

Deforestation and Reforestation of Latin America and the Caribbean (2001–2010)

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ABSTRACT

Forest cover change directly affects biodiversity, the global carbon budget, and ecosystem function. Within Latin American and the Caribbean region (LAC), many studies have documented extensive deforestation, but there are also many local studies reporting forest recovery. These contrasting dynamics have been largely attributed to demographic and socio-economic change. For example, local population change due to migration can stimulate forest recovery, while the increasing global demand for food can drive agriculture expansion. However, as no analysis has simultaneously evaluated deforestation and reforestation from the municipal to continental scale, we lack a comprehensive assessment of the spatial distribution of these processes. We overcame this limitation by producing wall-to-wall, annual maps of change in woody vegetation and other land-cover classes between 2001 and 2010 for each of the 16,050 municipalities in LAC, and we used nonparametric Random Forest regression analyses to determine which environmental or population variables best explained the variation in woody vegetation change. Woody vegetation change was dominated by deforestation ($-541,835 \text{ km}^2$), particularly in the moist forest, dry forest, and savannas/shrublands biomes in South America. Extensive areas also recovered woody vegetation ($+362,430 \text{ km}^2$), particularly in regions too dry or too steep for modern agriculture. Deforestation in moist forests tended to occur in lowland areas with low population density, but woody cover change was not related to municipality-scale population change. These results emphasize the importance of quantifying deforestation and reforestation at multiple spatial scales and linking these changes with global drivers such as the global demand for food.

Abstract in Spanish is available in the online version of this article.

Key words: food production and consumption; forest cover; globalization; land change; MODIS; population; Random Forests.

LATIN AMERICA AND THE CARIBBEAN (LAC) HAS THE LARGEST AREA OF TROPICAL FOREST, the globe's greatest amount of biodiversity, a large proportion of global aboveground carbon stock, and extensive protected areas (Eva *et al.* 2004, Wright 2005, Houghton 2007). These attributes are threatened by both internal and external drivers, including increases in human population and *per capita* consumption (Morton *et al.* 2006). The local population, often landless peasants or small landholders, are important actors in tropical deforestation and the expansion of an agriculture frontier (Perz 2001, Carr 2009), but current trends of rural-urban migration (Barbieri & Carr 2005, McDonald 2008) and decreasing local population density in rural areas could promote reforestation through natural regeneration (Aide & Grau 2004, Wright & Muller-Landau 2006). Although examples of reforestation exist in LAC (Aide *et al.* 2000, Hecht & Saatchi 2007, Chazdon 2008,

Walker 2012), particularly in regions too steep or dry for modern agriculture (Lambin *et al.* 2003, Grau & Aide 2008), areas that lose population can still experience deforestation as modern mechanized agriculture replaces traditional farming (Morton *et al.* 2006, Sloan 2007).

Given these contrasting dynamics, how and where trajectories of land change will be altered remains uncertain. Furthermore, land-change dynamics suggest that external drivers, such as the growing global population, increasing *per capita* wealth, and the increasing global demand for agricultural products, can be as important as local drivers of land change. For example, these external drivers have created land change pressures in LAC, including the expansion of the agricultural zone for both food and biofuels (FAO 2010), an increase in mining and fossil fuels extractive activities, and new infrastructure projects, such as roads (Laurance *et al.* 2001). These pressures impact forest cover directly through deforestation or indirectly through 'displacement deforestation' *e.g.*, sugar cane and soybean expansion into

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pastures in southern Brazil and the deforestation of Amazon forests for new pasture lands (Barona *et al.* 2010, Walker 2012).

Historically, studies of forest change in LAC have focused on deforestation (Lambin *et al.* 2003), particularly in the humid tropics and Amazon Basin (Achard *et al.* 2002, Hansen *et al.* 2008). Studies that include all of LAC have usually been limited to national statistics with varying degrees of data quality (FAO 2010). Most importantly, broadscale studies based on remotely-sensed data have not analyzed deforestation and reforestation simultaneously (Lepers *et al.* 2005, Hansen *et al.* 2008, Killeen *et al.* 2008). In the few cases where both processes have been included, the studies were restricted to relatively small areas (Sloan 2008, Lele *et al.* 2010) or the data quality did not permit a direct comparison (Asner *et al.* 2009). Measuring the extent and location of deforestation and reforestation at the continental scale is essential for understanding how biophysical and demographic factors influence these processes, and for developing strategies to respond to the rapid changes impacting major ecological and biogeochemical processes.

To determine the extent and the spatial distribution of deforestation and reforestation, we used satellite imagery to quantify land change between 2001 and 2010 for the 16,050 municipalities within the 45 countries in Latin America and the Caribbean. Here, we use a liberal definition of both deforestation and reforestation: deforestation includes woody vegetation (*i.e.*, trees, shrubs) loss through conversion, selective logging, and degradation; reforestation includes woody vegetation gain through natural regeneration, encroachment, or direct human intervention. In this context, what constitutes forest is biome dependent – trees in moist forests and shrub or small trees in deserts. In our analysis, we also determined the relationship between woody vegetation change and key human demographic and environmental variables. Specifically, we addressed the following questions: (1) where are the hotspots of woody vegetation gain and loss? (2) which biomes are experiencing the greatest change in woody vegetation cover? and, (3) which variables are associated with these changes?

MATERIALS AND METHODS

We generated annual land-cover maps based on 250-m Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data for the period 2001–2010 for all countries in LAC at the second administrative, or municipality scale ($N = 16,050$). Land change was also reported for the ten major biomes within LAC (Olson *et al.* 2001, Fig. 1). We followed the United Nations geoscheme definition of Latin America and the Caribbean, which includes all countries in the Americas south of the United States. Methods are summarized below, and followed Clark *et al.* (2010) and Clark and Aide (2011a).

REFERENCE DATA.—Reference data for classifier training and accuracy assessment were collected using the Virtual Interpretation of Earth Web-Interface Tool (VIEW-IT) (Clark & Aide 2011b). VIEW-IT integrates a 250×250 m interpretation grid centered

on MODIS pixels, high spatial resolution imagery from Google Earth, a user interface for assigning date and visual interpretation of percent cover of land-cover classes, and a data base for verification and data processing. Following definitions in Clark *et al.* (2010) and summarized in Table S1, reference samples were assigned to seven classes: woody vegetation, herbaceous vegetation, agriculture, plantations, built-up areas, bare areas, and water if the dominant class covered ≥ 80 percent of the interpretation grid. An additional class, mixed-woody vegetation, was assigned to areas with 20–80 percent woody vegetation, with a bare, herbaceous vegetation, or agriculture component. We used VIEW-IT to collect 40,432 reference samples from all biomes in LAC.

LAND CHANGE MAP PRODUCTION.—Annual land-cover maps were produced by classifying the MODIS satellite MOD13Q1 Vegetation Indices 250 m product for the period 2001–2010. The product is a 16-d composite of the highest quality pixels from daily images and includes the Enhanced Vegetation Index (EVI), blue (459–479 nm), red (620–670 nm), near infrared (NIR: 841–876 nm), and mid-infrared (MIR: 2105–2155 nm) reflectance and pixel reliability, with 23 scenes per year from 2001 to present (Huete *et al.* 2002). For each pixel, we calculated the mean, standard deviation, minimum, maximum and range for EVI, and blue, red, NIR, and MIR reflectance values from each year between 2001 and 2010. These statistics were calculated for all 12 mo, two 6-mo periods, and three 4-mo periods. The pixel reliability layer was used to remove all unreliable samples (value = 3) prior to calculating statistics.

We produced a continental-scale map of LAC with the eight classes described above for each year between 2001 and 2010. We used the Random Forests (RF) tree-based classifier (Breiman 2001), implemented using the R statistical program and the ‘randomForest’ package (v. 4.6–2). To produce each map, we divided LAC into nine zones, with boundaries modified to follow municipalities. Municipalities were assigned a zone and then to a biome (Olson *et al.* 2001) with the greatest area. A separate RF classifier was then generated for each zone/biome ($N = 26$), in each case using only VIEW-IT reference samples within a zone-biome mapping region. On average, 1555 VIEW-IT reference samples and their associated MODIS statistics were used for training and validation of each RF classifier. For increased accuracy, we performed a postclassification reclassification on all maps to five classes: woody vegetation, plantations/mixed-woody vegetation, agriculture/herbaceous vegetation, bare/built-up areas, and water. Based on RF sample cross-validation statistics, the average overall accuracy of the 26 RFs was 84.6 percent ($\pm 6.5\%$). The pixel level accuracy for the woody class in the tropical moist forest biome (46% of the total area) was 93 percent (Table S2).

LAND CHANGE ANALYSES.—Land change was analyzed for the period 2001–2010 at the municipality scale. We calculated the area of each cover class during each year for each municipality, and then used a linear regression model to determine if there was a statistically significant change in the area for the 10-yr period. When calculating the change in a class between 2001 and 2010,

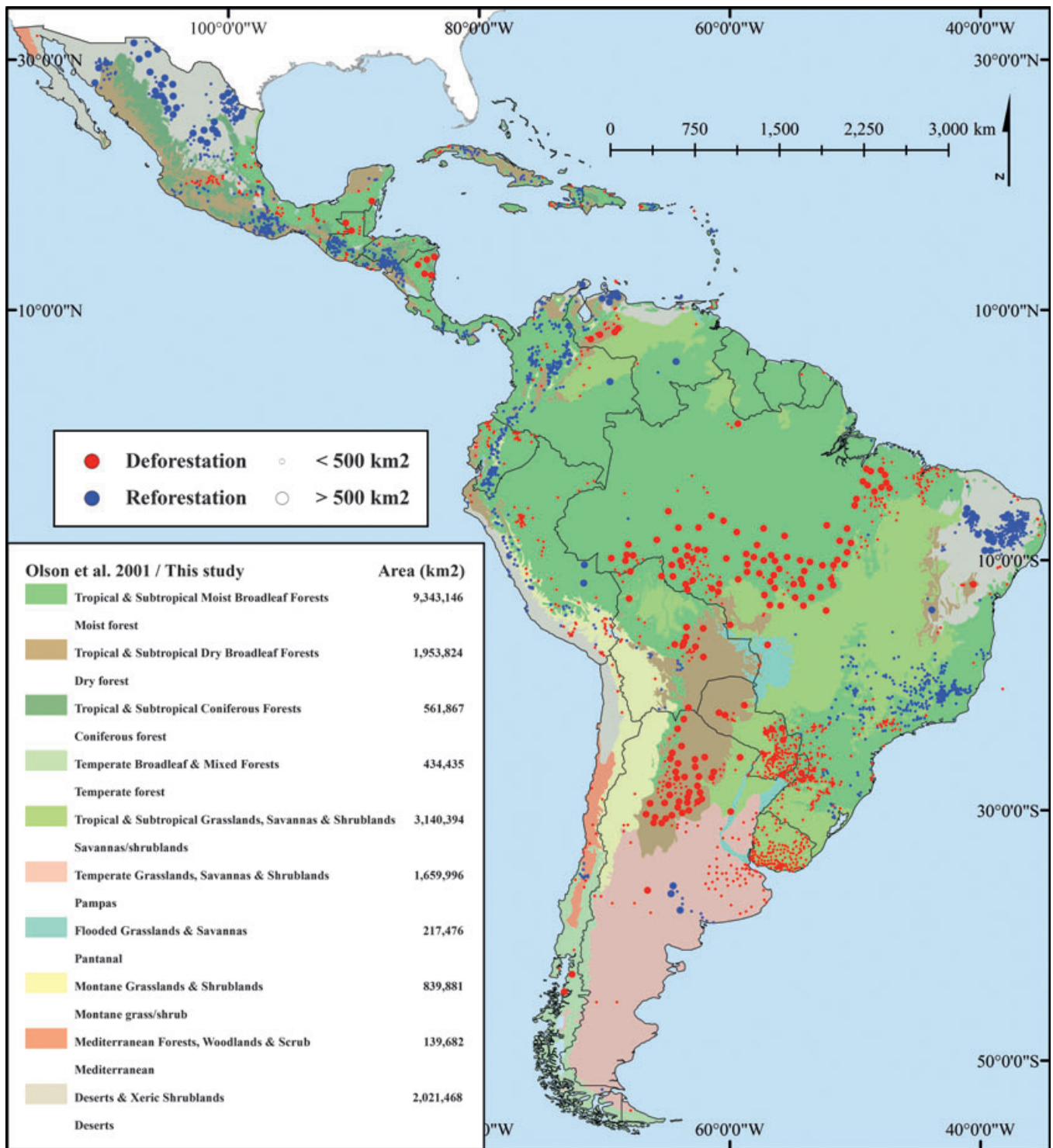


FIGURE 1. The distribution of hotspots of deforestation and reforestation relative to the ten major biomes in Latin America and the Caribbean as proposed by Olson *et al.* (2001). Included in the legend are the original biome names, the names used in this study, and the area of each biome based on municipality boundaries, as calculated for this study. Each dot represents one of the 2513 municipalities that had a significant change in woody vegetation over the 10-yr period (2001–2010).

we used the values from the regression and not the raw data. Subsequent analyses focused on the municipalities that had a statistically significant ($P \leq 0.05$) change in woody vegetation area.

Throughout the text, reforestation (*i.e.*, natural regeneration or secondary succession) is used as the antonym of deforestation, and refers to a significant increase in the woody vegetation class

within a municipality over the 10-yr period, and does not include changes in mixed-woody vegetation or plantations.

POPULATION DATA COLLECTION.—To generate municipality-level estimates of population for 1990 and 2000, we used national census data (Table S3). For the majority of the countries, this information was accessed through the census office website of each country. To extrapolate the official population estimates to 1990 and 2000, we first calculated an average annual growth rate using the data from the two census years, and then applied this estimated growth rate to 1990 and 2000. This extrapolation method is the same as the one applied in the Gridded Population of the World, v. 3 (CIESIN [Center for International Earth Science Information Network] & CIAT [Centro Internacional de Agricultura Tropical] 2005). If a municipality boundary changed between censuses (*e.g.*, one municipality split into two municipalities), we often used the boundary from the first census and combined the population data from the two new municipalities.

PREDICTORS OF WOODY VEGETATION CHANGE.—We used Random Forests (RF) regression (Svetnik *et al.* 2003) to determine which environmental or population variables best explained the variation in woody vegetation change. Temperature and precipitation data were acquired from the Climatic Research Unit Datasets, University of East Anglia (<http://www.cru.uea.ac.uk/cru/data/hrg-interim/>). Elevation data were acquired from the CGIAR–CSI (Consultative Group on International Agriculture Research–Consortium for Spatial Research) SRTM (Shuttle Radar Topography Mission) 90 m Data base (<http://srtm.csi.cgiar.org>). RF regression is an effective way to rank the importance of independent variables in explaining a dependent variable. It can handle nonlinear relationships, nonparametric data, and categorical data, and it can reduce problems of spatial autocorrelation that can bias parametric linear models (Segal 2004). In our RF analysis, we included the 2513 municipalities that had a significant ($P < 0.05$) positive (*i.e.*, reforestation) or negative (*i.e.*, deforestation) linear trend of woody vegetation change over 10 yr. Variable importance was determined by calculating how much the percent increase in the mean square error changed when a particular independent variable was randomly permuted. An increase in mean square error means that the variable had more importance in the RF regression model. Independent variables with the highest predictive power were then compared with changes in the woody vegetation class by creating a RF partial dependence plot.

To further examine the relationship of population change, we determined if there was an association between population (gain or loss) and woody vegetation (gain or loss) using a two-by-two Pearson's chi-square. For this analysis, we only used the 2513 municipalities that had a significant ($P < 0.05$) linear trend of woody vegetation change. These municipalities were divided into two groups (<50 and >50% woody cover in 2001) given that this was the most important variable in the RF regression analysis. We compared population change (absolute, percent, and density) in the decade prior to that of land change because we expected a lag time between population change and land change.

The tropical moist forest biome (>9 million km²) is the largest biome in LAC, and is of great conservation concern due to the high levels of biodiversity. Previous studies have suggested that elevation and population density are good predictors of forest cover change in this biome (Aide & Grau 2004, Wright & Muller-Landau 2006). To test these hypotheses, we selected the municipalities that had significant change in woody vegetation (deforestation: $N = 603$; reforestation: $N = 503$), and then compared the distributions of elevation and population density between the deforesting and reforesting municipalities using a Student's *t*-test.

RESULTS

Between 2001 and 2010, LAC experienced both extensive deforestation and reforestation (Fig. 1). We estimated a net loss of $-179,405$ km² of woody vegetation resulting from $-541,835$ km² of deforestation and $+362,430$ km² of reforestation (Table S4).

REGIONAL AND COUNTRY LEVEL CHANGE.—In the Caribbean, there was a net gain in woody vegetation (Fig. 1; Table S4). The majority of this increase occurred in Cuba, where we estimated a net gain of $+2524$ km² of woody vegetation. Puerto Rico and Haiti also had a net gain in woody vegetation ($+167$ and $+151$ km², respectively). Trinidad and Tobago and Jamaica were the countries with the greatest area of woody vegetation loss (-203 and -299 km², respectively).

The Mexico/Central America region also experienced a net increase in woody vegetation (Fig. 1; Table S4); the majority of which occurred in Mexico ($+96,089$ km²). Honduras, Costa Rica, and El Salvador had a net gain in woody vegetation ($+3460$, $+1628$, and $+586$ km², respectively). Guatemala and Nicaragua were the countries with the greatest area of woody vegetation loss (-3019 and -7961 km², respectively).

Deforestation prevailed in South America, and Argentina, Brazil, Paraguay, and Bolivia accounted for 80 percent of the deforestation in all of LAC (Fig. 1; Table S4). Argentina and Brazil both had a net loss of approximately $-100,000$ km² of woody vegetation. Although Brazil lost the most area of woody vegetation ($-245,767$ km²), it was the country with the greatest area of woody vegetation gain ($+146,342$ km²). Bolivia and Paraguay also had net losses of woody vegetation ($-27,650$ and $-42,778$ km², respectively). Colombia and Venezuela were the two countries in South America with the largest net gains in woody vegetation ($+16,963$ and $+5830$ km², respectively).

BIOME LEVEL CHANGE.—Country- or regional-level land change statistics combine 'woody vegetation' from different biomes, and vegetation in this class can vary from shrubs to trees. For example, the large increase in woody vegetation in Mexico was mainly due to an increase in the desert/xeric shrub biome in the north (Fig. 1; Table S4), where woody vegetation is mainly shrubs and small trees. In contrast, deforestation in southern Mexico affects high diversity and high biomass forests of the moist forest biome.

For this reason, we present the trends at the biome level, where there is less variation in the characteristics of woody vegetation.

Deforestation and reforestation varied greatly among the ten major biomes in LAC (Fig. 2A), and these changes were closely matched by a corresponding gain or loss in the mixed woody/

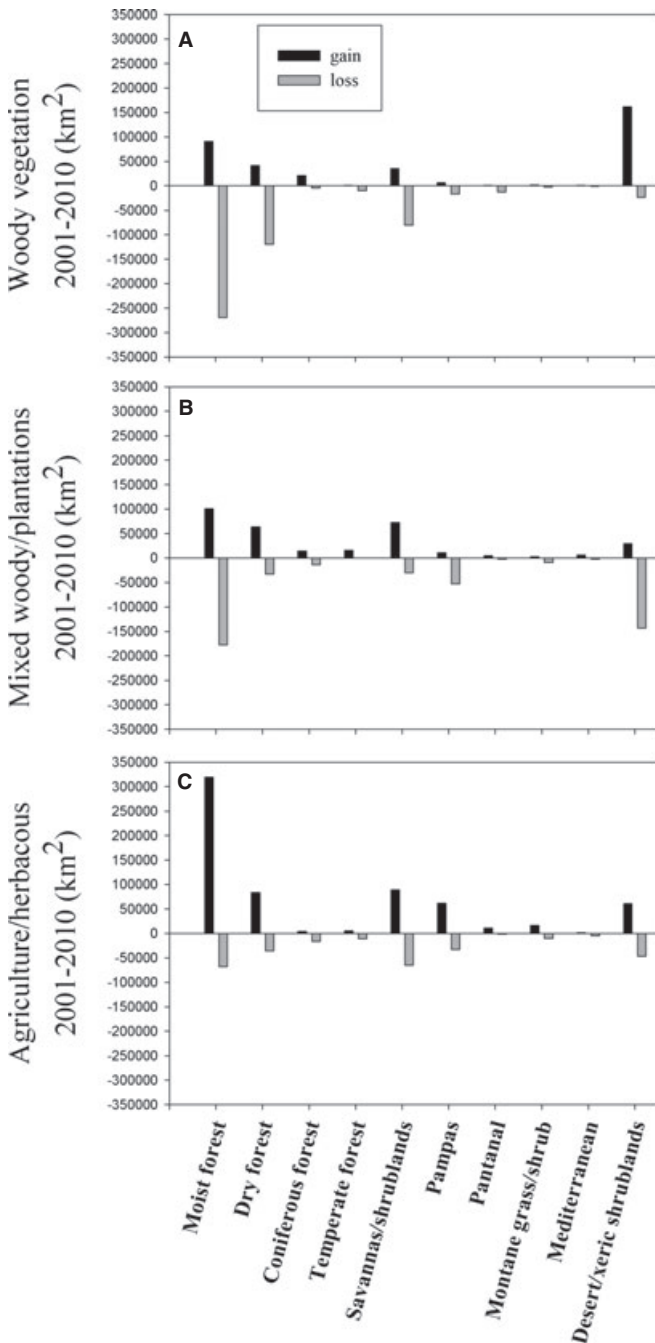


FIGURE 2. Losses and gains in the three major cover classes. The change in cover for (A) woody vegetation, (B) mixed woody/plantations, and (C) agricultural/herbaceous vegetation between 2001 and 2010 are presented for each of the ten major biomes in Latin America and Caribbean (25). The analysis includes all 16,050 municipalities.

plantation and agriculture/herbaceous vegetation classes (Figs. 2B and C). For example, more than 80 percent of deforestation occurred in the moist forest, dry forest, and savannas/shrublands biomes. These biomes also had the largest increase in the agriculture/herbaceous vegetation class. Major areas of deforestation in the moist forest biome included the Brazilian ‘arc of deforestation’, eastern Paraguay and southwest Brazil, the Pucallpa region of Peru, northwestern Ecuador, the Caribbean coast of Nicaragua, and the Selva Maya region of Guatemala and Mexico (Fig. 1). In the dry forest biome, the majority of woody vegetation loss occurred in the dry Chaco in northern Argentina, the Santa Cruz region of Bolivia, western Paraguay, and south of Lake Maracaibo in Venezuela.

More than 40 percent of the increase in woody vegetation occurred in the desert/xeric shrub biome, particularly in northeast Brazil and northcentral Mexico (Figs. 1 and 2A). This increase in woody vegetation mostly originated from the mixed woody/plantation class (Fig. 2B). Other large gains of woody vegetation occurred in the Andes of Colombia, Venezuela, Peru, and Ecuador, the savannas/shrublands biome of eastern Brazil, dry forest ecoregions of Mexico, Cuba and Peru, and the coniferous forest of Mexico and Central America (Figs. 1 and 2A).

PREDICTORS OF LAND CHANGE.—At the municipality scale, the multivariate RF regression analysis showed that environmental variables, not demographic variables, best explained the variation in significant woody vegetation change among municipalities (Fig. 3). This model explained 76 percent of the variation in the change in woody vegetation. The three most important variables were the percent of woody area in 2001, biome, and standard deviation of mean monthly temperature. The partial dependency plot of the percent of woody area in 2001 showed that municipalities with little vegetation in 2001 were more likely to experience reforestation, whereas municipalities with a high proportion

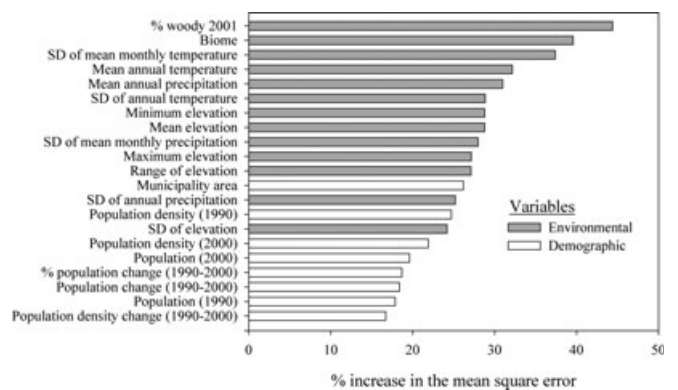


FIGURE 3. Random Forests regression results for the relationship between woody vegetation environmental and demography variables. The analysis included the 2513 municipalities that had a significant change in woody vegetation over the 10-yr period (2001–2010). Variable importance was determined by calculating how much the percent increase in the mean square error changes when a particular independent variable is randomly permuted.

of woody vegetation in 2001 were more likely to undergo woody vegetation loss in the following 10 yr (Fig. S1).

Given the importance of the percent of woody area in 2001, we analyzed the effect of population in two groups: municipalities with more or less than 50 percent woody cover in 2001. There was no significant association between population change (1990–2000) and woody vegetation change (2001–2010) at the municipality scale for municipalities with <50 percent woody vegetation in 2001 ($\chi^2 = 1.85$, $P = 0.17$, Table 1). Many municipalities lost population, providing the potential for extensive forest transition, but only 56 percent of these municipalities had a significant increase in woody vegetation (Table 1). Of the municipalities that had >50 percent woody cover in 2001, there was a significant effect of population change on woody vegetation change ($\chi^2 = 26.0$, $P < 0.001$, Table 1); in this case, the majority of municipalities that gained population lost woody vegetation. If both groups are combined, 994 of the 2513 municipalities gained population and gained woody vegetation (Table 1).

Within the tropical moist forest biome, 1106 of the 7369 (15%) municipalities had a significant increase or decrease in woody vegetation. There was a significant difference in elevation between municipalities that were deforesting and reforesting (Kruskal–Wallis nonparametric ANOVA: $KW = 291.4$, $P < 0.001$, Fig. 4A); the majority of municipalities that were deforested occurred at low elevations (<250 m), whereas the average elevation of the reforesting municipalities occurred mainly between 300 and 1000 m. There was also a significant difference in population density between municipalities that were deforesting and reforesting ($KW = 171.8$, $P < 0.001$, Fig. 4B). The majority of municipalities that were deforested had relatively low population densities (median = 17 people/km²), whereas population densities in the reforesting municipalities were much higher (median = 42 people/km²).

TABLE 1. The relationship between population change and woody vegetation change at the municipality scale. The analysis includes the 2513 municipalities that had a significant change in woody vegetation over the 10-yr period (2001–2010) and a gain or loss in population (1990–2000). The municipalities were divided into two groups based on the percent area of woody vegetation in the municipality in 2001, (A) the 2061 municipalities that had <50% woody cover in 2001, and (B) the 452 municipalities that had >50% woody cover in 2001.

Woody vegetation change	<50% woody in 2001*		>50% woody in 2001†	
	Loss	Gain	Loss	Gain
Loss	256	586	42	234
Gain	337	882	64	112

* $\chi^2 = 1.85$, $P = 0.17$.

† $\chi^2 = 26.0$, $P < 0.001$.

DISCUSSION

Our study concurs with previous studies that have documented extensive deforestation in LAC; however, we also show that forest recovery is occurring throughout the region. Prior to this study, forest recovery was generally documented by local-scale studies, with different levels of resolution and accuracy, which made it impossible to compare with broad-scale satellite-based estimates of deforestation (Asner et al. 2009). The present study is based on a methodology that evaluates a 10-yr trend in woody vegetation for each of the 16,050 municipalities in LAC using consistent datasets and methodology; and most importantly, it simultaneously evaluates patterns of deforestation and reforestation providing a comprehensive assessment of the relative extent and spatial distribution of both processes. Although this approach offers several advantages, it also comes with spatial limitations. Our analyses are based on the aggregate tendency (10-yr trend) of all 250 × 250 m pixels within a municipality, and changes at the sub-pixel (e.g., forest degradation, cutting for small-scale agriculture) could be underestimated. Finer resolution satellite imagery, such as Landsat or SPOT, could help to detect sub-pixel land changes, but these higher resolution images can also

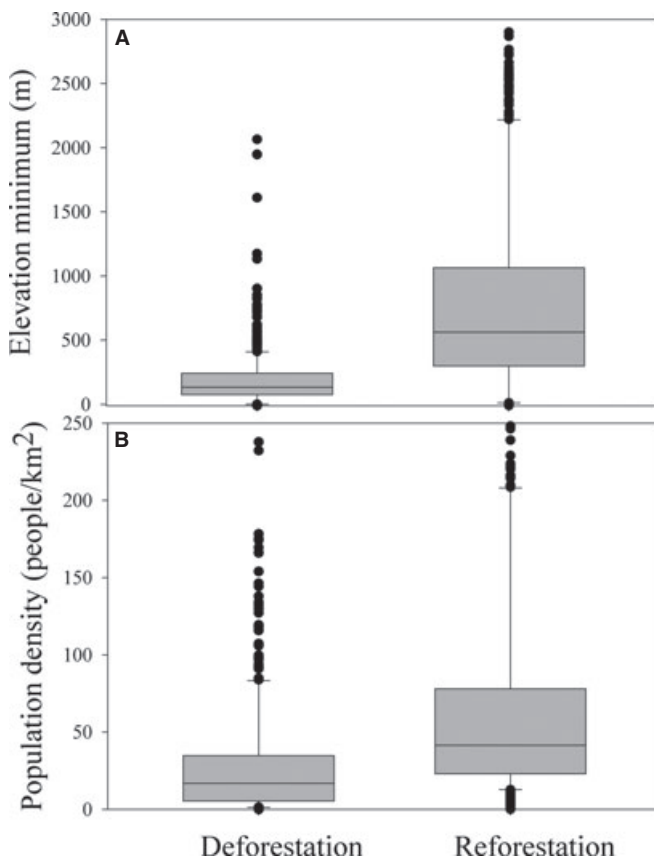


FIGURE 4. A comparison of (A) elevation and (B) population density between municipalities that had a significant change in woody vegetation (deforestation: $N = 603$; reforestation, $N = 503$) over the 10-yr period (2001–2010) in the tropical moist forest biome.

introduce error into a classification of similar temporal and spatial scale as our study because they lack the ability to capture cloud free data across large areas due to the relatively infrequent revisit time (*e.g.*, 16 d for Landsat).

PATTERNS OF CHANGE AND ECOLOGICAL CONSEQUENCES.—The moist forest biome, with its high level of biodiversity, continues to be the major area of woody vegetation loss in LAC (Fig. 2), with most of the deforestation concentrated in the Legal Amazon of Brazil (Fig. 1). We estimated that the moist forest biome in Brazil lost approximately 17,975 km²/yr of woody vegetation between 2001 and 2010 (Table S3 – Brazil, moist forests), consistent with the estimate of 17,486 km²/yr reported by the Brazilian government for the period 2001–2009 (INPE [National Institute for Space Research] 2011, Espindola *et al.* 2012). Another important region of deforestation was the Caribbean side of Central America, particularly in Nicaragua and Guatemala (Fig. 1). The deforestation in these areas directly affects areas of high biodiversity and the connectivity of the Mesoamerican Biological Corridor (Miller *et al.* 2001).

The dry forest and savanna/shrub biomes also experienced extensive deforestation. Together these two biomes lost approximately 200,000 km² of woody vegetation (Fig. 2), and most of this loss was concentrated in northern Argentina, southeastern Bolivia, and western Paraguay (Fig. 1). The conversion of these dry forest and savanna/shrub habitats into agricultural and pasture lands or the degradation to mixed woody/plantation class represents a major loss in aboveground biomass (Gasparri *et al.* 2008), and has fragmented the largest continuous area of dry forest in the world (Gasparri & Grau 2009). The deforestation in Argentina has mainly been associated with the expansion of soybean production (Grau *et al.* 2005, Grau *et al.* 2008). Bolivia has also had large areas of dry forest converted into agriculture and pastures (Killeen *et al.* 2008, Redo & Millington 2011). Paraguay lost extensive area of forest between 1990 and 2000 (Huang *et al.* 2009), and our data show that this trend has continued with more than 42,000 km² of woody vegetation converted to another cover class between 2001 and 2010 (Fig. 1; Table S4).

Perhaps the most surprising finding was the extensive expansion of woody vegetation in the desert/xeric shrub biome of northern Mexico and northeast Brazil, which contrasts with studies that have emphasized desertification in LAC (Geist & Lambin 2004). Although some of these gains in woody vegetation in the desert/xeric shrub biome can be attributed to a decrease in agricultural or grazing activities, most of the increase came at the expense of the mixed-woody vegetation class (Fig. 2B). In Mexico, this shift occurred simultaneously with increasing precipitation. Between 2001 and 2009, the average annual precipitation in the three northern states of Chihuahua, Coahuila, and Nuevo Leon was 38, 16, and 21 percent, respectively, higher than in the previous 60 yr (Fig. S2). In the Caatinga ecoregion in Brazil, there was also an increase in precipitation and a decrease in agricultural activities (Redo *et al.*, in press). Although some studies have reported woodland expansion in deserts, and related this process with changes in land use, climate, and CO₂ fertilization

(Archer *et al.* 1995), this is the first study to show the extent of this process at a continental scale.

Although most conservation research in LAC has focused on deforestation (*e.g.*, Hoekstra *et al.* 2005) and related processes (*e.g.*, habitat conversion, fragmentation, desertification), our results show that both reforestation and deforestation are affecting large areas. The two processes are often spatially segregated (*e.g.*, lowland deforestation and montane reforestation), suggesting that conservation and land-use planning could benefit from a more balanced treatment of land change that considers opportunities for ecosystem recovery, in addition to deforestation and degradation. Today, these areas of recovering forest have lower biodiversity or biomass in comparison with undisturbed areas (Gibson *et al.* 2011), but if these ‘new forests’ are allowed to grow, they can support a high diversity of flora and fauna, and provide ecosystem services at levels similar to mature forests (Chazdon 2008).

MUNICIPALITY-SCALE DRIVERS.—At the municipality scale, the best predictors of woody vegetation changes were the percent of woody vegetation in 2001, biome, and the standard deviation of mean monthly temperature. In very general terms, municipalities with little vegetation in 2001 were more likely to reforest, whereas municipalities with a high proportion of woody vegetation in 2001 were more likely to lose woody vegetation in the following 10 yr. This is not surprising, given that a municipality must have woody vegetation to deforest or a municipality must have lost woody vegetation before it can reforest. Although percent of woody vegetation in 2001 was correlated with woody change, it does not explain why a municipality deforested or reforested.

Overall, environmental variables were better predictors of woody vegetation change at the municipality scale than were population variables. One explanation for the importance of the environmental variables (*i.e.*, temperature, precipitation, and elevation), which are encompassed by the variable ‘biome’, is that they place physical limits on the types of land-use practices that are feasible in a region. For example, in the tropical moist forest biome, reforestation occurred mainly at high elevations (*e.g.*, cooler temperatures, steeper slopes) (Fig. 4A), whereas deforestation occurred in the lowlands, which are more appropriate for large-scale mechanized agriculture. The relatively high importance of temperature variability in modeling woody vegetation change suggests that near-future climatic change may have significant influences on land-cover patterns.

Our continental-scale analysis showed that municipality-level population variables were poor predictors of woody vegetation change, as deforestation occurred in municipalities that gained and lost population. Deforestation also occurred in areas of low population density (Santa Cruz, Bolivia; Amazon, Brazil; Chaco, northern Argentina) and relatively high population density (eastern Paraguay; southern Brazil). Similarly, reforestation occurred in areas of low population density (northern Mexico) and high population density (Caatinga, Brazil). Within the tropical moist forest biome, population density did help explain differences in patterns of deforestation and reforestation (Fig. 4B). Deforestation was concentrated in areas of low population density, presumably areas that were being colonized, while reforestation mainly occurred in

areas of high population density where forests had already been transformed. A possible limitation of our analyses is that they only included changes in the total population of each municipality and did not include the change in the rural and urban population separately because these data were not available for the majority of the countries. Although rural population changes can impact land change (Carr 2009, Izquierdo *et al.* 2011, Robson & Berkes 2011), other studies using our land-change dataset, and which included rural population change at the municipality scale in Mexico (Bonilla-Moheno *et al.* in press) and Bolivia (Redo *et al.* 2012a), did not show a significant effect, thus providing support for the claim of a diminishing influence of local population on land use (DeFries *et al.* 2010).

GLOBAL-SCALE DRIVERS AND LAND-USE PLANNING IMPLICATIONS.—Although our study did not focus on the external drivers of LUCC in LAC, our results suggest that increasing affluence and *per capita* consumption associated with global urban populations (DeFries *et al.* 2010) can be a major driving force of the extensive deforestation in South America during the last decade. The increase in the agricultural/herbaceous class in Brazil, Bolivia, Paraguay, and Argentina (Figs. 1 and 2C), where 80 percent of the deforestation in LAC occurred, was predominantly export-oriented agriculture related to the increasing global demand for meat products (Grau *et al.* 2005, Morton *et al.* 2006). This is illustrated by the positive relationship between the global pig and poultry production and the area of soybean production in Brazil, Bolivia, Paraguay, and Argentina (Fig. 5A). Soybeans are produced in these countries, but they are exported globally where they are used as a major component of feed for pig and poultry. Similarly, a dramatic increase in beef exports from these four countries was correlated with an increase in 6.8 million hectares of pastures lands (Fig. 5B). The increase in these two land-use categories, based on country-level statistics from FAO, accounts for 75 percent of the increase we detected in our agricultural/herbaceous vegetation class in these four countries. Although global demands for food products are an important driver in this hotspot of deforestation, in other regions, such as Mexico/Central America and Caribbean which accounted for 8 percent of the total deforestation, soybeans and beef exports are not the major drivers of change. Instead, in Central America, deforestation was associated with subsistence agriculture and pastures primarily in moist forest in eastern Nicaragua and the Selva Maya region of Guatemala (Redo *et al.* 2012b).

Given that the global demand for food is expected to increase greatly over the next 40 yr, it is likely that large areas of intact forest in LAC will continue to be converted to modern agriculture and pastures (Dros 2004, Gibbs *et al.* 2010, Richards 2011), with major consequences for carbon emissions and biodiversity conservation (Wright 2005, Houghton 2007). How to accommodate this growing demand for agricultural products without jeopardizing the high levels of biodiversity and ecosystems services in LAC will be a major scientific and policy challenge. To reduce the impact of beef production, McAlpine *et al.* (2009) suggested eliminating subsidies, limiting the areas for future expansion of pasturelands, and promoting forest regrowth or alternative land uses. Currently, more than 25

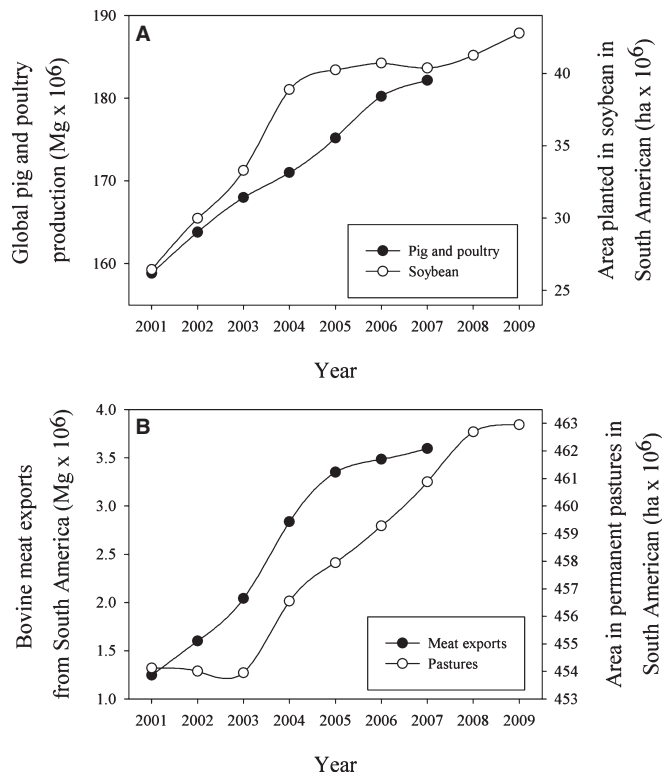


FIGURE 5. The relationship between export products and land-cover change in South America. (A) the relationship between global pig and poultry production (left *y*-axis) and soybean production in South America (right *y*-axis). Between 1995 and 2007, the Pearson's correlation between these variables was 0.93 ($N = 13$, $P < 0.0001$), and (B) the relationship between bovine mean exports (left *y*-axis) and permanent pasturelands in South America (right *y*-axis). Between 1995 and 2007, the Pearson's correlation between these variables was 0.77 ($N = 13$, $P < 0.002$). Data are from FAOSTAT (<http://faostat.fao.org>); accessed on 1 February 2012.

percent of the land area of LAC is classified as pastures and permanent meadows (FAOSTAT 2011), a large proportion of which is used for extensive cattle ranching. Given that cattle is one of the least efficient meat-producing livestock (Smil 2000), and that meat productivity can be substantially increased by more intensive management techniques or replaced by agriculture, land-use policies should favor intensification rather than favoring food production in low productivity systems.

CONCLUSIONS

During the first decade of the 21st century, land change in Latin America and Caribbean included extensive deforestation, but there was also an increase in $>360,000$ km² of woody vegetation across the region; equivalent to approximately 66 percent of the deforestation. The majority of deforestation in LAC occurred in South America (92%), particularly in Argentina, Brazil, Bolivia, and Paraguay, where extensive areas were converted to agricultural lands (*e.g.*, soybeans) and cattle pastures, a response we attribute to the increasing global demand for meat.

Reforestation mainly occurred in the desert/xeric shrub biome and mountainous regions, which are less appropriate for large-scale mechanized agriculture. These changes in the distribution of forests and shrublands have important implications for the developing United Nations Reducing Emissions from Deforestation and Forest Degradation (REDD) program (Angelsen *et al.* 2009), particularly in identifying the baseline of forest dynamics. For example, how will REDD incorporate the increase in >300,000 km² of woody vegetation across LAC given that most of this recovery has occurred without active intervention? These changes also provide conservation opportunities in the Andes, Central America, and Caribbean, where land has presently lost agricultural value. Furthermore, these complex land-change dynamics provide an insight into the enormous challenge we face trying to balance biodiversity conservation with human needs.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

TABLE S1. *Description of the land-use/land-cover classes.*

TABLE S2. *Average pixel level producer accuracies for the five classes for each of the ten biomes.*

TABLE S3. *Population dynamics for the 45 countries in Latin American and Caribbean between 1990 and 2000.*

TABLE S4. *Estimated change in woody vegetation area between 2001 and 2010.*

FIGURE S1. Map of percent woody vegetation in 2001 for municipalities with significant trends of woody vegetation.

FIGURE S2. A comparison of the 9-yr trend of precipitation during the period of the study (2001–2009).

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