respectively (FAO 2015D, Table 1A). To better understand how definitions and methods may impact this baseline estimate, we compare the values derived from the global canopy cover map (Hansen et al. 2013). When forest includes any land with a tree canopy cover greater than 10 percent, the total estimate is 19.8 million ha, while increasing the tree canopy cover threshold to 75 percent or greater reduces the estimate of total forestland area in 2000 to 14.5 million ha. The variation in the estimates of total forested area for 2000 are partially attributed to differences in the operational definition of forest between reporting agencies and, to some extent, measurement uncertainties (Keenan et al. 2015, Tropek et al. 2014). Additionally, all maps have errors and biases (Olofsson et al. 2014). Because the global canopy cover maps (Hansen et al. 2013) do not include a sample-based area adjustment for national level Lao PDR values, the uncertainty of the forested area is unknown.

Our photo interpretation sample-based inventory results indicate that approximately 945,000 ha of forests have been converted to other land uses or degraded land covers since 2000 (Figure 2). To get an estimate of the percent of forest loss, we can compare this to the Laos contribution of the global forest resource assessment estimates of forest cover. This then represents a loss of 4.6 percent of the forests and woodland areas from 2000 (FAO 2015D). However, while this comparison of loss to the FRA baseline estimate provides some context, caution needs to be taken when interpreting the percent loss estimates since the studies have a different definition of forestland. To some extent our definition aligns with the combined forest and woodland estimate from FAO (2015A): forest is any half ha patch (or greater) with trees higher than 5 meters and a canopy cover of more than 10 percent that is not in predominantly agricultural or urban land use. Woodland is nearly the same but the canopy cover is from 5 to 10 percent or has a combined cover of shrubs, bushes and trees above 10 percent (ibid). However, these do include rubber and other tree plantations, so it is not a direct comparison with definitions used in this study; our definition of forest cover excluded canopy cover and forest patch size thresholds.

Regardless of the definition of forests, all the tree cover and changes in tree cover are distributed across four different tropical ecozones: moist deciduous forest, rainforest, mountain system, and dry forest. The majority of forest loss occurred in the tropical moist deciduous forest ecozone: 423,000 ha, roughly 45 percent of all clearing (Figure 1). However, this ecozone only covers 33 percent of the country, lying across 7.6 million ha. Tropical rainforest, mountain system, and dry forest each account for 31, 20, and 16 percent of the remaining ecozone distribution across Lao PDR. However, not all of this ecozone is still supporting forestlands; the same is true for the other ecozones. Approximately 25, 17, and 13 percent of the total deforestation activities were distributed in the tropical rainforest, mountain system, and dry forest ecozones, respectively (Figure 1). The tropical rainforest zone runs through the central portion of Lao PDR (Figure 1). The southern end of the country includes all four zones but is primarily within the tropical moist deciduous forest zone. The northern uplands include a mixture of tropical moist deciduous forest, tropical dry forest and tropical mountain forest system. This region also has the largest concentration of shifting agriculture (Ingalls et al. 2018).

The majority of land experiencing deforestation is now supporting herbaceous crop production, 255,000 ha or 27 percent of the forest loss (Figure 2). As expected, most of the deforestation for agriculture that we observed in our sample was in areas adjacent to existing croplands, following road networks (Thongmanivong et al. 2009), Figure 4. There is also a substantial region that is covered with other non-forest and non-crop vegetation, 400,000 ha or 42 percent of the total observed clearing. This vegetation includes shrubland, grasslands, and herbaceous cover. While we were not able to label it as such, a portion of these lands are likely a combination of temporary land use changes due to shifting agriculture. Further, there may have been different initial or additional drivers of deforestation and land uses in between the current state and 2000 that are not presented in these results. For example, in southeast Asia, deforestation is often initially driven by selective logging, then the land is subsequently converted to agriculture (Saunders et al. 2014). Because we have assessed land cover at just two time points in time, not the full trajectory of Landsat images, the results do not represent the potential intermediary land covers and uses or proximate drivers of deforestation.

Of the 500,000 ha of crop expansion that replaced forestland, nearly 255,000 ha support herbaceous crops. The main crops in this category are herbaceous crops that are difficult to identify to a specific type without additional field work, such as non-rice cereals, sugarcane, or cassava (Figure 2). They account for over 51 percent of the total area of forest that was lost to agricultural expansion. This expansion does not show

TABLE 2: ABOVEGROUND BIOMASS CARBON STOCKS

	monoculture		agroforestry		
commodity	averaged (tonnes C/ha)	in Laos PDR (tonnes C)	averaged	in Laos PDR	total in Laos PDR
coffee	5.4	11,794	11	33,242	45,036
pulpwood	23	2,064,457	NA	NA	2,064,457
rubber	31.8	3,266,114	NA	NA	3,266,114
rice	1.1	1,554	NA	NA	1,554
tea	15.5	1,566	NA	NA	1,566
other herb crops	6.8	1,489,608	20	697,120	2,186,728
other tree crops	43.3	813,001	43.3	594,206	1,407,207
other shrub crops	10.5	11,907	16.5	52,982	64,889
crop support	6.8	46,267	NA	NA	46,267
TOTAL		**7,706,268**		**1,377,550**	**9,083,818**

	total tonnes C monoculture	total tonnes C agroforestry	total in Laos PDR
herb crops	1,491,162	697,120	2,188,282
shrub crops	25,267	86,224	111,491
tree crops	6,143,572	594,206	6,737,778
crop support	46,267	NA	46,267
TOTAL	**7,706,268**	**1,377,550**	**9,083,818**

Top: Aboveground time-averaged biomass carbon factors of commodity crops. Values for commodities were compiled from peer-reviewed and grey literature. Time-averaged values are used to estimate the carbon storage of rotational commodity crops because they average the carbon in freshly replanted and mature commodities. These values are then used to calculate aboveground biomass carbon contained in the total area of commodities in Lao PDR. Calculations are restricted to those commodities in areas that lost natural canopy cover between 2000-2015. **Bottom**: total area of crops, grouped by life form, and total carbon contained in crops by life form.

a strong geographic pattern, other than an association with road networks (Figure 4A). Overall, the observed crop expansion is occurring outside of protected areas (Figure 3).

Tree plantation expansion is also prevalent, accounting for 225,000 ha of forest loss. The most prevalent identifiable tree crops were rubber plantations, which covered 102,710 ha of previously forested area, and pulpwood plantations, which occupy 89,759 ha of forest loss. The expansion of crop cultivation along road networks was particularly evident for pulpwood (Figure 4C). Rubber cultivation expanded primarily in the north and south, with a few sites along the Cambodia border. The rubber clusters in the northern uplands correspond with large-scale conversions to rubber (Ziegler 2009). Most of the coffee in Lao PDR is grown on the Bolaven Plateau in the south, where several clearing events appear (Delang et al. 2013).

CARBON STORAGE IN LAO PDR: IMPACTS AND OPPORTUNITIES

An estimated 9.08 million tonnes C is stored in crops in 2015. This is just 16 percent of the 2000 forest carbon pool that was replaced, which was 56.9 million tonnes C (Table 3). We find that the greatest loss has happened in the transition of tropical moist deciduous forest to agriculture, with 23.3 million tonnes of C stored in biomass stock lost. This is 41 percent of the total carbon pool lost between 2000 and 2015, or 56.9 million tonnes C. Table 3 provides a summary of changes in AGB between natural forests and crops classified by ecofloristic zone. This table shows the stark differences between carbon storage in natural forests versus carbon in herbaceous crops or tree crops, though 32,499 hectares of tree crops were established between 2000-2015 (Figures 2 and 5).

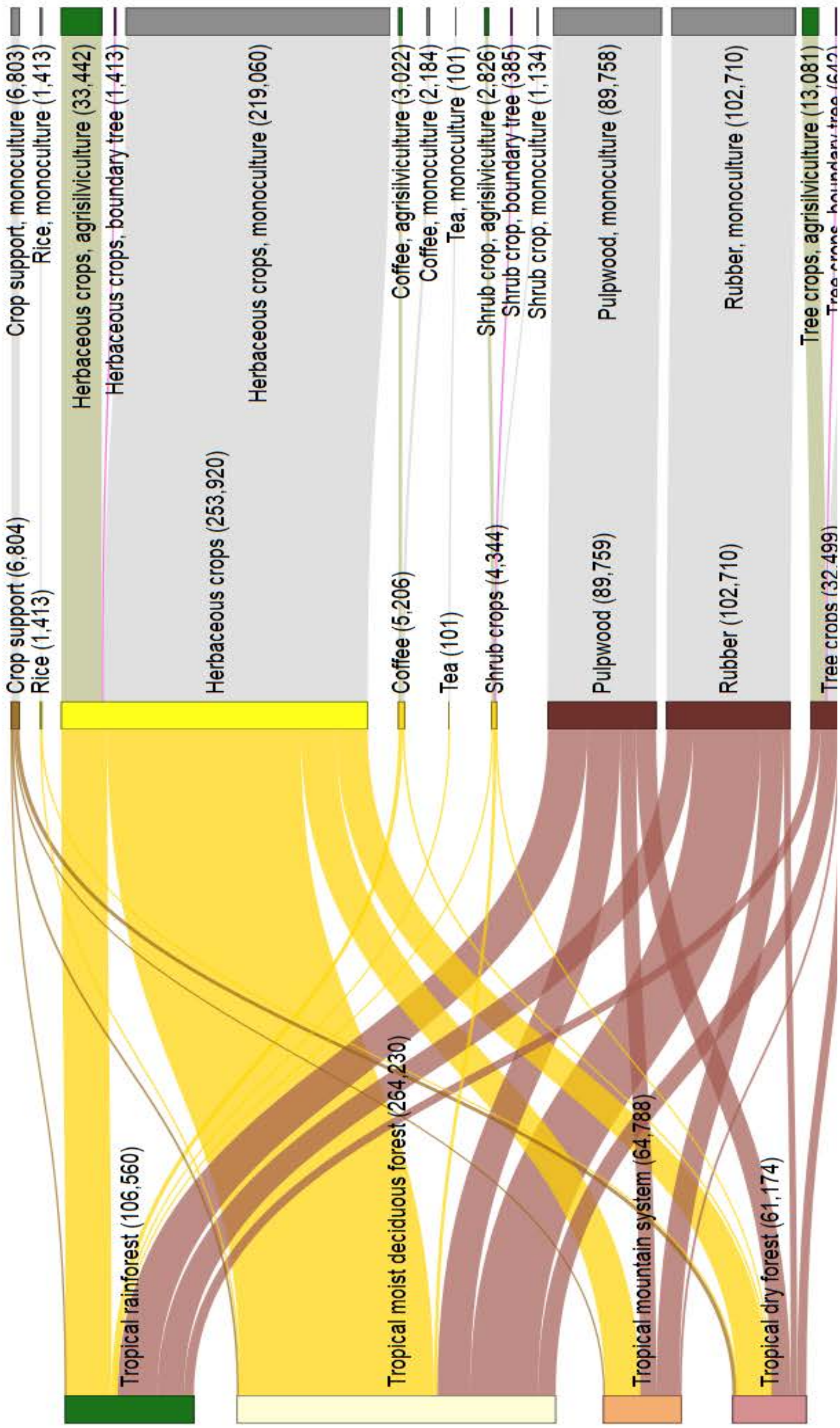
The differences in carbon storage due to native forest vs. crops are large. For example, in the tropical moist deciduous forest ecofloristic zone — the one with the highest magnitude of change — there was a net emission of 23.3 million tonnes of carbon, which is 84 percent of the gross C emissions for this particular ecofloristic zone. This clearly indicates the inability of herbaceous crops, tree crops or the combination of both to replicate the carbon storage capabilities of natural forests. Deforestation of tropical rainforests resulted in net emissions of 17 million tonnes of carbon. Proportionally speaking the tropical dry forest and the tropical mountain system ecofloristic zones had the lowest net emissions, with approximately 6 to 7 percent of the gross C emission for each class.

Certain types of land use change, for example from tropical rainforest to agriculture, have significant negative consequences on carbon stocks even if crops are grown in agroforestry systems. This is because tropical forests are among the most carbon-rich ecosystems on Earth. On average, tropical rainforests store 180 tonnes C/ha in aboveground biomass (AGB) (IPCC, 2006). Agriculture systems, by comparison, store only about 5 tonnes C/ha and up to 50 tonnes C/ha of AGB if crops are grown in combination with trees (Cardinael et al. 2018, Ruesch and Gibbs 2008). Estimates of carbon stored as AGB in native forests vary by region and by forest condition (Table 2). In the table, the plant morphology categories with the 'other' in the title refers to agricultural land cover in the plot that was not identifiable to a specific crop type; therefore, it was classified into a broader crop commodity label based on the growing form of the plant—herbaceous, shrub, and tree growth forms. Crop support is the land that is associated with the cultivation of crops, but not covered by the crop. Examples include the barren land in between rows of plants, ditches, and fence lines.

Table 2 contains the aboveground biomass (AGB) current stock estimations for those lands that transitioned from forest to crops in the 15-year period. Herbaceous crops such as cereal, sugarcane, or cassava account for 24 percent of the total AGB in these lands. Tree crops represent 16 percent of the total accumulated AGB. This highlights the remarkable difference between carbon storage in trees versus carbon in herbaceous crops. Figures 2 and 5 showed that the area of herbaceous crops was almost ten times larger than that of tree crops, but the difference in AGB between herbaceous crops and trees is just twofold. Other crops such as coffee, rice, tea and others represented less than one percent of the accumulated AGB, and thus can be considered contribute a negligible amount to the total AGB in these lands that changed from natural forests to crops.

National estimates of agroforestry carbon factors are within the ranges found in recent global meta-analyses of carbon stocks and stock change factors (Kim et al. 2016; Feliciano et al. 2018). No Lao PDR-specific data were available describing carbon stocks for many of the crops or agroforestry systems. In these cases, carbon factors from neighboring countries, such as Vietnam, were used. In such cases, we used the most conservative approach for estimating carbon storage in agroforestry systems: we assumed that the trees provide the majority of biomass and thus the same

Figure 5: The composition of crop commodities on land that had natural forest cover in the year 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in the year 2000; the middle section represents the crop type in 2015, with the agroforestry system indicated on the right. Area estimates, in hectares (ha), are included adjacent to the label.



carbon storage factors were used for both agroforestry systems and monocultures. A similarly conservative approach was taken for rice systems, where trees typically occur only as boundary plantings, but can contain non-trivial amounts of carbon (Feliciano et al. 2018). The values in Table 2 may underestimate some of the carbon in the landscape, though that is likely justified given it is a relatively small sum compared to the carbon emissions from the loss of forest cover.

Table 2 (lower) indicates the area and carbon stored in the four crop types, within either a monoculture or an agroforestry system. Across the herbaceous, shrub, palm and tree crops, we find that agroforestry provides greater carbon storage than monoculture-based crops. However, even the most carbon-rich agroforestry systems, such as fruit, nut, and rubber plantations, typically contain far less carbon than natural forests. They store only 30 to 40 percent of the average amount stored in tropical moist deciduous forests. Such differences in carbon storage between agroforestry systems and natural forests highlight the significant influence forest loss has on carbon balance, and the importance of reducing forest conversion to crops. In those landscapes where conversion to crops has already occurred, turning monoculture systems into agroforestry systems will have a positive impact on carbon storage.

There may be opportunities for integration of rubber agroforestry into shifting/upland agricultural systems; this could be a way to transition to more spatially stable cropping systems in Lao PDR (Thongmanivong et al. 2009; Baird 2010). In Lao PDR, rubber plantations appear to be most successful when grown by smallholders operating under a contract system, rather than through concession-driven plantation systems (Manivong and Cramb 2008; Baird 2010). The appropriation of forest and village land for large rubber concessions has been met with resistance in both northern and southern Lao PDR, even when there has been support for growing rubber by the villagers themselves (Laungaramsri 2012; McAllister 2015). This resistance often stems from the fact that concessions typically reallocate land that had already been designated as “belonging” to villagers, including forest set aside for conservation or protection purposes (Kenney-Lazar 2012). In this context, smallholder-implemented rubber-based agroforestry systems might be one way to encourage upland people to adopt permanent agriculture.

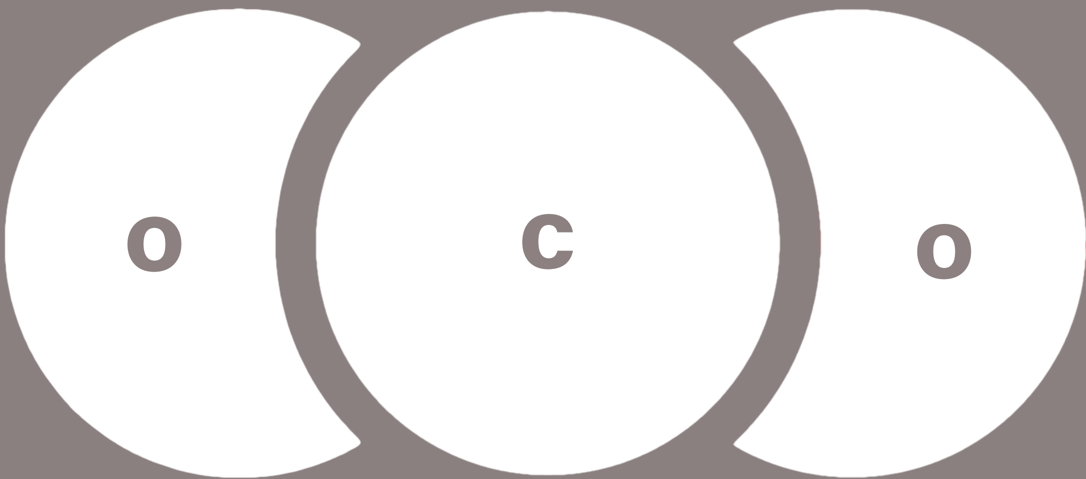
Coffee concessions have also failed to be more productive than smallholder’s coffee cultivation in the southern region of the country, even though large areas of land have been formally set aside, often for foreign companies (Delang et al. 2013). The low productivity of large coffee concessions has its roots in 1) the allocation of unsuitable land, 2) conflict with other stakeholders, 3) insufficient resources to continue development once started, and 4) lack of actual interest in coffee production. In many cases less than 60 percent of these coffee concession lands are actually planted with coffee and maintained within three years of allocation (Schönweger and Messerli 2015).

Overall, the process of allocating concessions has tended to be riddled with conflict because of double allocation, limited oversight of boundaries, and poor labor practices (Baird 2010; Kenney-Lazar 2012; Laungraramsri 2012). There may exist, however, opportunities for development of commercial concessions that also produce good outcomes for local populations and forests through collaborative work at the village level. Existing low-utility degraded lands could be identified, cleared of unexploded ordinance, and turned into agroforestry systems that support food security while producing commodities like pulpwood (Barney 2014). This process aligns with the government’s goals of helping villagers achieve higher standards of living through intensive, rather than extensive, production systems while reducing impacts on the landscape.

While countrywide programs aimed at reducing shifting agriculture appear to have been moderately successful, it is difficult to determine whether or not these policies have preserved forest. That is because much of the former fallow shifting agriculture land has been converted into rubber, maize, sugarcane, or other crops, and thus has transitioned into agricultural lands (Vongvisouk et al. 2014). In addition, while long-rotation shifting agriculture systems do disturb forests, they are capable of storing as much or more carbon as a rubber plantation, with much higher agro-biodiversity (Bruun et al. 2018).

In Central Lao PDR, traditionally practiced shifting systems have not tended to expand with population growth as long as alternative forms of income are also present (though this effect may vary with ethnic group; see Robichaud et al. 2009). Given this, it is unclear if the state efforts to reduce forest disturbance from shifting agriculture have resulted in reduced carbon emissions or increased carbon storage. The magnitude and dynamics of shifting agriculture should be reviewed carefully before assuming that it is an environmentally destructive practice (Messerli et al. 2009). As noted by Ingalls et al. (2018), shifting fallows are used for crops and non-timber forest products that provide nutrition, medicine and household income opportunities. In the Lao PDR, up to 69 percent of agricultural households

IN TOTAL, 47.8 MILLION TONNES OF CARBON WERE LOST DUE TO FOREST CONVERSION TO CROPLANDS BETWEEN 2000-2015 IN LAO PDR



depend on non-timber forest products, and almost 50 percent of these benefits were derived from shifting fields and fallows (Ingalls et al. 2018). This clearly indicates the these shifting systems are important for sustaining communities.

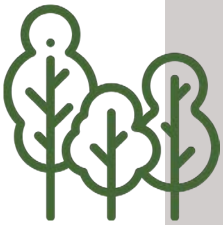
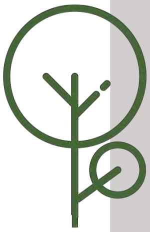
CONCLUSIONS AND RECOMMENDATIONS FOR LAO PDR

Prioritizing investments to improve the sustainability of landscapes requires knowledge of how agriculture has replaced natural forests and the associated net greenhouse gas emissions. This research in Lao PDR shows that the dominant crops being cultivated in lands that were formerly forested include vast expanses of herbaceous crops (cereal, sugarcane, or cassava), and smaller areas of tree (rubber, pulpwood) crops. Herbaceous crops occupy close to 50 percent of those lands that were once forest. This transition from natural forest to agriculture has resulted in huge net GHG emissions (the gross emissions as a result of agricultural conversion is in the order of 9.1 million tonnes C). Even though as many as 225,000 hectares of tree crops have been established on previously forested lands; this difference in net emissions clearly demonstrates the disadvantage of substituting native forests with monoculture plantations.

While some of the following policy and program recommendations are outside of the scope of this study, our results, combined with a brief literature review of Lao PDR forestry and land use policy and practice, suggest that some of the following options may require further consideration.

As of 2015, coffee made up 80 percent of the agricultural exports of Lao PDR (Setboonsarng and May 2015). The cool climate in the upper elevations and the red volcanic soils in the south are particularly suitable for growing high-quality coffee. But as noted above, poor productivity of coffee plantations is an issue, largely because land is poorly allocated, there are insufficient resources to continue production, and there is a lack of interest in large-scale plantations. That said, coffee has great export potential and can be grown in agroforestry systems, thereby generating income and sequestering carbon. One study (Minoo A. 2017) found that one issue

TABLE 3: CHANGES IN ABOVEGROUND BIOMASS (AGB) IN NATURAL FORESTS AND ALTERNATIVE CROPS BY ECOFLORISTIC ZONE (TONNES C/HA)

		average C/ha in AGB	C in forest (2000)	C in crops replacing forest (2015)	C lost due to conversion
	TROPICAL RAINFOREST	180	19,180,800	2,187,492	**16,993,308**
	TROPICAL MOIST DECIDUOUS FOREST	105	27,744,045	4,444,127	**23,299,918**
	TROPICAL DRY FOREST	78	4,771,494	1,171,567	**3,599,927**
	TROPICAL MONTANE SYSTEM	81	5,247,909	1,280,631	**3,967,278**
	TOTAL		**56,944,248**	**9,083,817**	**47,860,431**

with coffee production in Lao PDR was a distrust of government Fair Trade pricing policies. Many coffee producers prefer to sell to middlemen because they are immediately paid; this however leaves them at a financial deficit when they are competing with farmers who accept the risk of delayed-payment Fair Trade pricing. The solution presented is to pay farmers Fair Trade prices immediately at point-of-sale to overcome mistrust. Another study found that electronic certification systems for trade might also improve trade and profits for farmers (ADB 2015). Therefore, focusing on smallholder coffee agroforestry in the South, ensuring that farmers are paid Fair Trade prices when selling, and setting up electronic certification schemes may enable coffee farmers to grow incomes while improving land use and carbon sequestration.

Rubber, as noted above, sequesters significant amounts of carbon. While adding rubber to monoculture systems is a regional-level recommendation, it appears this recommendation may be particularly relevant to Lao PDR. Smallholder rubber plantations combined with agroforestry practices have already been gaining traction in parts of Lao PDR. Rubber plantations may be the best use for many of these degraded lands. In addition to carbon sequestration, rubber also produces relatively quick financial returns for growers. If rubber could be planted on degraded lands and incorporated with agroforestry, or incorporated into shifting agriculture, smallholders would have a means to produce food for their families/communities while still earning extra income from both fallow and cultivated lands.

A study done by FAO (Lestrelin et al. 2012) found that conservation agriculture had significant potential in Lao PDR and was gaining momentum in those areas where farmers were instructed in proper techniques. Conservation agriculture is suggested to reduce soil erosion, increase soil fertility, and keep more carbon in the ground since the ground is always planted with cover crops. In particular, they found that conservation agriculture techniques were compatible with some forms of shifting agriculture, for example, small shifting rangelands could be regenerated by a cycle or two of soybean, or rice could be seeded into a non-forage legume in sloped lands. The biggest obstacles to conservation agriculture were poor knowledge about practices, and insufficient capital to invest in the round or two of seeds or fertilizer that would be needed to get it started. Encouraging farmers that use shifting agriculture to transition to conservation agriculture practices by financing small loans and providing training might be a good way to make better use of fallow lands without disrupting traditional shifting practices.

Documenting and securing land tenure for local people, including by creating a system that will prevent the double allocation of forest land, is another key activity. Doing so will reduce conflict associated with economic development and enable local people to take responsibility for and protect their lands. This is of course an extremely complicated issue throughout the developing world, and especially in Lao PDR, where lands are owned by levels of government that do not necessarily communicate with each other. One study (Bourgoin et al. 2012) found that participatory land use planning backed by GIS maps and skilled trainers was useful in alleviating conflict and clearly defining land boundaries. This technique showed villagers maps of their land, helped them define current land use and land values, and allowed them to negotiate land use with neighboring villagers through value trade-offs. It also allowed them to co-govern land when needed, reducing conflict. Part of the key to this process was that government officials were involved, and in the end, maps were officially endorsed by all present. While such participatory techniques will undoubtedly not solve all the land tenure issues in Lao, it may work in remote areas where large land concessions are not present. It is important in such processes that women and ethnic minorities are fully at the table.

Broker deals between the government and land owners using long-term and neutral third parties, such as NGOs or donor-led land and forest allocation processes (Fujita and Phengsopha 2008). There are huge gaps between policy and practice in Lao PDR, which are exacerbated by the multiple layers of land rights. Using long-term trainers or brokers to facilitate training and help villagers adapt to shifting land use needs and ecological realities has been more useful than government-led initiatives (Fujita and Phengsopha 2008), in part because NGOs and long-term donors retain institutional knowledge and gain village trust better than ever changing government officials do. In order to minimize ecological degradation, restore forests, and maximize harvests, we recommend investing in long-term regional NGOs who have the trust of the communities and can help them negotiate better land use rights, finance, and land use decisions.

Microfinance, farmer cooperatives, and expanded access to markets needs to be supported. Cooperatives have a storied history in Lao PDR where they have been allowed and dissolved numerous times over due to changes in government strategies and priorities; however, such cooperatives or self-help groups have been successful in in increasing food security, market access and livelihood opportunities for farmers (EDC 2002). In the field of agriculture, cooperatives provide members with credit, input supplies, marketing, and guidance. They also provide vertical linkages to large suppliers and buyers and local communities, and they develop their own infrastructure: warehouse, transport systems, and value-added processing centers (Castella and Bouahom 2014). By increasing monetary returns from agricultural products, NTFPs and timber itself, people may be incentivized to preserve natural forests. This may especially be the case in the upland teak forests of Lao PDR, where teak returns, though high, take years to realize (Smith et al. 2017). If villagers are trained, and given financing to start new industries with NTFPs, the wait to harvest teak may not feel so long (RECOFTC, unpublished data).

Many documents, such as the 8th National Socio-Economic Development Plan (2016-2020) mention the Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanism as a priority activity to mitigate climate change. Currently, 83 percent of Lao PDR's emissions are from the AFOLU sector. REDD+ and Forest Law Enforcement, Governance and Trade (FLEGT) are mentioned by the government of Lao PDR as key international mechanisms to contribute to the emission reduction commitments of the country. To this end, the government signed a "letter of Intent" with the World Bank in 2016 that opens space for Lao PDR to receive REDD+ payments, ideally reducing or eliminating 10 million tCO_2e in the next seven years (Christopher 2018). However, the institutional arrangements for receiving REDD+ payments and distributing them to communities are largely missing. Supporting the establishment of simple, transparent community-based REDD+ funds will likely have notable positive impacts on forest cover and community livelihoods.

These recommendations are just a representative sample of the interventions that could reduce deforestation and land degradation in Lao PDR. As is true throughout much of the developing world, improved science-to-policy communication, better education of local land users, enhanced trust and cooperation between communities and governments, easy-to-access finance and marketplaces, and intensification of already degraded lands are the overarching solutions to better land use and improved rural livelihoods. Lao PDR is unique in that the government is particularly focused on reducing shifting agriculture; we argue that this may not be necessary, as shifting practices do maintain local biodiversity and may simply be improved by the incorporation of trees into the landscape. Whatever interventions are chosen, it is clear that community participation and long-term engagement are key, so that strategies for reducing land degradation are adaptive to changing community needs and ecological conditions. With adoption of such adaptive strategies, it will be possible for commodity development to contribute poverty eradication and food security while still promoting sustainable life on land.

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MYANMAR

KEY MESSAGES

A TOTAL OF 1.2 MILLION HECTARES (HA) OF FOREST WERE LOST BETWEEN 2000 AND 2015; APPROXIMATELY 760,000 HA OF THAT LAND NOW SUPPORT CROPS.

IN TOTAL 386,000 HA (37 PERCENT) OF LANDS WITH TREE COVER WERE CONVERTED TO HERBACEOUS CROPS AND 327,000 HA (32 PERCENT) TO TREE CROPS; TREE CROPS INCLUDED PULPWOOD (108,090 HA), RUBBER (56,534 HA), AND OTHER CROPS THAT WERE NOT IDENTIFIABLE WITHOUT FIELD OBSERVATION.

THE TOTAL CARBON WITHIN THE ABOVEGROUND PLANT BIOMASS OF CROPS REPLACING FORESTS IS **16.8 MILLION TONNES C.** IF THESE LANDS WERE STILL FORESTED, THEY WOULD HOLD 95.2 MILLION TONNES C, **MEANING THEY LOST 82 PERCENT OF THEIR ABOVEGROUND CARBON.**

At the beginning of the 21st century, Myanmar was the most heavily forested country in Southeast Asia, with as much as 65 percent of the country occupied by forests (Leimgruber et al. 2005; Bhagwhat et al. 2017). This forested area was split between 18.3 million hectares (ha) of intact, broadleaved dense forest (with 60-80 percent canopy cover), and 25.7 million ha of degraded forests (with canopy cover of less than 10 percent) (Bhagwhat et al. 2017). After 2000 the country experienced localized, substantial deforestation, with some hotspots in the country experiencing very high rates of forest loss, particularly the Ayeyarwady Delta (Leimgruber et al. 2005; Webb et al. 2014; Wang and Myint 2016; Bhagwhat et al. 2017). Regardless, as of 2010, it was still 48 percent forested and was the country with the highest percentage of forest cover globally (FAO 2010). That situation is unfortunately changing rapidly: it now has one of the highest deforestation rates in the world (FAO 2014) and the highest of all the Himalayan countries (Brandt et al. 2017).

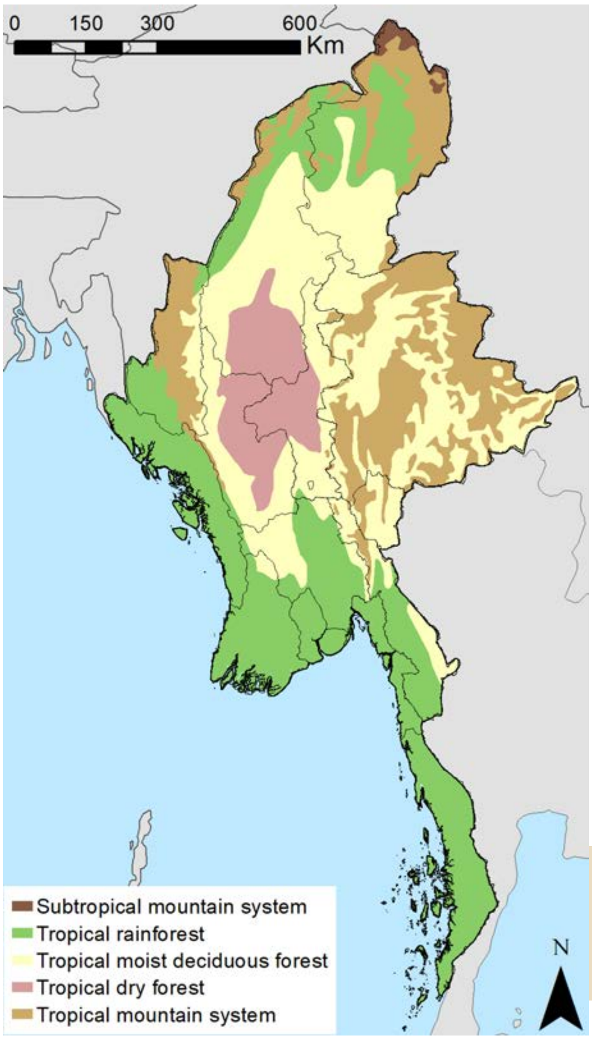


Figure 1: Ecozones of Myanmar, from Ruesch and Gibbs, 2008.

Myanmar has had a centralized forestry system since the days of colonial rule (Springate-Baginski et al. 2016) and as result of this, forest management is still very top heavy, with a focus on establishing and patrolling borders of reserves and concessions and punishing illegal harvesters of forest products (Prescott et al. 2017). The government has been making significant efforts since at least 2001 (Veetiil et al. 2018) to decentralize forest management, establish more community forests (MacQueen 2015; Kaung 2016; Fuerer et al. 2017) and clarify land rights, but the progress has been slow. Part of the reason it has been slow is because government departments have been reorganizing and reforming in the past decade, and in many cases, communication between agencies that oversee land use is minimal or entirely absent (J.Jadin, personal communication).

Deforestation rates in Myanmar increased partially due to the influence of the colonial system and rapidly changing mandates of government agencies, but for other reasons as well. The long civil conflict, for one, has been significant. Fighters in the conflict have cleared forest to prevent enemy attacks, and vast numbers of internally displaced people (IDPs) have unintentionally caused land degradation as they have been evacuated from turbulent homelands. Further, opening the country to international trade and development after 2010 has unintentionally promoted deforestation, through increased trade in timber products. Mining, hydropower, and infrastructure development are other drivers of deforestation in this rapidly growing economy, as is the expansion of agriculture to feed a growing domestic population and support trade. Overarching all of this is an enabling environment defined by land

Table 1: Volume (in millions of constant 2015 US dollars) of agricultural commodities traded in Myanmar in 2000 and 2015 (from www.bea.gov). Values derived from Chatham House, resourcetrade.earth (2018).

Commodity	USD value 2000	USD value 2015	% change
rice	7	222.4	3,068
rubber	21.5	121.6	465
tree nuts	5.5	40.9	641
tree fruits	12.4	36.6	194
banana	-	16.8	-
cereals	6.8	14.8	119
tobacco	0.05	1.1	1,996
pulpwood	0.6	3.1	434
tea	0.08	2.6	3,208
coffee	0.4	2.4	510
palm oil	0.05	1.1	1,996
coconut	-	0.01	-
cocoa	-	-	-

reform efforts by the central government which have seized land from various ethnic minorities, and given titles to concessions and other businesses through a less-than-transparent process (Webb et al. 2014; Donald et al. 2015; Woods, 2015; Lim et al. 2017; Prescott et al. 2017).

Many of the large concessions in Myanmar have been granted courtesy of the Vacant, Fallow, and Virgin (VFV) land law — which has also had the unfortunate consequence of displacing the original smallholders who farmed the land. This has particularly impacted ethnic minorities along the border with China and Thailand, and has changed the ways forested lands are traditionally used (Byerlee et al. 2014; Scurrah et al. 2015; Burnley et al. 2017). Despite the already negative consequences, the VFV law was updated in 2018 to have harsher penalties; it now requires residents of VFV lands (some 20 million hectares) to have had them registered by March of 2019. If they did this, they can acquire a 30-year claim to use it—otherwise they face eviction, fines, or prison time for "trespassing" (Chau and Daudier 2019; Human Rights Watch, 2019). This update to the law is likely to have significant negative consequences for the ethnic minority communities who do not speak Burmese, but occupy roughly three quarters of this land. In fact, a recent survey estimated that 95 percent of the people impacted by the law had no knowledge of it (Goldberg 2019).

Myanmar's history of deforestation is relatively short, but rapid; its history of forest protection is long, but with mixed results. The country has established and managed a series of officially protected forest reserves and national parks. These areas have had significantly lower rates of deforestation than unprotected forests, but they have experienced deforestation nonetheless. One example is the Chatthin Wildlife Sanctuary. This land was initially a fuelwood reserve but in 1941 was converted into a sanctuary. The area surrounding the sanctuary lost 62 percent of its forest cover between 1973 and 2005, likely due to the expansion of agriculture and fuelwood extraction associated with sugar cane production; the sanctuary itself lost 16 percent of its forest cover (Songer et al. 2009). Some reserves, particularly those bordering on major rivers in the country's central dry zone, lack tree cover altogether and others are composed almost entirely of degraded forest (Treue et al. 2016). This is likely due to the high demand for valuable timber such as teak (Tectona spp.), pyinkado (Xylia xylocarpa), and padauk (Pterocarpus spp.) which grows in the reserves.

In contrast, the Lenya National Park and Lenya National Park Extension in the Tanintharyi region of southern Myanmar is one example where official forest protection has been notably effective. While forests outside Lenya National Park decreased from 76.9 to 48.9 percent between 2002 and 2016, the forest cover in the park area decreased by less than 3 percent (98 to 95.2 percent) during the same period (Conette et al. 2017). Forest losses outside the park were largely driven by concessions for oil palm and subsequent timber extraction (Conette et al. 2017). Unfortunately, examples like Lenya are the exception, not the rule.

AGRICULTURAL DEVELOPMENT TRENDS IN MYANMAR

The Government of Myanmar has allocated a large area of the country for economic concessions, totaling 5.2 million hectares as of 2013 (Woods, 2015). The vast majority of these concessions were intended to be planted with rubber, oil palm, rice, jatropha, sugarcane, and cassava (Byerlee et al. 2014). However, it appears that concession holders have extracted timber more than they have cultivated crops: less than 30 percent of lands were planted with the intended crops (Byerlee et al. 2014; Scurrah et al. 2015). Despite this, Myanmar has seen substantial increases in exports of various commodity crops (Table 1).

There are no consistent maps depicting the location, coverage, or growth of specific commodities; however, the census statistics on the growth and volume of agricultural commodities traded, presented in Table 1, provide some baseline information about which crops have experienced growth driven by agricultural markets. Rice was the most economically important crop exported in 2015: its economic value increased by more than 3,000 percent since 2000 (currently valued at 220 million USD). This gain is unsurprising given that Myanmar was the world's largest exporter of rice (Scurrah et al. 2015) prior to World War II and the subsequent years of political unrest.

Rubber was second to rice in trade importance in 2015, when Myanmar exported more than 120 million USD of rubber. Rubber exports are likely to continue growing, given that more than 600,000 ha of rubber had been planted as of 2014. Clearly, the sustainability and social

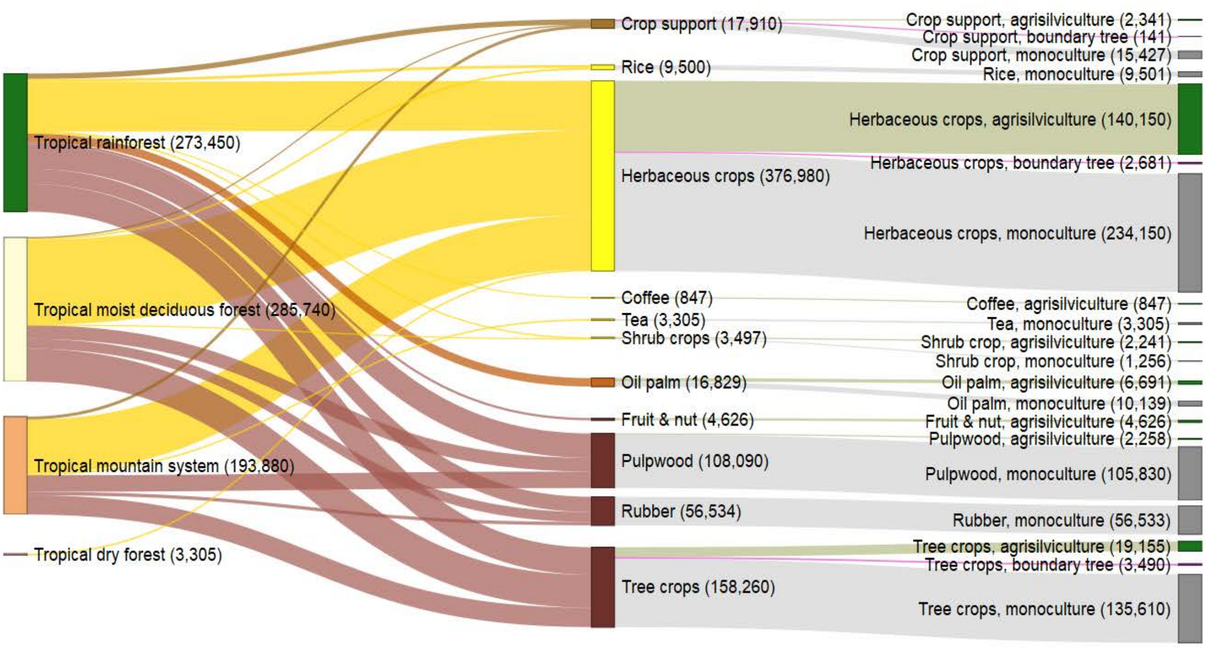


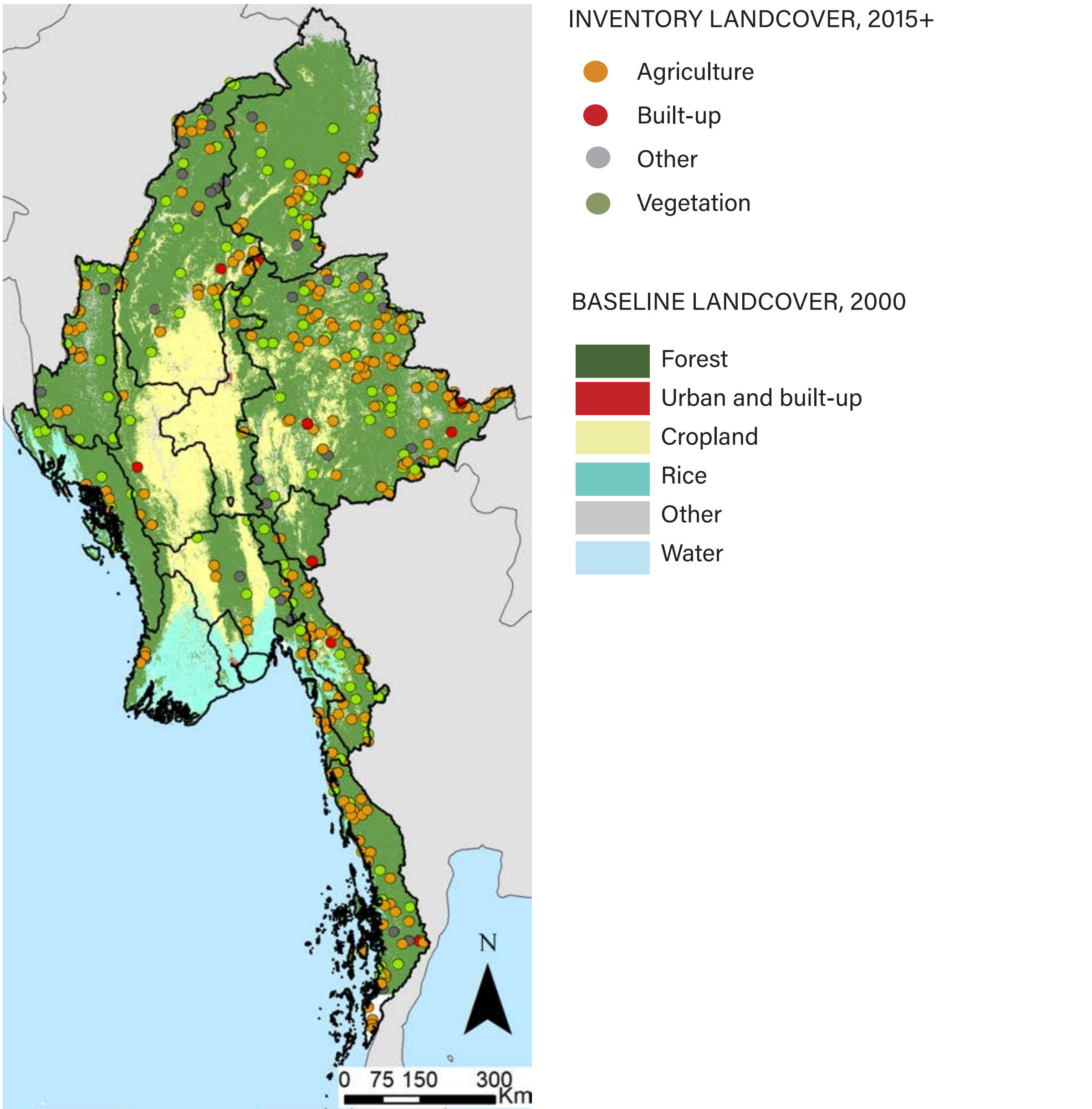
Figure 2: Composition of land use and crops in lands that underwent forest loss since 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in 2000, while the right side represents the land cover after 2015. The total area of all crops is represented by the croplands bar in the middle. Area estimates (ha) are adjacent to the labels.

impact of this industry will need to be addressed (Kenney-Lazar et al. 2018). Other crops such as fruit, nuts, tobacco, cereal crops, pulpwood, coffee, tea, and palm oil also experienced significant growth. However, all of these crops added together are still valued less than rubber alone.

Interestingly, Curtis et al. (2018) found that the main driver of natural forest loss in Myanmar was shifting agriculture (also known as slash-and-burn or swidden), followed by rotational plantation forestry concessions and establishment of non-tree commodity crops. The same study also reports that the loss of natural forest due to shifting agriculture has been widespread across the country, while commodity crop-driven deforestation has particularly large clusters in the north and north-east regions that border China. This is likely because many Chinese companies invest in Myanmar's agriculture, buy and trade commodities, and operate through contract farming agreements with local producers. These investments focus on cash crops, including rubber, cassava, sugarcane and fruits, maize for poultry feed, and biofuel crops; much of this in the north due to geographical proximity (Grimsditch 2017; Kubo 2018; Woods 2015).

Tree commodity (rotational plantation forestry) driven deforestation is mostly aggregated near the coastal areas of the Bay of Bengal and regions bordering India and Bangladesh. Commercial timber exports are the

Figure 3: Spatial distribution of plots in the sample that have been deforested over the study period, overlaid on a land cover map from 2000 (Saah et al. 2020).



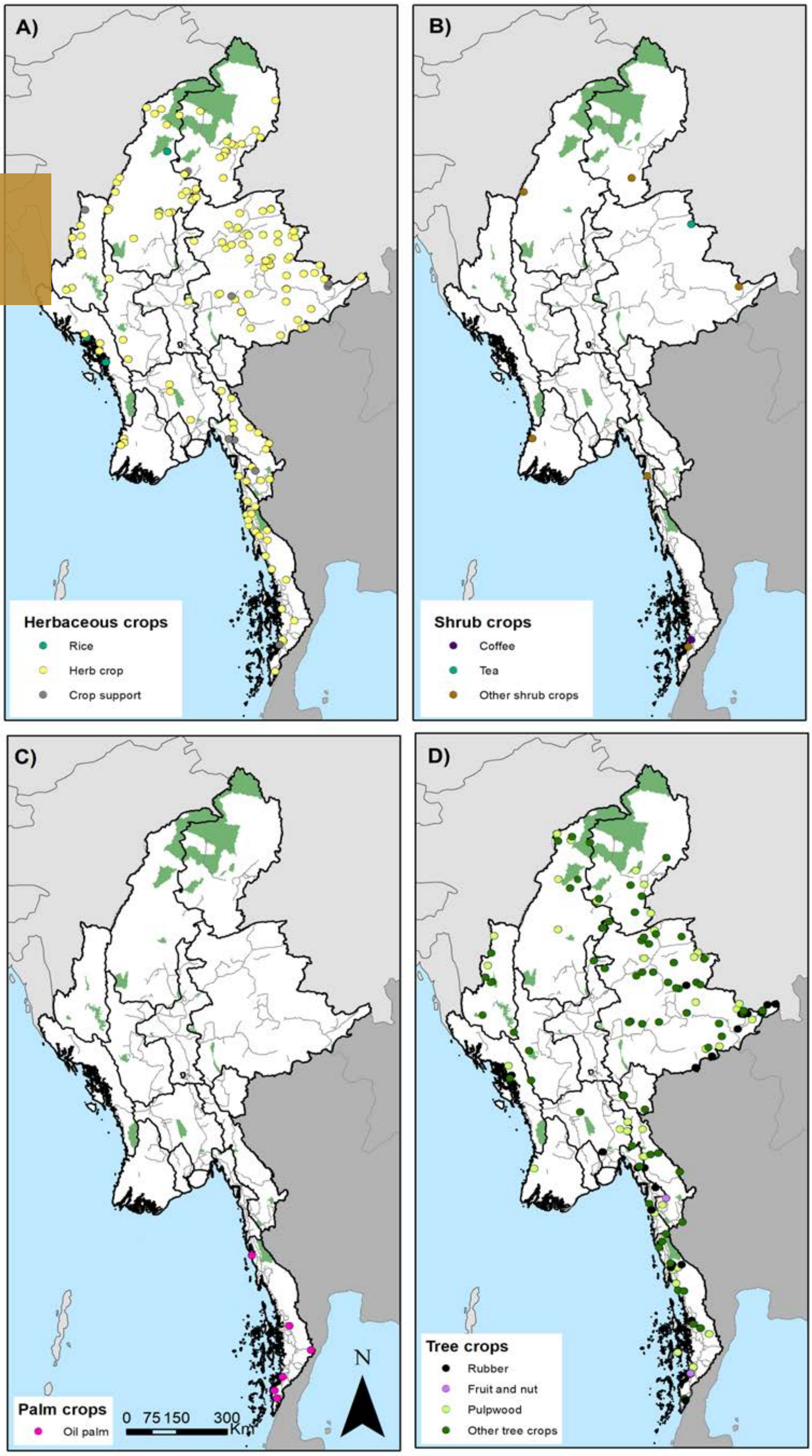
second most important source of foreign currency in Myanmar (Springate-Baginski et al. 2014). India has recently become Myanmar's second most important timber export market, which may explain why tree-commodity driven deforestation is concentrated near the Indian border.

TREE CANOPY COVER LOSS IN MYANMAR

We estimate that from 2000 to 2015 Myanmar experienced a total forest loss of 1.2 million ha (Figure 2), which is comparable to an earlier study that reported 1.6 million ha of loss (Bhagwat et al. 2017). To get an estimate of the percent of forest loss, we can compare this to the estimate of cover from the global forest resource assessment (FAO 2015E). This is just a loss of 2.2 percent of the total of forest and woodland areas from 2000. However, while this comparison of loss to the FRA baseline estimate provides some context; caution needs to be taken when interpreting the percent loss estimates since both studies have a different definition of forestland. To some extent our definition aligns with the combined forest and woodland estimate from FAO (2015A): forest is any half ha patch (or greater) with trees higher than 5 meters and a canopy cover of more than 10 percent that is not in predominantly agricultural or urban land use. Wooded land is nearly the same but the canopy cover is from 5 to 10 percent or has a combined cover of shrubs, bushes and trees above 10 percent (ibid). However, these do include rubber and other tree plantations, so it is not a direct comparison with definitions used in this study; our definition of forest cover excluded canopy cover and forest patch size thresholds.

The area of forest and woodland in 2000 was estimated to total 54.6 million ha—34.9 million ha and 19.7 million ha, respectively (FAO 2015E, Table 1A). To better understand how definitions and methods may impact this baseline estimate, we compare these values with other baseline estimates. Map based forest cover estimates for Myanmar vary significantly. Wang et al. (2016) estimated that the total forest cover was 43 percent (29.1 million ha) in 2000; in that study, forest was defined as an area having 10 percent or more tree canopy cover. Leimgruber et al. (2005) estimated Myanmar's forest cover to be 65 percent (44 million ha) in the early 2000s, defining forest as areas with at least 50 percent tree canopy cover. Bhagwat et al. (2017) estimated forest cover to be 65.4 percent in 2002, and 63 percent in

Figure 4: Spatial distribution of crop types at plots within the sample where deforestation events were followed with crop cultivation (depicted by orange dots in Figure 4) overlaid on top of the road network. Dark green areas are protected forests; light green indicates boundaries of other protected areas such as national parks and wildlife sanctuaries (ODC 2020).



2014, using a definition of at least 10 percent tree canopy cover. Out of these three studies, the latter two used methods that relied on Landsat imagery with a spatial resolution of 30 meters. The former study used MODIS vegetation product with a 500 m^2 resolution. The variation in the estimates of total forested area for 2000 are partially attributed to differences in the operational definition of forest between reporting agencies and, to some extent, measurement uncertainties (Keenan et al. 2015; Tropek et al. 2014). For example, all maps have errors and biases (Olofsson et al. 2014), and the map-based estimates (Leimgruber et al. 2005; Wang et al. 2016; Bhagwat et al. 2017) should include an area correction using an independent inventory of forestland to adjust for map bias and uncertainty if these are to be used to report on forest area.

Tree cover is distributed across five different tropical and subtropical ecozones: rainforest, moist deciduous forest, mountain system, dry forest, and subtropical mountain system. Out of the five ecofloristic zones, three were highly impacted by land use change; while two experienced little to no change. The clearing and land use changes were pretty evenly distributed across forests in the tropical rainforest, moist deciduous, and mountain system with roughly 435,000 (36 percent of all clearing), 434,000 (36 percent) and 334,000 (28 percent) respectively (Figure 2). Less than 1 percent of the loss was in the tropical dry forest ecozone; none was observed in the subtropical mount system. The dominant ecological zone is the tropical rainforest, which is located along the coastline and in the lowlands of the northern region (Figure 1). The second most prominent ecological zone is the tropical moist deciduous forest, which is widespread in the lowlands of the central region as well as in the western area in the Salween river watershed that borders Thailand. The tropical dry forest ecological zone is found exclusively in the northern part of the Ayeyarwady river delta and includes the cities of Mandalay and the capital Naypydaw. The tropical mountain forest ecological zone is widely distributed in the highlands, and most highly concentrated in high altitude areas bordering China and India. The smallest ecofloristic zone is the subtropical mountain system, which is only found in the highest elevations near the dual-border region with India and China.

Most of the forest loss (63 percent, or 760,00 ha) was due to conversion to croplands, including herbaceous (51 percent) and tree crops (43 percent). Conversion to shrublands and grasslands accounted for 27 percent of the natural forest loss, 332,000 ha. This vegetation includes shrubland, grasslands, and herbaceous cover. The remaining 10 percent of natural forest loss was due to other non-forested land uses, such as human settlements and mining. Figure 2 shows the amount of forest loss between 2000 and 2015, along with the type of land use or cover that has resulted from the forest conversion.

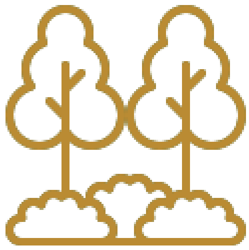
There may have been different initial or additional drivers of deforestation and land uses in between the current state and 2000 that are not presented in these results. For example, in southeast Asia, deforestation is often initially driven by selective logging, then the land is subsequently converted to agriculture (Saunders et al. 2014). Because we have assessed land cover at just two points in time, not the full trajectory of Landsat images, the results do not represent the potential intermediary land covers and uses or proximate drivers of deforestation.

The conversion of forested land took place mostly near international border areas as well as along the southern coast of Bengay Bay. Figure 3 provide the location of plots within our sample that experienced forest loss and what the land cover was changed to by 2015. Within our sample, little to no natural forest loss took place in the dry central region. This is likely because this region contains the bulk of Myanmar's population and already underwent significant forest loss previous to 2000 (Leimgruber et al. 2005; Htun et al. 2009; Songer et al. 2009).

Much of the natural forestlands were converted to herbaceous commodity crops, which are widespread throughout the country. Figure 2 disaggregates forest loss according to replacement crop type. We found that 386,000 ha of herbaceous crops — including rice — had replaced native forest, of which 63 percent are growing in monocultures. Herbaceous crops that could not be identified to a specific type without additional field work, such as cereals and tobacco, were the predominant category in our sample and were largely observed adjacent to the road network (Figure 4) adjacent to the edge of intact forestlands in 2000 (Figure 3). They are relatively unimportant with respect to economic value of trade despite their large impact on forest conversion.

Rice, on the other hand, has the highest trade value at 222.5 million USD, nearly double the second highest valued commodity, rubber. As previously mentioned, rice experienced a 3,000 percent growth in trade, but we found less than 10,000 hectares of forest loss due to conversion to rice farming from 2000 to 2015. The land that was converted was primarily in the Southeast (Figure 4). We suspect the reason that rice conversion caused little forest loss is because rice farming is

TABLE 2: ABOVEGROUND BIOMASS CARBON STOCKS



commodity	monoculture averaged (tonnes C/ha)	monoculture in Myanmar (tonnes C)	agroforestry averaged	agroforestry in Myanmar	total in Myanmar
coffee	NA	NA	11	9,317	9,317
fruit and nut	NA	NA	51.63	238,840	238,840
oil palm	38.97	395,117	38.97	260,748	655,865
pulpwood	23	2,434,113	23	51,934	2,486,047
rubber	31.83	1,799,477	NA	NA	1,799,477
rice	1.05	9,975	NA	NA	8,839
tea	15.53	51,327	NA	NA	51,327
other herb crops	6.82	1,596,896	20	2,856,580	4,453,476
other tree crops	43.28	5,869,287	43.28	980,076	6,849,363
other shrub crops	10.46	13,148	16.5	36,960	50,108
crop support	6.82	105,219	20	49,640	154,859
TOTAL		**12,274,559**		**4,484,095**	**16,758,654**

	total tonnes C monoculture	total tonnes C agroforestry	total in Myanmar
herbaceous	1,606,871	2,856,580	4,463,451
shrub crops	64,475	46,277	110,752
palm crops	395,117	260,748	655,865
tree crops	10,102,877	1,270,850	11,373,727
crop support	105,219	49,640	154,859
TOTAL	**12,274,559**	**4,484,095**	**16,758,654**

Top: Aboveground time-averaged biomass carbon factors of commodity crops. Values for commodities were compiled from peer-reviewed and grey literature. Time-averaged values are used to estimate the carbon storage of rotational commodity crops because they average the carbon in freshly replanted and mature commodities. These values are then used to calculate aboveground biomass carbon contained in the total area of commodities in Myanmar. Calculations are restricted to those commodities in areas that lost natural canopy cover between 2000-2015. **Bottom**: total area of crops, grouped by life form, and total carbon contained in crops by life form.

already widespread, and the land that could support this use was already converted before 2000. Also, the discrepancy between exports and increases in area under cultivation for rice may be partially explained by cultivation practices that yield more production by land area, such as multiple crop cycles per year.

Tree crops were nearly as abundant in recently cleared forests as herbaceous cover crops. Nearly 328,000 ha of tree crops replaced forests, 43 percent of the total crop expansion into forestlands. Within the tree crop sub-group, we found that pulpwood plantations accounted for 33 percent of the total land that transitioned from natural forests to commercial tree plantations (108,090 ha, Figure 2). Rubber comprised 17 percent of this total, 56,534 ha. Rubber has the second highest trade value after rice and has replaced a large area of natural forests, primarily along the southeastern border with Thailand (Figure 4D). Oil palm cultivation in Myanmar has a relatively low trade volume/value, in contrast to much of the rest of Southeast Asia. Natural forest conversion to oil palm plantations was minimal, covering 16,829 ha, and restricted to the far southern peninsula (Figure 4D). Overall, the observed crop expansion is occurring outside of protected areas (Figure 4).

Agroforestry systems make up just 24 percent (185,000 ha) of the agricultural systems that replaced forests in Myanmar. This differs from many of the other countries in Southeast Asia where a much larger percentage of land is used for agroforestry systems. In Myanmar, lands that had one been tropical moist deciduous forests or rainforests and were now being used to cultivate herbaceous crops made up for the vast majority of agroforestry lands. This seems to be a missed opportunity in Myanmar, as it is well-known that agroforestry systems capture more carbon than monocultures (Wibawa et al. 2006, among many others), produce more ecosystem services (Jose 2009), and are more productive, providing multiple food and livelihood benefits (Krishnamurthy and Krishnamurhty 2011; Tiwariet al. 2017; Nath 2005).

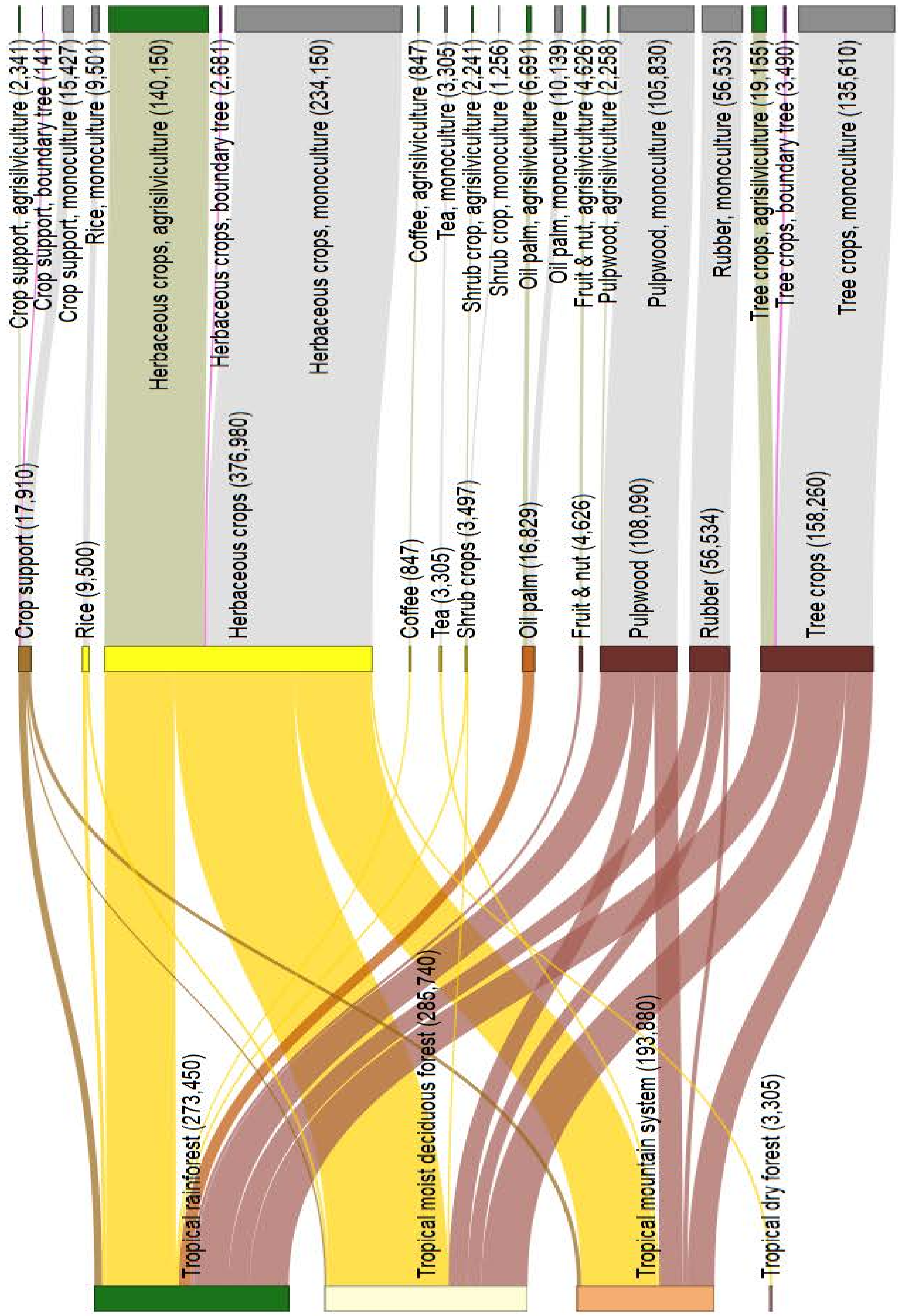
Few to no studies have addressed this relative dearth of agroforestry systems in Myanmar, so it is difficult to speculate why this might be the case. Certainly, agroforesty has long been practiced in some community forests (J.Jadin, personal observation), and this would not have been captured in our study. Additionally, while the concept of agroforesty is not new, planting both herbaceous and woody crops in what were otherwise planned as monoculture plantations is a relatively new concept that has only been gaining traction in the agricultural policy and development world in the past 20 or so years. It is possible that if we investigated the prevalence of agroforesty systems now, we may find their total area to be significantly greater.

Generally we found that deforestation is largely occurring outside of protected forests, although some clearing activity is taking place within protected areas (Figure 3). Herbaceous row crops are commonly grown along the edges of the cropland belt running from the northeast in Oddar Meanchey province to the southwest provinces of Kratie and Tboung Khmum (Figure 4A). Rubber and fruit and nut orchards also are in cultivation along this belt running southeast through the center of the country (Figure 4D). Two additional clusters of rubber plantings occur in the northeast in Ratana Kiri and in the south in Kampong Speu. Oil palm is clustered near the coast in Preah Sihanouk province. These trends appear to align well with previously published descriptions of trends in forest loss, agriculture, and establishment of state-owned rubber plantations (Dararath et al. 2011; Kong et al. 2019).

By itself, the high-resolution imagery that was available did not allow us to identify specific crop types on the vast majority (1.8 million or 90 percent) of the deforested lands. Most (1.2 million ha) of these unidentifiable crops were low growing herbaceous plants other than rice, such as cassava, soybeans and maize (Figure 5), while 602,000 ha were tree crops and 15,000 ha were shrub crops. The tree crops did not match the expected patterns of a monoculture plantation of rubber, coconut, oil palm, banana, or fruit and nut trees. This allows us to infer that these trees could be teak, other trees, or a mix of tree crops. Of the identifiable crops, there were 142,200 ha of forest converted to rubber—less than 1 percent—within the tropical moist deciduous and dry forest ecofloristic zones. There were 40,431 ha of fruit and nut and 13,762 ha of pulpwood tree plantations. There were also small amounts of oil palm (5,477 ha), banana (576 ha), coffee (13,889 ha), tea (11,208 ha) and rice (7,845 ha). Many of the herbaceous and tree crops were interplanted following agroforestry practices. For example, only 3 percent of the broad tree crop group and 32 percent of the broad herbaceous crop group are grown as monocultures.

The general pattern of commodity crops replacing forest roughly aligns with their export value (Table 1 and Figure 5); the largest exception to this is rice, as only 7,845 ha of rice were found on previously forested land. It should be noted that because this study only analyzes the area of a crop that has replaced forest, there may be crops that experienced growth in non-forest

Figure 5: The composition of crop commodities on land that had natural forest cover in the year 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in the year 2000; the middle section represents the crop type in 2015, with the agroforestry system indicated on the right. Area estimates, in hectares (ha), are included adjacent to the label.



lands. Such growth would be reflected in the trade data shown in Table 1, but not reflected in the results of this study. Rubber and tree fruits/nuts both experienced large gains in export value over the study period and this is reflected in the large areas of previously forested lands that was converted to rubber and fruit/nut crops.

CARBON STORAGE IN MYANMAR: IMPACTS AND OPPORTUNITIES

The net carbon emissions resulting from replacing natural forests with crops between 2000 and 2015 totaled almost 78.4 million tonnes (Table 3). Deforestation in the tropical rainforest zone made up for the bulk of this lost carbon: from 2000 to 2015, 42.4 million tonnes of C stored in plant biomass was removed from this ecofloristic zone. Though beyond the scope of this report, such a large areal loss of tropical rainforest no doubt equates to large losses of ecosystem services and biodiversity as well.

Land conversion from natural forests to agricultural lands has significant negative consequences on carbon stocks, even when commodities are grown in agroforestry systems. For example, tropical forests are among the most carbon-rich ecosystems on Earth and on average store 180 tonnes of C/ha (IPCC, 2006). Agriculture systems, by comparison, store only about 5 tonnes C/ha and up to 50 tonnes C/ha if crops are grown in combination with trees (Cardinael et al. 2018; Ruesch and Gibbs 2008). Estimates of carbon stored as AGB in native forests vary by region and by forest condition (Table 3).

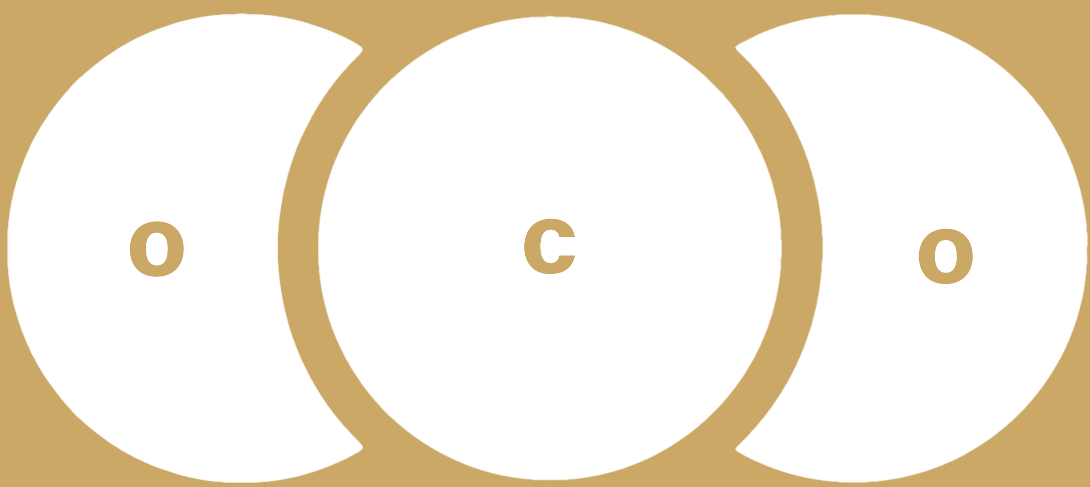
Our findings show that approximately 16.8 million tonnes of carbon are stored in aboveground plant biomass across the 1.2 million ha that were forested in 2000 but are now under cultivation (Table 3). If these areas had remained natural forests, we estimate that 95.2 million tonnes of carbon would be stored in aboveground plant mass on these same lands. This estimate is derived by multiplying the country and commodity specific carbon factors (Table 2) by the area estimates of land converted to agricultural cultivation (Figure 5). In these recently deforested lands, herbaceous crops are the most prevalent crop type; however, they store only a quarter of the total aboveground carbon (more than 4.4 million tonnes) compared to other crops that have replaced forests (Table 2).

Tree crops (e.g. rubber, pulpwood, and non-identifiable tree crops) accounted for only 43 percent of the converted forest area (Figures 2 and 5); however, they store more than 68 percent (11.4 million tonnes) of the total biomass (Table 2). Therefore, if one is concerned with carbon storage, it is evident that planting tree crops is a better option than planting herbaceous crops. Further, with the exception of rice, tree crops (rubber, fruits, nuts, bananas) are the top exports and bring more revenue into the country than all of the herbaceous crops combined. Most aboveground carbon in agricultural landscapes was stored in monoculture tree plantations, including pulpwood (2.49 million tonnes C, 15 percent of the total), rubber (1.80 million tonnes C, 11 percent of the total), and other trees (5.87 million tonnes C, 35 percent of the total). In contrast, identifiable agroforestry systems in Myanmar contained just 27 percent of the total aboveground biomass. Given that agroforesty systems almost always store more aboveground carbon than monocultures (Table 3), there is obviously a great opportunity to improve carbon storage in Myanmar by planting herbaceous crops in monoculture tree plantations, and vice versa. This is shown amply in Table 2, where agroforestry indicates better carbon storage per unit area for the herbaceous, shrub and tree crops. We note that the palm crop contributions are from palm oil crops only, and since their carbon emission factor is the same for either type of agriculture system the overall carbon stored per hectare is the same despite the monoculture-based crops taking up a larger area and thus storing a larger amount of carbon.

Generally, national estimates of agroforestry carbon factors are within the ranges found in recent global meta-analyses of carbon stocks and stock change factors (Feliciano et al. 2018; Cardinael et al. 2019). However, no Myanmar-specific data were available describing carbon stocks for some agroforestry systems. In these cases, this analysis used a conservative approach and assumed that trees are the majority of the biomass in tree crop agroforestry systems; we thus used the same carbon factors for both agroforestry systems and monocultures where trees were the predominant crop. A similarly conservative approach was taken for rice systems, where trees typically occur only as boundary plantings, but can contain non-trivial amounts of carbon (Reppin et al. 2019; Feliciano et al. 2018). Given these assumptions, there is a risk that our results may underestimate some of the carbon in the landscape. These are likely justified given that any underestimation will be relatively small compared to the carbon lost due to natural forest conversion.

As noted above, agroforestry is one approach to increasing carbon storage benefits, and a number of other ecosystem services (Krishnamurthy and Krishnamurhty 2011; Tiwari et al. 2017; Nath 2005; Cardinael

**IN TOTAL,
78.4 MILLION TONNES OF CARBON WERE LOST DUE TO FOREST CONVERSION TO CROPLANDS BETWEEN 2000-2015 IN MYANMAR.**



et al. 2018). Agroforestry systems may, for example, provide more carbon storage than secondary growth forests. Estimates of aboveground carbon stocks for secondary forests in Southeast Asia have been reported to range from 18 tonnes C/ha to 160 tonnes C/ha, depending on age, type of plant cover, and other factors (Sum et al. 2012; Avitabile et al. 2016). Some agroforestry systems therefore may provide more carbon storage than secondary regrowth forests (Table 2) and could be used as a tool to improve landscape carbon storage in secondary forest landscapes. This may also be an opportunity for the country to improve its agro-biodiversity, ecosystem services, and sustainable livelihoods for smallholders. Such systems are, of course, still far less effective stores of carbon than rich, intact primary forest.

Even the most carbon-rich agroforestry systems—fruit and nut orchards—store only roughly 20 percent of the carbon stored in intact natural tropical rainforest systems. Such a large difference in carbon storage values between natural forests and human-altered forest landscapes highlights the importance of preserving natural forest when carbon storage is a national or regional priority. Where conversion to commodities has already occurred, shifting systems toward agroforestry will almost always have a positive impact on carbon storage. Further, though not explicitly discussed in this analysis, turning fallow or degraded lands into productive agricultural systems will also typically have a positive impact on carbon storage in the landscape.

To prevent large carbon emissions from the AFOLU sector, Myanmar must first and foremost preserve existing natural forests. This may prove to be difficult since most of the areas of large, intact forests in Myanmar were not under protected status as of 2017 (Bhagwat et al. 2017). Treue et al. (2016) provide suggestions for protecting the remaining forests in Myanmar. Key among these suggestions is to cancel concessions that do not meet their stated goals. For instance, it has been documented that in many concessions less than 30 percent of the planned crop area was cultivated. Focusing on the recovery of production forests, developing the capacity of the Myanmar Forestry Department, and addressing the long-standing forest land tenure issues that drive conflict between the government and ethnic communities that are other near-term actions that must be taken to preserve Myanmar's forests.

Forestland can also be spared from conversion by focusing on improving the production capacities of

TABLE 3: CHANGES IN ABOVEGROUND BIOMASS (AGB) IN NATURAL FORESTS AND ALTERNATIVE CROPS BY ECOFLORISTIC ZONE (TONNES C/HA)

	average C/ha in AGB	C in forest (2000)	C in crops replacing forest (2015)	C lost due to conversion
TROPICAL RAINFOREST	180	49,221,180	6,818,643	**42,402,537**
TROPICAL MOIST DECIDUOUS FOREST	105	30,002,175	6,028,324	**23,973,851**
TROPICAL DRY FOREST	78	257,790	66,100	**191,690**
TROPICAL MONTANE SYSTEM	81	15,704,442	3,845,588	**11,858,854**
TOTAL		**95,185,587**	**16,758,655**	**78,426,932**

smallholders. Better extension services, investment into quality seed production, and legal support for contract farmers would all improve production and lessen pressure to open up new land for agriculture (Byerlee et al. 2014; Burnley et al. 2017). Improving the production of smallholders generates more sustainable outcomes because it avoids deforestation and large-scale monoculture plantations while generating social benefits that large-scale corporate investments often fail to produce (Kenney-Lazar et al. 2018).

Myanmar has demonstrated a reduction in the export of teak to one fifth of previous volumes, and other hardwoods by a third, by implementing a national timber certification scheme (Chan, 2018). The government is also working to meet the European Union's Forest Law Enforcement, Governance and Trade criteria for a Timber Legality Assurance. However, many opportunities remain for improving Myanmar's timber system. This may include extensive reforestation, a clear and conflict-free land use policy and map, and substantial capacity building for forest monitoring and management (Treue et al. 2016; Chan 2018).

CONCLUSIONS AND RECOMMENDATIONS FOR MYANMAR

We have photo-identified crop types growing on land that used to be forest in Myanmar, and compiled research on carbon emissions lost in the transition from natural forest to agriculture. Overall, our work shows that as much as 75 percent of what the natural forest would have stored (78.6 million tonnes C) has been lost over just a 15-year period in Myanmar. Our analysis is simple, easily replicable, and has provided greater resolution on carbon losses from agriculture conversion than previous attempts because of our use of photo-interpretation, disaggregated crop classes, and Tier 2 localized carbon factors. The information provided by this analysis helps policymakers prioritize investments into landscapes so as to minimize GHG emissions and maximize sustainable land use.

Our research in Myanmar shows that the dominant crop commodities being cultivated in regions that were formerly forested include herbaceous crops and tree commodities, including pulpwood, rubber plantations, and many crops that could not be identified to a specific commodity type beyond plant structural form. Interestingly, our results show that forest cover is not being replaced by crops at rates consistent with their relative economic importance in Myanmar. In economic terms, rice, rubber, fruit and nut trees and banana are the most economically important exports, yet most natural forest was lost due to conversion to herbaceous crops. This result is odd, given that in all other countries studied in this volume, natural forests were being converted to crops in proportion to the trade value of the crops. While we have no definitive explanation for why this is the case, we surmise that it may be due to the relatively recent opening of Myanmar's government and economy. We suspect that for much of our study period (2000-2015) Myanmar's forest conversion was a response to domestic food needs, rather than export priorities. If this study is repeated in another 15 years, we expect that the area of land under cultivation of any given crop will more closely correlate to the export value of that crop.

Agriculture is an important economic engine for developing counties, and it will likely continue to be for decades into the future, especially as expanding populations must be fed. Myanmar historically had relatively little land conversion compared to other countries in Southeast Asia; as the economy continues to open, this will likely change. Explosive expansion of agriculture has potentially severe implications for pledges that Myanmar has made to cut carbon emissions and follow a path to sustainable development. There are, however, ways to reconcile economic and environmental goals and still follow a path to sustainable development. Our review of Myanmar forestry and land use policy and trends suggest both general best practices (discussed in the regional results section) and Myanmar-specific solutions, including:

First, we recommend addressing land tenure conflicts caused by large concession assignments via revision of the VFV Law. The recent changes requiring immediate registration of the land should be repealed, and all future changes should be communicated to impacted communities in their native language. This will lead to a more transparent, fair, and accessible tenure granting process. However, simply repealing the recent amendment is likely not enough because the VFV law has always allowed the government to grant village lands to large (often foreign) investors, robbing people of their traditional lands. Studies have shown that very high deforestation rates are associated with forest policies aimed at maximizing profits in areas with unstable tenure regimes (Brandt et al. 2017; Holland et al. 2016). Further, unclear and unfair land titling practices exacerbate conflicts and in the case of Myanmar could negatively impact the ongoing peace process (Myanmar Times 2019). Plans for dealing with land rights for returning refugees and IDPs should also be incorporated into land titling laws. This would not only mitigate further conflict but would reduce deforestation driven by human displacement (Rosenow-Williams and Behmer 2015; Fureder et al. 2015; Fangama and Bakheet 2018).

Another land tenure issue that could impact deforestation rates falls is the issue of community land rights. As noted elsewhere in this volume, community forestry has shown to be successful in avoiding deforestation and sustainably managing lands (Bastakoti and Davidson 2014; Santika et al. 2017). Because of this, the trend to establish community forests should be accelerated. In Myanmar, communities have established community forest areas even without land rights and have gained a variety of other benefits, including watershed protection, tenure security, coastal protection, and subsistence needs for fuel and medicine (Macqueen, 2015). While this is a regional-level recommendation, we will note that land rights and consultative development practices may be particularly important for Myanmar as it tries to settle numerous internal ethnic disputes.
A final issue around rights is that a centralized public land map and record system that records land titles and uses is essential for a fair and transparent tenure system. The OneMap Myanmar initiative has been working on doing just this, and we recommend continuing to support its expansion and use. An organized and transparent system of land titling, that government officials and community leaders know how to use and access, is one of the keys to promoting democratic land policy, reducing conflict, and sustainably managing lands.

Another general recommendation that has specific relevance in Myanmar is to scale up agroforestry systems. In Myanmar, teak is an especially profitable crop that is already cultivated in some areas, and further development of this crop and its value chain should be explored (Kosaka and Takeda 2017; Banikoi et al. 2019). Sterculia is another good option: Japan and China have recently signed agreements with Myanmar to buy gum stericulia, so the export potential is poised to rise (Myanmar Times, 2019). Sterculia requires low investments from farmers and can be grown in mixed farming systems (Udawatta et al. 2019; Muruts and Birhane 2017). The large concession areas in the north that appear to be growing herbaceous crops are another area that could be targeted with tree plantings.

Finally, deforestation could be addressed through better trade and value chain policies. Better value chain practices and better distribution of wealth along the value chains will reduce pressure to open more areas for timber production and increase the productivity of those areas already opened. Banikoi et al. (2018) investigated the value chains of timber in Myanmar and came out with several recommendations. First, there needs to be more timber processing in country (Dong and He 2018). Currently, most of the high-grade timber is exported and turned into furniture or other products internationally, with Myanmar losing out on these value-added profits. This is particularly true along the Sino-Burmese border, where timber processing plants could be built as part of the “One Belt One Road" initiative to transfer some of the profits from Myanmar’s timber back into the country. Second, the current Myanmar Selection System (MSS) for logging is considered by many to be excellent. It improves the quality of logs going into the value chain and improves growth conditions for saplings. It needs to be more broadly applied. Third, elephants should be used more widely for logging.

The current mechanized system requires roads, heavy equipment and the clearing of vast areas of trees and underbrush in order to bring select logs out, reducing profits for landowners and reducing usable forest area. Elephants are able to do this much more efficiently and with far less disturbance to the environment. The local knowledge and tradition of using elephants is there and should be reinvigorated as a logging tool. Regarding value chains for NTFPs, there is also a huge demand among both communities and forestry officials to develop these; capacity-building programs and networks to access market actors are needed (J. Jadin, personal communication).

Reconciling economic development with sustainable environmental is not easy, especially in countries with rapidly growing populations, or in countries that supply raw materials to large consumers like China. In such places, the pressure to harvest more natural resources from the environment will not abate without government and civic intervention. However, the approaches suggested above can slow land use change without slowing economic growth. Myanmar’s deforestation rate is alarmingly high, and policymakers, development practitioners and citizens invested in Myanmar’s future must act quickly to maximize economic returns from those lands that are already degraded and rehabilitate degraded lands while improving local livelihoods. By rethinking economic growth, involving and educating communities, and engaging in fair and transparent governance, Myanmar, and all of the developing world, will see progress in achieving multiple Sustainable Development Goals concurrently.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PHILIPPINES

KEY MESSAGES

A TOTAL OF 327,000 HECTARES (HA) OF FOREST WERE LOST BETWEEN 2000 AND 2015; APPROXIMATELY 165 THOUSAND HA OF THAT LAND IS NOW SUPPORTING COMMODITY CROPS.

A TOTAL OF 80,000 HA OF LANDS WITH TREE COVER IN 2000 WERE CONVERTED TO HERBACEOUS CROPS BY 2015. FORESTLANDS WERE CONVERTED TO TREE AND PALM CROPS, SUCH AS OIL PALM (9,396 HA), AND OTHER TREE COMMODITIES (28,013 HA) TO A MUCH LESSER EXTENT THAN HERBACEOUS CROPS.

THE CARBON STORED IN THE ABOVEGROUND BIOMASS OF CROPS THAT HAVE REPLACED FORESTED LAND IS **4.2 MILLION TONNES.** IF THESE LANDS WERE STILL FORESTED THEY WOULD STORE 36.4 MILLION TONNES, **A LOSS OF 89 PERCENT OF THE CARBON.**

When the Spanish entered the Philippines in 1521, about 27 million ha (90 percent) of the country was covered with lush tropical rainforest (Lasco et al. 2000). Over the next nearly 400 years, deforestation slowly progressed as the population grew, so that by 1900, two years after the Americans replaced the Spanish, about 70 percent of the country was still forested (Garrity et al. 1993, Liu et al. 1993). The rate of deforestation increased as the first modern logging operations were introduced in 1904 (Roth 1983), and by 1941 forest cover declined to around 57 percent of the land area. Forest cover continued to decline, and a 1988 survey found that only 21.5 percent (6.46 million ha) of the total land was still forested (Bautista 1990).

While deforestation has occurred over a long period of time, reforestation efforts have been long ongoing as well. The first known rehabilitation initiative dates back to 1910 when the country's first Forestry School was established in Luzon (Pulhin et al. 2006). In 1916, the government attempted to begin planting barren lands under Act 264, which aimed to reforest 4,095 ha in Cebu province (Orden 1960). In 1975 the government issued P.D. 705, which called for nationwide reforestation activities that included the private sector (Pulhin et al. 2006). In the early 1980s, the government began numerous people-centered forestry programs, such as the Integrated Social Forestry Program in 1982 and the Community Forestry Program in 1987 (ibid). Numerous other initiatives were started throughout the 1990's and early 2000s.

One of the more recent and ongoing approaches has been the National Greening Program (NGP) (Government of the Philippines 2011). The first iteration of the NGP had the goal of planting 1.5 billion trees on 1.5 million hectares of land by 2016, which it met and exceeded (Israel 2016). The follow-on Expanded NGP (E-NGP) has the goal of rehabilitating the remaining 7.1 million hectares of unproductive and degraded forest lands by 2028 (Government of the Philippines 2015).

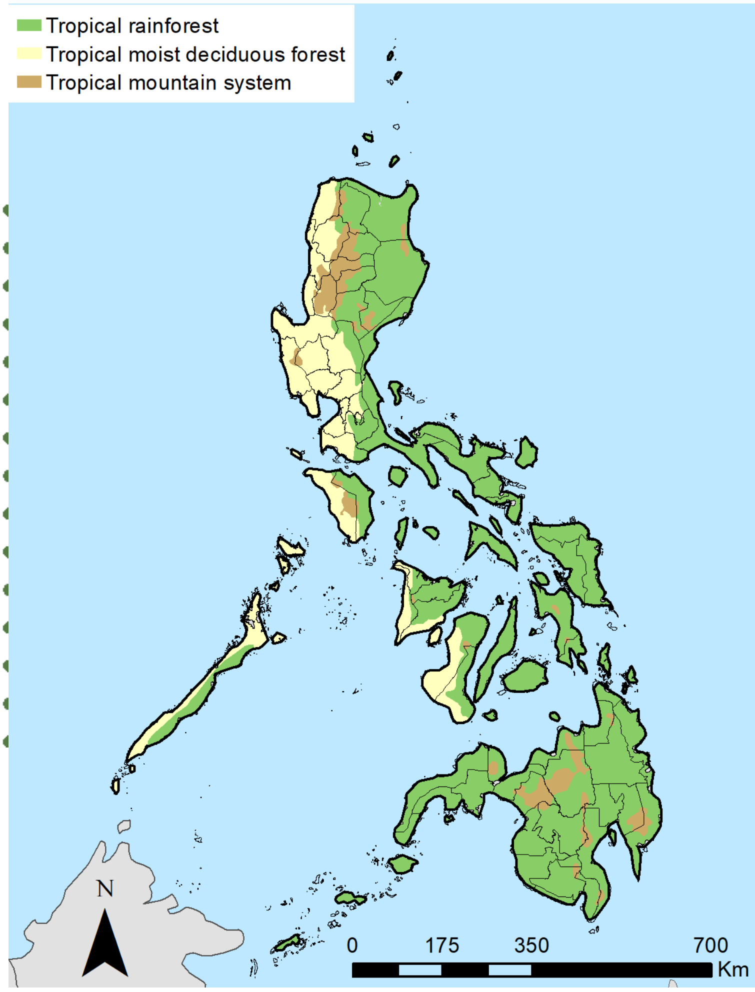


Figure 1: Ecozones of Philippines, from Ruesch and Gibbs, 2008.

Table 1: Volume (in millions of constant 2015 US dollars) of agricultural commodities traded in Philippines in 2000 and 2015 (from www.bea.gov). Values derived from Chatham House, resourcetrade.earth (2018).

Commodity	USD value 2000	USD value 2015	% change
banana	1800.90	736.2	145
coconut	1526.90	799.3	91
tree fruits	215.2	519.3	141
pulpwood	67.9	143.6	111
tobacco	31.1	126.8	308
rubber	28.3	76.5	170
palm oil	6.1	25.1	310
cereals	1.8	19.4	977
cocoa	9.7	9.7	0
rice	0.3	1.5	376
coffee	1	1.2	12
tea	0.1	1	520
tree nuts	0.3	0.8	158

Generally, reforestation efforts have been most successful (in terms of establishment, survival, and positive socio-economic outcomes) when 1) they have used a mixture of species, including introduced species, and 2) where the government directly paid for the project (Le et al. 2014; Le et al. 2015). The country has also established 3.2 million ha of forest reserve and 1.3 million ha of national parks (Forest Management Bureau 2018) in an attempt to protect forests. However, protected forest areas appear to be only marginally better in conserving forest: though there is substantial variation, forest loss rates are only 0.1 percent lower in protected areas than in other types of forest-dominated lands (Apan et al. 2017). This suggests that law enforcement around forest protection is weak in the Philippines, as it is throughout much of the developing world.

Current reforestation and land protection efforts are framed within the ongoing Comprehensive Agrarian Reform Program (CARP). CARP has a goal of distributing 9 million ha of land to roughly 5.8 million landless farmers or farm workers (Vista et al. 2012). Such a large-scale distribution of land has the potential to have serious negative consequences for greenhouse gas emissions in the land use sector if not planned carefully. Presumably farmers will not be given native forests to transform with slash-and-burn rotational farming practices, but they likely will be given lands abutting natural forests. This may lead to further forest degradation if forest protection laws are not fully recognized and enforced under the CARP program.

In a recent attempt to improve forest management, the Government of the Philippines (GoP) has invested in agroforestry practices, particularly in upper watershed areas that are prone to erosion. In such areas, those trees that best protect the soil are planted along with alley crops in a semi-terraced landscape (Lasco et al. 2010). Such a planting regime protects delicate soils against erosion and preserves watershed ecosystem services. Other GoP programs have encouraged intercropping with trees or incorporating livestock into coconut-dominated landscapes (Moog and Faylon 1994; Rodriguez et al. 2007). The GoP is also trying to introduce more agroforestry through its community-based forest management (CBFM) program, which it introduced in 2011. While such approaches to forest management are widely considered to be successful, CBFM in the Philippines has been beset with challenges related to capacity and desire. Communities often have low knowledge about conservation and related government initiatives, and practitioners that support them have insufficient experience managing communities and natural resources (Cagalanan 2015).

A recent analysis used remote sensing to determine the drivers of tree cover loss globally between 2001 and 2015 (Curtis et al. 2018). The analysis showed that for Southeast Asia as a whole, 61 percent (± 13 percent) of the land with natural tree cover was converted for commodity crops, 20 percent (± 10 percent) was cleared for rotational agriculture, 14 percent (± 6 percent) was converted to rotational plantation forestry, and less than 3 percent was lost due to wildfire and urbanization.
In the Philippines, the pattern was different: shifting agriculture (slash-and-burn) was the biggest driver, accounting for 52 percent of forest loss. This loss was notably concentrated in the Mindanao Islands and Palawan, where such concentrated loss diminishes habitat connectivity and the capacity of landscapes to deliver ecosystem services.

Multiple studies have documented increases in exports of commodity crops that correlate with increases in deforestation and forest degradation across Southeast Asia (Leblois et al. 2017; Curtis et al. 2018; Hurni and Fox 2018; Taubert et al. 2018). Generally, this increase in deforestation has been linked to large-scale agro-industrial operations. However, the Philippines again deviates from the Southeast Asian norm: 92 percent of the increase in forest loss in the Philippines after 2000 appears to be due to smaller clearing events (Austin et al. 2017).

Deforestation not only leads to biodiversity, ecosystem service and habitat loss, it is also a major source of carbon emissions. This is a concern for countries like the Philippines that are trying to find paths to low-emission development and minimize their vulnerability to climate change. Recent estimates have found that global carbon emissions due to deforestation are about 4.8 billion tonnes per year (WRI 2018). Two recent studies that estimated carbon emissions from all land use change in Southeast Asia (the bulk of which is deforestation) found that anywhere from 1.75 – 6.6 million tonnes carbon per year were released in the period from 1980-2013 (Tian et al. 2016; Cervarich et al. 2016). Estimates for all of Asia suggest that 67 percent of these carbon emissions have been due to clearance for commodity crops (Carter et al. 2018).

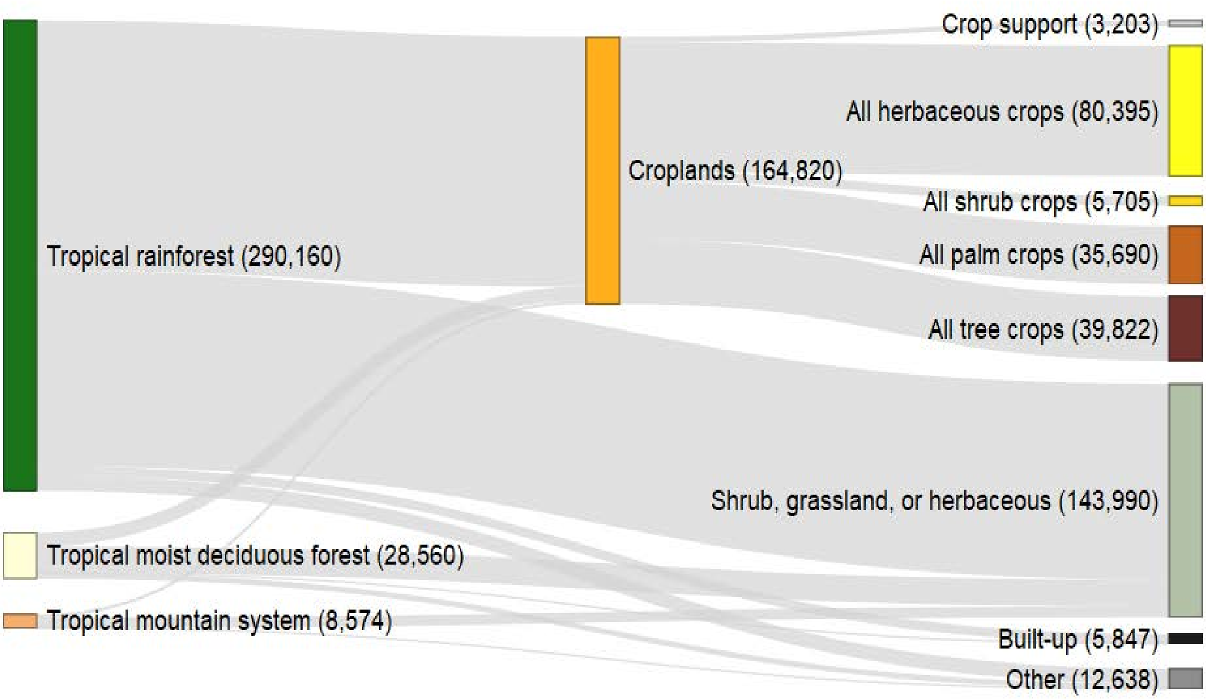


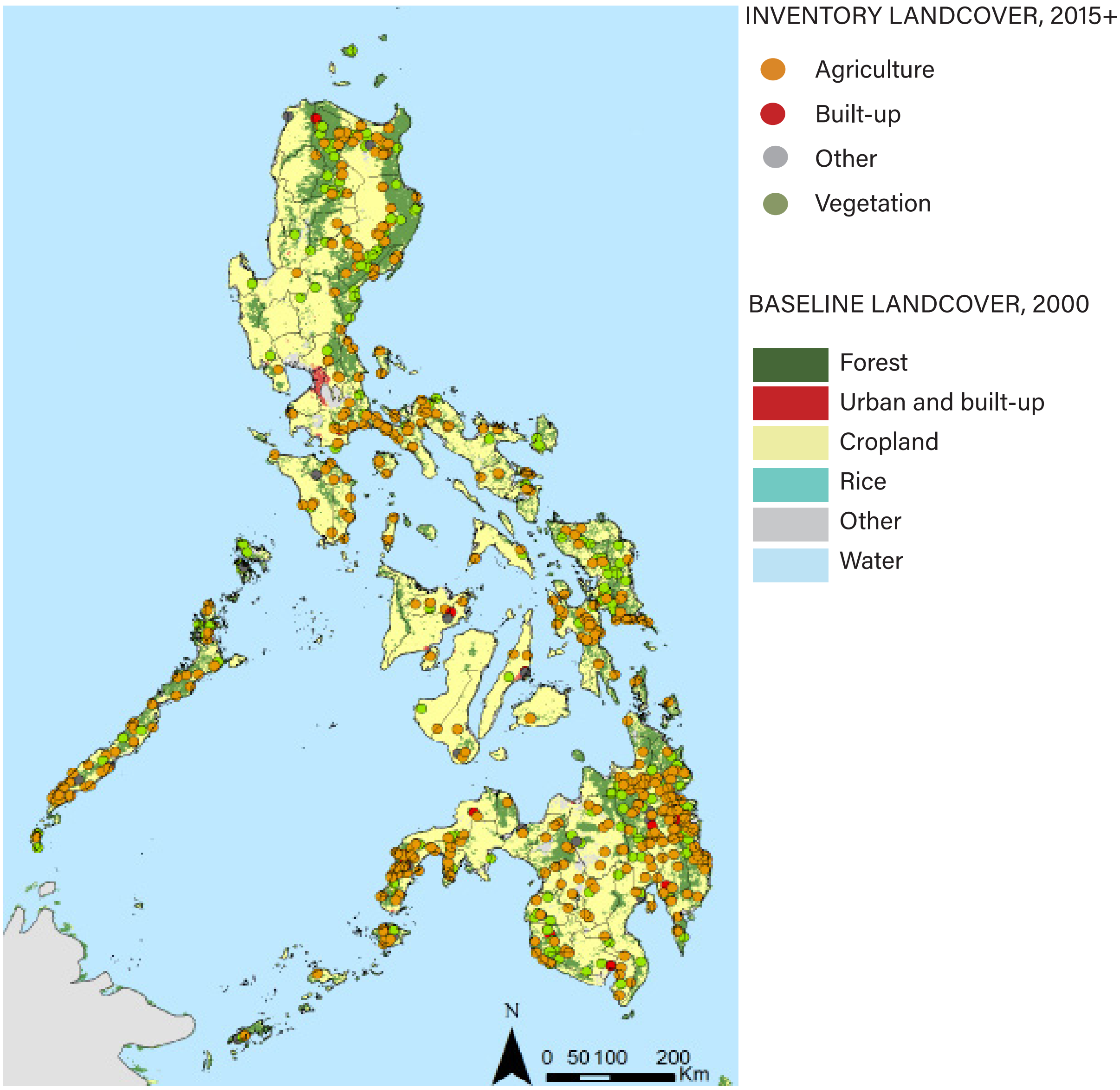
Figure 2: Composition of land use and crops in lands that underwent forest loss since 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in 2000, while the right side represents the land cover after 2015. The total area of all crops is represented by the croplands bar in the middle. Area estimates (ha) are adjacent to the labels.

AGRICULTURAL DEVELOPMENT TRENDS IN THE PHILIPPINES

Table 1 shows the commodity crops analyzed in this study, and how exports of most of these crops substantially increased between 2000 and 2015. The commodities investigated in this study were selected based on their economic importance, area of cultivation, potential role in driving forest conversion, and the ability to be identified via photo-interpretation. This last factor is especially important to keep in mind because herbaceous crops are difficult to identify with photo-interpretation in available remote sensing imagery. Land conversion for herbaceous crops may, however, have been an important driver of deforestation, and therefore, the impact of such conversion may be underestimated in this study.

Exports of most economically important commodity crops from the Philippines more than doubled between 2000 and 2015; the only exception was coconut, which only grew by 91 percent (Table 1). Exports of rubber, the sixth most economically important commodity crop, grew by 170 percent over the same period (Table 1). The numbers in Table 1 provide information on the growth in exports by commodity; however, there is no associated measure of the amount of land that transitioned to cultivation in support of these commodities. Other studies document rubber plantations as a major driver of forest conversion in Southeast Asia (Blagodatsky et

Figure 3: Spatial distribution of plots in the sample that have been deforested over the study period, overlaid on a land cover map from 2000 (Saah et al. 2020).



al. 2016). These plantations have a high carbon sequestration potential (Corpuz et al. 2014), so the conversion of degraded forest lands to rubber plantations can increase carbon sequestration compared to clearing and growing herbaceous crops. However, their carbon storage potential is surpassed by that of native forests, and therefore the carbon impacts are mixed if forested lands are cleared (Blagodatsky et al. 2016).

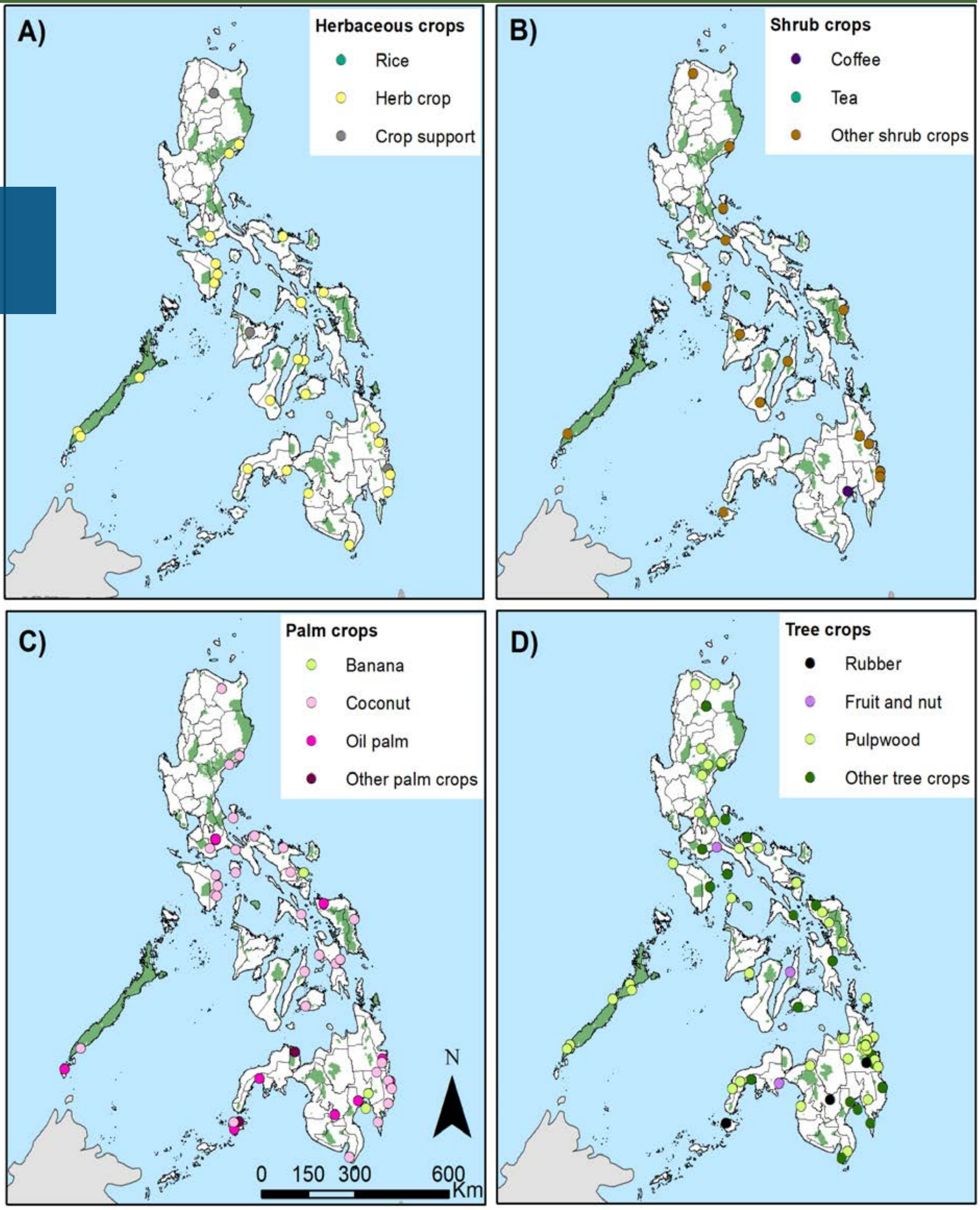
Oil palm is the 7th most economically important commodity crop in the Philippines. The rate of oil palm expansion has more than tripled in the Philippines since 2000. This rate is similar or higher than the rest of Southeast Asia, which has on average expanded at a rate of 125 percent (Vijay et al. 2016) between 2003-2013. More importantly, experts suggest that because most of the land in Southeast Asia that can grow oil palm already is, future regional expansion may target the Philippines (Colchester et al. 2011).

TREE CANOPY COVER LOSS IN PHILIPPINES

The area of forest and woodland in 2000 was estimated to total 13.7 million ha—7 million ha and 6.7 million ha, respectively (FAO 2015, Table 1A). To better understand how definitions and methods may impact this baseline estimate, we compare these values with other baseline estimates. The Forest Management Bureau (FMB) estimated that in 1997 forests covered an area of 5.39 million ha, and 7.17 million ha in 2003 (FMB 2000, 2009, 2013, and 2015). The variation in the estimates of total forested area for 2000 are partially attributed to differences in the operational definition of forest between reporting agencies and, to some extent, measurement uncertainties (Keenan et al. 2015, Tropek et al. 2014). For example, Estoque et al. (2018) compared the results of eight different forest cover mapping efforts in the Philippines with the estimates obtained from analyzing a 10,000-point reference data set for 2010. They found that while the government estimate for that year (6.84 million ha) was lower than the forest cover estimates from the reference data set (11.07 million ha), most of the other mapping efforts found values closer to the FMB estimates than the reference data set.

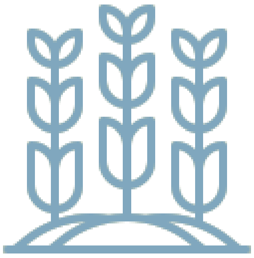
We estimate that from 2000 to 2015 the islands making up the Philippines archipelago experienced a total forest loss of approximately 327,000 ha (Figure 2). To get an estimate of the percent of forest loss, we can com-

Figure 4: Spatial distribution of crop types at plots within the sample where deforestation events were followed with crop cultivation (depicted by orange dots in Figure 4) overlaid on top of the road network. Dark green areas are protected forest boundaries; light green indicates other protected areas such as national parks and wildlife sanctuaries (ODC 2020).



pare this to the estimates of forest cover in 2000 from the global forest resource assessment. This represents a loss of 2 percent of the forest and woodland areas from 2000 (FAO 2015). However, while this comparison of loss to the global forest resource assessment (FRA) baseline estimate provides some context, caution needs to be taken when interpreting the percent loss estimates since the studies have different definitions of forestland. To some extent our definition aligns with the combined forest and woodland estimate from FAO

TABLE 2: ABOVEGROUND BIOMASS CARBON STOCKS

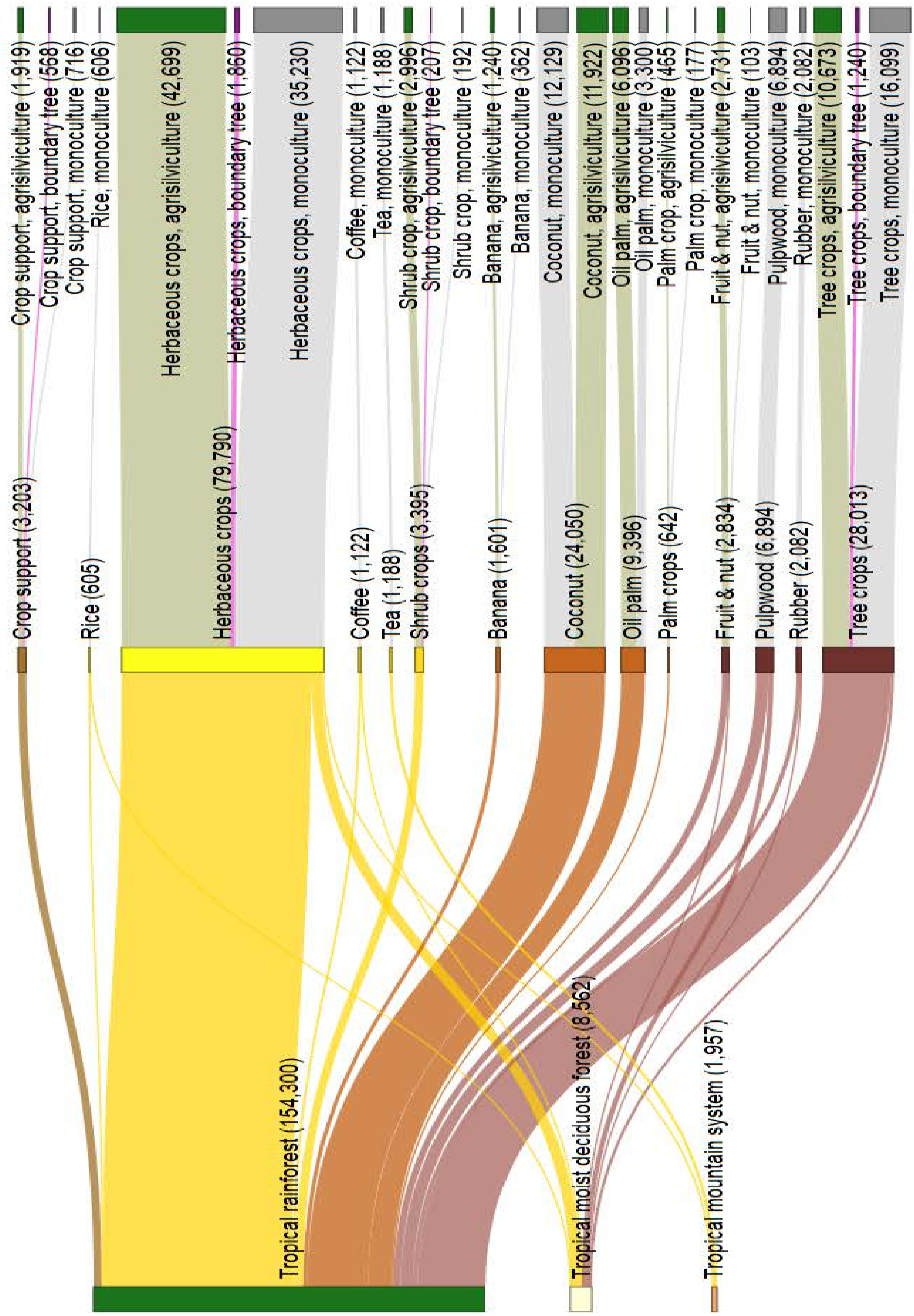


commodity	monoculture averaged (tonnes C/ha)	monoculture in Philippines (tonnes C)	agroforestry averaged	agroforestry in Philippines	total in Philippines
banana	5.7	2,063	5.7	7,068	9,131
coffee	5.4	6,059	NA	NA	6,059
fruit and nut	43.8	4,511	44.3	120,983	125,494
oil palm	39	128,700	39	237,744	366,444
pulpwood	23	158,562	NA	NA	158,562
rubber	107.3	223,399	NA	NA	223,399
rice	3.1	1,876	NA	NA	1,876
tea	15.5	18,414	NA	NA	18,414
coconut	24.1	292,309	30.8	367,198	659,507
palm crops	22.9	4,053	28.7	13,346	17,399
other herb crops	5.1	179,673	20	891,180	1,070,853
other tree crops	49.5	796,950	49.7	592,076	1,389,026
other shrub crops	10.5	2,016	16.5	52,850	54,866
crop support	6.5	4,654	20	49,740	54,394
TOTAL		**1,823,239**		**2,332,185**	**4,155,424**

	monoculture total tonnes C	agroforestry total tonnes C	total in Philippines
herb crops	181,549	891,180	1,072,729
shrub crops	26,489	52,850	79,339
palm crops	427,125	625,356	1,052,481
tree crops	1,183,422	713,059	1,896,481
crop support	4,654	49,740	54,394
TOTAL	**1,823,239**	**2,332,185**	**4,155,424**

Top: Aboveground time-averaged biomass carbon factors of commodity crops. Values for commodities were compiled from peer-reviewed and grey literature. Time-averaged values are used to estimate the carbon storage of rotational commodity crops because they average the carbon in freshly replanted and mature commodities. These values are then used to calculate aboveground biomass carbon contained in the total area of commodities in Philippines. Calculations are restricted to those commodities in areas that lost natural canopy cover between 2000-2015. **Bottom**: total area of crops, grouped by life form, and total carbon contained in crops by life form.

Figure 5: The composition of crop commodities on land that had natural forest cover in the year 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in the year 2000; the middle section represents the crop type in 2015, with the agroforestry system indicated on the right. Area estimates, in hectares (ha), are included adjacent to the label.



(2015): forest is any half ha patch (or greater) with trees higher than 5 meters and a canopy cover of more than 10 percent that is not in predominantly agricultural or urban land use. Woodland is nearly the same but the canopy cover is from 5 to 10 percent or has a combined cover of shrubs, bushes and trees above 10 percent (ibid). However, these do include rubber and other tree plantations, so it is not a direct comparison with definitions used in this study, while our definition of forest cover excluded canopy cover and forest patch size thresholds.

Tree cover is distributed across three different tropical ecozones: rainforest, moist deciduous forest, and mountain systems (Figure 1). The tropical rainforest zone had by far the highest baseline area, and therefore unsurprisingly lost the greatest total area of land to agricultural conversion (nearly 290,000 ha, or 89 percent). Just over 28,000 acres of moist deciduous forests were lost; while the small tropical mountain zone experienced just 8,600 ha of loss. Most of the forest loss occurred along the eastern coastal areas of the Philippines, except in Palawan and Mindanao, where forest losses were more spatially distributed across the lowlands (Figure 2). This finding and the geographic pattern was similar to the results found in Curtis et al. (2018).

Our results showed that as of 2015 or later, crops were being cultivated across 165,000 ha of land that were previously natural forests, 50 percent of the total forest clearing activities (Figure 2). Conversion to shrublands and grasslands accounted for 44 percent of the natural forest loss, 144,000 ha. This vegetation includes shrubland, grasslands, and herbaceous cover. Figure 2 shows the amount of forest loss between 2000 and 2015, along with the type of land use or cover that has resulted from the forest conversion. Most of the observations are occurring at the interface of forests and agricultural land along the eastern edge of the Philippines (Figure 4).

There may have been different initial or additional drivers of deforestation and land uses in between the current state and 2000 that are not presented in these results. For example, in southeast Asia, deforestation is often initially driven by selective logging, and then the land is subsequently converted to agriculture (Saunders et al. 2014). Because we have assessed land cover at just two time points in time, not the full time series of Landsat images, the results do not represent the potential intermediary land covers and uses or proximate drivers of deforestation.

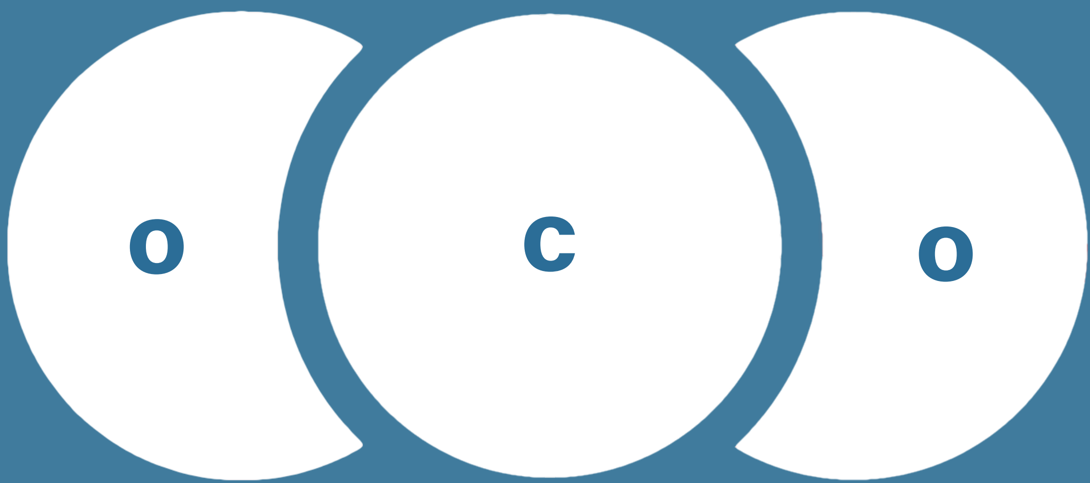
Herbaceous crops that are unidentifiable from high resolution imagery without additional field work, such as grains, sugarcane, and cassava, predominated (Figure 2 and 4A). These crops were grown on 48 percent of the area of cleared forests (79,790 ha) and were more evenly distributed between agroforestry systems and non-agroforestry systems. However, coconut and oil palm plantations also occupied significant areas and were widely distributed (Figure 3 and 4C). Coconut plantations were the most prevalent identifiable crop type, covering 24,050 ha (Figure 3), comprising 15 percent of the forest area converted to crops during this period. Approximately 50 percent (11,922 ha) of the new coconut plantations are grown as agroforestry systems. Coconut expansion appears to be mainly associated with coastal areas (Figure 4C), while herbaceous crops occur across much of the landscape (Figure 4A).
Oil palm plantations occupied 9,396 ha (6 percent) of the converted land. Tree crops occupied 28,013 ha of previously forested land (17 percent of the total). Figure 5 indicates that the bulk of the natural forest to tree crop conversions occurred in the tropical rainforest zone, while forest conversions in the tropical mountain zone were almost exclusively for herbaceous crops. Other crops amounted to less than 1 percent of the converted forest area. Rubber production and pulpwood was more scattered geographically (Figure 4D).

CARBON STORAGE IN PHILIPPINES: IMPACTS AND OPPORTUNITIES

Tropical rainforests store large amounts of carbon in their aboveground and belowground biomass. This carbon, along with soil carbon, is released after forests and soil are cleared or disturbed. Carbon storage potential in future years is also eliminated when trees are removed, making the area where forests once stood poor carbon sinks for years to come. In this regard, we found that from agricultural land use, from 36.4 million tonnes C in 2000 to 2015, only 4.16 million tonnes C were retained in crops which indicates a loss of 89 percent. Most losses in carbon occurred from the conversion from tropical rainforest, in which 31 million tonnes C was lost (Table 4).

The impact of deforestation from agriculture on carbon emissions depends on how the replacement land is used. It is generally accepted that tree crops have much more carbon storage potential than herbaceous crops, but even their storage potential is low compared to native forest. Herbaceous crops on their own have relatively very low storage potential: on average, biomass in standing tropical rainforests store 180 metric tonnes of

IN TOTAL,
32.2 MILLION TONNES OF CARBON WERE LOST DUE TO FOREST CONVERSION TO CROPLANDS BETWEEN 2000-2015 IN PHILIPPINES.



carbon per ha (C/ha), whereas most herbaceous crops store only about 5 tonnes C/ha (IPCC, 2006). Those grown in systems with trees can store up to 50 tonnes C/ha (Cardinael et al. 2018; Ruesch and Gibbs 2008). Estimates of carbon stored in AGB in natural forests vary by region, forest condition and risks. Aboveground carbon storage potentials of crops are shown in Table 2. The total carbon is underestimated because of our focus on aboveground carbon stock, due to the paucity of studies that report on belowground carbon pools.

On recently deforested lands, the total aboveground carbon storage in 2015 was largest for tree crops, at 1.39 million tonnes C. The next largest amount of total carbon storage was from trees grown in association with herbaceous crops, followed by palm crops (Table 2, lower).

Agroforestry generally stores substantially greater amounts of carbon than monoculture cropping, and this is shown across all crop types in Table 2. For example, coffee monoculture stores 5.4 tonnes C/ha in aboveground biomass while agroforestry production systems for coffee can store 8 times that amount (41.3 tonnes C/ha). Rubber tree plantations can store nearly as much aboveground carbon as natural highland forests (Table 2; Corpuz et al. 2014), but still store far less carbon than intact primary rainforest. In the Philippines, many of the crops that have replaced natural forests were being managed in monocultures (see Figure 2 and total row in Table 2), rather than agroforestry systems. We believe agroforestry systems have the potential to be large carbon stores in the Philippines (Brakas and Aune 2011).

National estimates of agroforestry carbon factors used in this study were within the ranges found in recent global meta-analyses of carbon stocks and flow changes (Kim et al. 2016; Feliciano et al. 2018; Cardinael et al. 2019). However, country-specific data were not available on carbon stocks in some types of agroforestry systems. Therefore, this analysis adopted the conservative assumption that tree crops accounted for the majority of the aboveground biomass in these agroforestry systems and used the carbon storage factors for monocultures when calculating aboveground biomass in agroforestry systems without other estimates. Such an assumption undoubtedly underestimates carbon storage in the landscape. One striking example is in rice production systems, where trees typically occur only as boundary plantings. These are believed to contain non-trivial amounts of carbon, but were not counted as carbon stores in our analysis (Feliciano et al. 2018). Further, we did not differentiate

TABLE 3: CHANGES IN ABOVEGROUND BIOMASS (AGB) IN NATURAL FORESTS AND ALTERNATIVE CROPS BY ECOFLORISTIC ZONE (TONNES C/HA)

	average C/ha in AGB	C in forest (2000)	C in crops replacing forest (2015)	C lost due to conversion
TROPICAL RAINFOREST	225	34,716,825	3,908,664	**30,808,161**
TROPICAL MOIST DECIDUOUS FOREST	169	1,446,978	224,423	**1,222,555**
TROPICAL MONTANE SYSTEM	122	238,754	22,336	**216,418**
TOTAL		**36,402,557**	**4,155,423**	**32,247,134**

between flooded paddy rice and upland rice. However, having this additional level of detail would allow us to quantify estimates of methane from paddy rice cultivation and assess deforestation of mangroves. Further analysis linking could be undertaken to differentiate the rice regions by type. However, the amount of rice being grown in areas that underwent forest loss is quite small, just 585 ha.

Fruit and nut tree orchards typically contain far less carbon than natural forests because the density of trees is much lower and other vegetation is removed. Although fruit or nut orchards store more carbon than herbaceous crops, they only have 20 percent of the average aboveground carbon of a tropical rainforest (Table 2). When deforestation for agriculture has already occurred, a shift to orchards or other agroforestry systems will have more positive impacts on carbon stocks, but will not compensate for the carbon already lost.

There may be opportunities for scaling up integration of rubber trees in rotational agriculture systems in the uplands of Palawan, where indigenous farmers have already demonstrated some willingness to plant rubber trees in fallow areas (Montefrio 2016). These same farmers have shown resistance to oil palm planting, possibly because of the more centralized governance associated with oil palm production. Such governance clashes with the diverse and flexible approach to earning incomes and producing crops that these farmers tend to embrace (Josol and Montefrio 2013). Given this, we believe approaches that fit flexibly into existing, varied farming and forest systems are more likely to be adopted by upland populations in the Philippines (Dressler et al. 2016).

CONCLUSIONS AND RECOMMENDATIONS FOR PHILIPPINES

We have photo-identified crop types growing on land that used to be forest in the Philippines, and compiled research on carbon emissions lost in the transition from natural forest to agriculture. From about 36.4 million tonnes C in aboveground biomass from cleared forestland, only 4.16 million tonnes C were retained as crops in 2015. Our analysis is simple, easily replicable, and has provided greater resolution on carbon losses from agriculture conversion than previous attempts because of our use of photo-interpretation, disaggregated crop classes, and Tier 2 localized carbon factors.

The visual trends we uncovered of crop-driven deforestation (Figure 2) align well with the respective growth in economic importance of each crop in the Philippines (Table 1). This result of deforestation being associated with agricultural crop expansion is consistent with other findings throughout Southeast Asia, the Amazon, and parts of Africa. Agriculture is an important economic engine for these regions, and it will likely continue to be for decades into the future, especially as continually expanding populations must also be fed. Such explosive expansion of agriculture has potentially severe implications for pledges the Philippines, and similar countries, have made to cut carbon emissions and follow a path to sustainable development.

There are, however, ways to reconcile economic and environmental goals. Globally, scientists and development practitioners have outlined a number of policy and programmatic options for tropical countries aiming to rehabilitate degraded forest lands. These include introducing agroforestry into monoculture systems; focusing restoration efforts first on degraded or fallow lands; focusing also on lands far from transportation hubs; providing technical and financial assistance to farmers to increase intensity of farming on existing lands; decreasing food waste through better transport and cold chains; advocating for policy change that values ecosystem services; addressing tenure issues so that forest communities have rights to use their lands sustainably; and begin all programming with a thorough social evaluation so that indigenous and women's knowledge is captured, and interventions do not exacerbate existing social inequalities or cause social conflict.

A literature review also suggests a number of possible solutions to the GDP growth vs. ecosystem service/biodiversity dilemma specific for the Philippines. One is to add livestock selectively into cropped land. Integrated crop-livestock systems are believed to maximize greenhouse gas storage potential and minimize emissions in aboveground biomass and soil (Lemaire et al. 2015). Such systems also reduce erosion, improve soil nutrient cycling, and intensify land use, improving profits (Gupta et al. 2012). This is in part due to a reduction in need for fertilizers (Cecelio 2001). In the Philippines, livestock could be incorporated into many tree landscapes, but might work best initially in coconut landscapes, since they offer the most hospitable ground cover and space for ruminants. There has been a rapidly increasing Chinese demand for goat and goat-milk products (Chemlinked 2018; Miller and Lu 2019); goats may therefore be a good option, as might fish ponds (Cecelio 2001). Before any investments are planned, a market analysis of livestock, livestock products and trade routes could help pinpoint which livestock Filipino farmers should invest in.

Another way to increase carbon storage in the landscape more quickly is to target E-NGP activities to "rehabilitate all the remaining unproductive, denuded and degraded forestlands estimated at 7.1 million hectares from 2016 to 2028," first to those areas where success is most likely. First and foremost, these would be areas where communities are already using forests successfully and sustainably, and thus have formed habits which will be conducive to reforestation. Also, as discussed later in the regional results section, areas far away from existing transport hubs should be avoided for agricultural activities. This is because the long transport distance generates extra GHGs and cuts into the farmers' profits. These areas should also be the first ones the E-NGP try to address.

As noted above, rubber has a high carbon storage capacity and it is in high demand globally. Regionally, rubber should be integrated into monoculture herbaceous cropping systems, and agroforestry with rubber can be used to replant degraded lands where natural reforestation will not work. In the Philippines, rubber should be integrated into upland rotational agriculture systems. This may help balance interests between the E-NGP and other programs (such as CARP) intended to generate growth and improve livelihoods of farmers. Farmers in Palawan have already expressed interest in planting rubber in fallow areas, so piloting such work there, and later expanding once success has been demonstrated, might be the most useful approach.

Finally, agriculture value chains in the Philippines must be improved (Andriesse 2018). The Philippines has been singled out as being unique in Southeast Asia for how little agriculture (and fishing) have been able to reduce poverty. Andriesse (2018) shows that while the absolute number of people engaged in agriculture has gone up markedly since 1997, the share of agriculture in the GDP has consistently decreased. The reason for this is that compared to the rest of the region, the Philippines have been poor at linking upstream (trades and exporters) and downstream (growers) market actors. The result is that financial returns do not trickle down to farmers. Growers need to be fully integrated into value chains, they need to self-identify what they would like to grow, and they need to be given access to sustainable finance that can support growing improvements. Andriesse (2018) notes that despite slight improvements in land ownership due to CARP, agriculture is still not alleviating poverty in the Philippines because of poor technical approaches, little finance, and the exclusion of poor farmers from well-functioning and equitable value chains.

In most ways, the Philippines is not unique among developing economies: it is spatially and culturally heterogeneous, it has a rapidly growing population and much of the population lives below the poverty line. Any homogenous approach that attempts to simultaneously achieve multiple environmental goals is unlikely to be effective, as will any approach which does not address the challenge of population growth and income disparity. Also, like most of the world, the Philippines faces major water-related difficulties (Rola et al. 2015), which are exacerbated by incohesive water governance plans, and must be addressed during an environmental intervention. The Philippines is unique in that it has a very high level of deforestation, which appears to be contributing to growing poverty, growing out-migration and growing social conflict. Reforesting lands and finding ways to sustainably value them will undoubtedly bring about economic and environmental improvements. However, the key to making sure these interventions are successful in the Philippines—and everywhere—is to ensure whole communities, including women and other disadvantaged groups, are fully aware of and participating in development processes and have the chance to self-determine their own futures.


SAN ANTONIO
SPURS
OVERALLS
86
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THAILAND

KEY MESSAGES

A TOTAL OF 896,000 HECTARES (HA) OF FOREST WERE LOST BETWEEN 2000 AND 2015; APPROXIMATELY 650,000 HA (73 PERCENT) OF THAT LAND NOW SUPPORTS THE PRODUCTION OF COMMODITY CROPS.

392,000 HA OF LAND WITH TREE COVER WERE CONVERTED TO TREE CROPS, WHICH IS 60 PERCENT OF THE FOREST AREA LOST TO AGRICULTURAL CULTIVATION. PREDOMINANT TREE CROPS INCLUDED PULPWOOD, RUBBER, AND OIL PALM.

THE TOTAL CARBON STORED IN THE ABOVEGROUND BIOMASS OF CROPS REPLACING FORESTED LAND IS 17.2 MILLION TONNES C. **DEFORESTATION CAUSED A 82 PERCENT REDUCTION OF THE CARBON STORED IN THE LANDSCAPE.**

Nearly every country on Earth has exploited its natural resources for economic gain. For the now industrialized countries, this happened over a century ago; but for the developing world, this process didn't start until after WWII and in most cases is still very much ongoing. This exploitation is particularly true for forests: as of 2002, only 20 percent of the world's forest remained (World Rainforest Movement 2002). Thailand has been no exception to this rule. Deforestation in the once abundantly forested country began in earnest in 1855 when the Treaty of Friendship and Commerce was signed with Britain, opening up Siam (much of which later became the Kingdom of Thailand) for commercial business with the West (Akira 1989). The country had become the main rice exporter of the world, and the government cleared forests and expanded canals so they could continue meeting market demand. Logging concessions and teak plantations also expanded rapidly in the 1880s, causing widespread deforestation in northern Thailand (Akira 1989).

Beginning in 1964, the Thai government worked to reverse this trend by issuing the National Reserved Forests Act, BE 2057, which was a policy issued by the Royal Forest Department (RFD) and intended to survey and gradually set aside more protected forest areas. Forest area grew, but competing interests, including export of herbaceous cash crops, like corn and jute, led to a reversal in the positive trend. That was until 1985, when the government forest policy was re-examined

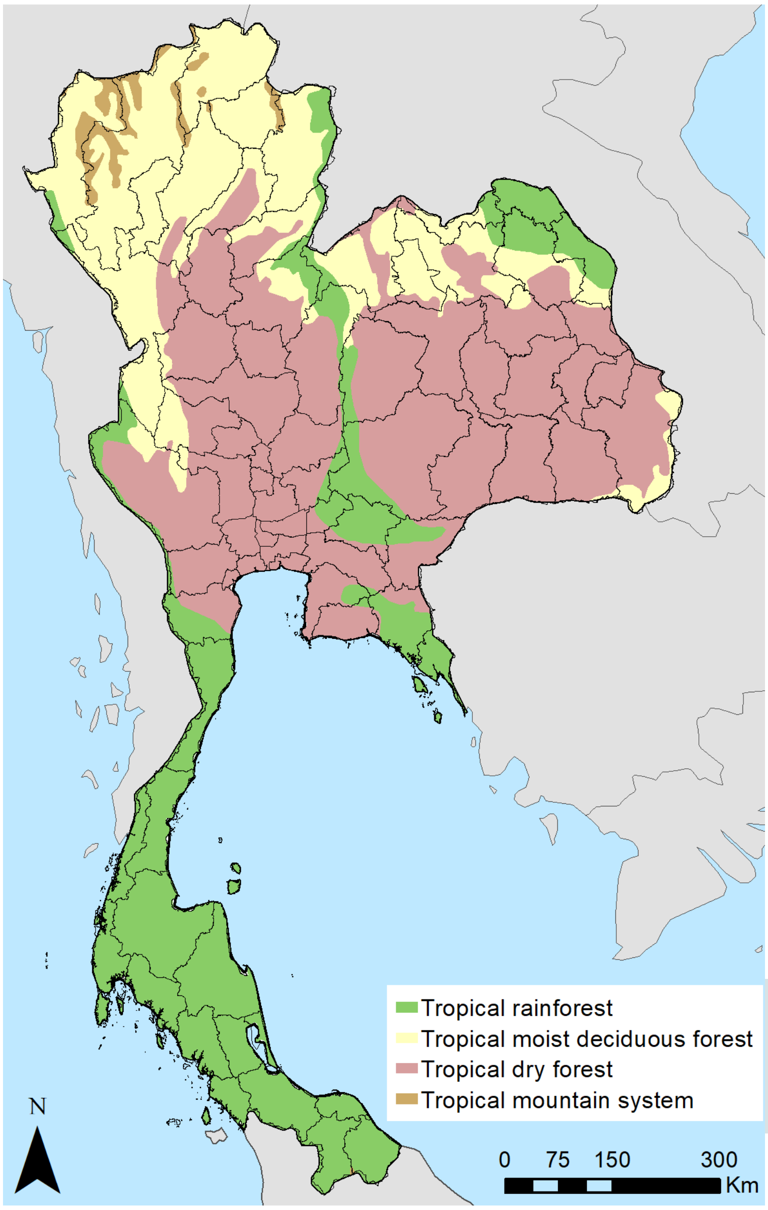


Figure 1: Ecozones in Thailand, from Reusch and Gibbs, 2008.

Table 1: Volume (in millions of constant 2015 US dollars) of agricultural commodities traded in Thailand in 2000 and 2015 (from www.bea.gov). Values derived from Chatham House, resourcetrade.earth (2018).

Commodity	USD value 2000	USD value 2015	% change
rubber	2,662.40	5,320.70	100
rice	2,277.40	4,434.10	95
tree fruits	486.1	2,036.80	319
pulpwood	304.7	511	68
cereals	46.8	281.80	503
coconut	11.8	136.4	1060
palm oil	41.1	101.5	147
cocoa	18.6	78.8	324
tobacco	103.9	66.2	-36
tree nuts	23.9	38.4	60
banana	6.3	32.4	416
tea	1.4	8.65	493
coffee	67.6	7.9	-88

and the Cabinet committed to retain 40 percent of forested areas (25 percent for economic uses and 15 percent for forest conservation) (Samukketham 2015).

Since then, while deforestation has not stopped, reforestation has progressed, and the overall forest cover has increased, making Thailand unique among countries in Southeast Asia (WRI 2019). While an increase is certain, there are some differences in published estimates about the extent of that increase. This is likely due to different methods and definitions of forest cover—such as classifying rubber as a crop or forest (Leblond et al. 2014). For examples of the range of estimates: Thai Government statistics report 12.9 million hectares in 1998, 16.7 million ha in 2004, and 17.1 million in 2008 (RFD 2019); FAO (2015) reports approximately 14 million ha in 1990, 17 million in 2000, 16.1 million 2005, and 16.2 million in 2010. Another investigation and meta-analysis of past forest cover estimation methodologies place Thailand's forest cover at around 17 million ha (33 percent) as of 2009 (Leblond et al. 2014).
Forest cover increase in Thailand is thought to be driven by the rapid regeneration of upland fields formerly cleared for shifting (slash-and-burn) agriculture throughout the northern uplands. The Thai government, like many other regional governments, have been criminalizing or discouraging such traditional agriculture practices, which has resulted in increased forest cover, though with mixed social and environmental costs. Upland hill tribes have instead been encouraged to abandon these traditional farming practices and adopt permanent agriculture, commonly in the form of agroforestry systems (Sato 2000; Fukushima et al. 2008; Pibumrung et al. 2008). The government has also instituted policies to create large protected areas such as national parks, and restrict forest clearing within these areas (Fukushima et al. 2008), both of which have also led to reforestation.

A remote sensing-based assessment of causes of tree cover loss identified that in Thailand loss was driven by commodity crop expansion, rotational plantation forestry, and shifting agriculture (Curtis et al. 2018). Because the creation of new upland shifting agricultural areas essentially ceased, and large areas of the north were already long being used for rotational crops, much of the recent agriculturally driven deforestation has taken place in the south (Leblond and Pham 2014). There was also significant loss of mangrove forests from 1970s to 2009 (WWF 2013). Although new conversion of mangroves for shrimp ponds may have ceased or slowed, land use and tenure policies have largely prevented restoration, with relatively few exceptions (WWF 2013). Converting these southern lowland forests to commodity crops has resulted in a significant loss of biodiversity in addition to carbon emissions (Aratrakorn et al. 2006).

The purpose of our study was to understand the dynamics between forest loss and commodity crop expansion, and to estimate the carbon losses and gains in aboveground biomass as a result of these dynamics. This research builds on previously published global or national studies by disaggregating commodity crop-driven deforestation based on crop types. It also uses land use and location-specific carbon estimates. Together, these two approaches improve the accuracy of results as compared to other studies which do not use such discrete data. Finally, the research provides an analysis at national and local scales, which can help policy makers identify location-specific issues.

With such tailored information, the government can set priorities for natural resource use, supply chain actors can estimate commodity-driven deforestation risk, and development practitioners can understand where their investments can best support both sustainable land use and low-carbon development for Thailand. Such information is also essential if Thailand wants to reach emissions reductions targets set out in its Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC), achieve other Sustainable Development Goals (SDGs), and follow its own path of sustainable development.

AGRICULTURAL DEVELOPMENT TRENDS IN THAILAND

Thailand, like all of Southeast Asia, is a major exporter of a number of agricultural products, both food and industrial. There are no consistent maps depicting the location, coverage, or growth of specific commodities available. However, census on the growth and volume of traded agricultural commodities, presented in Table 1, provide some baseline information about which crops have experienced growth driven by agricultural markets. Topping the list is rubber. Thailand is one of the top exporters of rubber in the world: statistics show that rubber exports exceeded five billion US dollars in 2015 (Table 1). Remarkably, in 2008 it was reported that

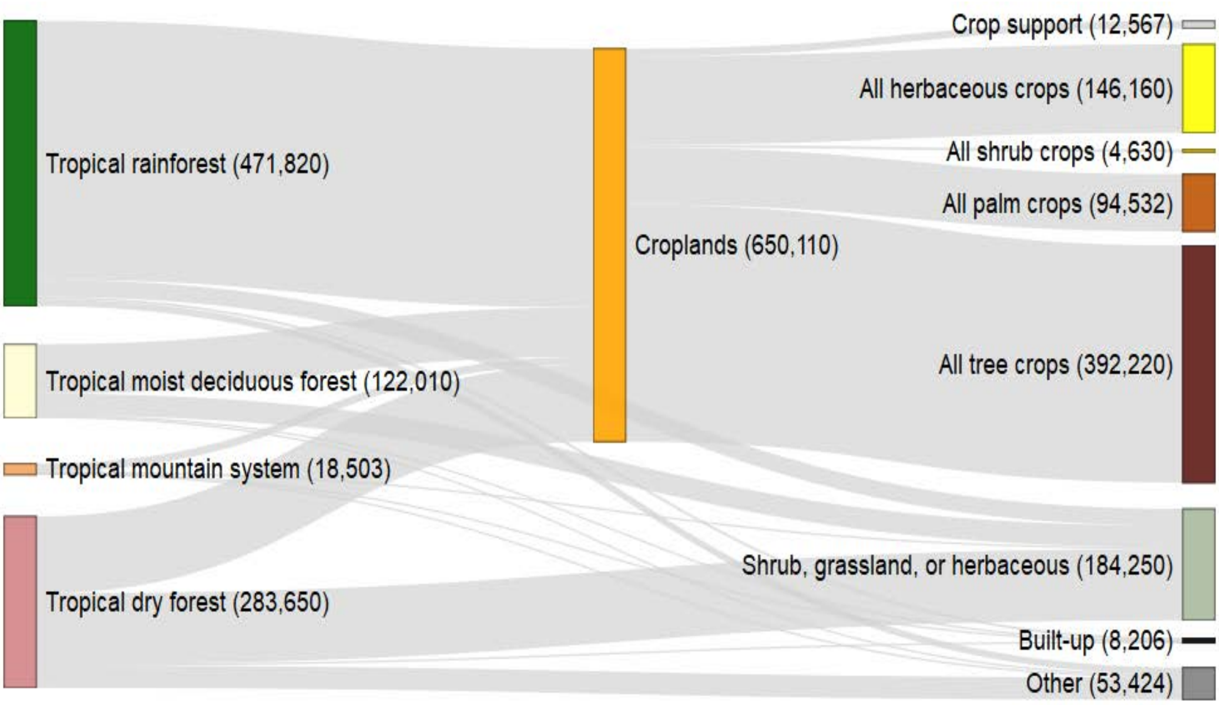
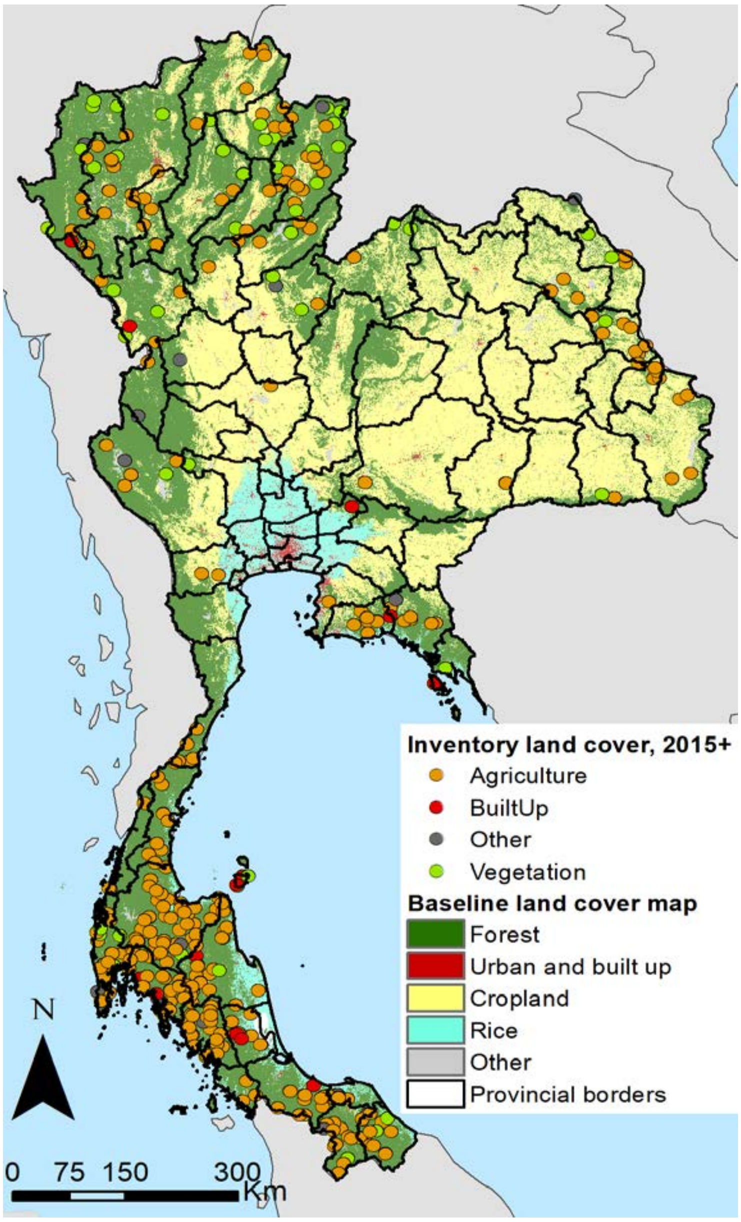


Figure 2: Composition of land use and crops in lands that underwent forest loss since 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in 2000, while the right side represents the land cover after 2015. The total area of all crops is represented by the croplands bar in the middle. Area estimates (ha) are adjacent to the labels.

approximately 90 percent of Thai rubber is produced by smallholders, who typically practice integrated forestry, often growing rice or vegetables or raising animals amongst the rubber trees (Viswanathan, 2008); more recent research is needed to confirm if these trends are still valid. Growing valuable timber species, such as teak (Tectona sp.), and native shrubs, such as Gnetum sp., is also fairly common (Penot et al. 2017).

The other primary commodity crop of Thailand, oil palm, has expanded in part to produce biofuels intended for internal use. The government has a stated goal to establish 905,600 ha of oil palm plantations in Thailand by 2021; of this, 600,000 ha were already mature and in production as of 2012 (Permpool et al. 2016). This emphasis on domestic use of palm oil may explain the relatively slow growth in palm oil exports between 2000 and 2015 compared to other export crops (Table 1). There has been movement within the country towards certifying palm oil by the Roundtable on Sustainable Palm Oil, which would reduce the greenhouse gas emissions and environmental impact from this crop, excluding emissions associated with land conversions (Saswattecha et al. 2015). For example, certified mills and growers had as much as 97% lower emissions, mostly due to the adoption of closed loop systems

Figure 3: Spatial distribution of plots in the sample that have been deforested over the study period, overlaid on a land cover map from 2000 (Saah et al. 2020).



where mulched organic waste materials where added back into the plantation soil, rather than burning it or allowing it to anaerobically decompose into methane (Saswattecha et al. 2015).

Aside from rubber and palm oil, Thailand is also a major exporter of rice, tree fruits, pulpwood, cereals, and numerous other crops (Table 1). Since at least 2000, Thailand has been exporting crops which are bringing in significant economic revenue (Table 1). This is in contrast to many of its neighbors, who began exporting much later, or are still struggling to develop their export markets (as in the case of Myanmar, for example). So, despite the comparatively slow growth in palm oil exports, the country has still seen substantial growth in the export of other agricultural commodities, making agriculture commodity export a major driver of growth in Thailand's economy.

TREE CANOPY COVER LOSS IN THAILAND

The Thailand contribution to the global Forest Resource Assessment estimated that 17 million ha of forests were present in 2000, which is 33.2 percent of the Thailand landscape; national data were not available to calculate the area of other wooded land (FAO 2015). The official Royal Forest Department (RFD) reported 12.9 million hectares in 1998 and 16.7 million ha in 2004 (RFD 2019). Global Forest Watch (2019) places the natural forest cover for 2000 slightly higher at 19.8 million ha, or 38.3 percent, based on global canopy cover and forest loss maps (Hansen et al. 2013). The variation in the estimates of total forested area for 2000 are partially attributed to differences in the operational definition of forest between reporting agencies and, to some extent, measurement uncertainties (Keenan et al. 2015, Tropek et al. 2014). For example, because the global canopy cover maps (Hansen et al. 2013) do not include a sample-based area adjustment for national level forest estimates, the uncertainty of the reported coverage in Thailand is unknown.

We estimate that from 2000 to 2015 a total of 896,000 ha of forest were lost in Thailand (Figure 5). To get an estimate of the percent of forest loss, we can compare this to the estimates of forest cover in 2000 from the global forest resource assessment. This then represents a loss of 5 percent of the forest areas from 2000 (FAO 2015). However, while this comparison

Figure 4: Spatial distribution of crop types at plots within the sample where deforestation events were followed with crop cultivation (depicted by orange dots in Figure 4) overlaid on top of the road network. Dark green areas are protected forest boundaries; light green indicates other protected areas such as national parks and wildlife sanctuaries (ODC 2020).

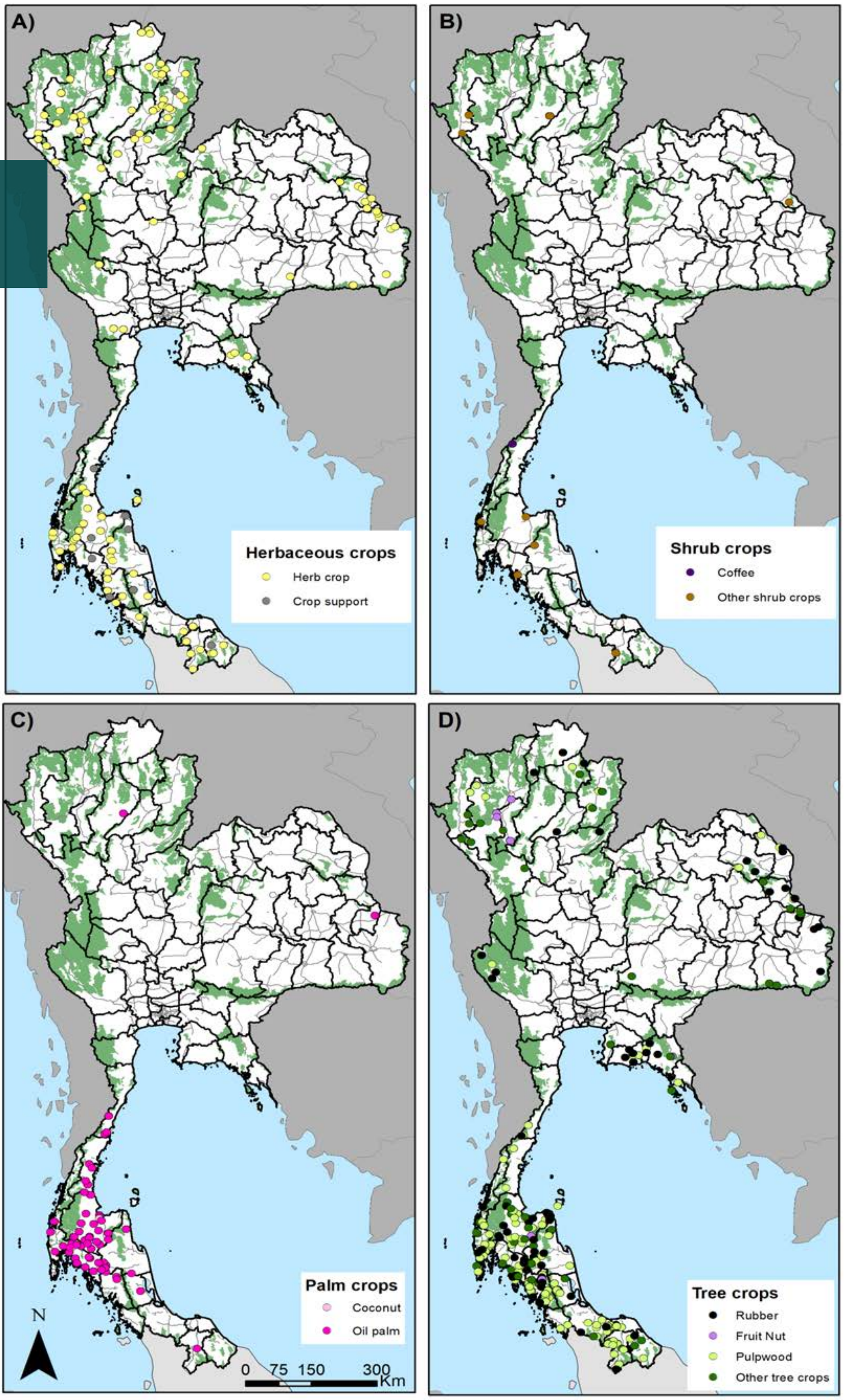


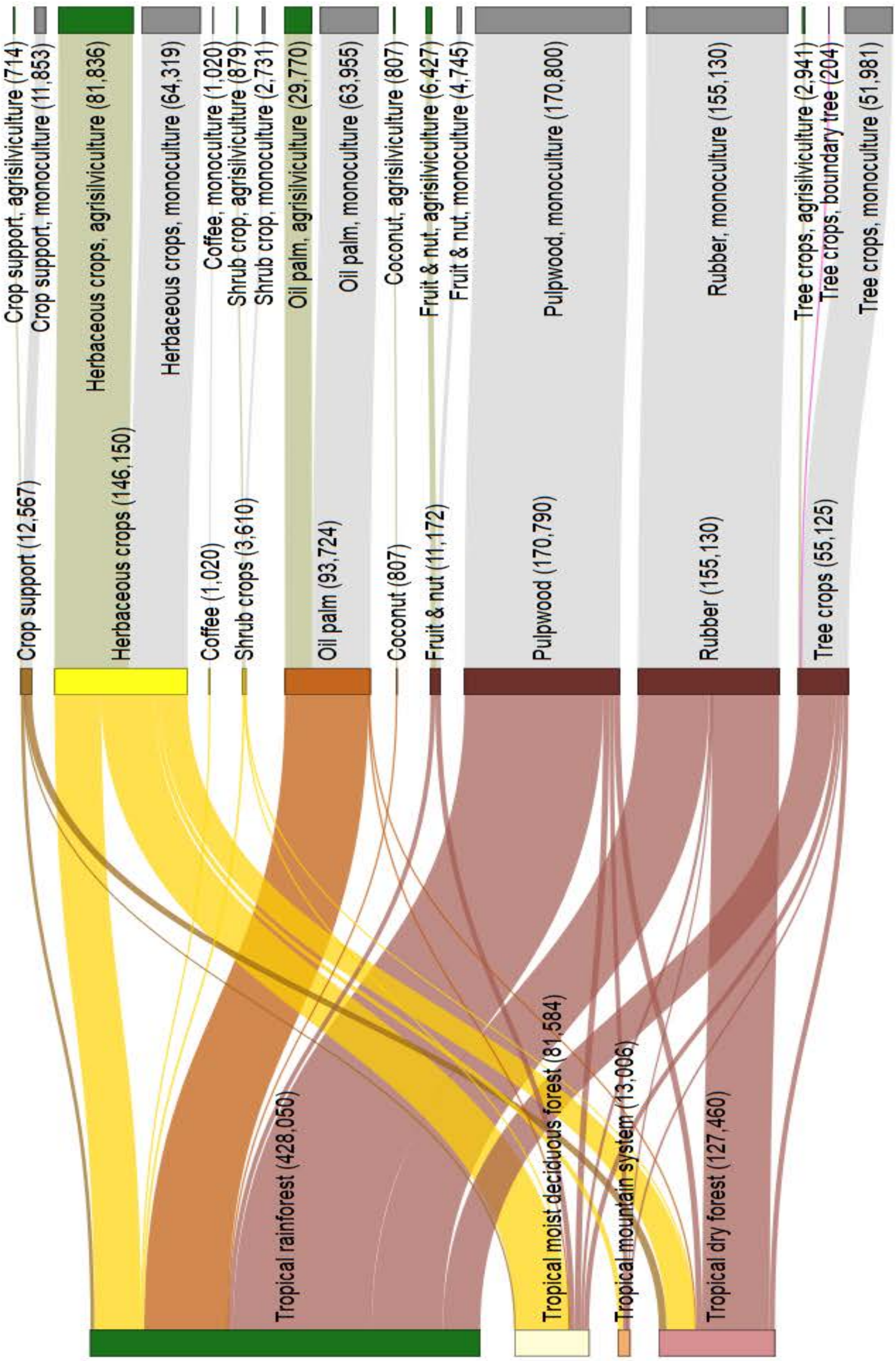
TABLE 2: ABOVEGROUND BIOMASS CARBON STOCKS

commodity	monoculture averaged (tonnes C/ha)	monoculture in Thailand (tonnes C)	agroforestry averaged	agroforestry in Thailand	total in Thailand
coconut	NA	NA	56.3	45,434	45,434
coffee	5.4	5,508	NA	NA	5,508
fruit and nut	67	317,982	67	430,542	748,524
oil palm	39	2,494,245	39	1,161,030	3,655,275
pulpwood	23	3,928,262	NA	NA	3,928,262
rubber	31.8	4,933,134	NA	NA	4,933,134
other herb crops	8.1	520,984	10.1	826,534	1,347,518
other tree crops	43.3	2,250,734	43.3	136,178	2,386,912
other shrub crops	10.5	28,676	16.5	14,504	43,180
crop support	6.8	80,600	20	14,280	94,880
TOTAL		**14,560,125**		**2,628,502**	**17,188,627**

	total tonnes C monoculture	total tonnes C agroforesty	total in Thailand
herbaceous	520,984	826,534	1,347,518
shrub crops	34,184	14,504	48,688
palm crops	2,494,245	1,206,464	3,700,709
tree crops	11,430,112	566,720	11,996,832
crop support	80,600	14,280	94,880
TOTAL	**14,560,125**	**2,628,502**	**17,188,627**

Top: Aboveground time-averaged biomass carbon factors of commodity crops. Values for commodities were compiled from peer-reviewed and grey literature. Time-averaged values are used to estimate the carbon storage of rotational commodity crops because they average the carbon in freshly replanted and mature commodities. These values are then used to calculate aboveground biomass carbon contained in the total area of commodities in Thailand. Calculations are restricted to those commodities in areas that lost natural canopy cover between 2000-2015. **Bottom**: total area of crops, grouped by life form, and total carbon contained in crops by life form.

Figure 5: The composition of crop commodities on land that had natural forest cover in the year 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in the year 2000; the middle section represents the crop type in 2015, with the agroforestry system indicated on the right. Area estimates, in hectares (ha), are included adjacent to the label.



of loss to the FRA baseline estimate provides some context; caution needs to be taken when interpreting the percent loss estimates since both studies have different definitions of forestland. To some extent our definition aligns with the combined forest and woodland estimate from FAO (2015): forest is any half ha patch (or greater) with trees higher than 5 meters and a canopy cover of more than 10 percent that is not in predominantly agricultural or urban land use. Wooded land is nearly the same but the canopy cover is from 5 to 10 percent or has a combined cover of shrubs, bushes and trees above 10 percent (ibid). However, these do include rubber and other tree plantations, so it is not a direct comparison with definitions used in this study; our definition of forest cover excluded canopy cover and forest patch size thresholds.

Tree cover and forest loss dynamics are occurring in four different tropical ecozones: tropical dry forest, rainforest, moist deciduous, and mountain system. The tropical dry forest zone lost the greatest total area of forest—78 percent, or 2.2 million ha (Figure 2). This ecozone covers 48 percent of the country, and runs through the center of the nation (Figure 1). Tropical rainforest and moist deciduous forest both cover 25 percent of the country but accounted for 17 and 4 percent of the forest loss, respectively. The tropical rainforest occurs in higher elevations to the east, the southern and coastal portions of the country. The northern highlands are composed of tropical moist deciduous forest, with tropical mountain system, as well as small areas of tropical rainforest forest. Less than one percent of forest loss occurred in the tropical mountain system.

Approximately 650,000 ha, 72 percent of the forest loss, was for agricultural conversion. Approximately 6 percent of forest cover was converted to barren land cover, such as clearings for mining. There may have been different initial or additional drivers of deforestation and land uses in between the current state and 2000 that are not presented in these results. For example, in southeast Asia, deforestation is often initially driven by selective logging, and then the land is subsequently converted to agriculture (Saunders et al. 2014). Because we have assessed land cover at just two points in time, not the full trajectory of Landsat images, the results do not represent the potential intermediary land covers and uses or proximate driver of deforestation.

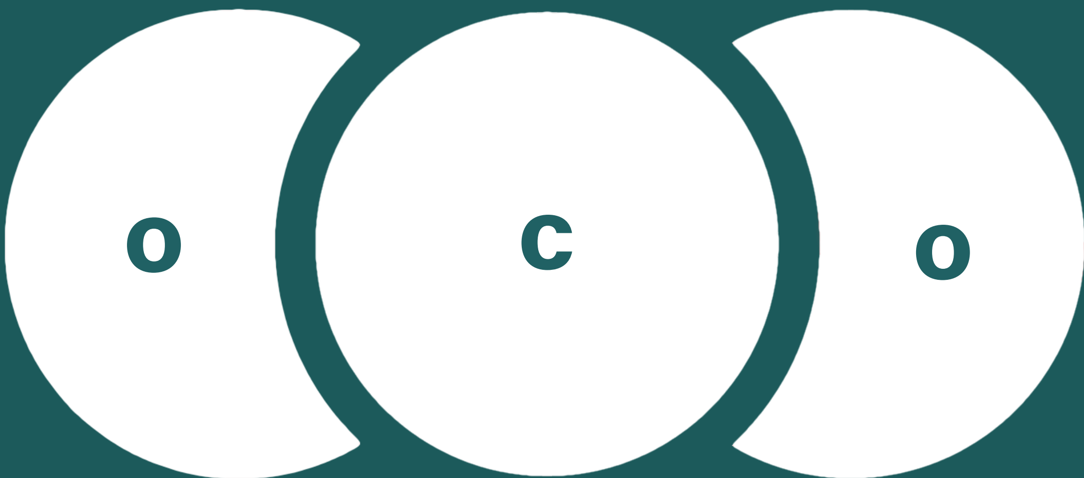
Figure 3 provides the location of plots within our sample that experienced forest loss and what the land cover was changed to by 2015. Our results showed that the majority of the forest loss took place mostly in the south, with some additional areas occurring in the northern and eastern edges of the country. This is likely because the dry central region—which contains the bulk of Thailand's population—had already undergone very significant forest loss previous to the year 2000 (Delang 2002, 2005).

Of the 650,000 ha of forest land converted to crops between 2000 and 2015, 171,000 ha (26 percent) were planted with pulpwood (Figure 4). The next largest commodity crop was rubber, at 155,000 hectares (24 percent). Oil palm was the third most abundant commodity crop, with an area of 94,000 hectares (14 percent). Conversions to oil palm, rubber, and pulpwood are common in the peninsular south (Figure 4 C and D). Herbaceous crops that were not identifiable to a specific type also occupied a substantial area, at 146,000 ha (22 percent). Much of the natural forest loss in the north and east is associated with conversion to herbaceous crops and rubber (Figure 4 A and D).

The commodity crops that are currently cultivated in previously forested lands are proportionate to Thailand's export of those crops, with the exception of rice and tree fruits. This was likely because rice has long been cultivated in Thailand, and the cultivation area of rice was established well before 2000 and did not show an impact on forests in our study. Tree fruits also have a very long history of cultivation in Thailand and this may be the case for this crop as well. However, it may also be the case that areas of reforestation (which we did not assess) are now used for tree fruits, which could explain the relative economic importance of these crops.

Agroforestry was commonly practiced alongside herbaceous crops, accounting for 81,836 ha or 56 percent of the total area of herbaceous crop plantings. Some oil palm was grown using agroforestry systems (29,770 ha or 32 percent of the total); however, this was less common for other tree crops, and essentially no rubber appeared in agroforestry systems. This result suggests that rubber is largely grown in monoculture plantations and was unexpected: other reports have documented that rubber is commonly grown in agroforests among smallholders in Thailand (Penot et al. 2017). It is possible that there was some consolidation of (older smallholder) rubber holdings, which used agroforestry systems, into fewer large companies which decided to grow the trees in monocultures; additional research would be needed to confirm. One explanation for this anomaly between current and past results is that recent conversions may be associated with industrial

IN TOTAL,
79.4 MILLION TONNES OF CARBON WERE LOST DUE TO FOREST CONVERSION TO CROPLANDS BETWEEN 2000-2015 IN THAILAND



plantations, rather than traditional smallholder production. However, it is also possible that some rubber agroforestry systems may have been misidentified as monocultures; because rubber can have a very closed canopy, it is often difficult to identify if an understory (agroforest) is present.

CARBON STORAGE IN THAILAND: IMPACTS AND OPPORTUNITIES

Land use conversion from natural forest cover to commodity crops in Thailand resulted in a loss of 79.4 million tonnes C (Table 3). The original amount of 96.6 million tonnes C has been reduced by an overall 83 percent, with 12.3 million tonnes C remaining in 2015. Of this overall loss, the major land use changes which resulted in the most net losses in carbon have resulted from tropical rainforest (80 percent) and tropical dry forest (10 percent) conversion to agriculture. Certain types of land use change—for example from tropical rainforest to commodity crop agriculture—have significant negative consequences on carbon stocks, even if the commodity crops are grown in agroforestry systems. This is because tropical forests are among the most carbon-rich ecosystems on Earth. On average, tropical rainforests store 180 tonnes of aboveground carbon per ha (IPCC 2006). Agricultural systems, by comparison, store only about 5 tonnes C/ha, and up to 50 tonnes C/ha if crops are grown in combination with trees (Cardinael et al. 2018; Ruesch and Gibbs 2008). Estimates of carbon stored as aboveground biomass in native forests vary by region and forest type and for this study are shown in Table 3.

Results from this study show that approximately 17.2 million tonnes C are stored in aboveground plant biomass across lands that were forested in 2000 but are now under cultivation (Table 2). This estimate is derived by multiplying the country- and commodity-specific carbon factors (Table 2) by the total commodity crop area (Figure 2). In previously forested lands in Thailand, the crop that currently stores the most carbon is rubber; it stores more than 4.93 million tonnes aboveground, which is more than 28 percent of the total aboveground carbon stored in agricultural lands that were previously forest (Table 2). For comparison, the forest that these rubber plantations replaced stored 96.6 million tonnes C. Therefore, with conversion, the amount of carbon in aboveground biomass was reduced by 83 percent. Pulpwood plantations contain the second largest stock of aboveground carbon at 3.93 million tonnes, or 23 percent of the total carbon. Oil palm stored the third largest amount

TABLE 3: CHANGES IN ABOVEGROUND BIOMASS (AGB) IN NATURAL FORESTS AND ALTERNATIVE CROPS BY ECOFLORISTIC ZONE (TONNES C/HA)

	average C/ha in AGB	C in forest (2000)	C in crops replacing forest (2015)	C lost due to conversion
TROPICAL RAINFOREST	180	77,049,360	12,266,374	**64,782,986**
TROPICAL MOIST DECIDUOUS FOREST	105	8,566,320	1,481,394	**7,084,926**
TROPICAL DRY FOREST	9,942,036	3,171,130	6,770,906	**94,912**
TROPICAL MONTANE SYSTEM	81	1,053,486	269,728	**783,758**
TOTAL		**96,611,202**	**17,188,626**	**79,422,576**

of aboveground carbon, at 3.6 million tonnes, also approximately 15 percent of the total.

Previously published estimates of carbon storage in secondary forests in Southeast Asia have ranged from approximately 18 tonnes C/ha to 160 tonnes C/ha as they age (Sum et al. 2012; Avitabile et al. 2016). This means that some agroforestry systems, such as fruit/nut orchards, coconuts, oil palm or rubber can store more carbon than some secondary forests; they are also significantly better at storing carbon than crops grown without trees. Therefore, establishing tree commodities, especially fruit/nut trees, in agroforestry systems on degraded lands or monoculture herbaceous crop lands will sequester more carbon than any other cropping system. However, while long-rotation shifting agriculture, orchards, and other tree commodities are able to store similar amounts of carbon to secondary natural forest, the actual amount stored is highly variable and depends on the age and condition of the forest (Ziegler et al. 2012). Regionally, the only land conversion that is certain to be a net positive in terms of carbon stocks is reforestation.

The national-level estimates of agroforestry carbon factors used in this study are within the ranges found in recent global meta-analyses of carbon stock factors (Kim et al. 2016; Feliciano et al. 2018; Cardinael et al. 2019). We note that across all four crop types, agroforestry stored more carbon per unit areas (ha) as compared to monoculture systems (Table 2, lower). We find that a majority of the conversion has been for tree crops in the monoculture system, with 11.4 million tonnes C representing 79 percent of the overall carbon storage in crops.

It should be noted, however, that for some crops and agroforestry systems, there was no Thailand-specific data available. In these cases, this analysis adopted the most conservative approach: we assumed that trees provide the vast majority of biomass in any agricultural system and thus we used the same carbon stock factors for both agroforestry and tree monoculture systems. Given this assumption, the values presented here may underestimate some of the carbon in the landscape. We believe this is justified given that the difference in carbon storage between agroforestry and monoculture tree plantations is quite small compared to the difference in carbon storage between natural forest cover and agricultural systems. However, the overall finding in Table 2 with crop type differentiation indicates that agroforestry practices store carbon better than monoculture practices for all four crop types.

CONCLUSIONS AND RECOMMENDATIONS FOR THAILAND

Policymakers working to reduce Thailand's GHG emissions or to establish Thailand's forests as a source of carbon offset credits need to know how and where to prioritize investments in the land use sector. This requires knowledge of the relative GHG emissions and carbon storage capacity associated with different land use and land cover types. We found that this conversion of natural forest to agricultural land has released significant amounts of carbon into the atmosphere, possibly as much as 79.4 million tonnes (83 percent) of the carbon that was stored in the natural forest prior to conversion. Because we have assessed land cover at two points in time, we know only which sample points were forested in 2000 which were then later converted to agriculture. We do not have information on all potential proximate and indirect causes or the timing of the actual deforestation. While we are unable to directly attribute agriculture as the driver of deforestation, we can determine the amount of agriculture that has ultimately replaced forestlands.

This study has also shown that commodity crops are mostly replacing natural forest in proportion to their value as export products. This implies that if historical trends in land use change continue as Thailand grows its economy, land will continue to be converted to cultivate commodity crops. Of course, the country may go on other development trajectories, such as intensifying its land use through new technologies, developing its service sector, or increasing manufacturing. While these development paths will also impact Thailand's GHG emissions, predicting those impacts is well beyond the scope of this study. However, we can say conclusively that a continuation of the forest conversion trends of the past 15 years will have serious negative impacts on national greenhouse gas reduction pledges—in addition to minimizing the ecosystem services that natural forests provide.

Thailand has made notable efforts towards reforestation and environmental protection over the last two decades, and hopefully this will continue. However, as pressure to emerge as a high-income country grows, landscape protection will also need to be facilitated through other policy-level and participatory approaches. Research on reconciling economic development and environmental protection in Southeast Asia as well as other regions of the world suggests a number of possible solutions discussed later in this volume. A literature review done for this study also uncovered a number of Thailand-specific solutions.

First, community forestry has been a form of sustainable forest management that has positively impacted local livelihoods and improving local health (Laosuksri and Gubo 2014; RECOFTC 2014). While the vast majority of forests in Thailand are officially owned and managed by the State (which bans the export of timber), the government does occasionally recognize the success of community forestry, and as such has partnered with local groups to allow more localized control (Sudtongkong and Webb 2008; On-prom 2014;

Kumsap et al. 2016). There are currently approximately 14,000 community forest sites in Thailand, over 8,300 of which are registered with the RFD; in total these forests encompass 500,000 ha of land (RECOFTC 2014).

None of these, however, lies within protected areas, which has long been a source of debate within the conservation community in Thailand. As of February 2019, a long-awaited Forest Community bill was passed (Bangkok Post Online 2019), which will legally allow residents living in these forests to work with the state to sustainably manage and use natural resources. The bill came into effect in August of 2019, so the impacts of it have yet to be analyzed. This bill must continue to receive policy support, more local land rights must be recognized, and communities must be supported as they monitor their forests and develop forest management plans (Elliott et al. 2019; Kaiser et al. 2012). Similarly, a compelling case for opening protected lands to other carefully monitored uses needs to be made to Thai government land use policymakers. All of Thailand's protected areas are no-use zones; however, studies have shown that strictly protecting forests may have many other adverse consequences, such as social conflict, overuse of adjacent land, and decreased eco-tourism value (Ferrero et al. 2013; Samukkethum 2015; Prayong and Srikosamatara 2017).

Ecotourism is an option for preserving landscapes that has both detractors and supporters (Kontogeorgopoulos 2005) worldwide. There have been numerous examples of successful eco-tourism ventures in Thailand that have improved community livelihoods while preserving landscapes (Chemnasiri 2012; Michaud and Ovesen 2013; Nuttavuthisit et al. 2014; Auesriwong et al. 2015). For communities in or near lands that have natural forests or high carbon stocks, ecotourism options should be presented as one option for local economic development.

There may be ways to tackle forest protection through Thailand's subsidy policies. At least one previous study (Pongkijvorasin and Teerasuwannajak 2015) found that government-subsidized maize farming has been a driver of deforestation in the northern uplands. Where government subsidies are needed, and encourage farming of herbaceous plants, the policy should be re-examined. Subsidies could be given to tree crops, reforestation, irrigation or recovery of other ecosystem services instead. And, as noted throughout this volume, at the very minimum trees should be planted to turn herbaceous monocultures into agroforestry systems. Restoration of Thailand's' ecosystem services should also be a top priority. As one example, in highland areas where there is flash-flooding or low water tables, teak appears to be successful at improving water-based ecosystem services (Sumanochitraporn et al. 2014). Teak is also a high-value species that can significantly increase farmers' incomes and can store large amounts of carbon. The caveat to teak farming is that it takes up to 30 years for teak to reach peak economic value, and farmers need income in the interim. Agroforestry within teak plantations can be difficult due to the growth patterns of teak, but it is not impossible and has been successful in improving farmers livelihoods in other parts of Southeast Asia (Roshetko et al. 2013). There have been successful attempts at reforesting land with teak in the north (Gillogly 2004; Sumanochitraporn et al. 2014), and with adequate support for interim profitable activities, teak could be a viable and sustainable agricultural crop in parts of Thailand.

Finally, though not specifically addressed in the current study, mangrove ecosystems are among the most carbon-rich ecosystems in the world and have been replaced by paddy or shrimp farms in parts of coastal Thailand (Richards and Friess 2016). Where coastal paddy is degraded, mangroves may need to be rehabilitated. This will not only store carbon in the landscape but will protect coastal assets from sea level rise and any increases in monsoon duration or intensity brought about by climate change.

These are but a few policy and programmatic options that would enable more sustainable land use sector-based economic development in Thailand. Thailand, unlike many of its neighbors in Southeast Asia, is already on the path towards reforestation, and as a middle-income country, has already found some sustainable pathways. However, like its neighbors, it has rich forest and land resources, and will be pressured to deplete those resources as populations expand.

There is no one-size-fits all approach to development that works for all of Southeast Asia, or all of Thailand. However, one consistent theme throughout the literature is that full community participation in development decisions tends to lead to the best outcomes for both people and lands. Engaged people are invested in their lands, and once invested, typically want to maintain or grow that investment. Community involvement can rely on both technology and local knowledge, and should ensure full engagement of everyone, including women, the elderly and ethnic minorities. Approaches that keep local people at the heart of development will help Thailand, meet SDG targets across not only environmental sectors, but in health, sustainable consumption, human rights, and education as well.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VIETNAM

KEY MESSAGES

BETWEEN 2000 AND 2015, APPROXIMATELY 759,000 HECTARES OF FOREST WERE CONVERTED TO OTHER LAND USES OR COVERS. GROWTH IN COMMODITY PRODUCTION ACCOUNTS FOR ABOUT 519,000 HA OF THAT LOSS.

THESE COMMODITIES STORE 11.9 MILLION TONNES OF CARBON AS ABOVEGROUND BIOMASS. **IF NATURAL FORESTS WERE STILL IN PLACE, 51.5 MILLION MG MORE CARBON WOULD BE STORED; THIS IS AN 81 PERCENT LOSS.**

AGROFORESTRY PRESENTS AN ATTRACTIVE OPPORTUNITY FOR INCREASING CARBON STOCKS ON PREVIOUSLY DEFORESTED LAND, PARTICULARLY IN VIETNAM, BECAUSE IT IS ALREADY WIDESPREAD THROUGHOUT THE COUNTRY.

Considering the country endured 30 years of civil conflict, and did not attempt democratic reform until 30 years ago, Vietnam has made amazing economic progress. In the last three decades, Vietnam has transformed itself from a country at persistent risk of famine into an emerging economy (Tarp 2017; World Bank 2013). Poverty rates have dropped from 58 percent in 1993 to 14.5 percent in 2008 (Begun 2012). Economic and market reforms, beginning with Doi Moi in 1986, have catalyzed this economic growth while also improving production of food staples such as rice, and commercial crops such as coffee and tea. Food security in Vietnam has also improved with Vietnam becoming one of the biggest rice exporters in the world since 2010. Thanks to a series of policy reforms, this growth has been less destructive than such rapid growth in other parts of the world has been.

In 1992 Vietnam began integrating sustainable development strategies into the country's policy frameworks. One of the most notable of these was adopted in August 2004, and it was known as the Strategic Orientation for Sustainable Development. This plan ensured economic, social, and environmental growth happened concurrently, including in the agricultural sector, which accounts for over 22 percent of the country's GDP, 30 percent of the country's exports, and 52 percent of the country's employment (IFAD 2012). This growth has accelerated thanks to a combination of better land use practices, more efficient irrigation, and incentives for agricultural investment (Van Khuc et al. 2018). In the midst of this growth, Vietnam is also a participant in United Nations Framework Convention on Climate Change (UNFCCC) and Sustainable Development Goals (SDGs) processes. For the former, the country

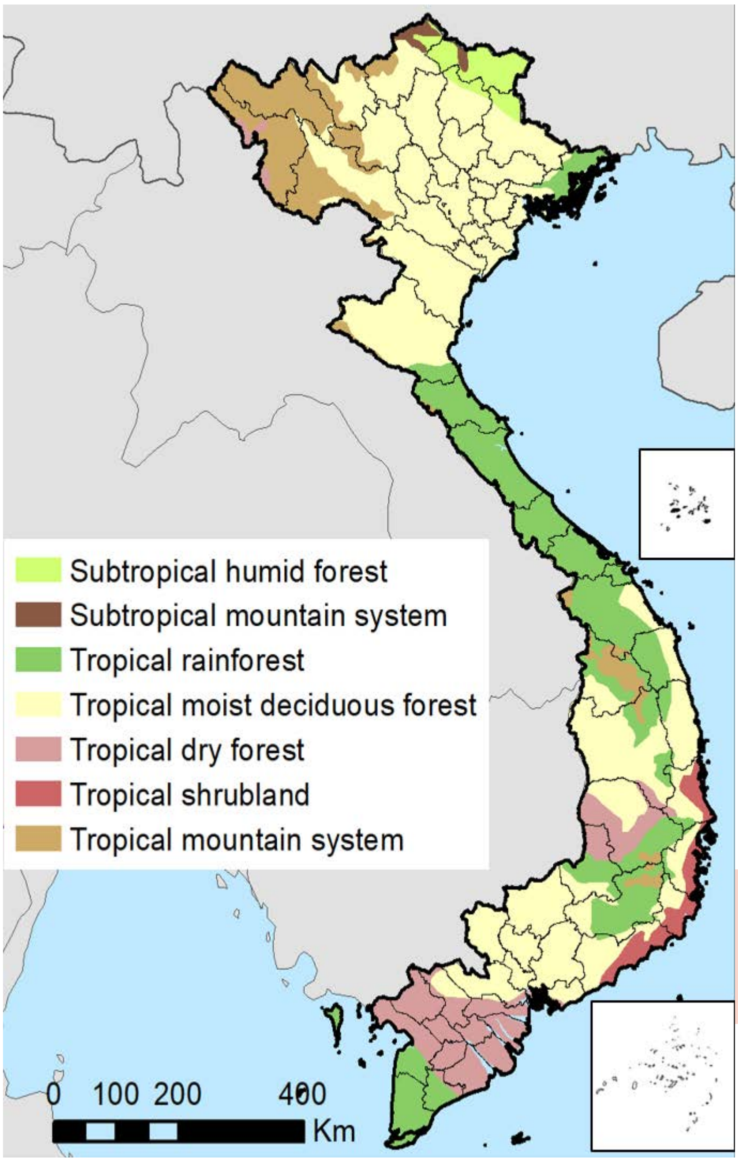


Figure 1: Ecozones in Vietnam, from Reusch and Gibbs 2008.

Table 1: Volume (in millions of constant 2015 US dollars) of agricultural commodities traded in Vietnam in 2000 and 2015 (from www.bea.gov). Values derived from Chatham House, resourcetrade.earth (2018).

Commodity	USD value 2000	USD value 2015	% change
coffee	780.9	2,697.1	245
rice	1002.7	2,574.7	157
tree nuts	212.4	2,201.9	937
pulpwood	54.7	1,386	2,434
rubber	222	1,118.3	404
tree fruits	201.5	814.7	304
tea	94.4	220.2	133
cereals	38.6	136.7	254
coconut	37.2	126.4	240
palm oil	46.6	36.7	-21
tobacco	7.7	27.5	255
banana	2.1	12.4	491
cocoa	0.01	9	83,492

has identified agriculture as an important sector in its Nationally Determined Contributions (NDC) to the UNFCCC. For the latter, the country has disseminated a National Action Plan for 2030 Sustainable Development Agenda (Government of Vietnam 2017). Vietnam has also committed to the Zero Hunger Challenge launched by the United Nations' Secretary-General at the Rio+20 Conference and is on the way in formulating a National Action Plan to meet this Challenge (FAO 2015).

Vietnam watchers have reason to be cautiously hopeful about its ability to meet these commitments. That is because Vietnam is showing progress in environmental conservation, in part because it has experienced what is known as a 'forest transition.' A forest transition occurs when the pattern of decreasing net tree canopy cover reverses and forests begin to expand (Meyfroidt and Lambin 2008). Forest cover in Vietnam declined from nearly 43 percent in 1943 to between 16 and 27 percent in 1993 (DeKonick et al. 1999). This drastic decrease in forest cover was brought on by defoliants used in the second Indochina war (the "Vietnam War"), followed by expansion of urban centers, use of forests for wood, and clearing for the expansion of agriculture and aquaculture. However, this downward trend began changing in the 1990s and today, government estimates of forest cover are at 44 percent (GSO, 2018). This transition has been supported to some extent by studies using remote sensing (Cochard et al. 2016; Poortinga et al. 2019) which have shown that agricultural expansion has been on hold for at least three decades.

However, while there has been a net increase in tree cover, increases are not consistent across the country, and primary forest losses are still occurring (WWF 2013). Estimates suggest that 1.76 million ha of forest was lost between 2000 and 2010 (though the rate appears to be decreasing), and these losses have been found to be strongly associated with poverty, population density and agricultural production. In Central Vietnam much of this forest loss appears to be taking place in secondary forest (60 percent) and in plantations (29 percent), rather than in primary forests (Avitable et al. 2016). This may be due to better policy in that part of the country, as effective provincial governance appears to play a role in reducing forest loss (Khuc et al. 2018).

AGRICULTURAL DEVELOPMENT TRENDS IN VIETNAM

Table 1 shows the commodity crops analyzed in this study, and how exports of most of these crops substantially increased between 2000 and 2015. The commodities investigated in this study were selected based on their economic importance, area of cultivation, potential role in driving forest conversion, and ability to be identified via photo-interpretation. This last factor is especially important to keep in mind because herbaceous crops are difficult to identify with photo-interpretation in currently available remote sensing imagery. Land conversion for herbaceous crops may however have been an important driver of deforestation, and therefore the impact of such conversion may be underestimated in this study.

Coffee exports from Vietnam increased substantially from 2000 to 2015, growing by 245 percent (Table 1, Chatham House 2018). Vietnam is now the 2nd largest coffee producer in the world. While this benefits economic development, it has come with the cost of deforestation. Rice is the second most economically important agricultural commodity. As of 2019, Vietnam is the fifth largest producer of rice in the world (USDA 2018); as of the early 2000s, it was the second largest producer (Ghoshray 2016). We don't expect rice to have had a major impact on deforestation during the 15 year period we investigated. That is because in Vietnam, like elsewhere in Southeast Asia, much of the land cover change to rice paddy likely took place prior to 2000 and thus would not be detected in our analysis. After rice, tree nuts are the third most important crop. Tree nuts grown in Vietnam are largely cashews, with smaller areas of macadamia nuts, walnuts, and others.

The most economically important non-food crop is Acacia mangium (pulpwood). The cultivated area of Acacia has expanded by roughly 400,000 ha between 2010 and 2015, and accounts for 39 percent of all tree plantations in Vietnam as of 2015. The increase in its export value exceeds 2,000 percent (Nambiar et al. 2015; Smith et al. 2017; Chatham House 2018), which was the second largest increase in export value in any of the commodities in this study. It is largely cultivated by smallholders in plots less than 5 ha, and is used as a supplemental source of income, though larger scale holdings do exist (Smith et al. 2017). Rubber, the 5th most valuable commodity crop in Vietnam, has been rapidly expanding throughout all of Southeast Asia, and thus is an important part of the regional economy.

Tree fruits are the sixth most valuable agricultural commodity. As of 2006, Vietnam was the second biggest

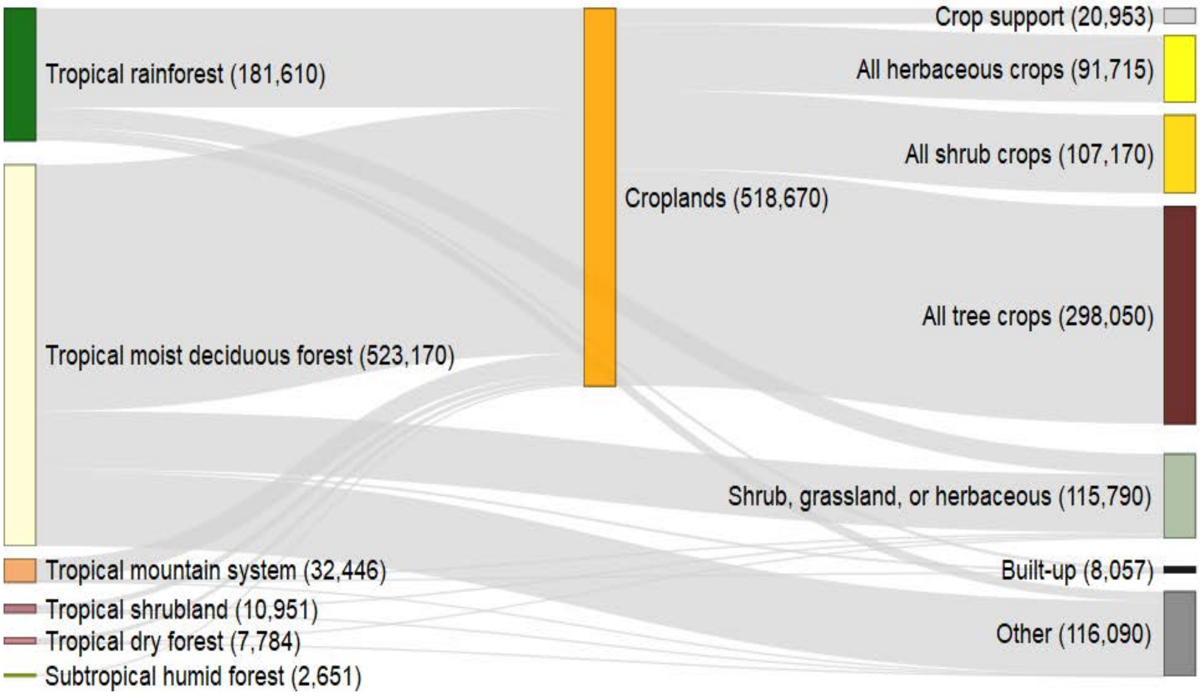
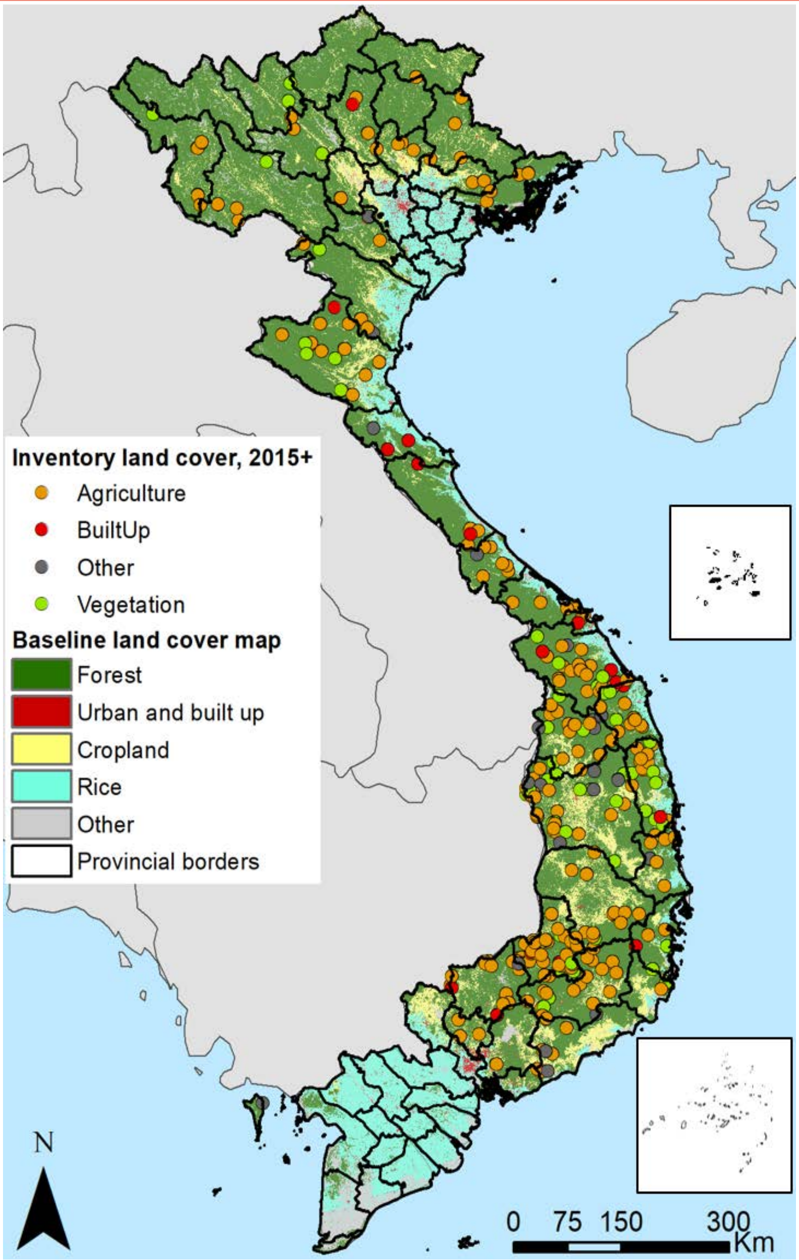


Figure 2: Composition of land use and crops in lands that underwent forest loss since 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in 2000, while the right side represents the land cover after 2015. The total area of all crops is represented by the croplands bar in the middle. Area estimates (ha) are adjacent to the labels.

producer of fruit, both tree and non-tree varieties, in the world according to the FAO (2006). While that ranking has been superseded today by China, India and others, fruits are still a large component of Vietnam's export economy. The country produces approximately 30 different types of fruits, 27 of which have commercial value. Tree fruits produced there include oranges, mango, lychee, rambutan, longan and dragonfruit, for which Vietnam is the world's leading producer.

Finally, two more agricultural commodities which are worth mentioning are oil palm and cocoa. Oil palm is the one commodity crop studied that actually decreased in value over the study period. Vietnam, unlike the rest of southeast Asia, has not aggressively expanded oil palm production. This is for a few reasons, but is largely because there are many other high value crops being cultivated across the country, and there is little land left appropriate for oil palm expansion (Colchester 2011). Vietnam is therefore a net importer of palm oil, largely from Indonesia. Some cite a need to expand production so as to be less reliant on foreign imports (Vietnam News 2011). Cocoa, unlike palm oil, has expanded drastically in value over the study period, experiencing an almost 85,000 percent increase. This is due to the modest expansion in crop area, as well as the increasingly high value of cocoa on world markets. Almost 40 percent of the cocoa in Vietnam recently

Figure 3: Spatial distribution of plots in the sample that have been deforested over the study period, overlaid on of a land cover map from 2000 (Saah et al. 2020).



won the International Cocoa Organisation fine flavor cocoa (FFC) distinction, making it the second country in Asia to receive this designation (Vietnam News 2016), and just last year it began exporting organic cocoa to discriminating Japanese markets.

TREE CANOPY COVER LOSS IN VIETNAM

Vietnam reported in the Global Forest Resource Assessment that total forest coverage was 11.7 million ha, with 1.8 million ha of woodlands, in 2000 (FAO 2015, Table 1A). In 2000, national estimates recorded 11.9 million ha of forests, of which 4.5 million ha were regrowth or poor-quality, low-density forest (Government of Vietnam 2016). The variation in the estimates of forested area for 2000 are partially attributed to differences in the operational definition of forest between reporting agencies and, to some extent, measurement uncertainties (Keenan et al. 2015; Tropek et al. 2014).

We estimate that from 2000 to 2015 Vietnam experienced a loss of 759,000 ha of forest (Figure 2). To get an estimate of the percent of forest loss, we can compare this to the estimates of forest cover in 2000 from the global forest resource assessment. This then represents a loss of 6 percent of the forests and woodland areas from 2000 (FAO 2015). However, while this comparison of loss to the FRA baseline estimate provides some context, caution needs to be taken when interpreting the percent loss estimates since both studies have different definitions of forestland. To some extent our definition aligns with the combined forest and woodland estimate from FAO (2015): forest is any half ha patch (or greater) with trees higher than 5 meters and a canopy cover of more than 10 percent that is not in predominantly agricultural or urban land use. Wooded land is nearly the same but the canopy cover is from 5 to 10 percent or has a combined cover of shrubs, bushes and trees above 10 percent (ibid). However, these do include rubber and other tree plantations, so it is not a direct comparison with definitions used in this study; our definition of forest cover excluded canopy cover and forest patch size thresholds.

The ecosystem most impacted by forest loss was tropical moist deciduous forest, followed by tropical rainforest; small areas of forest loss also occurred in the tropical mountain system and tropical dry forest. Vietnam forests are located within seven different tropical and subtropical forest and shrubland zones (Figure 1).

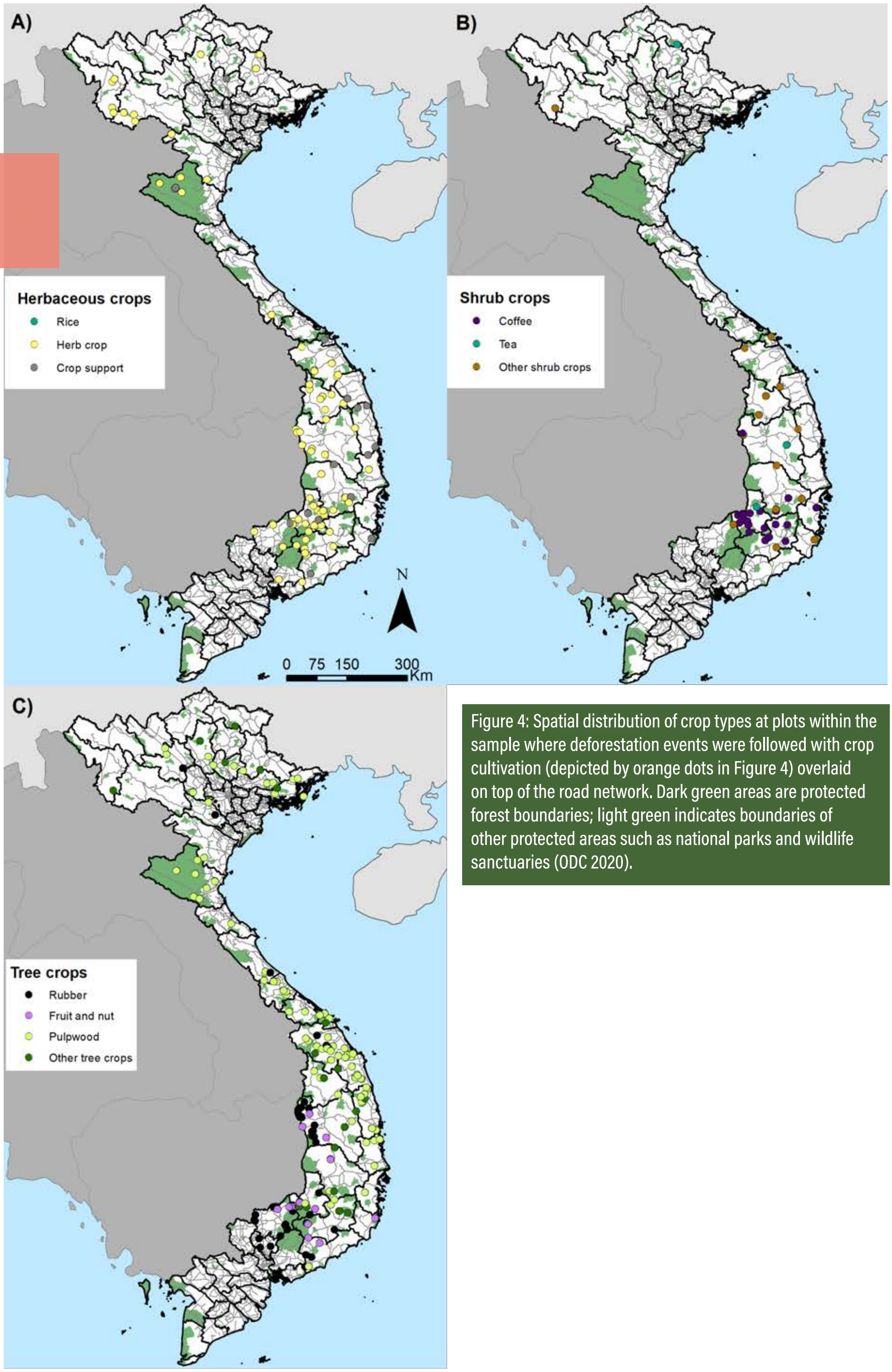
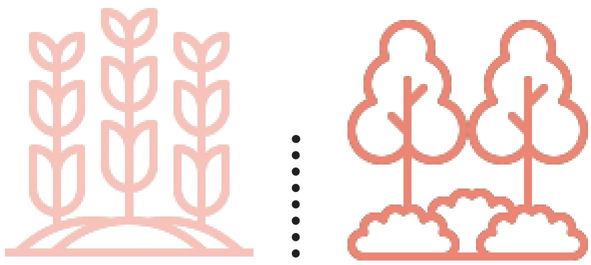


Figure 4: Spatial distribution of crop types at plots within the sample where deforestation events were followed with crop cultivation (depicted by orange dots in Figure 4) overlaid on top of the road network. Dark green areas are protected forest boundaries; light green indicates boundaries of other protected areas such as national parks and wildlife sanctuaries (ODC 2020).

TABLE 2: ABOVEGROUND BIOMASS CARBON STOCKS

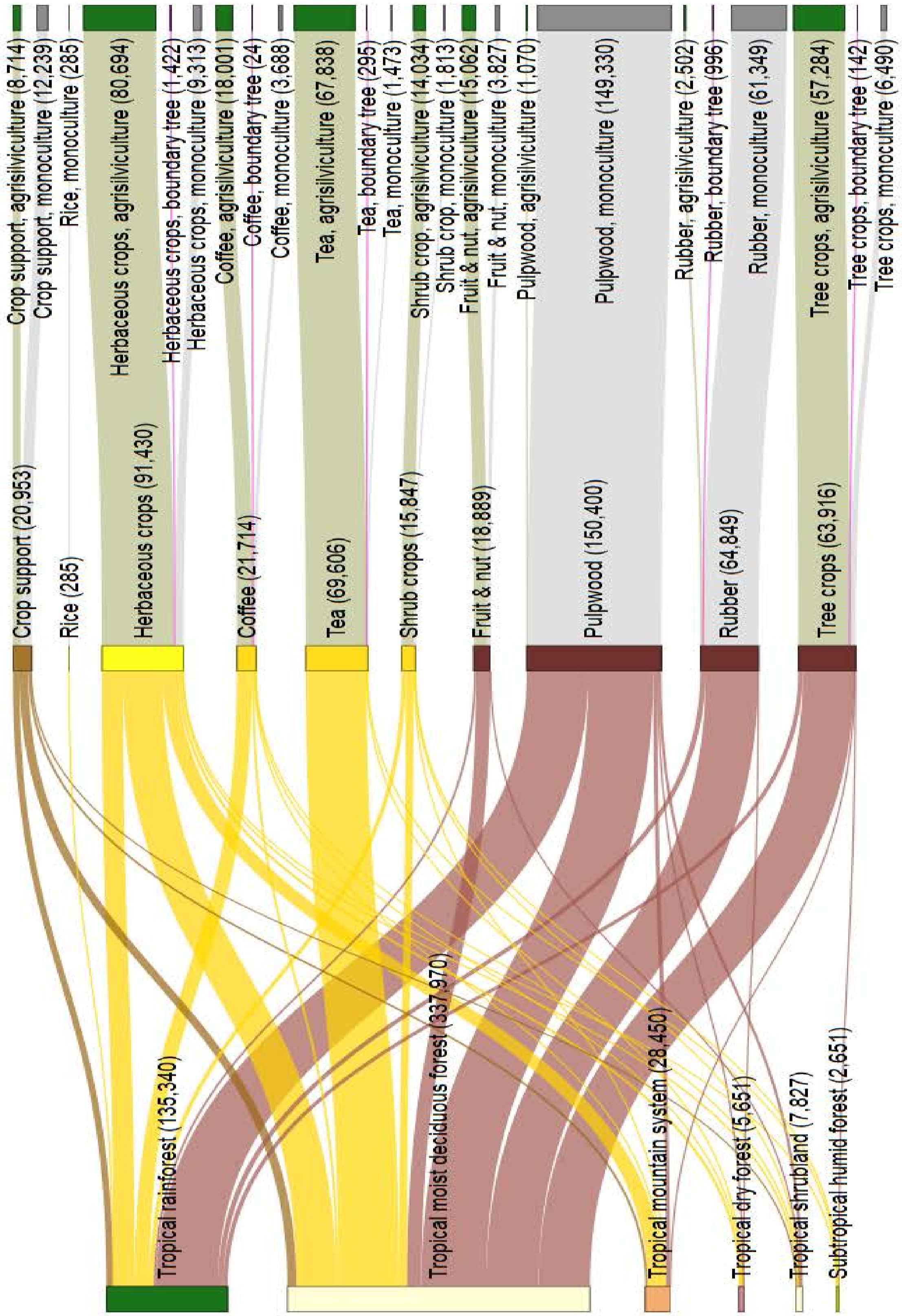


commodity	monoculture averaged (tonnes C/ha)	monoculture in Vietnam (tonnes C)	agroforestry averaged	agroforestry in Vietnam	total in Vietnam
coffee	5	18,440	11	198,275	216,715
fruit and nut	34.07	130,386	34.07	513,162	643,548
pulpwood	23	3,434,521	23	24,633	3,459,154
rubber	31.74	1,947,249	31.74	111,027	2,058,276
rice	1	285	NA	NA	285
tea	15.3	22,537	22	1,498,926	1,521,463
other herb crops	4	37,256	20	1,642,340	1,679,596
other tree crops	29.5	191,455	29.5	1,694,067	1,885,522
other shrub crops	10.15	18,392	16.5	231,578	249,970
crop support	4	48,960	20	174,280	223,240
TOTAL		**5,849,481**		**6,088,288**	**11,937,769**

	total tonnes C monoculture	total tonnes C agroforesty	total in Vietnam
herbaceous	37,541	1,642,340	1,679,881
shrub crops	59,369	1,928,779	1,988,148
tree crops	5,703,611	2,342,889	8,046,500
crop support	48,960	174,280	223,240
TOTAL	**5,849,481**	**6,088,288**	**11,937,769**

Top: Aboveground time-averaged biomass carbon factors of commodity crops. Values for commodities were compiled from peer-reviewed and grey literature. Time-averaged values are used to estimate the carbon storage of rotational commodity crops because they average the carbon in freshly replanted and mature commodities. These values are then used to calculate aboveground biomass carbon contained in the total area of commodities in Vietnam. Calculations are restricted to those commodities in areas that lost natural canopy cover between 2000-2015. **Bottom**: total area of crops, grouped by life form, and total carbon contained in crops by life form.

Figure 5: The composition of crop commodities on land that had natural forest cover in the year 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in the year 2000; the middle section represents the crop type in 2015, with the agroforestry system indicated on the right. Area estimates, in hectares (ha), are included adjacent to the label.



The northern highlands are composed of subtropical humid forest, subtropical mountain system, and tropical moist deciduous forest. The central portion of the country is dominated by tropical rainforest, with some areas of tropical mountain system in the central highlands. The southern portion of the country is the most diverse, with a mix of tropical shrubland, tropical dry forest, tropical moist deciduous forest, and tropical rainforest.

Of this forest loss estimate, crops are cultivated across 518,000 ha, accounting for 68 percent of the land use on lands that experienced forest loss (Figure 2). Nearly 116,000 ha (15 percent) of former forest lands are now supporting non-crop and non-forest vegetative land cover such as grasslands and shrubs. There may have been different drivers of deforestation and land uses in between the current state and 2000 that are not presented in these results. For example, in southeast Asia, deforestation is often initially driven by selective logging, then the land is subsequently converted to agriculture (Saunders et al. 2014). Because we have assessed land cover at just two time points in time, not the full trajectory of Landsat images, the results do not represent the potential intermediary land covers and uses or proximate drivers of deforestation.

Most of the forest loss occurred in the Central Highlands and South Central Coast (Figure 3). The majority of lands that have undergone forest conversion are now supporting cultivated lands. A comparison of our trends in relationship to those mapped by Curtis and team (2018) show similar geographic results (Figure 4A). In the middle of the country, the belt of pulpwood expansion corresponds to the region of tree commodity expansion in Curtis' (2018) data. Much of this pulpwood expansion is taking place in the tropical rainforest ecoregion (Figure 4B). The southern region that Curtis mapped as crop commodity expansion is where much of the rubber, tea, coffee, and fruit and nut orchard expansion is occurring. This region largely falls within the tropical moist deciduous forest ecoregion (Figure 1). In the northern parts of the country, the prevalence of herbaceous crop commodities in the inventory sample are located within or adjacent to the region previously mapped as shifting agriculture.

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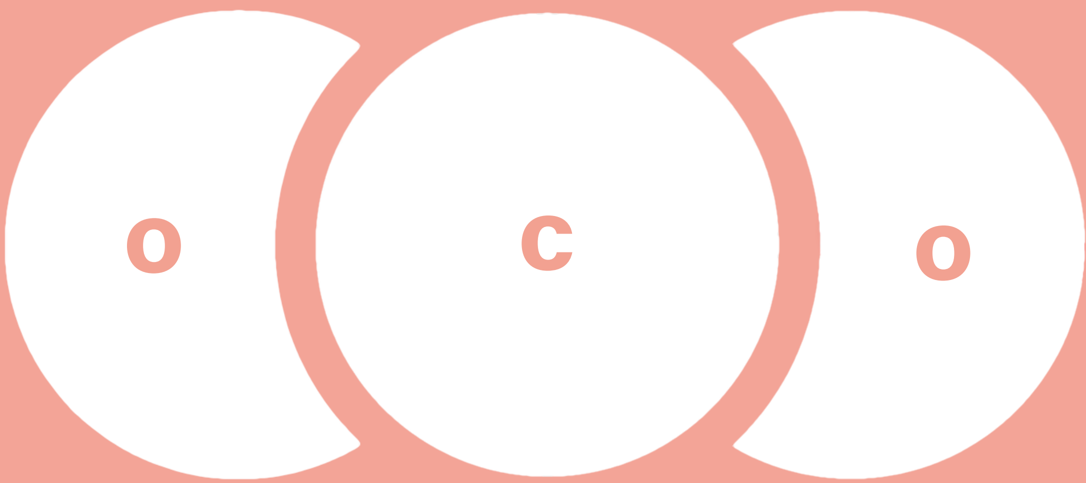
The predominant crops currently in cultivation in lands that were forested in 2000 include pulpwood crops (e.g., acacia or eucalyptus), herbaceous crops, tea, rubber plantations, coffee, fruit and nut trees, and tea (Figure 4B and 5). At 150,000 ha, pulpwood plantations comprise 29 percent of the total amount of cultivated crops on lands that were previously forested. As shown in Figure 4C, pulpwood plantings are dispersed throughout the country, in all regions except the far south. Pulpwood plots are typically planted by diverse smallholders and act as a source of supplemental income, which may partly explain their spatial homogeneity. Larger plots of Acacia held by companies, committees, or other organizations are also typically spatially dispersed (Smith et al. 2017). Herbaceous crops, excluding rice, were grown across 91,000 ha of deforested land, 18 percent of crop expansion. At 65,000 ha rubber is the third most prevalent tree commodity in previously forested lands, accounting for 13 percent of the forestland converted to crops. Tea, coffee plantations, and fruit/nut orchards were the 4th, 5th, and 6th most prevalent commodities in the lands of interest with coverage accounting for 13, 4, and 4 percent of the total forest loss, respectively.

The commodity crops that are cultivated in previously forested lands align with the major crops grown in the country, with the exception of rice and other herbaceous crops. Low-growing annual and perennial crops (cassava, maize, etc.), rice, acacia, rubber, native tree plantations, and coffee are the primary crop commodities grown in Vietnam (Table 1) (Vietnam General Statistics Office 2017; Smith et al. 2017; Nambiar et al. 2014). Those that expanded at the greatest rate were low-growing annual and perennials, paddy rice, coffee, pepper, and fruit and nut trees (Vietnam General Statistics Office 2017). It is not possible to identify the crop commodity types of low-growing plants using high resolution imagery. However, based on trends reported by the General Statistics Office, it is likely that the three most abundant crops making up our "other shrub crop" category include cassava, maize, and sugarcane. Over-

IN TOTAL,
51.5 MILLION TONNES OF CARBON WERE LOST DUE TO FOREST CONVERSION TO CROPLANDS BETWEEN 2000-2015 IN VIETNAM.



all, forest/canopy cover seems to be being replaced by commodities at expected rates given the extent of their areal expansion in Vietnam.

CARBON STORAGE IN VIETNAM: IMPACTS AND OPPORTUNITIES

Approximately 11.9 million tonnes of carbon are stored in aboveground plant biomass across lands that were forested in 2000 but are currently under cultivation (Table 3). This is only 19 percent of the original amount of 63.5 million tonnes C from 2000 or the loss of 81 percent forest area over 15 years. In recently deforested lands, the crop cultivar with the largest carbon pool is pulpwood, storing more than 3.5 million tonnes of aboveground carbon, or 29 percent of the total (Table 2). The second largest carbon stock is represented by rubber plantations, with 2.1 M tonnes C, or 17 percent of the total. Tea in agroforestry systems was the third most important commodity crop providing carbon storage benefits, with 1.5 M tonnes of aboveground carbon stock, or 12 percent of the total. Overall, the carbon emissions resulting from the conversion of forests to crops is 51.5 M tonnes C (Table 3).

Various non-commodity trees in agroforestry landscapes store 3.7 M tonnes C. Our compilation of Vietnam-specific farming system carbon stocks shows that agroforestry stores greater amounts of carbon than their monoculture counterparts (Table 2), oftentimes significantly so. Coffee monoculture, for example, contains 5 tonnes C/ha in aboveground biomass while the agroforestry coffee systems store over double that amount (11 tonnes C/ha). Estimates of regrowing secondary forest have been reported at approximately 18 tonnes C/ha (Avitabile et al. 2016). Published literature suggests that some agroforestry systems provide more carbon storage than regrowing secondary forests, and therefore can play an important role in storing carbon in the landscape. It is important to remember though that even the most carbon-rich agroforestry systems, i.e., fruit and nut, contain far less carbon (roughly 20 percent) than natural forests. And even native forests vary in their ability to store carbon depending on their region and ecofloristic zone (Table 3).

No Vietnam-specific data were available describing carbon stocks for some agroforestry systems. In these cases, this analysis adopted the most conservative approach: it assumes that tree crops provide the majority of biomass in tree crop agroforestry (e.g., rubber) and thus the same carbon stock factors were used for both agroforestry systems and monocultures. Effectively,

TABLE 3: CHANGES IN ABOVEGROUND BIOMASS (AGB) IN NATURAL FORESTS AND ALTERNATIVE CROPS BY ECOFLORISTIC ZONE (TONNES C/HA)

	average C/ha in AGB	C in forest (2000)	C in crops replacing forest (2015)	C lost due to conversion
TROPICAL RAINFOREST	180	24,360,660	2,797,136	**21,563,524**
TROPICAL MOIST DECIDUOUS FOREST	105	35,486,850	8,260,083	**27,226,767**
TROPICAL DRY FOREST	78	440,856	114,051	**326,805**
TROPICAL MONTANE SYSTEM	81	2,304,450	560,135	**1,744,315**
TROPICAL SHRUBLAND	78	610,506	160,390	**450,116**
SUBTROPICAL HUMID FOREST	105	278,355	45,973	**232,382**
TOTAL		**63,481,677**	**11,937,768**	**51,543,909**

ground crops were ignored in agroforestry systems. A conservative approach was also taken for rice systems, where trees typically occur only as boundary plantings. These trees can contain non-trivial amounts of carbon, but because we could not accurately estimate their areal extent, we ignored boundary trees in rice systems (Reppin et al. 2019; Feliciano et al. 2018). Given these assumptions, the values reported here underestimate some of the carbon in the landscape, though that is likely justified given this amount is relatively small compared to the carbon lost from tree canopy cover loss.

The changes in the composition of tree cover have had significant impacts on the carbon balance of Vietnam. We were able to aggregate available monoculture versus agroforestry statistics across the crop types with an overall finding that all had a better carbon storage per ha for agroforestry (see Table 2, lower). A substantial proportion of forest land use is currently plantations of exotic trees species such as acacia, eucalypts, pines, and rubber. Rich primary forests in central Vietnam contain on average about 167 tonnes C/ha in AGB (Avitabile et al. 2016), with a national average of 137 tonnes C/ha (Government of Vietnam, 2016). By comparison, plantation forests in Vietnam range from 11 to 34 tonnes C/ha depending on age, species, agroclimatic, and management conditions (Mulia et al. 2018). While areas of evergreen forest continued to decrease between 2000 and 2015, it is likely that Vietnam has seen an increase in carbon stocks due to increases in plantation area and the regrowth of natural forestlands (Government of Vietnam 2016). The carbon impacts of this may be mixed, as carbon stocks in plantations are typically surpassed by those of native forest. Although these plantations may enhance carbon stocks when they are established on already degraded landscapes instead of replacing primary forests (ibid).

CONCLUSIONS AND RECOMMENDATIONS FOR VIETNAM

This study characterized a selection of photo-identifiable crop commodities in previously forested landscapes to identify the dominant commodities, summarize the carbon consequences of land use change, and inventory common agroforestry practices used throughout Vietnam. Of the commodity crops analyzed, those most frequently cultivated in formerly forested lands include pulpwood, rubber, tea, fruit and nut trees, and coffee plantations. This study sampled areas of likely forest losses, and results agreed with overall estimates of commodity areas in Vietnam given the relative economic importance of each crop. Pulpwood (acacia and eucalyptus) and rubber plantations are the commodity crops with the largest carbon storage capacity in Vietnam (3.4 and 2.0 million tonnes C respectively). Herbaceous crops and other tree commodities uses also stored a significant amount of carbon. The majority of these crops occurred in agroforestry systems, which store much more carbon than monoculture systems and provide other ecosystem services.

Vietnam, unlike most other countries in Southeast Asia, shows an overall trend towards reforestation, rather than forest loss. This, as noted above, is likely due to the low forest baseline (because of conflict-driven deforestation in the 1960s) and the progressive policies of Doi Moi that put forests under multi-sectoral control. While this trend is good for both Vietnam and the world, it needs to be accelerated. Domestic and regional population growth will place increased demands on Vietnam's agricultural lands. If forests are to continue to regrow, the country will need to find ways to use existing agricultural lands more productively.

Vietnam will also need to identify the most important lands for rehabilitation based on carbon storage potential. The country has committed to reduce emissions by 8 percent unconditionally and 25 percent with additional external financing by 2030. Net emissions can be reduced if high carbon storage landscapes, such as mangroves, can be restored. Mangroves, though not explicitly covered in this study, are considered to be one of the most carbon rich ecosystems in the tropics. In addition, they provide invaluable ecosystem services, such as coastal protection, aquatic creature habitat, and water regulation. In Vietnam, over 400,000 ha of mangroves were lost in the 20th century, in large part thanks to pesticides sprayed during the war. Since then, mangroves have continued to decline due to the provisioning services they provide (wood for fuel and construction), growth of coastal populations, and shrimp farming. Policies that rehabilitate mangroves or increase their productivity (such as by restoring disused shrimp ponds) will go a long way towards improving carbon storage in Vietnamese landscapes.

As with every other country studied in this volume, improved agroforestry practices will help Vietnam recognize both economic and environmental gains. Recent studies in Vietnam indicate that agroforestry systems can sequester as much as 2.25 tonnes C/ha annually over 10 years (Mulia et al. 2018; Simelton et al. 2019). Given that agroforestry in Vietnam could expand by up to 10 million ha, the carbon sequestration of agroforests would be anywhere from 185 to 349 million tonnes. Another study (Simelton et al. 2015) found that households in the Northwest region of Vietnam who practiced agroforestry had a faster economic recovery after extreme weather events than monoculture farmers. By integrating trees, farmers reduce yield losses in annual crops due to weather and increase crop resilience to climate variability (van Noordwijk et al. 2014). Vietnam is already taking positive steps in this direction: the Ministry of Agriculture and Rural Development recently initiated a national Agroforestry Technical Working Group that is meant to for reviewing existing policy and devise a more conducive policy environment for agroforestry development (Catacutan et al. 2018).

Agroforestry might first be expanded by planting cocoa in monoculture tree plantations. Vietnamese cocoa is high-quality and the most profitable commodity (per unit volume) of any commodity investigated in this study. Cocoa must be grown under shades trees in areas with high soil moisture, and might be most appropriate as a second crop in areas that were once rainforest or moist deciduous forest. One study found that cocoa agroforestry systems raise and stabilize farm incomes and result in greater dietary diversity. New food products are available year round, ensuring continuing food security, and the economic return from the sales of the diversified products from coca agroforestry stabilize farmers' incomes and enhance the farmers' buying power with respect to additional food, especially when the main crop cocoa fails (Nunoo et al. 2015). Such an approach might also be best accompanied by efforts to collectivize small-scale cocoa farmers so cooperatives can get better market prices.

Crop diversification is an important technique for the improving economic value and carbon storage potential of existing croplands. This of course includes agroforestry (which will be discussed more thoroughly later) but also includes transitioning farmers to higher-value crops. A study (Vernooy 2015) on crop diversification in Vietnam found that many projects focused on crop diversification resulted in poverty reduction, especially in the mountainous parts of the north. Such projects also improved social stability by allocating secure long-term land-use rights, and they encouraged investments that increased production and ensured food security.

Given the large area of rice that is cultivated in the country, interventions that minimize GHG emissions from rice paddy would be an effective approach to reduce the country's overall emissions. Alternate wetting and drying (AWD) is an approach that has been in use since the 1990s, and found to be effective in reducing methane emissions by 40 percent as compared to continuously flooded paddy (Wassmann et al. 2009). A meta-analysis of AWD projects in Vietnam found that this technology was successful at reducing GHGs, but faced numerous challenges to upscaling nationwide (Westermann et al. 2015). These included: improving irrigation systems so that it can work more widely; engaging more farmers in the "small farmer, large field or large-scale rice field program" and testing AWD through this participatory approach; and improving the cooperation between irrigation suppliers, pump owners, input suppliers, and local farmer groups.

Finally, forest cover could be enhanced if improvements in policy and practices related to the Forest Land Allocation (FLA) policy were made. The FLA, which began in the 1990s, allows for the allocation of forestland to rural farm households—who are now the second largest forest user group in the country (Lambini and Nguyen, 2014). The FLA policy has contributed to reforestation, and has reduced shifting agriculture; however, its uptake has been limited by a number of factors, including off-farm labor, agricultural income, house size, soil quality and slope, road quality, governmental support, and the availability of loans (Dinh et al. 2017). Solutions include demonstrating agroforestry techniques to farmers, providing loans so farmers can purchase more trees, improving roads so that farmers have access to supplies to support planting, and securing land tenure rights for people. One of the biggest factors influencing whether or not farmers would plant trees was their perception of continuing land rights. Those that suspected the government might take over their lands in the near future were unlikely to invest in reforestation.

In addition to these Vietnam-specific recommendations, there are a number of regional-level policy and program options that would be effective for reducing GHG emissions and improving carbon storage in the FOLU sector in Vietnam. These include first replanting or cultivating fallow or degraded lands, improving farmers' access to technology and information that would help them sustainably intensify cultivation, making use of indigenous and women's knowledge to improve cultivation and sustainably manage forests, securing land rights for people, particularly through the use of community forestry (called village forestry in Vietnam), introducing animals into plantations to diversify income and improve soil quality, and paying attention to the impacts roads have on patterns of forest regrowth.

Vietnam, like all countries in Southeast Asia has tough decisions to make regarding its environmental and financial future. As it is becoming a middle-income country, it is also entering the middle-income trap (The Economist 2011). To avoid this trap Vietnam must identify strategies to introduce new processes, find new markets to maintain export growth, and ramp up domestic demand to create an expanded "conscious" consumer class. This will require investments in infrastructure and an educational system that encourages creativity and supports breakthroughs in science and technology.
It will be important that these investments prioritize sustainable production and consumption so that Vietnam can avoid the resource- and waste-intense path taken by its neighbors Thailand and Indonesia. Vietnam was an early REDD+ country, and it will also be important that the country maintains its commitment to the world to become a sink for GHGs. The government has already taken many progressive steps that have improved land use. With continued thoughtful international support, and inclusive internal processes, Vietnam will be able to be a regional leader for sustainable economic growth and development.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REGIONAL

KEY MESSAGES

A TOTAL OF 15.8 MILLION HA OF FOREST WERE LOST BETWEEN 2000 AND 2015; ABOUT 9.4 MILLION HECTARES OF THAT LAND NOW SUPPORTS VARIOUS CROPS.

IN TOTAL **3 MILLION HA OF FORESTLANDS WERE CONVERTED TO HERBACEOUS CROPS**, SUCH AS CASSAVA AND CEREAL GRAINS, WHICH IS **32 PERCENT OF THE LOST FORESTLAND** THAT IS NOW UNDER CULTIVATION. OIL PALM PRODUCTION ACCOUNTED FOR 26 PERCENT OF THE FOREST LOSS DUE TO AGRICULTURAL CONVERSION.

THE CARBON STORED WITHIN THE ABOVEGROUND BIOMASS OF THE CROPS REPLACING FORESTS IS **269 MILLION TONNES.** IF THESE LANDS WERE STILL FORESTED, **THEY WOULD STORE 1.7 BILLION TONNES, A LOSS OF 85 PERCENT.**

Southeast Asia, as an economic block, includes countries with diverse levels of economic development, highly varied political systems and rich natural resource endowments. Southeast Asia is also a place experiencing fairly significant population growth (the annual population growth rate currently is nearly 1.06 percent) and improved technical capacity, leading in part to impressive jumps in national GDPs in the past several decades. Many countries in Southeast Asia have also undergone significant structural changes in their economies over the past decades (OECD and FAO 2017), further supporting rapid and relatively high economic growth. Between 2000 and 2016, the average real Gross Domestic Product (GDP) increased nearly 5 percent per year for most of the countries in the region. The relatively large increase in per capita GDP in the region has brought about substantial improvements in poverty reduction, quality of life, and food security for many (OECD and FAO 2017).

Many Southeast Asian countries rely on agriculture for much of their economic growth. Indonesia, the Philippines, and the five countries of the Lower Mekong region (Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam) are still largely agricultural economies. This means that land use plays a large role in economic growth. For example, FAO (2017) reported an average regional increase of nearly 40 percent in cultivated agricultural land in the region between 1980 and 2014, and the increases in Cambodia, Indonesia, Myanmar and Vietnam exceeded 50 percent.

The expansion of agriculture has improved the livelihoods of the population as a whole, especially for farmers, and has had a positive impact on poverty reduction and food security. However, economic growth has come with substantial negative environmental impacts, most notably, massive deforestation and the loss of associated ecosystem services. As one example: approximately 63 percent of the oil palm expansion in Indonesia between 1990 and 2010 was associated with deforestation (Gunarso et al. 2013). Fires in these concessions lead to widespread decreases in air quality throughout the region (Spracklen et al. 2015) and peat

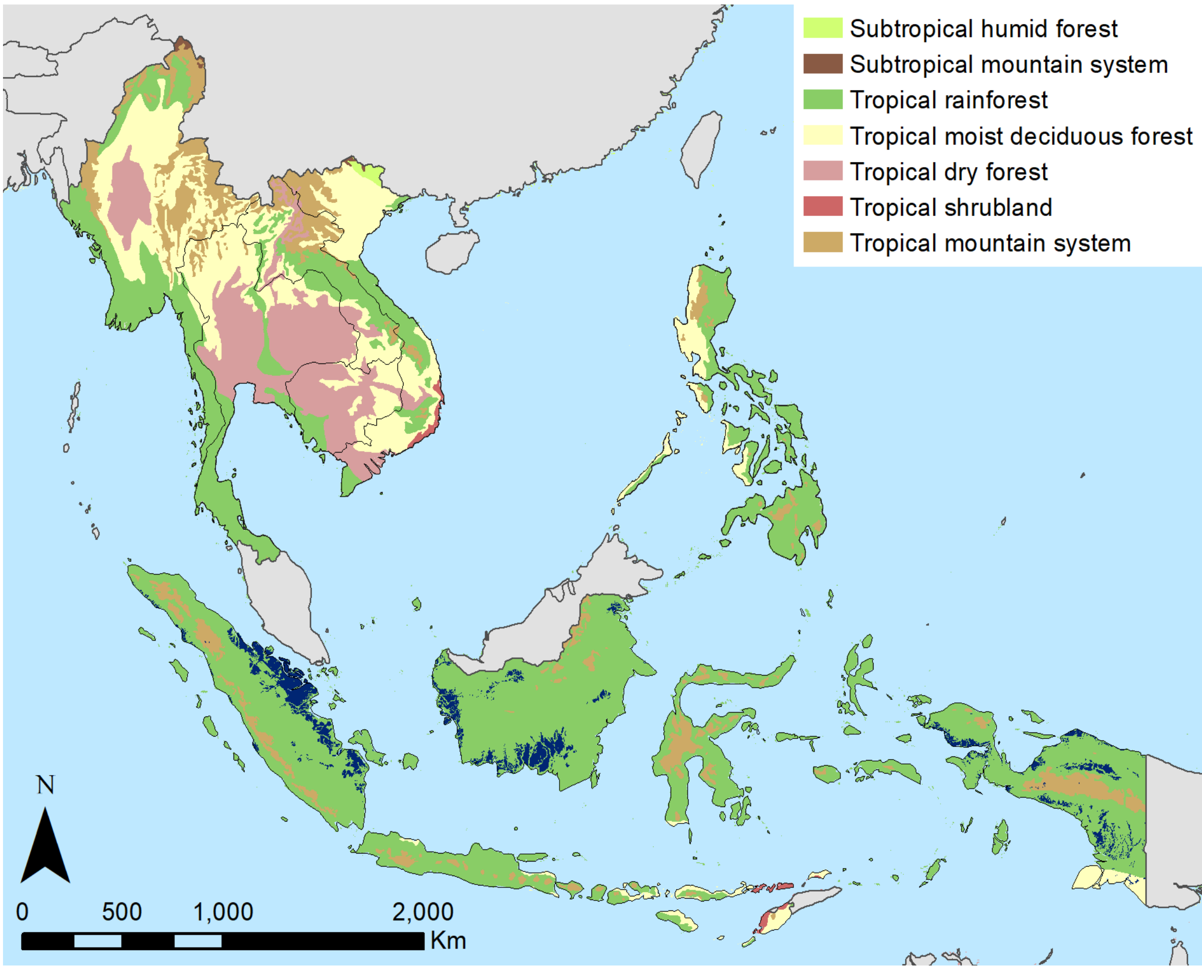


Figure 1: Ecozones across the study region, from Reusch and Gibbs, 2008.

Table 1: Volume (in millions of constant 2015 US dollars) of agricultural commodities traded in the region in 2000 and 2015 (from www.bea.gov). Values derived from Chatham House, resourcetrade.earth (2018).

Commodity	USD value 2000	USD value 2015	% change
rice	470.26	1,083.57	230.42
rubber	631.47	1,614.53	255.68
palm oil	297.69	2,581.57	867.19
tree nuts	49.80	398.33	799.86
cereals	13.49	76.53	567.18
pulpwood	270.81	654.60	241.72
tree fruits	137.20	503.99	367.35
cocoa	80.33	209.01	260.19
coffee	197.57	581.76	294.46
banana	258.47	114.47	44.29
coconut	316.56	320.88	101.36
tea	36.28	53.09	146.33
tobacco	20.39	33.26	163.08

dome collapse (in those on peat) leads to flooding both within and outside plantation boundaries (Wösten et al. 2008; Lupascu et al. 2020).

Such widespread deforestation, while particularly pronounced in Indonesia, is occurring region-wide. Estoque et al. (2019) reports that Southeast Asia has nearly 15 percent of the global tropical forests and four of the 25 global biodiversity hotspots, but one of the highest rates of forest loss. Zeng et al. (2018) reported that the region lost about 293 thousand km^2 of forest between 2000 and 2014, over 11 per cent of the total forest cover in the region in 1999. The same study reported that approximately 200,000 km^2 of the forest loss (94 percent) has occurred in lowland areas and was due to conversion for agriculture.

A 2013 study specific to the Lower Mekong region found approximately one-third of the forests in these countries were logged for timber or cleared for agriculture between 1997 and 2010 (WWF 2013), leading to deforestation and forest degradation. The forest cover losses during this period were 22 percent in Cambodia, 24 percent in Laos and Myanmar and 43 percent in Thailand and Vietnam. A more recently published study (Spruce et al. 2020) suggests that forest cover in the Lower Mekong went from 44 percent to about 32 percent between 1997-2010, but was inconclusive about the end land use after deforestation. As noted above, decreases in forest cover leads to a loss of ecosystem services and environmental benefits, ranging from decreased water and air quality, to insufficient water availability, to lost biodiversity to support human health (Brander et al. 2010; De Beenhouwer et al. 2013; Estoque and Murayama 2016). As forests decrease, therefore, it makes it harder for countries to reach multiple other Sustainable Development Goals.

Decreases in forest cover also lead to decreases in landscape carbon storage. This is an important consideration for nations trying to reduce their carbon emissions so that they can meet United Nations Framework Convention on Climate Change (UNFCCC) targets as well as attract REDD+ financing. Calculating landscape carbon storage is not, however, a straightforward process. To determine precisely how much carbon is being lost through land use change, scientists and policymakers require accurate data on soil types, above- and below-ground plant mass, rates of plant growth, and the carbon storage associated with all of those factors. This type of data can only be acquired through complex studies that measure carbon storage and emissions given explicit local conditions. As a first step, scientists try to estimate the extent of land use change; then define, in broad swaths, how that land is being used. This provides a baseline for emissions from the land use sector, which countries can then use to develop more locally specific interventions that reduce GHG emissions.

This first step—estimating the extent and type of land use change—is itself a time-consuming and expensive process. Traditionally, to get the most accurate data on the extent of land use change and cover types, teams completed on-the-ground field work and inventories, with extensive transect walks through difficult or unnavigable terrain. This is costly and can be dangerous or impossible. To cut costs and save time, many studies have tried to estimate global deforestation rates using satellite data (e.g. Gonzalez-Jaramillo et al. 2016; Cuaresema et al. 2017; Potapov at al. 2017). Some have gone a step farther and estimated the relative importance of agricultural conversion and other drivers of deforestation (Etter et al. 2006; Wijata et al. 2015). Yet, better information about the carbon storage potential of different types of soil and different types of land cover—both of which are variable between plant types and regions—can reduce the uncertainty in estimates of landscape level carbon losses or gains.

This study goes beyond previously published research on deforestation and carbon emissions from land use change in Southeast Asia. It does so by using freely available high-resolution satellite data verified and cross-checked with photo-interpretation to determine the exact type (or class when identification to type was not possible) of land cover. Once the land cover type (ie. rubber tree, oil palm, tea plant, coffee tree) was identified, region-specific Tier 2 carbon storage factors were applied. Tier 2 carbon factors have been calculated to be specific to not only plant or forest type, but are also specific to the region the land cover is grown in, as factors like humidity, water availability and sunlight impact the growing conditions and thus carbon storage of any vegetative land cover (IPCC 2019). By using freely available satellite data and an easily replicable, cost-effective methodology, this study has created an approach that could be employed worldwide to help national experts track land cover change and report on likely carbon gains and losses to comply with their Nationally Determined Contributions (NDCs) and other national and international carbon emissions reduction commitments.

REGIONAL AGRICULTURAL DEVELOPMENT TRENDS

As noted, many Southeast Asian countries rely on agriculture and associated land use changes as a key driver of their economic growth. FAO (2017) reported a 40 percent increase in the land area used for agriculture in Southeast Asia between 1980 and 2014. The agricultural land area increased by more than 50 percent in Cambodia, Indonesia, Myanmar and Vietnam. Approximately 60 percent of the oil palm expansion in Indonesia

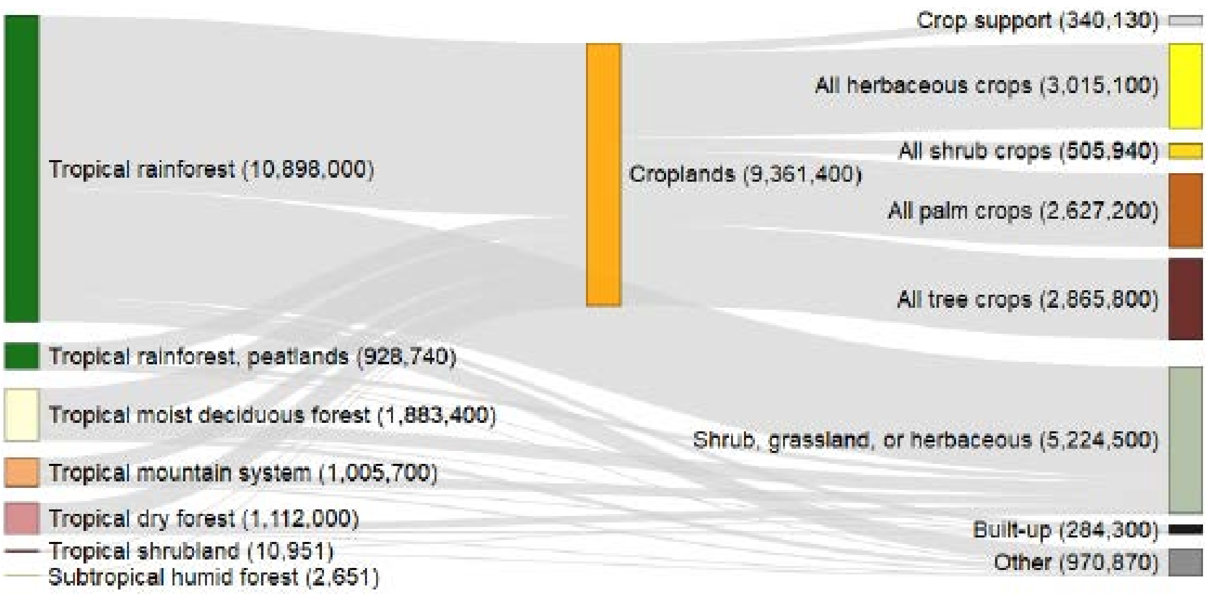
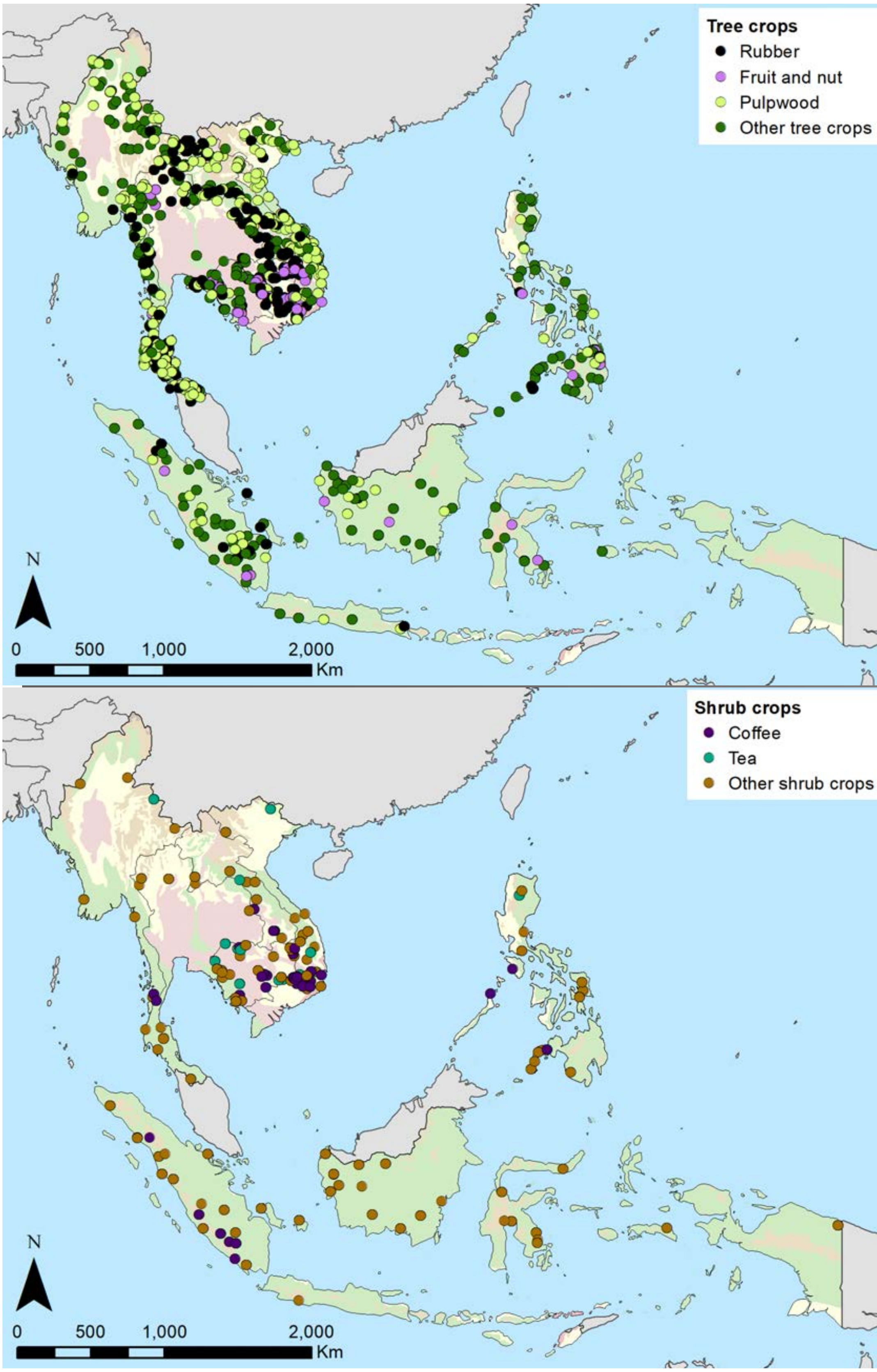
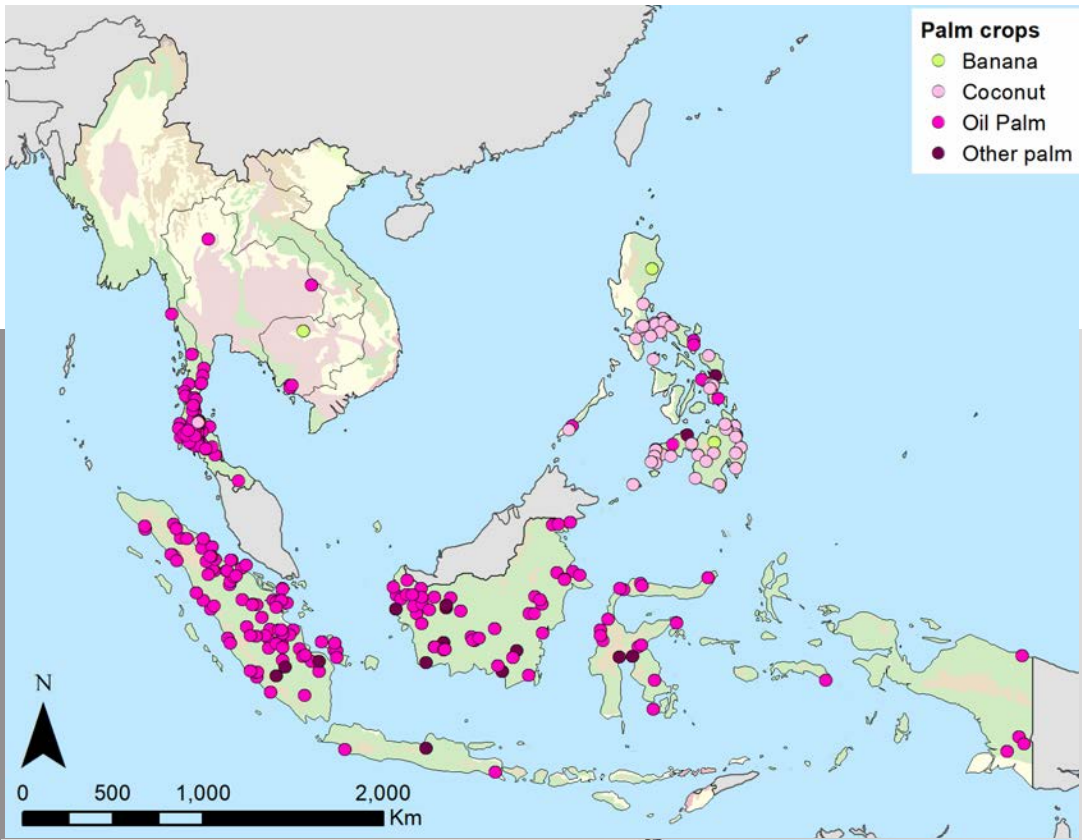


Figure 2: Composition of land use and crops in lands that underwent forest loss since 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in 2000, while the right side represents the land cover after 2015. The total area of all crops is represented by the croplands bar in the middle. Area estimates (ha) are adjacent to the labels.

FIGURE 3 (TWO PAGES): SPATIAL DISTRIBUTION OF CROP TYPES ACROSS THE REGION FOR FOREST LOSS SAMPLES WHICH ARE NOW COMMODITY CROPS, SEPARATED BY CROP TYPE.




Palm crops
Banana
Coconut
Oil Palm
Other palm
N
0
500
1,000
2,000
Km

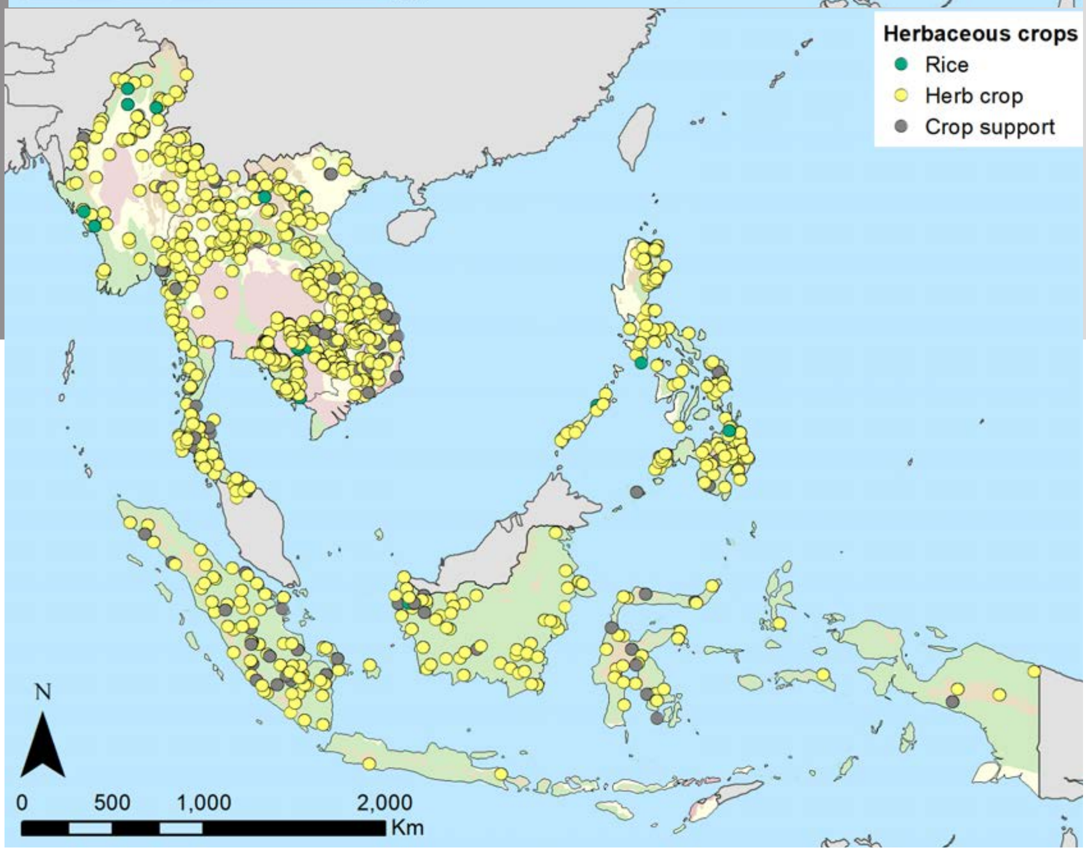

Herbaceous crops
Rice
Herb crop
Crop support
N
0
500
1,000
2,000
Km

TABLE 2: ABOVEGROUND BIOMASS CARBON STOCKS

commodity	monoculture averaged (tonnes C/ha)	monoculture in region (tonnes C)	agroforestry averaged	agroforestry in region	total in region
aquaculture		94,330		0	94,330
banana		2,063		8,750	10,813
coconut		825,781		610,008	1,435,789
coffee		41,801		1,407,118	1,448,919
fruit and nut		1,576,919		5,951,209	7,528,128
oil palm		45,256,583		48,416,362	93,672,945
pulpwood		25,545,026		104,109	25,649,135
rice		36,229		0	36,229
rubber		23,665,625		121,744	23,787,369
tea		263,584		1,511,906	1,775,490
other herb crop		5,458,327		41,159,754	46,618,081
other palm crop		1,757,813		3,873,026	5,630,839
other tree		34,382,135		10,866,090	45,248,225
other shrub		536,861		9,775,058	10,311,919
crop support		353,251		5,609,520	5,962,771
TOTAL		**139,796,328**		**129,414,654**	**269,210,982**

	total tonnes C	total tonnes C	total in region
herbaceous	5,494,556	41,159,754	46,654,310
shrub crops	842,246	12,694,082	13,536,328
palm crops	47,842,240	52,908,146	100,750,386
tree crops	85,169,705	17,043,152	102,212,857
TOTAL	**139,796,328**	**129,414,654**	**269,210,982**

Top: Aboveground time-averaged biomass carbon factors of commodity crops. Values for commodities were compiled from peer-reviewed and grey literature. Time-averaged values are used to estimate the carbon storage of rotational commodity crops because they average the carbon in freshly replanted and mature commodities. These values are then used to calculate aboveground biomass carbon contained in the total area of commodities in region. Calculations are restricted to those commodities in areas that lost natural canopy cover between 2000-2015. **Bottom**: total area of crops, grouped by life form, and total carbon contained in crops by life form.

was associated with the conversion of once biodiversity-rich tropical forests between 1990 and 2010, although the majority is occurring in already disturbed forests (Gunarso et al. 2013). That trend has decreased in recent years, and a more recent estimate suggests that the rate of conversion of natural forests to oil palm has decreased to 18 percent in the 2010-2015 period (Austin et al. 2017).

Between 2000 and 2016, the value of agricultural production has increased at an annual rate of 5.6 percent in Myanmar, 4.4 percent in Cambodia, 3.8 percent in Indonesia, 3.4 percent in Lao PDR and 3.2 percent in Vietnam; Malaysia (2.9 percent), Philippines (2.2 percent) and Thailand (1.6 percent) experienced slower growth. In the lower income countries (Cambodia, Lao PDR, Myanmar, Philippines) the economic growth in agriculture was mainly driven by an expansion of the cultivated area, technological changes, and crop diversification (Birthal et al. 2019). In the higher income countries (Indonesia, Malaysia, Thailand, Vietnam), economic growth in agriculture was largely due to increases in product prices and expanded international trade. Rice and other annual crops and perennial crops such as coffee, rubber, and fruit trees are the main agricultural commodities in Cambodia, Indonesia, Laos, Myanmar, Philippines, Thailand, and Vietnam. The expansion of perennial crop plantations has mainly been in the higher income countries (Birthal et al. 2019). In Indonesia, 20 percent of the total agricultural area was for oil palm and 9 percent for rubber. Oil palm, while a driver of deforestation (discussed later) has also expanded by being planted in some areas formerly devoted to less profitable crops, such as grains. Coffee accounted for 7 percent of the total cultivated area in Indonesia, 5 percent in Vietnam and 4 percent in Lao PDR.

Approximately 9.4 million ha of forested land in the region has been converted to agricultural crops. Figure 2 shows the land area in natural forest ecofloristic zones between 2000 and 2015 and the area converted for crop production through 2015. A large proportion of the forest land was cleared for herbaceous crops (e.g., cassava, grains, and sugar cane) and tree crops (such as coconut, fruits and nuts, oil palm, and rubber). A relatively small area of forest land was converted for perennial shrub crops (coffee and tea) and built-up areas, which include cities, industry, and rural buildings and other structures. Between 2000 and 2015, over 3.015 million ha of forest were converted to herbaceous crops, 2.866 million ha to tree crops, 2.627 million ha of oil palm and other palms, and 0.506 million ha to shrub crops. Approximately 9.9 million ha of pulpwood trees and 0.7 million ha of rubber trees were planted in formerly forested areas. Fruit or nut trees replaced 0.144 million ha of former forest and coconut trees replaced 0.048 million ha.

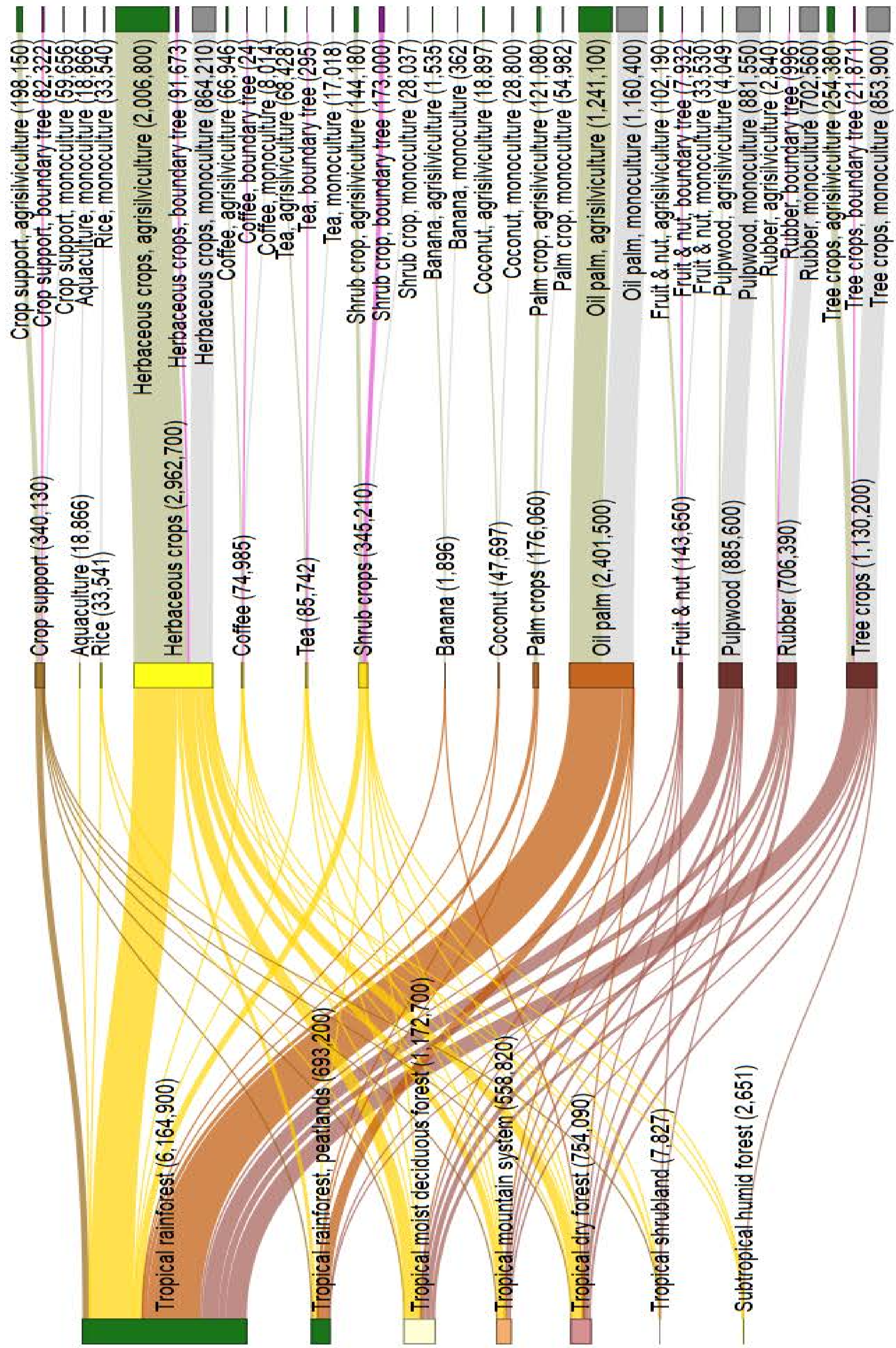
Figures 3a-3d show the spatial distribution of herbaceous crops, shrub crops, palm crops, and tree crops in Southeast Asia. Herb crops were more widely distributed than rice. Crop support is the land that is associated with crops but not covered with a specific crop; examples include the pathways to access fields and the soil in between rows. Figure 4 contains a more detailed disaggregation of the commodity crops grown in 2015 on land in the various ecofloristic zones.

CARBON STORAGE: IMPACTS AND OPPORTUNITIES

We found that, across Southeast Asia, conversion of tropical forests to agricultural lands reduced aboveground carbon sequestration in formerly forested landscapes by 85 percent between 2000 and 2015. This is equivalent to 1.43 billion MT of carbon lost from landscapes. Agricultural land conversions reduced aboveground carbon storage in the region from 1.737 billion MT in 2000 to 0.269 billion MT in 2015, an 85 percent decrease (Table 2). Approximately 66 percent of the carbon storage loss was from conversion of tropical rainforests. In Indonesia, the reduction in aboveground carbon storage was 0.971 billion MT, 65 percent of the regional total. Conservation, improved management, and restoration of tropical rainforests are important because of the high carbon storage potential of these ecosystems in Southeast Asia, particularly in Indonesia, Myanmar, the Philippines and Thailand. Forest restoration in a way that preserves ecosystem services and biodiversity is expensive and slow; monoculture reforestation does not provide the same benefits. It is generally cheaper to avoid deforestation than to restore forests.

In 2015, monoculture crops covered 30.6 million ha and agroforestry systems occupied 24 million hectares. However, per unit of land, agroforestry systems had higher carbon storage rates than monocultures. This is due to the extra carbon storage provided by ground cover herbaceous crops in tree plantations, or by border or interspersed trees in herbaceous monocultures. Accounting for the land area and carbon storage rates, the aboveground carbon stocks totaled 732 million MT C for monoculture crops and 674 MT C for agroforestry. Although the area of forest converted to monoculture crops was 27.5 percent higher than the area under agroforestry, the total aboveground carbon stocks were

Figure 4: The composition of crop commodities on land that had natural forest cover in the year 2000. The left side of the diagram indicates the ecofloristic zone of the tree cover in the year 2000, while the middle section represents the crop commodity type in 2015, with the agroforestry system indicated on the right. Area estimates, in hectares (ha), are included adjacent to the label.



only 8.6 percent higher for monocultures.

RECOMMENDATIONS

This study found that almost 1.5 billion MT of carbon has been lost from landscapes due to the conversion of forested lands to agriculture in Southeast Asia. While this figure is large, it is not insurmountable. There are substantial opportunities to reverse some of these carbon losses caused by forest conversion to agriculture. In previous chapters, we provided recommendations on reducing commodity-driven forest loss for each country, based on existing patterns of agricultural expansion in Southeast Asia. Some of these recommendations include:

- In Cambodia, where charcoal production is a driver of deforestation, provide cooking and energy alternatives such as fuel-efficient cookstoves, solar arrays, or "green" charcoal.
- In Indonesia, where much of the carbon emissions come from degraded peat, expand peat rehabilitation programs and paludiculture, so that communities and businesses can benefit economically from rewet peat.
- In Lao PDR, where coffee is by far the largest export commodity, improve Fair Trade policies and payments for smallholders so that they are incentivized to maintain highly productive coffee agroforests.
- In Myanmar, the Vacant, Fallow and Virgin (VFV) land law allows the government to grant VFV community lands to plantation companies, driving communities from traditional lands, exacerbating local conflict, and increasing land degradation. Recent amendments that are hard for communities to address must be repealed, and the original law must be revised.
- The Philippines has been notable among Southeast Asian nations in that while the number of people involved in agriculture has increased, the share of agriculture in the GDP has decreased. This appears to be due to poor market linkages and low technical capacity, both of which can be addressed through targeted interventions.
- In Thailand, where tourism is a major contributor to the economy (with estimates ranging from 12-21 percent), promote forest-based ecotourism. Many successful examples already exist, and there is existing demand to develop forest tourism further.
- In Vietnam, which produces high-quality and high-cost cocoa for export, carbon sequestration could be improved by planting cocoa trees in the rows of existing monoculture tree plantations. Such shaded growing conditions are ideal for cocoa and can help landowners improve both carbon storage and incomes.

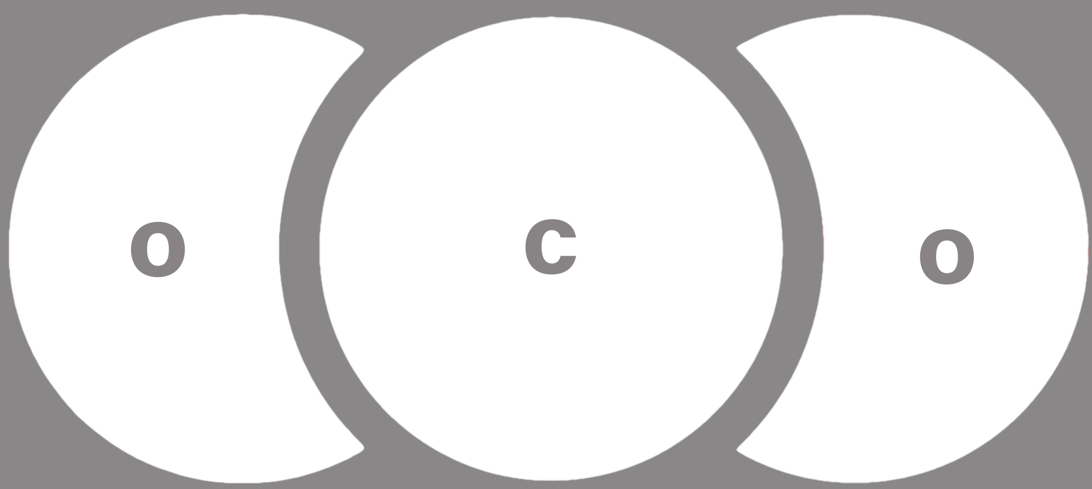
Here, we present regional level recommendations for forest rehabilitation that apply to many developing or middle-income countries in the study region. These recommendations can result in both improved carbon storage in landscapes and better economic outcomes. The first six recommendations are specific to the study, and are based on both results of the study and a literature review done in conjunction with the study. The last three recommendations are general best practices that are commonly discussed in the literature; the study did not directly address these recommendations.

Recommendation 1

Fallow lands should be better used. Carbon storage can be improved by directing new agricultural expansion to occur on fallow or degraded lands that currently sequester relatively little carbon (Smith et al. 2007). Carbon storage capacity will increase when tree crops or agroforestry crops are planted on these lands. In some locations, rubber trees grown in an agroforestry system may be the best use for many of these degraded lands. Rubber sequesters a significant amount of carbon and produces relatively quick financial returns for growers. However, while rubber does sequester large amounts of carbon, it is not a one-size-fits-all approach. The suitability of the soil and microclimate for rubber must be assessed, and community or national interests and capacity to develop a rubber sector must also be part of that decision.

Alternatively, fallow lands can be better used by carefully rotating crop types based on soil and climatic characteristics, reducing fallow periods between crop cycles, and increasing total landscape carbon storage. There is however debate about the carbon storage capacity of fallow lands; it appears that carbon storage in fallow lands increases with soil depth, and also increases over time (Hashimotio et al. 2000; Chan et al. 2016). Chan et al. (2016) in fact found that after 20-35 years, fallow forests could recover the total biomass of intact forests. This means that while fallow land should be considered for new agriculture expansion, the time

IN TOTAL, ALMOST
1.5 BILLION TONNES OF CARBON WERE LOST DUE TO FOREST CONVERSION TO CROP-LANDS BETWEEN 2000-2015 IN SOUTHEAST ASIA.

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span of that expansion as well as the desired ecosystem services that the forest area could provide (if natural or as a plantation) also need to be considered.

Recommendation 2

Carbon storage can be increased by replacing monoculture cropping with agroforestry systems or adding livestock into monocultures. This practice would have the most impact in areas where herbaceous crops and shifting agriculture practices currently exist; it would also be effective in areas where tree plantations exist without low growing crops in between. If conservation agriculture techniques were used, agroforestry could improve agriculture profits and improve soil nutrients and moisture without leading to further deforestation. Agroforestry systems contain more aboveground biomass than monocultures, increase soil carbon, reduce erosion, and prevent soil moisture loss (O'Connell et al. 2018). The interplanting of herbaceous crops with tree saplings can enable farmers to obtain income or food in the early years before tree crops begin producing. Herbaceous crop farmers can eliminate burning from their agricultural practices by combining trees and herbaceous plants and adding organic fertilizer to boost soil nutrients, at least in areas where access to organic fertilizer is possible and affordable. Agroforestry can also significantly improve household incomes and nutrition and the diversification of crops can increase resilience to weather, climate, pest, and disease risks (Mbow et al. 2014; Rahman et al. 2017).

Sustainable integration of livestock, including water buffalo, fish, and other aquatic animals, can also improve and diversify farm household livelihoods and may improve soil fertility and texture. Integrated crop and livestock systems were called out in the chapter on the Philippines, but could be implemented across the entire region. While adding animals to a cropping system to reduce carbon might seem counterintuitive, research has shown that such mixed systems are more carbon-efficient and less environmentally degrading than monocultures. This is because animal waste can improve soil nutrients, and in turn, crop residues can be naturally and efficiently cleaned away by animals, improving animal nutrition (Gupta et al. 2012; Lemaire et al. 2015).

TABLE 3: CHANGES IN ABOVEGROUND BIOMASS (AGB) IN NATURAL FORESTS AND ALTERNATIVE CROPS BY ECOFLORISTIC ZONE (TONNES C/HA)

	average C/ha in AGB	C in forest (2000)	C in crops replacing forest (2015)	C lost due to conversion
TROPICAL RAINFOREST		1,342,618,335	187,945,962	**1,154,672,373**
TROPICAL MOIST DECIDUOUS FOREST		123,679,683	25,825,952	**97,853,731**
TROPICAL DRY FOREST		58,819,410	18,718,360	**40,101,050**
TROPICAL MONTANE SYSTEM		55,870,589	13,326,991	**42,543,598**
TROPICAL SHRUBLAND		610,506	160,390	**450,116**
TROPICAL RAINFOREST, PEATLANDS		155,970,675	23,187,350	**132,783,325**
SUBTROPICAL HUMID FOREST		278,355	45,973	**232,382**
TOTAL		**1,737,847,553**	**269,210,978**	**1,468,636,575**

Recommendation 3

Improving yields associated with agroforestry by providing technical and financial assistance may help preserve forests. Some research has shown that when communities are able to derive sustainable livelihoods from natural forests, they are incentivized to keep forests in place (Chhatre and Agrawal 2009; Nepstad et al. 2013). Such livelihoods may include collection of forest products to support family consumption, and it might also include developing enterprises that generate income. However, evidence suggests that while improving farming within forests may help keep forests in place, improving farming efficiency in cleared lands may have the opposite effect and increase forest clearing (Morton et al. 2008; Phelps et al. 2013, among others). This means that any intensification, such as better cultivars, training on conservation agriculture approaches, modern farming machinery, tech solutions to increase connectivity and market access, and assistance with agroforestry systems, must be taken on a case-by-case basis, and must be combined with improvements in governance and enforcement of laws (Enriquez et al. 2020).

Recommendation 4

The ELC granting process and related resource rights issues need to be transparent so that decisions on land use are made with the full inclusion of all land users and potential stakeholders and people are fairly compensated for their lands. In most ELC granting processes, lands historically used by local communities are declared government property and granted or sold to concessions. This not only causes conflict (sometimes quite severe or deadly) between local communities and concessions, but may lead to severe forest degradation in the areas outside of the concession as communities set fires or otherwise exploit their limited remaining lands (Schiedel et al. 2013; Dhiaulhaq et al. 2015). Local people are also often unaware of who owns the concession or how the concession is operated, as these details may be purposely left murky to discourage litigation.

Further, lease prices are often very low, so ELCs are not incentivized to make long-term investments into the land. The result is that in many cases, ELC owners cut timber and then abandon the land, moving on to another low-cost parcel of land after a few years. On top of this, conflicts in mandates among government agencies mean there is often insufficient capacity or incentives for good governance of concessions, allowing land and social abuses to continue (Yasmi et al. 2006). Reforming the granting process so that it is fair, inclusive, considers historic rights, and is transparent about ownership and management regimes would go a long way towards more efficiently using land. While the results of this study did not discriminate ELC expansion from related smallholder crop expansion, data suggest that the bulk of the commodity crops investigated in this study are harvested from ELCs.

Many organizations have been created in recent years to attempt to drive reform in the ELC process. These include, but are not limited to, the Tropical Forest Alliance (TFA) 2020, the Consumer Goods Forum, and the Roundtable on Sustainable Palm Oil (RSPO). The RSPO is a not-for-profit that unites oil palm producers, processors or traders, consumer goods manufacturers, retailers, banks/investors, and environmental and social non-governmental organisations (NGOs), to develop and implement global standards for sustainable palm oil. It has been useful in improving the concession granting and operations processes for oil palm concessions; however, it is voluntary, limited to one sector and does not address concession approval processes. International public and private sector organizations can continue to help governments improve the transparency and fairness of ELC granting. Work with organizations such as these, as well as direct work with governments to encourage tighter concession laws and reduce corruption, will help improve ELC practices.

Recommendation 5

Limited shifting agriculture could be allowed, particularly in already degraded areas or where the other option is large scale ELCs (Ziegler et al. 2017; Dressler et al. 2017). As this and some other studies (Songer et al. 2009; Curtis et al. 2018; De Sy et al. 2019) have now shown, the primary drivers of deforestation or forest degradation today are land concessions for plantations, agricultural expansion of lowland people (in many cases to source concessions), and legal and illegal logging. There has historically been a tendency to lay the blame for deforestation on upland people who belong to minority ethnic groups and practice swidden agriculture. While it is true that shifting agriculture may have been the dominant driver of deforestation pre-2000, that has changed as countries have enacted policies favorable towards more permanent agriculture practices. While efforts to reduce shifting agriculture have sometimes produced improvements in the economic status and food security of upland people, this is not consistently true. Reducing shifting agriculture has also not consistently led to higher quality forested lands, as the fallow components of swidden systems are typically more biodiverse and store more carbon than the permanent agricultural lands replacing them. Allowing some traditional use of forest fallows may improve the livelihoods of marginalized upland populations. A better understanding of the most important drivers of deforestation can help governments improve policies, programs, and enforcement efforts and may promote partnerships with low-income communities living in or near the remaining forests.

Recommendation 6

Continue to work with international agribusinesses to improve their supply chains, to meet consumer and policy-driven demand for deforestation-free products. Over the course of the study period, there has been a movement for change around consumption patterns (as evidenced by RSPO, TFA2020 and movements worldwide for more eco-friendly products). While supply-side interventions (such as those noted above) will help reduce deforestation and make supply chains greener, demand-side and larger structural change is needed as well (Harris 2007; Isenhour 2011). As part of that structural change, many leading international agribusinesses have committed to deforestation-free and/or carbon-neutral supply chains by 2025, and they are doing this largely because of growing consumer demand. As these commitments are met, we would expect to see commodity-driven forest loss to drastically reduce.

One of many complications with greening supply chains is that they are complex and involve many actors. For example, smallholders often produce much of the original source product. Many large oil palm, rubber, coffee and cocoa producers get much of their source raw product from individual smallholders or cooperatives. These smallholders may use fire to clear land, may remove virgin forest, or may use any number of practices that would prevent a supply chain from being deforestation-free, or carbon neutral. It may be difficult for smallholders to adapt to some “green” demands without related adaptations in the pay for or processing of raw materials. Smallholders and public sector organizations that represent them must therefore be brought in early in the process to help agribusinesses understand the on-the-ground realities of supply chains so they can design policies that are climate-friendly and socially just. This study did not quantify the relative amounts of smallholder versus large-scale concession-driven deforestation. However, data shows that for the commodity crops studied here, whether grown at the large or small scale, most crops are typically still part of the same overall global supply chains. Therefore, improving both small- and large-holder practices are essential for reducing deforestation.

Recommendation 7

Land and resource use rights may need to be reformed to increase the incentives for sustainable management of forest resources. National governments throughout the region have historically claimed usage rights to all lands, and will grant usage rights to groups, like plantation corporations, who can quickly maximize revenue from natural resource exploitation. Communities who have used forests and adjacent land for generations often have no legal rights to their lands. Such insecure land tenure reduces the ability and incentive for local people to manage forests as a community and creates economic precarity; such communities may be more likely to engage in illegal forest clearing activities and are less able to act to prevent them. Establishing easily understood and navigated legal procedures for land rights, and granting individual and community rights to manage and use lands is key for encouraging effective management of forested lands (Suyanto et al. 2005; Cocklin et al. 2007).

Registering more community forests (CFs) is one way to address this issue. All countries in the region already have community, social, or village forestry policies or laws in place, but none have yet met their targets for areas under CF. Community forestry has been shown to be an effective tool for sustainable forest management (Gilmour 2016). RECOFTC, the leading community forest (CF) organization in Asia, as well as many other national NGOs, have been assisting communities as they clarify land rights and register community forests for decades. The process can be slow and cumbersome, but as more CFs are registered it has gained momentum. Recent work has found that landscape-wide approaches that expand tenure and usage rights, while reconciling competing land uses across all landscape stakeholders, may provide the best results (Sayer et al. 2013).

Recommendation 8

While this study did not try to quantify illegal logging, controlling illegal timber harvests and stopping the export or import of illegally harvested roundwood is an essential component of reduced deforestation. While logging bans, bans on unprocessed timber and tighter controls on timber harvest have been put into place, large-scale illegal logging remains an issue throughout Southeast Asia, particularly in border areas and in ELCs. Illegal logging is driven by the demand for high-value tree species (such as rosewood and teak) and large wood processing sectors in China and Vietnam, Korea and Japan. The factors enabling illegal logging vary by location, and include weak governance, corruption and patronage networks within militaries and government, and a willingness of neighboring countries to import illegally harvested roundwood. Illegal logging and land clearance most often lead to conversion to agricultural lands in association with ELCs for plantations, which expand beyond their boundaries (spillage). However, displaced or otherwise landless people may also end up converting illegally cleared areas to smallholder farms. Stopping such logging will require that countries recognize laws regarding roundwood export, minimize internal corruption related to forest clearing, and closely monitor the boundaries of ELCs to prevent spillage into neighboring forests and protected areas.

Recommendation 9

Rice cultivation also has a huge impact on carbon storage in landscapes. In addition to releasing carbon dioxide, flooded and drying rice paddies emit nitrous oxide (Majumdar et al. 2000) and methane (Corton et al. 2000), both far more powerful greenhouse gases than carbon dioxide. There are ways to reduce emissions from rice paddies, such as by altering wet/dry regimes, and adding different fertilizers or soil additives (Hussain et al. 2015). Rice was not a major contributor to deforestation in the 2000-2015 period covered in this study. That is likely because deforestation for rice cultivation to support domestic consumption and exports had largely happened in the previous decades or centuries, given that rice has long been a staple of Asian diets. Providing recommendations on reductions in or behavior change related to rice cultivation is outside the scope of this study. However, if the goal is to reduce greenhouse gas emissions from the land use sector, techniques to reduce emissions from rice paddies must be more widely scaled, along with practices, such as integrating border trees, that can capture carbon in the landscape.

CONCLUSIONS

This study found that almost 1.5 billion MT of carbon has been lost from landscapes due to the conversion of forested lands to agriculture in Southeast Asia. However, contrary to prevailing beliefs, recent deforestation and related landscape carbon loss was not due to economic land concessions (ELCs) of crops like oil palm and rubber. While these crops were the prime driver of deforestation in Indonesia between 2000 and 2015, they were not the main driver across the whole region. At a regional level, the dominant driver actually appeared to be traditional herbaceous row crops, rice, or orchards, or some combination of these. This does not mean that the contribution of oil palm and rubber to deforestation should be minimized. They are indeed significant; however, when policymakers are looking for ways to minimize deforestation across Southeast Asia, the focus should be broadened to include a wider array of commodity crops.

Of the seven types of forest covered by our study, the most significant reductions in stored landscape carbon were due to loss of tropical rainforest, which were primarily converted to herbaceous crops, or other land with unidentifiable herbaceous or grassy land cover, accounting for over 8 million hectares of converted forest. After herbaceous crops, the next most common crop to be grown on former rainforests were palm crops. Of those land covers that could definitively be identified as crops, 139,796,328 hectares were covered in monoculture crops, while just over 129,000,000 were covered in some form of agrisilviculture. Based on these findings, our primary recommendation is to focus on implementing agroforestry practices more broadly in existing monoculture plantations. This can quickly improve landscape carbon storage, while also likely improving production capacity and some ecosystem services.

Implementing the recommendations noted in this report will require significant commitments from subnational and national governments along with regional cooperation. Above all this will require improved governance in land administration and land tenure. Tropical deforestation and related agricultural expansion cannot be slowed through supply-side approaches alone. Demand-side approaches, such as awareness-raising about consumer choices, have been somewhat successful, in limited areas, but these must be expanded. Of course, there is no one-size-fits-all strategy for land conservation and management, and some sort of mix of the recommendations noted above, as well as others not touched on by this study, will need to be employed to meet both economic and environmental needs.

Maximizing economic and environmental benefits are complex problems that involve changing, contradictory and difficult to identify needs. To address these needs, future research on tropical land management and carbon storage should focus on a number of areas where practical data is still insufficient. This would include trials of different types of agroforestry practices, improved understanding of how to minimize inefficiencies in commodity supply chains so as to reduce waste, and improved deforestation-free business models that can help small-scale harvesters and producers to maximize economic gains while preserving their landscapes.

There is, however, no need to wait for future studies before taking action. Policymakers and practitioners across the region are already implementing all of the recommendations noted above, but the issue is that the implementation is limited in scale and scope, and is not always locally adapted. The onus now is on national and local governments to trial and scale those best practices which are appropriate for their nations and the communities in them. There are ways to reconcile economic and environmental goals, but they require governments to break free of business-as-usual policies. Only through innovative, pro-people, pro-environmental policy change will the region begin to follow a path of climate-friendly development that preserves life on land while still helping its people realize a life without hunger or poverty.

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ANNEX: SUPPLEMENTAL METHODS

A. Sample Design

The annual GFC maps indicate locations with forest canopy losses using the Landsat image archive (Hansen et al., 2013). Like the Landsat data, these maps have a 30 m2 resolution and thus allowed us to determine forest loss at the same scale. However, it includes canopy cover loss as a result of both natural forest conversion to agricultural use, and tree cover loss as a result of harvest cycles of established tree plantations. To differentiate between these two types of tree cover loss, we overlaid a regional land cover map for the year 2000 (Stibig et al., 2003a, 2003b, 2004). By combining these two maps we represented hot spots of canopy cover loss in areas classified as a both forested and non-forested land use.

Forested land use in the regional land cover map was defined using the following map classes:broadleaved, evergreen closed and closed to open tree canopy cover; broadleaved, deciduous, mainly open tree cover (including dry Dipterocarpus); regularly flooded mangrove tree cover; and regularly flooded swamp tree cover (Stibig et al., 2003a, 2003b, 2004). These regional land cover maps were created from the VEGA 2000 dataset, which is composed of 14 months of pre-processed daily global data acquired by the VEGETATION instrument on board the SPOT 4 satellite from the European Joint Research Centre; each pixel is an approximately 1 km2 (Bartholome and Belward, 2005).

Due to the large size of the map resolution, it is likely that the loss of forest fragments and small forest patches were excluded in this baseline forest loss strata. As a result, if we used this map strata alone, we would not capture changes in tree canopy cover that were small, fragmented forest patches. Therefore, we maintained the forest loss regions that were not co-located with the forest regions in the 2000 land cover maps (Stibig et al., 2003a, 2003b, 2004). The resulting map included three strata: 1) areas that are more likely to be large patches of intact 'natural' forest in 2000 and which experienced canopy cover loss, 2) areas with lower probability of being 'natural' forest in 2000 and which experienced canopy cover loss, and 3) all other areas. Stratum 3 is comprised of the areas that lie outside of the forest loss layer as defined by the GFC data. In this stratum we sampled a small number of points in order to assess the potential for forest loss in areas that were classified as either stable not forest or stable forest (i.e., no change or loss). Table 1 indicates the area in each stratum per country, and Table 2 indicates the sample allocation per strata by country.

Table 1. The area covered by each stratum in the study countries. "Loss Area" is the sum of strata 1 and 2.

Country	Strata 1 (ha)	Strata 2 (ha)	No Loss, Strata 3 (ha)	Total area (ha)
Cambodia	4.8% (875,284)	5.1% (922,311)	90% (16,329,763)	18,127,358
Indonesia	4.4% (8,324,441)	6.5% (12,512,668)	89.1% (169,619,791)	190,456,900
Laos	1.1% (242,460)	7.1% (1,631,055)	91.8% (21,115,898)	22,989,413
Myanmar	0.9% (599,379)	2.8% (1,863,779)	96.3% (64,255,959)	66,719,117
Philippines	0.5% (166,007)	2.3% (686,867)	97.2% (29,147,220)	30,000,094
Thailand	0.3% (178,405)	2.6% (1,334,277)	97.1% (49,901,653)	51,414,335
Vietnam	1.1% (348,394)	4% (1,319,799)	94.9% (31,059,507)	32,727,700

Table 2. Allocation of plots per strata in the sample for each country, and the overall number of samples for the region.

Country	Strata 1	Strata 2	Strata 3	Total
Cambodia	365	385	250	1,000
Indonesia	479	721	400	1,600
Laos	200	550	250	1,000
Myanmar	200	550	250	1,000
Philippines	200	550	250	1,000
Thailand	200	550	250	1,000
Vietnam	200	550	250	1,000
Regional	1,884	3,856	1,900	7,600

We also integrated a visually interpreted forest loss data set collected across the five Mekong basin countries using methods consistent with this effort (Potapov et al., 2019). All of these additional sample points were all located in strata 3. This allowed us to increase our sample size in order to reduce uncertainty in our area estimates of activity data. Their sampling unit was slightly different than ours, a square 30 m plot representing the Landsat pixel. They labeled net tree cover change and rotation at each plot . The label options for this work included NA (stable with respect to tree canopy), tree cover rotation, partial tree cover gain, partial tree cover rotation, tree cover gain, tree cover loss, and partial tree cover loss. The partial labels represent a change type that affects only a portion of the pixel. Any sample that experienced a forest loss was re-interpreted by our team to determine the subsequent 2015 land cover and use. This supplemental data was not available for the Philippines and Indonesia; therefore, the photo-interpreters labeled all plots in strata 3 in these countries.

Table 3. Summary of distribution of points in stratum 3.

Class	Cambodia	Laos	Myanmar	Thailand	Vietnam
NA	181	219	798	578	308
Tree cover gain	3	6	16	34	15
Tree cover gain, partial	2	6	11	19	9
Tree cover loss	22	14	28	22	17
Tree cover loss, partial	5	3	16	8	9
Tree cover rotation	8	55	108	55	58
Tree cover rotation, partial	2	8	41	13	9

B. Land Cover Definitions and Classification Key

Question 1, Land Cover: Rubber, Pulpwood (Acacia/Eucalyptus), Fruit/Nut, Oil Palm, Coconut, Banana, Coffee, Tea, Aquaculture, Rice, Other Crop, Other Tree, Other Palm, Other Shrub, Bamboo, Herbaceous, Non-vegetated, Water, Built-up, Other

Question 1a, Understory Present: Yes/No

Question 1b, Understory Cover: Coffee, Tea, Rice, Other Crop, Water

Question 2, Agricultural Land Use:

Plantation: tree commodities grown in a dense monoculture.

Terrace: Tree or shrub crops grown following the contours within the landscape. This system is typically done in a dense monoculture but may have other commodities or natural vegetation between rows while the primary commodity develops into maturity. Plantings in this system are often rubber or a shrub crop.

Agrisilviculture systems: Simultaneous growing of low-growing crops and trees; a highly variable system that may be made up of other structurally different subsystems like mixed, strip or boundary agrisilviculture. If one of these subsystems can't be identified, or if some other unidentifiable agroforestry is present, land use calls were grouped into agrisilviculture.

Mixed Agrisilviculture: Low growing crops intermixed with trees

Strip Agrisilviculture: Alternating patterns of tree and crop plantings, several rows wide

Boundary Agrisilviculture: Trees planted for delineation between farms or roads and farms

Silvopastoral systems: Agroforestry that integrates livestock, forage production, and forestry on the same land management unit

Natural Forest: Land with a minimum of ten percent tree canopy cover that remains mostly unchanged from its natural state

Other: All remaining land uses not classifiable or identifiable as one of the other label options, such as croplands with no trees present, open water, or cultural lands

Question 3, Land Use, Year 2000:

Forest Commodity: lands likely to be rotational tree commodity crops (e.g., pulpwood)

Natural Forest: lands likely to be natural forest

Other: all remaining land uses, such as croplands with few to no trees, water, or cultural lands

Classification key is accessible at https://rlcms-servir.adpc.net/docs/nwc96inp4h/class.pdf

C. Main agricultural commodities of the selected countries

In line with the objective of identifying main agricultural commodities which possibly involved conversion of forest for their expansion, we used their total expansion area in the country as a selection criterion. The expansion area is most often proportionally to the trading/export value. For example, Vietnam is one of main exporters for coffee and rice, and the cultivations of these two commodities are among the most expansive in the country. Indonesia is the biggest exporter of oil palm in the world on top of Malaysia, Thailand, Columbia and Nigeria, and the country has millions hectare of oil palm plantation.

Vietnam

Rubber and acacia are dominant commodities within the category of forest plantation, with a total expansion area reached 972 thousand ha for rubber (GSO 2017) and about 1.1 million ha for acacia (Nambiar et al. 2015). Related to perennial crops, coffee, tea and different kind of fruit/nut trees occupied a total area of about 1.45 million ha, and of this total, coffee occupied 665 thousand ha which is comparable to the total expansion area of fruit trees (sum of grape, mango, orange, mandarin, longan, litchi, rambutan, and cashew nut), while tea 129 thousand hectares (GSO 2017). Related to annual crops, paddy is the most dominant with a total cultivation area of 7.71 million ha, while different annual crops (maize, sugarcane, peanut, soybean, sweet potato, and cassava) account for 12.1 million ha. Of this, cassava occupied 10.3 million ha but mainly as an intercrop in acacia and rubber plantation.

Indonesia

The export value of the country's crude oil palm reached USD 18.6 million in 2016, from the total cultivation area of 11.8 million ha (GAPKI and Ministry of Agriculture of Indonesia cited in Indonesian Investment 2017a). Of the total area, around 70% is in Sumatra island, and the rest is mainly in Kalimantan. Another commodity with a large expansion area is rubber, namely 3.6 million ha in 2015, mainly located in North and South Sumatra province, Riau, Jambi, and West Kalimantan (Gapkindo cited in Indonesia Investment 2018). In 2017, coffee plantations in the country covered an area of approximately 1.24 million hectares, of which 933 thousand hectares of robusta and 307 thousand hectares of arabica plantations (AEKI cited in Indonesia Investment 2017b). The cultivation area spread in Bengkulu and Lampung province of Sumatra and South Sulawesi for robusta, and in Aceh and North Sumatra province for arabica. Tea is still one of main agricultural commodities in the country although its total expansion area has declined over the recent years to about 101.3 thousand ha in 2016 (Mahesa 2017). The cultivation spreads mainly in West Sumatra and across province of Java island, and the reduction in area was driven by the conversion of tea into other more profitable crops such as oil palm or vegetables. However, the tea production has remained relatively stable, due to higher productivity of remaining plantation (Indonesia Investment 2016).

Cambodia

According to the Census of Agriculture of Cambodia (2013), the agricultural commodity with the largest expansion area was rubber, namely 75.4 thousand ha, followed by cashew (60 thousand ha), mango (41 thousand ha), and banana (24 thousand ha). Other commodities such as coconut and fruit trees had cultivation area below 10 thousand ha. In terms of export, rice and cereals were likely the main products, with a record of 180.3 thousand tons of exported cereal and 174 thousand tons of exported rice in 2011.

Laos

According to the Trading Economic (2019), the exported agricultural products from the country include wood, coffee, maize and rubber, with Thailand, China and Vietnam as the main partners. Welcher and Prasertsri (2019) informed the volume of exported rice from Laos during the period of 2017-2018 produced from the total harvested area of about 900 thousand ha. The Ministry of Agriculture and Forestry of Laos (2015) reported the area of rice in the mountainous and plateau areas of the country was 13-15 thousand ha, and in plain areas was 650-800 thousand ha. In terms of perennial crops, coffee was cultivated mainly in the mountainous and plateau area with total area of about 130 thousand ha, and rubber mainly in plain areas with the total of cultivation area of 300 thousand ha.

Myanmar

JICA (2013) listed ten major crops of the country from the point of view domestic consumption or income from export, namely rice, sugarcane, cotton, maize, groundnut, sesame, sunflower, black and green gram, and pigeon pea. Koh (2013) added rubber and oil palm, and different kinds of fruit trees (mango, plum, avocado, jackfruits, dragon fruits, pineapples, orange) as major crops. In terms of area, the author reported that 34% from the total cultivation area was occupied by paddy, pulses 19%, oilseed 16%, and only 5% of industrial crops. Esler (2011) informed that related to forest plantations, woods of teak, acacia, bamboo, and ironwood have been exported.

Thailand

The main annual crops of the country include rice, soybean, cassava, and sugarcane. In terms of perennial crops, include coffee, rubber, coconut, oil palm, and different kinds of fruits such as durian, mangosteen, rambutan, longan, salak, and langsat. The country is the main exporter of rice in the world and about half of the national cultivation area is allocated for rice (Poapongsakorn and Chokesomritpol 2017). For coffee, in general, arabica variety is grown in northern part of the country, and robusta in the south. According to 2013 statistics from FAO, the cultivation of coffee reached about 51 thousand ha. The country is one of the top exporters of crude oil palm in the world, and nearly 85% of oil palm plantations are in southern part of the country. Another export commodity is rubber, with the total cultivation area of about 20.6 million rai (1 rai is equivalent to 1,600 m2) in 2018 (Arunmas 2018).

Philippines

Philippines Statistics Authority (2015) listed the top 19 crops which could be classified as the main crops of the country, other than paddy and maize, namely coconut, sugarcane, banana, pineapple, coffee, mango, tobacco, abaca, peanut, mung bean, cassava, sweet potato, tomato, garlic, onion, cabbage, eggplant, calamansi and rubber. Total harvested area of paddy was reported to expand from 4.35 to 4.74 million ha during the period of 2010 - 2014. The area of maize also expanded from 2.56 million ha in 2013 to 2.61 million ha in 2014. In terms of perennial crops, the cultivation area of coffee increased by 0.9% from 116.46 thousand ha in 2013 to 117.45 thousand ha in 2014. The most dominant variety was robusta with production accounted for 69.1% from the national production, on top of arabica (23.9%), excelsa (6.3%), and liberica (0.7%). For rubber, the total cultivation area reached 217.69 thousand ha in 2014, 17.4% larger than the area in 2013.

D. Area Estimation of Activity Data

The percent cover of the area for each commodity crop was estimated following the approach presented by Patterson (2012). The analysis was conducted using custom scripts written in the R statistical programming language (R Core Team, 2019). These estimators make use of an infinite population sampling framework and treat the plot-level systematic grid as a random sample, producing a conservative estimate of variance at the plot scale. The use of these estimators allows for a relatively straightforward calculation of the proportion of coverage of a single landscape element and the associated variance, and for the estimation of one landscape element occurring within another, with an associated variance.

This is done by converting the initial data into a series of binary (0/1) indicator variables for landscape elements of interest, using the following logic, where s denotes a given sample point:

$$y_c(s) = \begin{cases} 1, & \text{if } s \text{ is in condition } c \\ 0, & \text{otherwise} \end{cases}$$

$$y_o(s) = \begin{cases} 1, & \text{if } s \text{ falls on object } o \\ 0, & \text{otherwise} \end{cases}$$

$$y_{o|c}(s) = \begin{cases} 1, & \text{if } s \text{ is in domain } c \text{ and falls on object } o \\ 0, & \text{otherwise} \end{cases}, \text{ note } y_{o|c}(s) = y_c(s)y_o(s)$$

These indicator variables can then be used to calculate the proportion of coverage, using the following equation:

$$\hat{P}_c = \sum_{h=1}^{H} W_h \bar{p}_{ch}\text{, where } W_h = \|R_h\|/\|R\|$$

Where h indicates the stratum, R is the area of the study area and R_h is the area of the stratum, and p_{ch} is the average of y_c across all the plots within the stratum. The variance can similarly be calculated using an equation of the form:

$$\hat{V}(\hat{P}_c) = \sum_{h=1}^{H} W_h^2 \frac{1}{n_h(n_h-1)} \left| \sum_{i=1}^{n_h} p_{chi}^2 - \frac{1}{n_h}\left(\sum_{i=1}^{n_h} p_{chi}\right)^{-} \right|$$

Where n_h is the number of samples within the stratum, and p_{chi} is the proportion of cover of y_c for a given plot i in stratum h. The proportion of a particular landscape element occurring within some other element c is found using similar equations. Multiple conditions/objects can be used together to produce an estimate of areas that meet more than one criterion simultaneously. For example, one could use a condition that the sample location must have been 1) forest in 2000 and 2) a crop commodity of interest.

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