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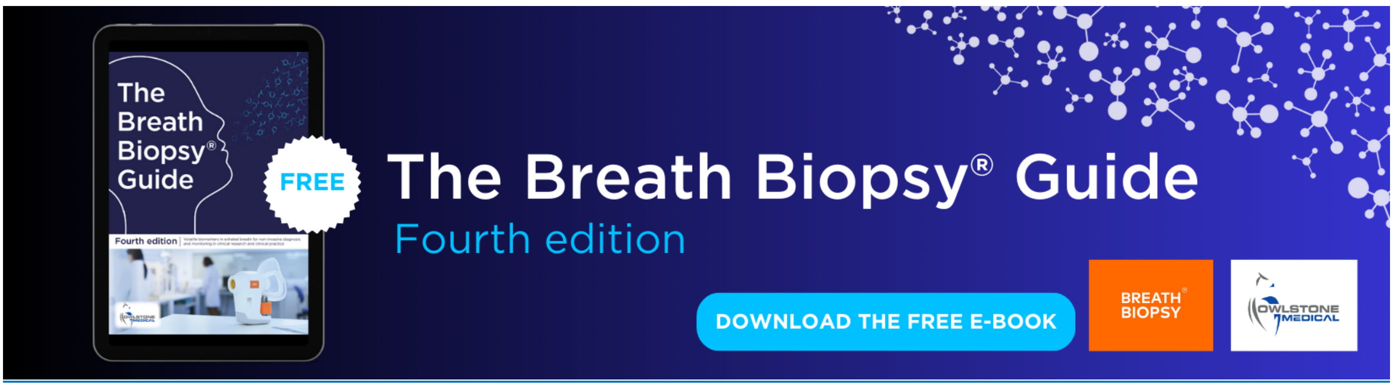

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Characterizing commercial oil palm expansion in Latin America: land use change and trade

Paul Richard Furumo[1,3] and T Mitchell Aide[2]

1 Department of Environmental Sciences, University of Puerto Rico-Río Piedras, San Juan, 00931 Puerto Rico
2 Department of Biology, University of Puerto Rico-Río Piedras, San Juan, 00931 Puerto Rico
3 Author to whom any correspondence should be addressed.

E-mail: pfurumo@gmail.com

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Abstract

Commodity crop expansion has increased with the globalization of production systems and consumer demand, linking distant socio-ecological systems. Oil palm plantations are expanding in the tropics to satisfy growing oilseed and biofuel markets, and much of this expansion has caused extensive deforestation, especially in Asia. In Latin America, palm oil output has doubled since 2001, and the majority of expansion seems to be occurring on non-forested lands. We used MODIS satellite imagery (250 m resolution) to map current oil palm plantations in Latin America and determined prior land use and land cover (LULC) using high-resolution images in Google Earth. In addition, we compiled trade data to determine where Latin American palm oil flows, in order to better understand the underlying drivers of expansion in the region. Based on a sample of 342 032 ha of oil palm plantations across Latin America, we found that 79% replaced previously intervened lands (e.g. pastures, croplands, bananas), primarily cattle pastures (56%). The remaining 21% came from areas that were classified as woody vegetation (e.g. forests), most notably in the Amazon and the Petén region in northern Guatemala. Latin America is a net exporter of palm oil but the majority of palm oil exports (70%) stayed within the region, with Mexico importing about half. Growth of the oil palm sector may be driven by global factors, but environmental and economic outcomes vary between regions (i.e. Asia and Latin America), within regions (i.e. Colombia and Peru), and within single countries (i.e. Guatemala), suggesting that local conditions are influential. The present trend of oil palm expanding onto previously cleared lands, guided by roundtable certifications programs, provides an opportunity for more sustainable development of the oil palm sector in Latin America.

1. Introduction

Globalization has fundamentally changed the way food is produced, and has shifted the drivers of land use change. As people migrate into cities and diets shift, the demand for land-based commodities has increased, and global market forces are now replacing rural population pressure as the principal driver acting on natural systems [1]. Sites of production are separated from those of consumption, creating telecoupled human-natural systems defined by consumer demand in one region that influences the crops planted in another [2, 3]. These are typically cash crops, increasingly grown on large, industrial scale plantations destined for export to affluent urban centers abroad instead of meeting subsistence needs locally [4]. Expansion of production landscapes that are oriented toward distal, urban consumption has emerged as an important driver of deforestation in the tropics [5, 6].

Pan-tropical cultivation of the African oil palm (*Elaeis guineensis*)—an oilseed commodity crop—has flourished under this globalized model of production, and has become a highly publicized, controversial issue between conservationists and the private sector. Palm oil recently surpassed soy (*Glycine max*) as the most widely consumed vegetable oil in the world. The oleaginous products of oilseed crops share similar

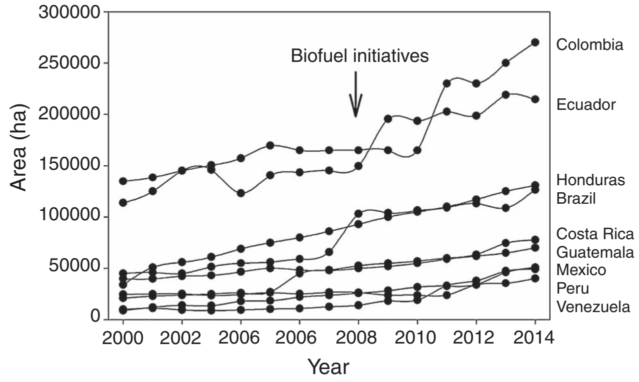

Figure 1. Recent expansion of oil palm harvested area in Latin America (2000–2014) as reported by FAO [16].

properties and are largely interchangeable as a ubiquitous ingredient in diverse supply chains including processed foods, cosmetics, detergents, and lubricants. Trade flows of this commodity reflect trends in globalization; palm oil accounts for nearly 60% of global oilseed exports [7], and this trade volume is generated from approximately half of its globally harvested area [8].

The bulk of increase in palm oil production has come from a proliferation in the area planted rather than improvements in yield [7]. Most of this expansion has been absorbed by forested lands in Southeast Asia—the epicenter of global oil palm cultivation. Between 1990–2005, at least 55% and 59% of oil palm expansion occurred on forested lands in Malaysia and Indonesia, respectively [9]. This equates to about 2.7 Mha of total forest loss. Similarly, ninety-percent (2.8 Mha) of oil palm expansion replaced forests on Kalimantan between 1990 and 2010 [10]. Land conversion from forest to oil palm monocultures has major implications for biodiversity [11, 12], ecosystem functioning [13, 14], and carbon emissions [10].

Increased demand for palm oil and limited availability of land in Southeast Asia [15] has opened up new frontiers of expansion. Latin America has more than doubled its output since 2000 (figure 1) [16]. Between 2001 and 2014, palm oil production (Mg) increased by 7% per annum, and land cover (ha) under oil palm expanded by 9% per annum [16]. Today, the region contains three of the top ten producing nations in the world (i.e. Colombia, Ecuador, and Honduras). Latin America also has the largest reserves of forest suitable for oil palm expansion, notably Brazil (2 283 000 km^2), Peru (458 000 km^2), and Colombia (417 000 km^2), forests which harbor much of the planet's biodiversity and carbon stocks [17]. Will oil palm expansion in Latin America lead to extensive deforestation as in Asia, or can the economic benefits of the oil palm sector be attained while mitigating environmental impacts [18]?

Research suggests that oil palm expansion in Latin America may be following a distinct land-use trajectory from Asia. In Colombia, oil palm expansion amounted to 155 100 ha between 2002 and 2008; 51% (79 000 ha) occurred on cattle pasture while only 16% replaced natural vegetation [19]. An additional 30% of this oil palm replaced croplands, suggesting that 80% of expansion during the time period occurred on previously intervened lands instead of natural areas. A recent global-scale assessment of deforestation caused by oil palm expansion estimated that only 2% of new plantations established in Central America and the Caribbean (Mesoamerica) between 1989 and 2013 were forested prior to oil palm [20]. This is encouraging considering the heavy environmental impact the industry has had in SE Asia, and may provide a major step toward a sustainable oil palm industry by alleviating the problems associated with destructive land use transitions. However, Vijay *et al* also report that 31% of oil palm expansion came from forested lands in South America. Furthermore, a detailed regional study in the Peruvian Amazon estimated that 72% of oil palm expansion occurred on forested lands between 2000 and 2010 [21]. These results suggest that land use change (LUC) trajectories can vary greatly within the Latin American and Caribbean (LAC) region.

If up to 70% and 98% of recent oil palm expansion in South America and Mesoamerica, respectively, is not replacing forests [20] then what types of land use are being replaced? If oil palm is replacing cropland, this could have indirect land use change (iLUC) consequences by displacing crops to forested frontier areas and driving up the local price of food items [22, 23]. On the other hand, landholders may be intensifying production and profits by planting oil palm on low-productivity cattle pastures, with neutral or even positive impacts on biodiversity and carbon storage [24–26]. Thus it remains pertinent to characterize LAC oil palm expansion in more detail to understand the economic and ecological consequences of this industry in the region.

To determine what land uses are being converted to oil palm in LAC, we mapped established oil palm plantations in 2014 using MODIS satellite imagery and determined prior land cover in these areas using high-resolution imagery in Google Earth (GE). We

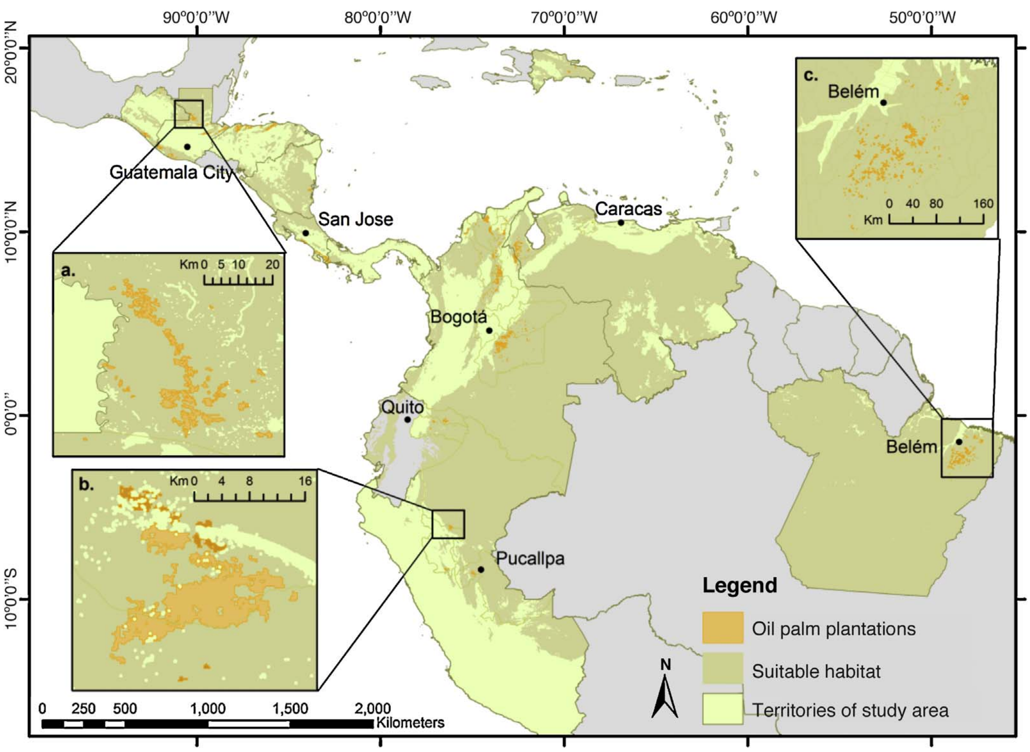

Figure 2. Map of oil palm plantations in LAC region for 2014 based on MODIS (250 m resolution) imagery *Light orange* polygons represent oil palm plantations included in LUC analysis, while *dark orange* polygons are plantations mapped in 2014 but not included in LUC analysis due to poor satellite imagery *Light brown* extent represents areas suitable for oil palm cultivation based on geophysical filters (includes areas <700 m a.s.l and 12% slope, and those contained within moist and dry tropical broadleaf biomes; see *SI Materials*) *Light green* layer represents the administrative boundaries of countries included in the study. Note that we only include the states of Chiapas in Mexico, Orellana and Sucumbíos in Ecuador, and Pará in Brazil. Inset panels represent areas of high deforestation from oil palm expansion ((*a*)—Petén, Guatemala; (*b*)—Loreto, Peru; (*c*)—Pará, Brazil).

also incorporated country-level trade data to derive a more holistic characterization of the Latin American oil palm industry and determine how well it aligns with trends in globalized commodity markets, specifically whether the majority of production is being driven by distal demand from international markets.

2. Methods

2.1. Mapping oil palm

We mapped plantations throughout major oil palm producing regions of LAC, encompassing twelve countries from southern Mexico to Peru (figure 2). To map oil palm plantations, we created annual 250 m resolution land use/land cover (LULC) maps derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images. These data are available free online from the National Aeronautics and Space Administration's Earth Observing System Data Service [27]. Our approach has been successfully implemented in mapping LULC changes on regional and intercontinental scales [28, 29]. In short, we used the web-based application *Land Mapper* developed by *Sieve Analytics* to integrate data sources, create classification models (figure S1), and produce LULC maps for 2014 [30]. The 2014 oil palm polygons ($n = 1479$) were exported to GE to determine the most immediate land use class prior to conversion to oil palm.

We used Land Mapper to collect references samples (225 000 MODIS pixels) throughout the study area for training the classifier algorithm. Land Mapper overlays the 250 × 250 m MODIS pixel grid with very high-resolution (VHR) satellite images in the GE platform. This enables the user to visualize high resolution LULC at the pixel scale and create training polygons for each LULC class. We collected training data for major LULC classes adapted from Clark *et al* (2010)—*Banana, Bare, Built-up, Croplands, Herbaceous Vegetation, Mixed Woody, Mature Oil Palm, Plantation Trees, Water,* and *Woody Vegetation* [28]. Land Mapper records the acquisition date for the high-resolution images from GE used to define each training sample, in order to reference the corresponding MODIS image(s) during the classification process. User-defined, high-resolution reference data is thus paired with MODIS time series variables for the year of image acquisition.

The MODIS time series variables are derived from the MOD13Q1 (Collection 5) Vegetation Indices 250 m product, which is a 16-day composite (23 scenes per year) of the highest quality pixels from daily images [31]. Each pixel contains data values based on the twelve MOD13Q1 scientific dataset (SDS) layers [32]. We performed our classification based on annual statistics—mean, maximum, minimum, standard deviation, kurtosis, and skewness—for ten of these time series variables, or SDS layers. These include two

Table 1. Percent mapped of total oil palm area harvested in each country in 2014 as reported by FAO [16], and expansion observed for land use change (LUC) analysis. Values are in hectares (ha).

Country	FAO total area harvested	Area mapped	Oil palm expansion	% of FAO total mapped
Colombia	270 000	233 456	144 396	86%
Ecuador	214 570	15 475	3 665	7%
Honduras	130 650	49 259	18 584	38%
Brazil	126 559	80 190	70 923	63%
Costa Rica	77 750	30 580	11 319	39%
Guatemala	70 000	58 296	47 689	83%
Mexico	50 868	12 477	7 462	25%
Peru	49 230	21 898	20 529	44%
Venezuela	40 198	16 170	12 010	40%
D. Republic	17 100	6 051	145	35%
Panama	5 510	7 292	5 455	132%
Nicaragua	5 000	7 289	n/a	146%
TOTAL	**1 057 435**	**538 433**	**342 032**	**51%**

vegetation indices (VI)—Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation index (EVI); three reflectance bands—red, near infrared (NIR), and mid-infrared (MIR); three observation angles—view zenith angle, sun zenith angle, and relative azimuth angle; and two quality assessment (QA) layers—VI quality and pixel reliability. Pixels with a reliability value of three (value = 3) were deemed unreliable and removed prior to calculating statistics.

2.1.1. Random forest classifier

For algorithm training (i.e. model building) and image classification we used a Random Forest (RF) tree-based classifier [33] implemented in R [v. 2.12.2; 34] with the RandomForest package [v. 4.6–2; 35]. The Random Forest classifier constructs a multitude of uncorrelated decision trees based on a random set of predictor variables (the annual MODIS time series variables), preventing overfitting of the training set. We assigned land cover classes to each pixel based on the RF per pixel probability, requiring that a pixel contain at least 60% probability of that class.

Due to such an expansive and heterogeneous study region encompassing two continents and varied biomes, we developed 16 region-specific land classification models (table S1). Most models were at the country scale, but larger countries (i.e. Colombia, Peru) required multiple models to capture variability between different production zones. Models were parameterized with 2000 trees, a minimum of 5 terminal nodes per tree, and an unlimited maximum number of terminal nodes per tree. The overall global accuracy of the models was 96%, with an oil palm producer's accuracy of 98%, and oil palm user's accuracy of 93%.

2.1.2. Map accuracy

We constructed annual LULC maps for 2014 using the 16 land use classification models. After a post-processing step that eliminated detections smaller than 50 hectares (see *SI Materials*), we manually assessed the accuracy of our oil palm classification. We created shapefiles of oil palm polygons (n = 2063) in ArcGIS 10.2 and overlaid them with high resolution GE imagery to visually inspect each polygon. Our classification of oil palm in 2014 had a total accuracy of 93% for the study region. Of the 7% error, most (48%) was associated with Mixed Woody land cover—heterogeneous mosaics of woody vegetation with other land covers, but no single class exceeding 40% coverage of a pixel [28]. We then removed the false positives and excluded polygons that could not be determined as oil palm before proceeding with the land use change analysis.

2.2. Land use change

We used the remaining confirmed oil palm polygons (n = 1479) to determine the land use in these areas prior to oil palm expansion. In each polygon, we manually surveyed and estimated the percent of each land cover class to the nearest 10% in the most recent GE image prior to conversion to oil palm. To the extent possible, we utilized VHR images for the LUC analysis, available as early as the year 2000 in some areas. Where VHR images were not available, we relied on GE base imagery composed of Landsat mosaics, which limited temporal specificity but enabled us to characterize a larger area of oil palm (see *SI Materials*). In particular, it is difficult to confirm the proximate driver of land clearing and the most immediate land cover converted to oil palm. For example, forested areas in base imagery that eventually became oil palm may have had an intermediate land use such as cattle pasture, which caused the initial land clearing. As a result, we may have overestimated woody vegetation conversion to oil palm plantations, especially in South America where image quality was less consistent.

Our sampled oil palm sites represented at least 25% of FAO reported oil palm area harvested (i.e. mature oil palm) in each country for 2014 (table 1). The only exception was Ecuador, where only 7% (15 475 ha) of reported oil palm was sampled due to poor satellite images. Reported country-level trends

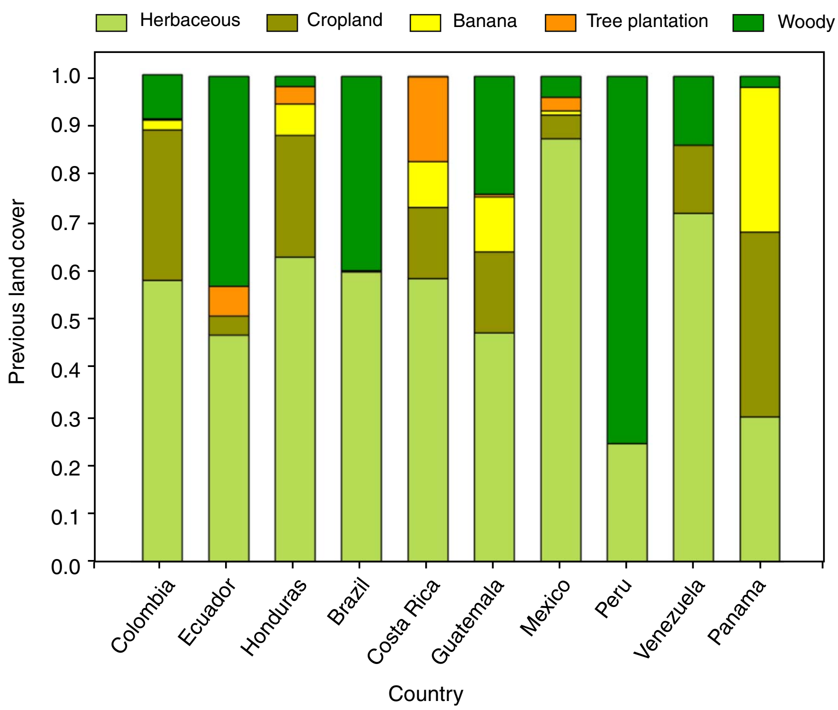

Figure 3. Land use land cover (LULC) change from oil palm expansion. Graph represents the proportion of each land cover class converted to oil palm, as a percentage of total oil palm expansion mapped in each country. The bottom categories (below 'Woody') represent the oil palm expansion onto previously intervened lands.

are based on the percentage change in each land cover class, relative to the area of oil palm expansion sampled in 2014. In order to scale up country-level data to make inter-regional comparisons between Central and South America, we normalized and aggregated country-level data by weighting it relative to the FAO reported total harvested area of oil palm for each country (table S2).

2.3. Trade data

To determine the economic trade flows of Latin American palm oil production we consulted international commodity trade databases [16, 36] and compiled the quantity of imports and exports of palm oil and its fractions for each country in the analysis from 2001–2014. Instead of taking a single year snapshot, we summed annual production and import/export quantities over a 14-year period to avoid single year anomalies in trade flows. We used these 14-year totals to compare trade flows *within* the region, palm oil traded between LAC countries, and *out* of the region, palm oil traded between LAC countries and the rest of the world.

3. Results

3.1. Land use change

We mapped a total of 538 433 ha of oil palm plantations in LAC for 2014 (figure 2). Nicaragua and the Dominican Republic were excluded from the LULC change analysis because there were no cloud free images available to classify land use in the case of the former, and we only detected 145 ha of oil palm expansion in the case of the latter. Of the remaining total, 35% (183 061 ha) had already been established as oil palm in the oldest available GE image and prior land use could not be determined. Thus we based our land use change analysis on 342 032 ha of oil palm expansion in ten countries throughout LAC (table 1).

We estimated that 21% of expansion came from the woody vegetation class, 56% from herbaceous vegetation, 18% from agriculture, 4% from banana, and 1% from plantation trees (figure 3). In other words, 79% of oil palm expansion has occurred on lands that were previously intervened or under some other form of production system, while 21% came from forest cover. The herbaceous vegetation class was dominated by pasturelands, distinguishable by cattle trails, watering holes, and remnant shade trees. Wetland grasslands and natural savannas contributed to a lesser extent. In the eastern plains of Colombia, oil palm production occurs in a predominantly natural grassland biome, yet most of the oil palm detected in this area was at the foot of the Andes in the department of Meta, a region with a long history of cattle production and land transformation [37].

Considering the study area as two sub-regions—Central America (CA) and South America (SA)—provides notable distinctions. Fifty-two percent of the current area under oil palm in CA was already in place upon reference of the oldest GE images, while only 42% had already been established in SA, suggesting a higher rate of recent oil palm expansion in SA (table S2). The majority of oil palm conversion in CA and SA came from herbaceous vegetation (64% and

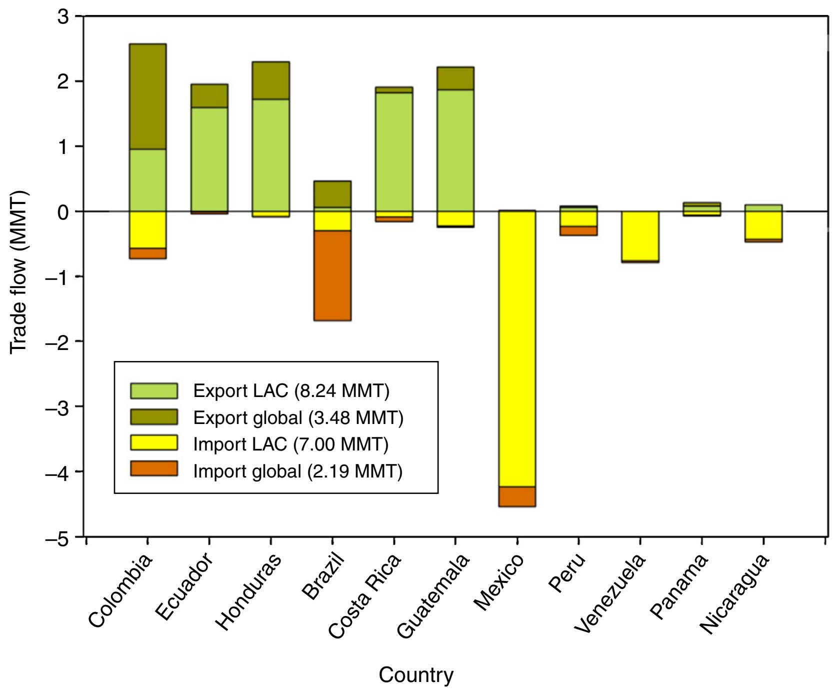

Figure 4. Trade flows of palm oil within LAC region (light green and yellow) and with the rest of the world (olive green and orange). Exports are depicted as positive values (top) while imports are depicted as negative values (bottom). Values are derived from FAO and UN Comtrade [16, 35] compiled from 2001–2014 and reported in million metric tons (MMT).

54%, respectively) and cropland (17% and 14%, respectively). Banana accounted for 7% of oil palm expansion in CA, but only 1% in SA; nearly three times as much area was converted from banana to oil palm in CA than SA. The *banana—oil palm* transition was concentrated in Guatemala (5 409 ha), Panama (1 627 ha), Honduras (1 186 ha), Costa Rica (1 066 ha), and the Magdalena department of Colombia (3 541 ha). Conversion of other types of plantation trees (e.g. eucalyptus) to oil palm was the least conspicuous transition pathway (3 720 ha in total), accounting for 6% of expansion in CA and 2% in SA.

3.2. Forest loss

In CA, conversion of woody vegetation to oil palm constituted a relatively minor land use change trajectory; only 6% of oil palm expansion replaced woody vegetation. This occurred almost exclusively in Guatemala (11 573 ha, or 93% of total forest loss detected in CA), with the majority of forest loss (10 296 ha) detected in the northern department of Petén. In SA, we found 59 848 ha of woody vegetation converted to oil palm, about five times the amount observed in CA, representing 30% of the total land area converted to oil palm in SA during the study period (table S2). Ecuador (13%), Brazil (7%), and Peru (5%) contributed most to this regional deforestation trend, as weighted by the total area harvested in each country.

On a national scale, Peru experienced the highest rate of woody vegetation loss from oil palm expansion (76%), amounting to 15 685 ha. This was particularly striking in the vast Loreto region of the Peruvian Amazon, where 86% (11 884 ha) of local oil palm expansion occurred at the expense of forest. In Ecuador, due to poor image quality we were only able to map oil palm in the Sucumbíos and Orellana departments of the Ecuadorian Amazon, where we detected 15 475 ha of oil palm plantations in 2014; 3 665 ha was associated with land conversion, including 1 582 ha of woody vegetation loss in these departments (43%).

The Brazilian Amazon state of Pará featured the largest area of country-scale forest loss associated with oil palm expansion in the study; 70 923 ha of oil palm expansion were detected, of which 40% (28 405 ha) replaced woody vegetation. In Colombia, only 9% (12 474 ha) of recent oil palm expansion replaced woody vegetation. This was concentrated in the central production zone of the Magdalena Medio region and the Catatumbo valley of the Eastern Andes along the Venezuelan border. The departments of Colombia with the most significant amount of woody vegetation loss during the study period were Norte de Santander (5 525 ha), Santander (2 484 ha), Cesar (1 638 ha), and Bolívar (1 283 ha).

3.3. Trade data

Between 2001 and 2014, LAC produced 29.95 million metric tons (MMT) of palm oil. LAC oil palm producing countries are net exporters of palm oil, but only slightly, given that they exported 11.84 MMT and imported 9.28 MMT. The majority of this trade remained within the region. Over three times as much palm oil was imported from *within* the LAC region than from the rest of the world, and 70% of palm oil exports stayed in LAC (figure 4). The net exporting countries were Colombia, Ecuador, Honduras, Costa

Rica, Guatemala, and Panama, while the net importing countries were Brazil, Mexico, Peru, Venezuela, and Nicaragua (table S3).

Mexico was by far the largest importer of palm oil in the region, accounting for about half (4.54 MMT) of total imports and 61% of imports from within the LAC region. Colombia, Mexico, and Brazil were the largest consumers of palm oil in LAC, respectively. Despite the propensity toward intra-regional trade, an exception among net importing nations was Brazil, which imported nearly five times as much palm oil (1.38 MT) from outside the region—mainly Indonesia—as it did from LAC nations; this influx has been mainly to replace soybean oil in the food industry [38]. Among net exporting nations, an exception was Colombia, which exported 1.62 MMT of palm oil outside the LAC region during the study period, representing 63% of its total exports. Most of this palm oil was destined for Europe, specifically the United Kingdom (37%) Netherlands (26%), and Germany (22%). In fact, Europe was the strongest external trading partner; 93% of total LAC palm oil exports outside the region were destined for Europe, and the bulk of remaining exports (6%) ended up in the USA and Canada.

4. Discussion

4.1. Expansion onto previously cleared lands

4.1.1. Pasture—oil palm transition

Oil palm expansion in Latin America is following a different land use change trajectory than the widespread deforestation associated with this industry in Southeast Asia. Each LAC nation in our analysis (except Mexico) is considered forested, or has half of its territory covered with forest [39]. Despite the fact that most of this forested area is suitable for cultivating oil palm [17], cattle pastures remain the most significant source of new oil palm plantings across LAC. This trajectory can be partially explained by Von Thünen principles of land rent and also reflects the land use legacy of the LAC region.

Latin America has a longer history of urbanization and lower rural population density compared to Asia, resulting in low-productivity cattle pastures as the defining feature of rural landscapes [40]. The predominance of the *pasture—oil palm* transition throughout the study area suggests the important role that the cattle industry may provide in clearing land for the eventual expansion of commodity crops, especially in Latin America [41, 42]. Cattle ranching can increase land rent, especially on the frontier, by clearing land for agriculture and increasing accessibility. Bid-rent theory predicts the *pasture—oil palm* transition as property values increase with proximity and connectivity to centers of commerce, favoring expansion into previously cleared lands with high accessibility over more remote areas [22, 43].

Our maps support the importance of infrastructure and connectivity to the oil palm industry, revealing the tendency for plantations to cluster into distinct production zones. These occur at different spatial scales, from an individual mill with nearby suppliers, to country-level production zones operating under completely different climatic and socio-economic conditions [44]. The clustering of production is also due to the fact that fresh fruit bunches (FFB) must be processed within 48 hours of harvesting to ensure oil quality, keeping plantings and mills in close proximity. Agglomeration of commodity plantations is further reinforced by economic factors such as competition, labor pool, and knowledge transfer [45]. The accumulation of these factors benefits the industry and when combined with the development of downstream processing activities (i.e. construction of mills, refineries) can lead to reinforcing loops characterized by economies of scale that increase agricultural rent and stimulate further expansion [46].

Infrastructure extension and cattle ranching can be thought of as proximate causes of oil palm expansion in Latin America. In tandem, these are two powerful land transforming agents that have been prominent in most cases of deforestation documented in Latin America [42], and may be similarly useful in considering the expansion of commodity crops in the region [41]. Oil palm may have largely avoided deforestation in Latin America simply because it is more feasible and profitable in the wake of cattle ranching, or because extensive pasturelands have long since deforested the productive landscapes of Latin America, isolating forested frontiers to margins where oil palm has yet to penetrate.

Because our approach took a snapshot of the most immediate land cover transition to oil palm, we acknowledge that this temporal limitation may ignore previous LUC dynamics important to the oil palm expansion narrative. In some cases it may be possible that the herbaceous vegetation absorbing oil palm expansion may have been recently cleared from forest as a speculative pretext in attempts to establish property rights while landowners await investment opportunities [47]. However, most of the herbaceous land cover classified in our study was established pasture (i.e. cattle trails, water holes), not recent land clearings, and other research shows that cattle ranching continues to be the primary proximate driver of deforestation in the region [48].

4.1.2. Banana—oil palm transition

The African oil palm was introduced to Latin America as early as the 1920s as an alternative cash crop to diversify the dominant banana industry [49]. With the spread of *Fusarium wilt* (Panama disease) in the first half of the 20th century, the banana sector was severely affected and other commodity crops began replacing banana plantations [50]. Commercial production of both banana and oil palm require similar infrastructure, with cultivated areas divided into smaller plots by roads or cable lines to facilitate extraction. The banana sector is also highly labor intensive, and transitioning from banana to oil palm would lead to labor pool abundance, potentially driving down wages and increasing agricultural rent (see *SI Materials*), contributing to further oil palm expansion in these areas [46].

Conversion from banana to oil palm was likely a more significant pathway in decades prior to our study period, and we are merely capturing the tail end of this transition. Indeed today's oil palm dominated coastline of Puntarenas, Costa Rica was once a banana hub for the United Fruit Company. In SA, the *banana—oil palm* transition was only found in the *Zona Bananera* of Magdalena, Colombia, which is now dominated by more oil palm than banana plantations. Oil palm has become valued over banana in the region for its relative price stability and resilience against stochastic events like drought, flooding, and high winds. However, with the recent strengthening of the USD against the Colombian peso making banana exports more profitable than palm oil, and the specter of spreading bud rot disease in the northern production zone of Colombia, some landholders are choosing to replant oil palm with banana (personal observation).

4.2. Intra-regional variability of forest loss

Though oil palm expansion generally occurred on previously cleared lands in the regional context, we observed important idiosyncrasies related to forest loss. While these have previously been discussed on a continental scale in Latin America [20], we found that intra-regional variability is even more acute, occurring at national and even sub-national scales. With previously cleared lands, particularly cattle pastures, a mainstay throughout the LAC region, differences in the extent of deforestation caused by the expanding oil palm industry are most likely attributed to local conditions. Economic and institutional factors, and to a lesser extent demographic factors, have been described as the most relevant contributors to deforestation in Latin America [42]. We explore the role of these variables as underlying drivers in national and sub-national contexts of deforestation from oil palm expansion.

4.2.1. National trends

Peru. In the Amazon, large areas of oil palm expansion have replaced primary forest. The oil palm production zones we mapped in this region expanded into large forest blocks on the edge of the agricultural frontier. Plantation size may be an important factor in the extent to which oil palm causes deforestation in frontier areas [51]. Our findings in Peru are in line with another study that reported large-scale commercial plantations as a significant cause of land clearing compared to smallholders [21]. We mapped two large industrial-scale plantations in the Loreto and San Martín departments, which together accounted for 77% (12 097 ha) of the total oil palm driven deforestation found in the country, but only 59% of national oil palm expansion during the study period. We found evidence for two additional industrial-scale plantations being developed in the Ucayali department totaling more than 10 000 ha [52], which we classified as herbaceous vegetation (land clearings) in 2014.

Large, industrial-scale operations will undoubtedly be responsible for more deforestation in remote areas where road access will limit smallholder penetration reliant upon commercial mills to sell FFBs. Only large-scale oil palm operations with sufficient capital to construct an on-site processing mill will find it feasible to venture beyond the agricultural frontier into wilderness areas. Rivers are often the primary infrastructure that connects these remote areas of production to markets. Considering the Von Thünen model of land rent (see *SI material*), the increase in access costs (v) may be offset by the lower costs of defending property rights (c) as the presence of the state is diminished in these remote areas, making these isolated concessions more profitable [46].

It is apparent that local conditions, particularly weak governance and enforcement, have enabled the conversion of large forest tracts to oil palm in Peru [53]. Though Peru's forestry laws prohibit land use activities that affect vegetation cover and the conservation of forestry resources, companies have acquired oil palm concessions in primary forested areas through a loophole that allows the changing of land use designation if the lands are deemed to have agricultural potential. This is a technical definition known as 'best land use capacity' (BLUC), which ignores standing vegetation and is based only on soil and climatic characteristics, subjecting forests to development under the Ministry of Agriculture [53].

Ecuador. The high rate of deforestation we and others [20] report in Ecuador, may be in part an artifact, given that the majority of the area sampled was heavily forested and much of the oil palm production occurs elsewhere. The availability of recent high-resolution images restricted our analysis to the eastern production zone—specifically, the provinces of Orellana and Sucumbíos in the Amazon—which represents only 7% (∼20 000 ha) of the total area planted in oil palm. The majority (84%) of oil palm production in Ecuador occurs in the western zone including plantations in southern Esmeraldas, Santo Domingo, Los Ríos, and Guayas [54]. Historical satellite images reveal that this area has had a long history of intervention with extensive areas of crops and pastures. Thus we would expect the national rate of oil palm driven deforestation in Ecuador to be less severe than our findings indicate.

Brazil. Expansion of Brazilian oil palm is concentrated in Pará, which currently represents 95% of national oil palm production [55]. Expansion typically replaced primary forest contained within larger landscape fragments; croplands were comparatively less dominant in this region. Though a national forest code has been in place since 1965, much deforestation in the region is associated with weak land tenure laws during the initial acquisition of lands by medium-large scale agricultural companies in the 1970s and 1980s, during a period of financial incentives for the economic development and integration of the Amazon frontier [56]. With the introduction of a new biodiesel law in 2005 (7% blend by 2014), another wave of investment and plantation expansion occurred, this time from large national and international investors. Today, nearly 75% of the area cultivated in oil palm is held by just three companies [56]. Deforestation concerns are being addressed with increased monitoring and adoption of the Sustainable Palm Oil Production Program (SPOPP) in 2010, which targets previously cleared lands in the Amazon for future expansion (ZAE-palma) and prohibits expansion into forests and onto lands deforested before 2008.

4.2.2. Sub-national trends

Guatemala. Petén is a vast frontier department that contains a large portion of the Maya Biosphere Reserve (MBR), and has undergone considerable cattle ranching expansion in the last decade [57]. We estimated that 24% of oil palm expansion in Guatemala came from woody vegetation, and 89% of that occurred in Petén. Similar to Peru, these were industrial-scale plantations located near Sayaxché, Petén that were among the largest documented in Guatemala (>3 000 ha), and have been associated with environmental degradation beyond land clearing [58]. Government regulations that have incentivized productive lands over natural areas and promoted colonization of frontier areas through subsidized development have contributed to the forest loss observed in this region of Guatemala [59]. Additionally, weak land tenure laws and rising land rent values from in-migration have created an extra-legal land market, further propping up land prices and incentivizing speculation, which has stimulated more land clearing [60]. Land in Guatemala has been historically concentrated into the hands of few, including foreign investors, and this trend has only worsened over time. In 2006, 50% of the population controlled 93% of the land [60]. Oil palm expansion is encroaching upon the buffer zone of the MBR, and researchers suggest that it may be causing indirect land use change in the reserve, as rural poor are displaced from non-protected areas into the forest [61].

Colombia. While only 9% of oil palm expansion in Colombia replaced forest at the country-scale, several departments had much higher deforestation rates, including Norte de Santander (35%), Bolívar (20%), Santander (18%), and northern Cesar (18%). The humid tropical forests of Magdalena Medio include some of the last remnants of tropical rainforest outside of the Amazon, yet remain among the least protected in the country [62]. These departments make up the central production zone of Colombia and coincide with areas where armed forces have historically been present. The involvement of para-military groups in the oil palm sector as a way to control territory has been well documented [63], and poses a proximate driver of forest loss. Sabogal [64] performed a spatial analysis of forced displacement in oil palm producing municipalities and found that over twice as many people were displaced than in non-oil palm municipalities between 2002 and 2009. While it is unclear whether these implicated plantations are most responsible for local trends in forest loss, the departments where we found most deforestation coincide with the oil palm municipalities that have the highest correlation with forced displacement [64]. Contrary to expansion in the Amazon and Petén, we found that most of the woody vegetation converted to oil palm in Colombia and the other LAC nations occurred on forest fragments and regenerating forests, instead of undisturbed blocks of primary forest [19].

4.2.3. Trade data and biodiesel initiatives

The ebb and flow of Latin American palm oil may illustrate a shift in underlying drivers of expansion. The region is a net exporter of palm oil, but only slightly, consuming over 90% of what it produces; less than 12% is exported out of the region. In contrast, only 9% of palm oil exports from Malaysia and Indonesia went to other SE Asian countries in 2013 [16]. Trade flows demonstrate a high demand for palm oil in LAC (see *SI Materials*), demand that is being met predominantly by the same LAC producing nations as opposed to other palm oil producing regions. This breaks from the conventional view of palm oil as a global South-North flowing commodity, and built-in assumptions about deforestation based on the unequal exchange theory [65].

A potentially important institutional factor contributing to this divergent trend is the creation of recent biofuel programs by governments in Latin America. Biofuel initiatives introduced after the 2006–07 global financial crisis and subsequent spike in petroleum prices have sustained further investment in the oil palm sector aimed to meet future energy goals [19, 66]. Though sugarcane based ethanol dominates the current biofuel agenda in the region, there are several ambitious biodiesel initiatives in Latin America that will likely be met by the growing oil palm sector. These include Colombia (B8-10), Brazil (B7), Ecuador (B5), Peru (B2), and Costa Rica (B20) [55, 67, 68]. Each nation has significant industrial palm oil production, but the extent to which this sector contributes to biodiesel targets varies. For example, Colombia's entire biodiesel mandate is fulfilled by approximately half of its national production, whereas the contribution of palm oil to Brazil's B7 mandate is currently less than 1%; soy and beef tallow are the primary feedstocks [38, 56].

Governments often require that biofuel targets be met by domestic consumption, creating the structure for financial incentives (e.g. tax breaks, credits) that help perpetuate expansion. How these financial instruments influence LUC both directly (e.g. zoning of biofuel feedstock) and indirectly (e.g. displacement of subsistence agriculture) will depend on local proximate and underlying forces. In the case of Colombia, state incentives have caused investors to acquire less productive land for oil palm expansion, mainly pastures [69]. Local institutional/policy factors can also create complex interactions between oilseeds including indirect trade signals that have consequences for land use. In Brazil, 75% of biodiesel production is being met by soybean oil. As more soybean production is dedicated to meeting national energy goals, palm oil imports are filling the vegetable oil supply vacuum for the processed foods industry, particularly for its consideration as a healthier oilseed alternative [38].

Palm oil is also becoming an important fuel source in Europe. From 2006–2012, the EU-27 increased its use of palm oil in biofuel production by 365%, equating to 1.6 MMT, or 20% of total biodiesel feedstocks [66]. Our data show that during this same time period, LAC exported 1.79 MMT of palm oil outside of the region and 1.67 MMT (93%) went to EU-27, or roughly the equivalent to EU-27 consumption of palm oil for biodiesel.

Beyond energy demands, another explanation for the retention of palm oil in the region is that LAC nations are not as competitive in global markets as their counterparts in SE Asia, where transportation and production costs (primarily labor costs) are lower [56]. For example, Brazil is considered to have the highest labor costs of any oil palm producing nation—65% higher than Indonesia—demonstrating the importance of price premiums from sustainable certification programs to access overseas markets [56, 70].

Because palm oil is a globally traded commodity rooted in diverse supply chains, efforts directed toward industry sustainability have been most effective via market based initiatives. The most notable example is the Roundtable on Sustainable Palm Oil (RSPO) which provides oil palm growers and other value chain actors a price premium for sustainably produced palm oil. These incentives are driven mainly by civil society and consumers in affluent markets, particularly USA and Europe. If palm oil is being retained in Latin America for domestic consumption, especially for use as fuel instead of food, there may be less pressure to certify local production. As it turns out, certification for sustainable production is building momentum in Latin America. The RSPO has made recent strides by doubling membership of certified growers in the last two years (11 total) and increasing the total certified area to 258 180 ha in 2016, a 65% increase from the previous year [71]. The regional supply of certified palm oil is now comparable to the global average (∽20%) [71]. It is likely that oil palm producers in Latin America will continue seeking certification to remain competitive and ensure access to international markets.

5. Conclusion

The oil palm industry has been the source of vitriolic debate for the deforestation it has caused in Asia. In Latin America, similar proportions of oil palm are converted from pastures instead of forest. Latin America has the greatest remaining potential for increased agricultural expansion [57] and the oil palm industry is only expected to grow [72]. The question becomes not whether the oil palm industry *should* continue, but rather, *how* this sector can continue down a more sustainable pathway. Seminal to this effort will be the land use change associated with establishing new plantations. Future expansion must avoid deforestation in order to lower socio-ecological costs and minimize trade-offs between economic and environmental priorities. Previously degraded lands are abundant throughout LAC, and could potentially accommodate future demand for palm oil without further forest loss [72, 73] but directing expansion onto these lands will require institutional guidance through regulation and incentives [74]. Policies directed toward the expansion of oil palm, like ZAE-palma in Brazil, which targets previously degraded lands and prohibits deforestation, could be effective, especially when combined with international sustainability certifications that are often more stringent than national policies [75]. Commitments to conservation, coupled with a regional land use trend toward the development of previously cleared lands, gives Latin America an opportunity for more sustainable palm oil production.

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