LETTER

Guiding Agricultural Expansion to Spare Tropical Forests

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Abstract

Commodity crop expansion in the tropics presents the challenge of preserving tropical moist forest (TMF) ecosystems and their role in carbon sequestration. We propose an algorithm, specific to the TMF biome, which identifies 125 million ha of degraded, low-carbon density land (LCDL) in the Pantropical TMF belt for agricultural expansion. About 65 million ha of LCDL are in contiguous tracts >5,000 ha and <500 m elevation, meeting the prerequisites for commercial-scale oil palm production, the fastest-expanding industrialized commodity crop in the TMF. These areas could support expansion of commercial agriculture for another 25–50 years without further conversion of TMF. Confining agricultural expansion to the LCDL can avoid the release of approximately 13 billion tons of CO_2 while saving valuable tropical biodiversity. The simplicity and transparency of this easily monitored metric could prove useful to producers, governments, investors, environmental stewards, and consumers and enhance good governance in tropical regions.

Introduction

Expansion of industrialized agriculture into tropical moist forests (TMF) has increased dramatically over the last century, compromising the survival of Earth's most biodiversity-rich forests (Laurance 1999; Gibbs *et al*. 2010; Foley *et al*. 2011). TMF conversion also contributes 6–17% of global anthropogenic CO_2 emissions (Ven der Werf *et al*. 2009). Despite the priorities assigned by biologists for biodiversity conservation, agricultural production goals tend to trump these considerations when expansion is planned (Foley *et al*. 2005). Achieving concurrent goals of provisioning the planet's growing human population and maintaining biological diversity, including vital necessary ecosystem goods and services from those forests, requires an urgent paradigm shift.

With this analysis, we provide one possible way to reconcile biodiversity conservation and agricultural expansion goals in the Pantropical TMF belt. We identify areas of very low above ground biomass (carbon density) that are likely anthropogenically produced, some of which may be assigned by local and federal governments for potential large-scale commodity crop expansion that will spare important biodiversity areas. Our rationale is TMF that has already been stripped of high carbon cover (or biomass) will also support less important biodiversity than intact forests. Because such degraded TMF can take decades, or even centuries, to recover and fully mature (Chazdon 2003), these lands will have less conservation value relative to intact forests that should be spared from agricultural development. With soil fertility improvement and

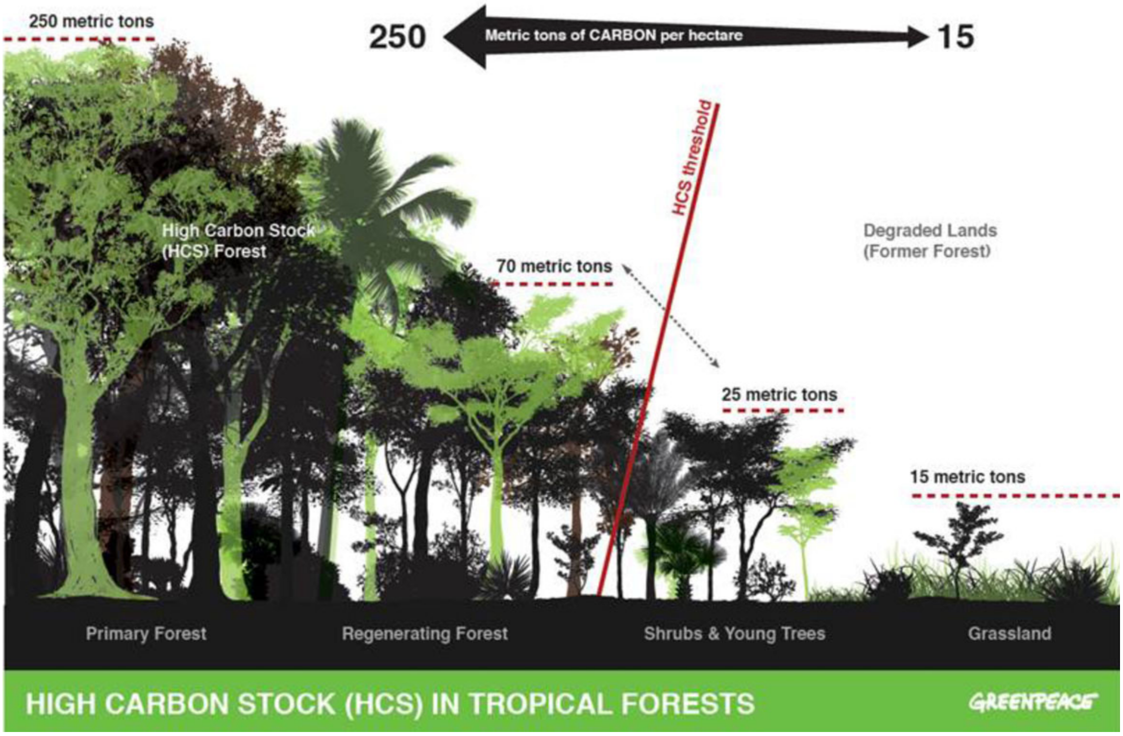

Figure 1 A cross-section of tropical moist forest illustrating the dramatic increase in biomass (and by extension carbon), and three-dimensional complexity as succession proceeds from cleared or scrub to intact primary rainforest. The 40 tons threshold line has been adopted by several leading producers of palm oil as the carbon density above which it will not source. The biological value of tropical moist forest lands above 40 tons of AGC/ha is clearly higher than areas below this threshold (figure modified and used with permission of Greenpeace).

other techniques, the degraded forests can be used for agriculture expansion with reduced loss of biodiversity and CO_2 emissions associated with deforestation (Foley *et al*. 2011; Mueller *et al*. 2012). Here, we offer a Pantropical delineation of areas we call low-carbon density lands (LCDL) in the TMF biome that can be used to direct commodity agriculture in order to spare intact, mature TMF from conversion.

We used Above Ground Carbon density (AGC) as a metric to identify LCDLs. We suggest that AGC is a useful parameter to avoid debate over what constitutes forest and high conservation value (HCV) forest and how to measure these uniformly. We chose $\leq$ 40 metric tons of AGC/ha as a threshold to identify low-carbon, degraded TMF because it very closely approximates the value used to assess High Carbon Stock Forests by Greenpeace, the Forest Trust, Golden Agri, and now a growing list of producers, as a way to avoid biodiversity rich forests during oil palm development and expansion (Greenpeace 2013; Figure 1).

In presenting this framework, we emphasize the following: (i) the $\leq$ 40 mTons/ha AGC density threshold is specific to the TMF biome; it is inappropriate for other tropical biomes where tree cover is naturally sparser (e.g., savannas and woodlands, monsoon and dry forests, and scrub), but which have high conservation values for representative biodiversity that includes large herbivores, carnivores, frugivores, and other keystone species; (ii) because of the Pantropical scale of this analysis, any agricultural initiatives in the LCDLs should be preceded by finer-scale biological assessments to determine that they do not support endemic species, are not vital to landscape connectivity and conservation, and are not important forests that are regenerating; (iii) socioeconomic analyses are necessary to ensure appropriate safeguards are in place to protect livelihoods and tenure rights of people in the area; and (iv) biophysical assessments to ensure appropriate safeguards for conservation of ecosystem processes and services.

Methods

We used WWF's Terrestrial Ecoregions of the World (Olson *et al*. 2001) and the global high-resolution map of range-restricted species (Jenkins *et al*. 2013) as initial filters to avoid high endemism forests (especially to deselect montane forests where vertebrate endemism is high).

Next, we identified the total amount of low-carbon density lands (LCDL-t) across the Pantropical TMF biome using a raster-based GIS model in ESRI ArcGIS software. We applied the ≤ 40 metric tons per hectare AGC threshold to the Baccini *et al*. (2012) Pantropical above ground biomass raster dataset.

We first applied several land use and terrain filters that serve as conservation and social safeguards to the LCDL-t (Figure 2). The output, LCDL-f, consists of a database that excludes all landuse areas important for conservation and socioeconomic values.

The first set of filters excludes (1) protected area polygons that include all designations and categories (in the TMF biome) from the WDPA database (IUCN UNEP 2013); (2) small-ranged hotspots consisting of 3 or more taxa from Jenkins *et al*. (2013); and (3) peat-dominated ecoregions, due to their vast stores of below-ground carbon (Olson *et al*. 2001) as an initial conservation safeguard.

The second set of filters included biophysical characteristics to exclude: (1) hill slope > 20% as too steep for agriculture, derived from the Shuttle Radar Topography Mission (SRTM) (Jarvis *et al*. 2008) 90 m global dataset by resampling to 500 m resolution and using a majority cell value method; and (2) water bodies identified by MODIS land cover product (MCD12Q1) category 0 following the International Geosphere-Biosphere Programme (IGBP) class scheme (https://lpdaac.usgs.gov/products/modis_products_table/mcd12q1).

The third series of filters addressed human-dominated areas, excluding: (1) existing urban areas identified by MODIS land cover product (MCD12Q1) category 13 following the IGBP class scheme; and (2) existing agriculture derived from MCD12Q1 croplands (category 12) and cropland/natural vegetation mosaic (category 14) following the IGBP class scheme.

Country statistics were generated using the Global Administrative Areas (GADM) Version 2.0 database (http://www.gadm.org/). Country boundaries were rasterized to match the 500 m results from the LCDL model and spatial statistics generated iteratively for each nation. A GIS zonal statistics approach was used to summarize LCDL extent within country boundaries.

For cost effectiveness, commodity crops require large areas; we identified remaining aggregations of low-elevation, low-carbon density TMF larger than 5,000 contiguous hectares to yield the set of LCDLs (LCDL-5000) for industrialized agriculture by: (1) excising areas above 500 m asl calculated from the SRTM dataset; and (2) retaining only contiguous aggregations ≥ 5,000 ha. We also projected the demand for the 23 most important

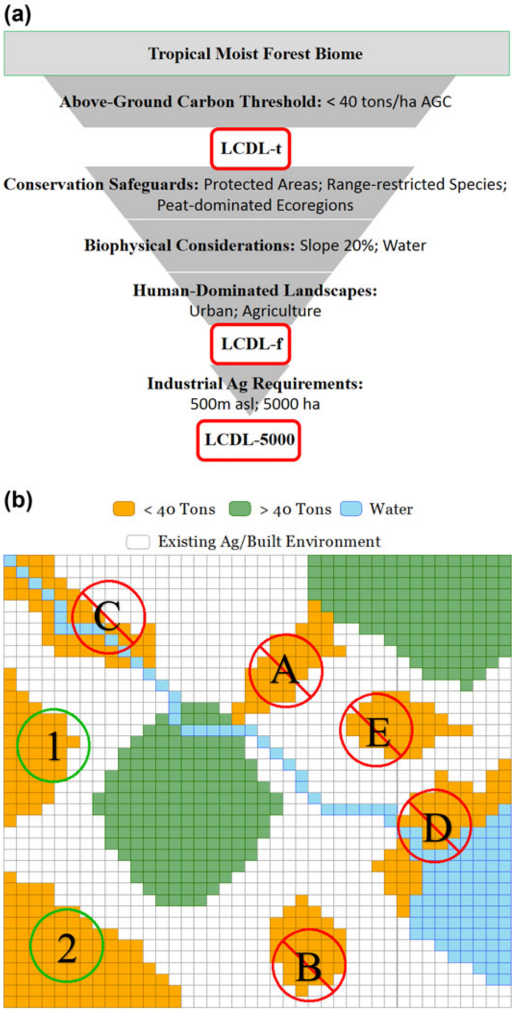

Figure 2 (a) A schematic of the filtering process and variables used to derive large, low-elevation industrialized agricultural lands (LCDL-5000) from all low carbon density lands <40 tons/ha located in the wet forest belt (size of filters is not to scale of results). An essential biological or biophysical safeguard missing from the above set is the need to classify and filter out all riparian buffers as set-asides. Future iterations of this algorithm will explore appropriate datasets by continent to incorporate this filter. (b) A schematic illustrating a second set of landscape-scale biological and social safeguards could prevent important areas for conservation and local livelihoods from being assigned to conversion even though they have passed through the first set of filters (Figure 2a) and are <40 tons of AGC/ha. Areas in white represent existing agriculture, settlements, or the built environment. In this hypothetical case, several sites were deselected (red "No" symbol) from consideration followed by the rationale: (A) stepping stone; (B) habitat for several endemic plants and vertebrates with narrow range; (C) in riparian zone, which should designate all buffers as off limits to development; (D) adjacent to a critical watershed; (E) land–tenure conflict. The remaining two sites of LCDLs, labeled 1 and 2 inside a green circle, have passed through all relevant safeguards and may be considered by appropriate administrative agencies for possible industrial agriculture expansion. Sites deselected by the landscape-scale filters can be monitored via new watchdog initiatives such as Global Forest Watch (www.globalforestwatch.org, Hansen *et al*. 2013).

crops using the trajectories from Balmford *et al.* (2005). In our estimation of the ability of LCDL-5000 to absorb the expanding industrialized agriculture "footprint," and to be relatively conservative, we chose to apply (from the Balmford *et al.* (2005) analysis) their intermediate-level relative production estimates (ranging from 17% to 29% above 2010 levels). Through FAOSTAT (FAO 2013), we compiled data related to the area of oil palm, sugar cane, and natural rubber harvested in 2011.

Assigning degraded lands to absorb the expansion of commodities agriculture is ultimately a sovereignty issue. Local, regional, or federal agencies, however, could incorporate science-based, landscape-scale features and attributes that help to determine suitability of LCDLs for commodities production. To this end, we offer a set of criteria that could assist the decision-making process and also avoid scenarios where LCDLs that appear suitable for the global scale filters are re-evaluated and even deselected using appropriate landscape scale safeguards (Figure 2b).

For this study, we considered only aboveground carbon—the largest forest carbon pool. We also considered only gross CO_2 emissions and assumed that all carbon will be released when forests are converted into industrial agriculture. We did not consider subsequent carbon sequestration in crops and plantations, as they will have different growth rates and will be harvested under the 50-year time horizon. We used mean aboveground biomass values for TMF (IPCC 2006) to derive mean AGC density for each country, and calculate the amount of CO_2 emitted when a hectare of mature TMF is cleared. For degraded (LCDL-5000) forest, we calculated CO_2 emitted when 40 tons of AGC/ha is removed. We computed the difference between CO_2 emitted from conversion of mature forest versus LCDL-5000 as the amount of gross emissions avoided.

Results

Distribution of LCDL by country

We identified 125 million ha of LCDL-f and 65 million ha of LCDL-5000 across the Pantropical belt (Figure 3). Ten countries hold 54,955,992 ha, or about 84% of the entire LCDL-5000 estate, with nearly 40% in Brazil, followed by India (14%), Mozambique (6%), Myanmar (5%), Indonesia (4%), Tanzania (4%), Democratic Republic of Congo (3%), Somalia (3%), Kenya (3%), and Colombia (2%), each holding more than 1 million ha (Table 1). Every country in the TMF belt has at least 0.2% of the total land area in LCDL-5000.

Distribution of LCDL by ecoregion

The Neotropic and Afrotropic ecoregions have the most LCDL-f, and the Neotropic ecoregions the most LCDL-5000 (Figure 3). Of the 192 TMF ecoregions, 121 have LCDL-5000; i.e., blocks > 5000 ha and < 500 m elevation. The 5 largest extents are in the Mata Grosso seasonal forests (Neotropics), Eastern highlands moist deciduous forest (Indo-Malayan), Northern Zanzibar-Inhambane coastal forest mosaic (Afro-tropics), Southern Zanzibar-Inhambane coastal forest mosaic (Afro-tropics), and Alto Paraná Atlantic forests (Neotropics).

Projected increase in additional agricultural area

With a projected increase of 17% to 29% for three key commodity crops, oil palm, sugar cane, and natural rubber, we estimated 60 and 66 million ha (corresponding to 17 or 29% increase) additional land needed for expansion to meet future demand over a 50-year time horizon (Table 2). In the Neotropics, expansion of industrial crops will be dominated by sugar cane, with over 2 to 3.6 million more ha under the 17% and 29% scenarios, respectively. The Afrotropics are projected to have 1.3 million ha of oil palm plantations under the 29% scenario, and in the Indo-Malayan/Australasian realm there will be between 2.5 and 3.2 million ha of new oil palm, rubber, and sugar cane plantations.

Potential for avoided emissions

About 13 billion tons of CO_2 emissions can potentially be avoided by shifting industrialized agriculture expansion to LCDL-5000 and away from intact forests (Table 1, Figure 4).

Discussion

Using the LCDL map

Forest clearing for industrialized agriculture is a dominant driver of biodiversity loss in the TMF belt (Geist and Lambin 2002; Gibbs *et al.* 2010; Wilcove and Koh 2010). Assuming all safeguards are accounted for and rigorous local Environmental Impact Assessments completed at candidate sites, our map can help to redirect industrialized agriculture expansion from biodiversity-rich TMFs to the LCDL-5000, with low biodiversity values. Clear partitioning of land will also help the commercial sector build demand for production and products that respect conservation safeguards and sustainability compliance (Auld *et al.* 2008), and provide civil society watchdogs with a transparent tool to verify compliance.

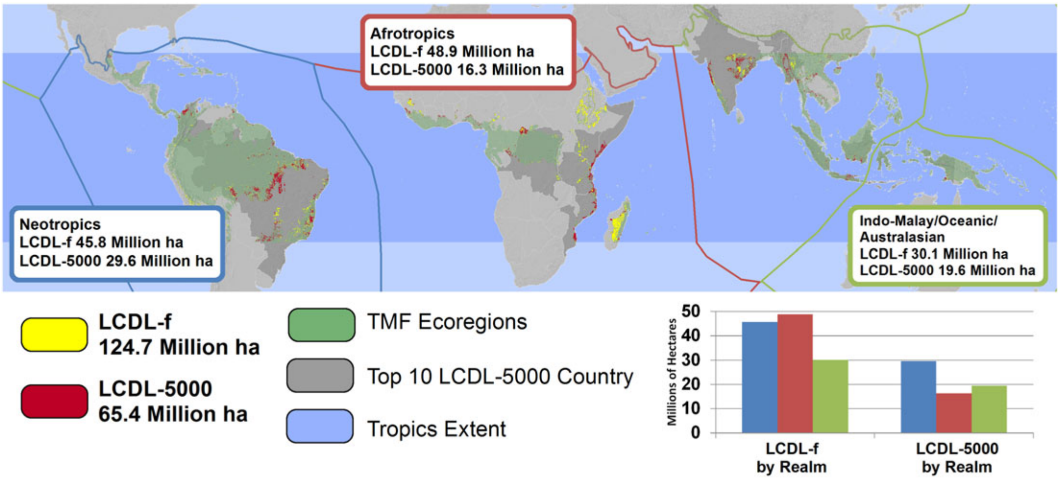

Figure 3 Global results of LCDL-f and LCDL-5000 lands identified and summarized by realm. The colors of the bars in the graphs correspond to the biogeographic biome boundary lines in the global map.

Table 1 Area distribution (ha) of low-carbon density lands (e.g., < 40 tons AGC/ha), LCDL-f, and LCDL-5000 (areas best suited in size and elevation for commodity crops) within the 10 countries holding the largest amounts of degraded lands. Shifting agricultural expansion to degraded lands (using IPCC data) illustrates a dramatic reduction in CO_2 emissions

Country	LCDL	LCDL-f	LCDL-5000	Realm	CO_2 emission tCO_2e converting non-LCDL forest	CO_2 emission tCO_2e converting LCDL-f forest	Reduction in CO_2 emission (tCO_2e) by converting LCDL-5000 instead of non-LCDL forest
Brazil	274,475,487	36,697,411	25,711,532	NT	9,748,098,832	3,771,024,693	5,977,074,139
India	128,874,952	14,192,605	9,378,235	IM	2,909,128,497	1,375,474,467	1,533,654,030
Mozambique	44,571,527	4,443,979	4,033,196	AT	1,807,140,688	591,535,413	1,215,605,274
Myanmar	16,275,733	5,007,211	3,308,234	IM	1,026,214,187	485,207,653	541,006,533
Indonesia	24,838,697	4,351,078	2,809,922	NT	1,401,214,437	412,121,893	989,092,544
Tanzania	66,271,442	4,185,925	2,609,003	AT	1,169,963,912	382,653,773	787,310,139
DRCongo	54,801,182	3,706,172	2,073,195	AT	928,929,573	304,068,600	624,860,973
Somalia	61,366,434	1,917,115	1,758,121	AT	787,755,416	257,857,747	529,897,669
Kenya	53,754,837	3,313,530	1,699,026	AT	761,276,916	249,190,480	512,086,436
Colombia	22,025,668	2,434,495	1,575,530	NT	597,335,941	231,077,733	366,258,207
Total	747,255,959	80,249,521	54,955,994		21,137,058,399	8,060,212,453	13,076,845,946

The map of terrestrial vertebrate distribution (Jenkins *et al*. 2013) as an additional filter had little impact on LCDL area. This is likely because most of these species were already included in conservation areas or in areas already removed by the >20% slope filter; the majority of endemic vertebrate species residing in TMF occur in upland areas. But, much of the endemism may be among the plants and invertebrates, two large groups that are unlikely to be surveyed uniformly across the tropical belt in the next several decades. Thus, by sparing the intact and mature TMF or in other words, the High Carbon Stock stands, this Pantropical LCDL map will serve as a proxy to save important forest-dependent biodiversity, including the "uncounted biodiversity."

We acknowledge that some of the LCDL may already be used by indigenous or local community groups, or support high-density rural populations adjacent to degraded forests and scrub. These occurrences could result in land use conflicts if considered for industrialized agriculture without social impacts assessment, especially in the LCDL-5000 fraction. By excluding indigenous reserves from the LCDLs, we include an initial safeguard. But we explicitly recommend that using this LCDL map as a guide to locate industrialized agriculture projects should be tailored by appropriate environmental and social risk analyses and safeguards at the relevant footprint scales (Figure 2b)—expected of any projects of industrial scales—to respect tenure

Table 2 Crop expansion calculated over next 50 years following Balmford *et al*. (2005) intermediate prediction curves and calculated for FAOSTAT production values

Region	Agriculture type	Area (ha) in 2011	Area (ha) with 17% increase	Area (ha) with 29% increase
Neotropics				
	Oil palm	838,106	980,584	1,081,157
	Rubber	239,761	280,521	309,292
	Sugar cane	12,686,710	14,843,450	16,365,856
Afrotropics				
	Oil palm	4,568,015	5,344,578	5,892,739
	Rubber	711,914	832,939	918,369
	Sugar cane	1,416,986	1,657,874	1,827,912
Indo-Malaya/Oceania/Australasia				
	Oil palm	10,971,328	12,836,454	14,153,013
	Rubber	8,760,681	10,249,996	11,301,278
	Sugar cane	10,937,579	12,796,968	14,109,477
Global	All crops	51,131,080	59,823,364	65,959,093

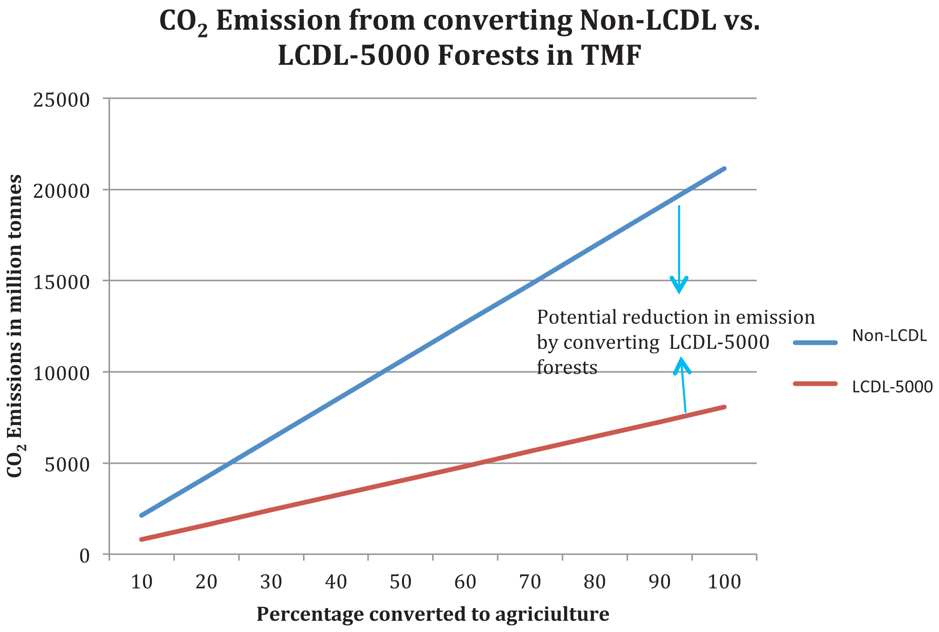

Figure 4 Shifting agricultural expansion from more mature tropical moist forests to LCDL-5000 degraded forest and former forested lands (i.e., 40 tons AGC/ha) can potentially lead to a dramatic reduction in CO_2 emissions.

rights and prevent potential conflicts with indigenous and local communities. In many cases, better livelihood options and opportunities—directly and indirectly—can accrue to local communities and small-scale landholders from agricultural development as witnessed by the large number of small holdings now profitably engaged in oil palm cultivation in parts of southeast Asian nations.

Missing from the global scale filters we employ is a biotic/biophysical screen that filters out riparian buffers, protecting them wherever they exist. Such a filter would remove them from consideration for development in favor of protection or restoration, regardless of the estimated density of AGC/ha. Furthermore, the land immediately adjacent to large streams and rivers, if planted to crops, should be allowed to revert to a more natural vegetation type, which in future calculations, might further constrain the estimates presented in the next section. Such a global filter presents its own challenges and sources of error if conducted at a continental scale. Considerations such as appropriate buffer distance to use, how buffer distance might vary by stream order or by region, the global hydrological dataset to use, and deciding on which stream segments in the hydro layer are active flowing rivers and which are merely topographic drainage channels. The alternative approach would be to require such filters in all EIAs and part of landscape scale filters (Figure 2b).

How much agricultural expansion can be accommodated within the filtered LCDLs?

The top six crops that occupy TMF areas are rice, maize, wheat, soybean, sugar cane, and oil palm (Phalan *et al.* 2013); the last two, along with rubber and pulp and paper plantations, are the most land-intensive in TMF. Of these, oil palm has the greatest rate of expansion; it has virtually saturated Malaysia and Indonesia, and is now expanding into Papua New Guinea, Africa, and the Neotropics (Butler and Laurance 2009; Wilcove and Koh 2010; Garcia-Ulloa *et al.* 2012). While our extrapolations (Table 2) indicate greater areal expansion of sugar cane in the Neotropics, oil palm is projected in the 29% scenario to increase in the Afrotropics by over 1.3 million ha. In the IndoMalayan/Australasian region alone, the 29% increase scenario predicts 8.8 million ha of new oil palm, sugar cane, and rubber plantations (Table 2).

Several of the largest palm oil producers have expressed an interest in a palm oil certification program for environmentally friendly plantation management, and have formed the Roundtable on Sustainable Palm Oil (RSPO) to protect high conservation value forest fragments within the large plantation areas (RSPO 2013). But studies have clearly shown that oil palm expansion results in large losses of important forest-dependent biodiversity (Buchart *et al.* 2004; Sodhi *et al.* 2010; Azar *et al.* 2011), including in forest fragments embedded within the plantations (Edwards *et al.* 2010). A more effective strategy would be to protect larger, contiguous forests in the landscape.

In some cases, oil palm expansion has become a "front" for companies to log intact forested lands; these companies obtain concession rights to forested lands for oil palm plantations, but the primary intent is to profit from logging (Nelson *et al.* 2014). Thus, government policies to direct these companies to LCDLs will discourage these dubious practices.

The LCDL-5000 estate identified in this analysis can accommodate such oil palm expansion in land with lower biodiversity values and carbon stocks. We estimate that the 65.4 million ha area spread across 55 countries could accommodate between 25–50 years of expansion for oil palm, as well as other crops such as sugar cane and natural rubber, without requiring additional clearing of mature TMF. This estimate can be further refined as new global, regional, or national data sets on carbon density, local rainfall and local or regional seasonality are available. In our estimation of the ability of LCDL-5000 to absorb the expanding industrialized agriculture "footprint," we chose intermediate-level relative production estimates (ranging from 17% to 29% above 2010 levels) on a 50-year time horizon for the tropics derived from yield, population, per capita crop harvest (PCCH), and trade variables. Deviations from these intermediate estimates would shrink the ability of LCDL-5000 to offset the coming expansion. However, even if our estimates erred by 50%, there would still, in theory, be over two decades of expansion without clearing more TMF, during which time other tropical forest conservation measures, perhaps built into a Global Climate Treaty, could have time to become viable and operational. Complementary investments to reduce the "yield gap"—raising productivity on existing, lower yield, agricultural lands—would also reduce pressures on increased conversion of TMF (Mueller *et al.* 2012).

Reducing carbon emissions by agricultural expansion into LCDLs

Mature TMF are estimated to store about 340 billion tons of carbon (West *et al.* 2010; Slik *et al.* 2013). Maintaining these carbon stocks are widely seen as critical to keep GHG emissions in check (Gibbs *et al.* 2007; Scharlemann *et al.* 2010). When mature TMF are cleared, they can release 95 to 215 more tons/ha of carbon than previously cleared lands (IPCC 2006). Increasing yield on existing tropical croplands and expanding agriculture into degraded forests is preferable to clearing mature TMF (Lambin & Meyfroidt 2011). Our analysis shows that by directing industrialized agriculture expansion toward LCDL-5000, approximately 62% of CO_2 emissions resulting from that expansion could be avoided. Such avoided emissions incorporated into national emission reduction plans could generate additional revenue for countries through REDD+ agreements.

Spatial safeguards for LCDL landscape-scale planning and implementation

The LCDL-f map that we present is Pantropical in extent. As a global-scale analysis, it glosses over finer scale forest patch distributions and their importance for ecoregion-specific biodiversity. Thus, we explicitly state that the use of this map to direct industrial scale agriculture to LCDLs include the following landscape-scale spatial analyses as part of the safeguards.

The first step in such an assessment or EIA would be to ground-truth the LCDLs for their potential role as buffer zones, corridors, or stepping stone habitats for dispersing or migrating species, or to sustain important ecosystem processes and services in the landscape (see Figure 2b). LCDLs that can contribute these ecological functions could be restored rather converted into agriculture. Upper watershed areas and riparian areas that fall within LCDLs should be excluded from conversion and identified for conservation during the landscape-scale assessments (see Figure 2b).

Small patches of LCDLs embedded in a landscape of mature forests should not be converted to agriculture because the larger footprint from such land use assignment can have detrimental impacts on the mature forests, including gradual encroachment in the future. These LCDLs should be allowed to regenerate back into forests. The size thresholds of the patches should be determined through local-scale spatial analyses that consider the configuration, biodiversity conservation values, and the species that can use these patches while regenerating. Degraded mosaics in places such as Southeast Asia's repeatedly logged forests can still have considerable conservation value for many species that are able to persist in scrubbier habitat, but not in oil palm plantations or large scale agriculture (Edwards *et al.* 2011). Fragments of rare habitats that are surrounded by agricultural or degraded scrub mosaics will also likely act as refugia for a much larger number of species than will a habitat fragment surrounded by palm oil. Since many tropical endemics have limited range distributions (Ricketts *et al.* 2005), LCDL-scaled assessments should be made to ensure that the LCDLs for such endemics are not converted during the project preparation assessments. In short, the global filters or safeguards to identify LCDL (Figure 2a) must be augmented by landscape-scale safeguards and filters (e.g., Figure 2b) before suitability for conversion is assigned.

In the months ahead, major producers and buyers of oil palm are likely to coalesce around a High Carbon Stock approach to source palm oil and perhaps other crops while avoiding clearing of valuable rainforests. Closing loopholes in agreements currently under consideration and monitoring progress of adoption of ecologically sound sourcing would be aided by three features: (1) acceptance of a low carbon-density threshold to avoid conversion of critical habitats as outlined here; (2) publication of landscape-scale analyses as a safeguard for protecting and deselecting degraded lands below the carbon-density threshold but sitting on unique soils, serving as stepping stone habitats, including riparian zones, etc. (Edwards *et al.* 2011) (Figure 2b) from being assigned to conversion; and (3) empowerment of public watchdogs such as Global Forest Watch (GFW) and related applications (GFW-Commodities, GFW-Fires, and GFW-Biodiversity, the last under development) to promote industry-wide adherence and media attention focused on companies that fail to live up to commitments (www.globalforestwatch.org, Hansen *et al.* 2013).

The stakes for tropical biodiversity

TMFs are the most species-rich terrestrial ecosystems (Turner 1996) and support the most endemic species under threat of imminent extinction (Ricketts *et al.* 2005). The remaining blocks of TMF are important refugia for these imperiled species and should be conserved. In most TMF areas, the protected areas cover only a modest part of irreplaceable biodiversity (Jenkins *et al.* 2013); further loss of forests, especially to large-scale plantations, can result in massive species losses and degradation of ecosystem processes and services while releasing immense amounts of GHGs into the atmosphere, accelerating global warming and climate change (DeFries *et al.* 2004; Foley *et al.* 2005; Foley *et al.* 2007; Phalan *et al.* 2011; Sodhi *et al.* 2012). These consequences will affect biological systems, human communities, and economic investments and aspirations. Our map of LCDLs sets the stage for fine-scale analyses that will better direct industrialized agro-development expansion onto lands that will minimize these impacts through sound land management and conservation for life on Earth.

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