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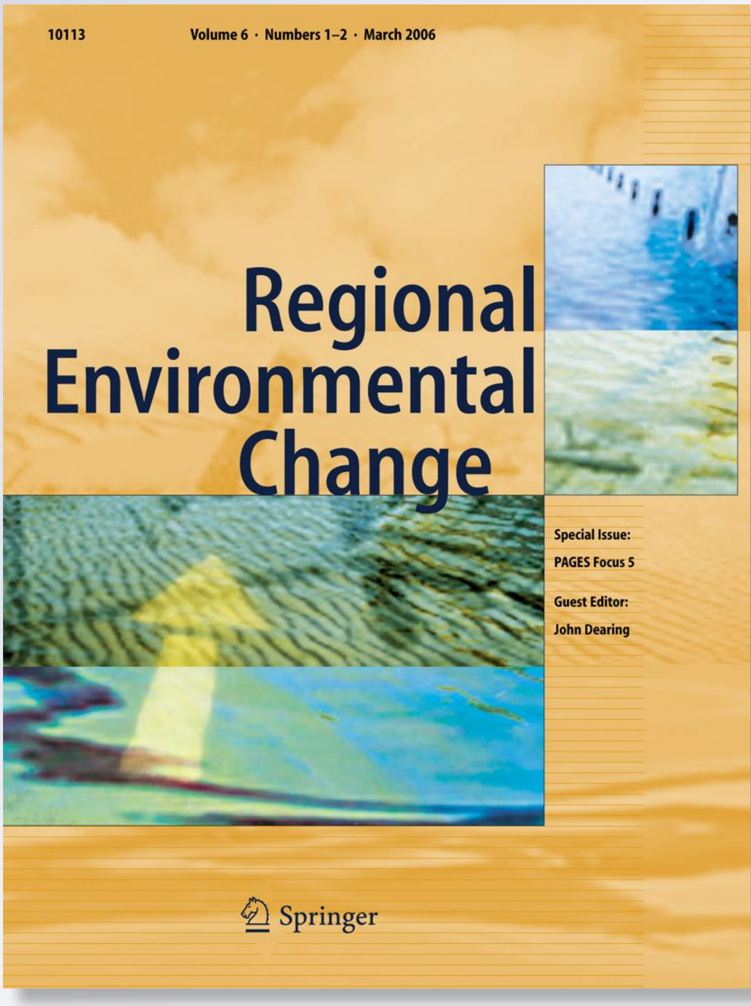

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ORIGINAL ARTICLE

The influence of socioeconomic, environmental, and demographic factors on municipality-scale land-cover change in Mexico

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Abstract Land-cover change is the result of complex multi-scale interactions between socioeconomic, demographic, and environmental factors. Demographic change, in particular, is thought to be a major driver of forest change. Most studies have evaluated these interactions at the regional or the national level, but few studies have evaluated these dynamics across multiple spatial scales within a country. In this study, we evaluated the effect of demographic, environmental, and socioeconomic variables on land-cover change between 2001 and 2010 for all Mexican municipalities ($n = 2,443$) as well as by biome ($n = 4$). We used a land-cover classification based on 250-m MODIS data to examine the change in cover classes (i.e., *woody, mixed woody*, and *agriculture/herbaceous vegetation*). We evaluated the trends of land-cover change and identified the major factors correlated with woody vegetation change in Mexico. At the national scale, the variation in woody vegetation was best explained by environmental variables, particularly precipitation; municipalities where woody cover increased tended to be in areas with low average annual precipitation (i.e., desert and dry forest biomes). Demographic variables did not contribute much to the model at the national scale. Elevation, temperature, and population density explained the change in *woody* cover when municipalities were grouped by biome (i.e., moist forest, dry forest, coniferous forest, and deserts). Land-cover change at the biome level showed two main trends: (1) the tropical moist biome lost woody vegetation to agriculture and herbaceous vegetation, and (2) the desert biome increased in woody vegetation within more open-canopy shrublands.

Keywords Biome · Municipality · Population change · Precipitation · Woody vegetation

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Introduction

Land-cover change is the result of complex interactions among social, economic, and environmental factors occurring at multiple temporal and spatial scales (Geist and Lambin 2002; Lambin et al. 2001). The increasing demand for food and other commodities, shift in regional economies, household level conditions, indirect effect of tourism, globalization of markets, and presence and effectiveness of social institutions (Aide and Grau 2004; Barbier et al. 2010; DeFries et al. 2004; Gaughan et al. 2009; Hecht 2010; Parés-Ramos et al. 2008; Perz 2004; Wright and Samaniego 2008) are all examples of multifactor, multi-scale dynamics that can influence patterns of land-cover change (e.g., reforestation and deforestation).

Demographic dynamics have often been identified as important underlying drivers of tropical forest deforestation

(Carr 2004, 2009; Geist and Lambin 2001), but the recovery of forests in lands previously used for agricultural or pastoral activities has been linked to regional population decline (Rudel 1998; Rudel et al. 2005, 2010; Uriarte et al. 2010). Although in many regions, there is a clear relationship between population change and forest change, other studies have shown that the direction of forest change can be modified by socioeconomic and environmental factors (Geist and Lambin 2002). For example, reforestation patterns alongside roads in Ecuador have been linked to changes in land-use practices, but not to land abandonment (Rudel et al. 2002). The increase in woody vegetation in Misiones, Argentina has been the result of the expansion of forestry plantations and not of population change (Izquierdo et al. 2008). In the Argentinean Chaco, favorable environmental conditions and technological improvements have accelerated the conversion of woody vegetation into soybean agriculture despite the fact that the region has experienced rural population decline (Gasparri and Grau 2009; Zak et al. 2008).

Local-scale analyses are needed to identify the proximate (e.g., agriculture or pastureland expansion) and underlying (e.g., socioeconomic or demographic) factors driving deforestation and reforestation (Geist and Lambin 2002; Lambin et al. 2003; Scrieciu 2007). However, a limitation of local-scale analyses is that because they are usually geographically constrained and may include only one or a few case studies, the results cannot easily be generalized to broader spatial scales. To solve this problem, here we evaluate the relationship between land change and a suite of demographic, socioeconomic, and environmental factors at the municipality scale for all municipalities in Mexico ($n = 2{,}443$) from 2001 to 2010. Municipalities are the smallest administrative unit of the country at which demographic and socioeconomic information is collected in a standardized way. In addition, they share a number of potential drivers of land-cover change (e.g., political and economic programs, similar environmental conditions, social and demographic context), which makes them a useful unit for multi-scale land change analyses. In a sense, this is the equivalent of thousands of local-scale studies that share a common methodology, but span a gradient of environmental and socioeconomic factors. This data consistency and gradient should help to understand which factors are associated with forest change. In our study, we address the following questions related to land change in Mexico: (1) Does population change at the municipality level explain the patterns of land change?; (2) Can environmental or socioeconomic factors explain patterns of land change?; and, (3) How does land change vary among the four major biomes (moist forest, dry forest, coniferous forest, deserts) in Mexico?

Study area

Mexico represents an interesting example to evaluate the effect of population change on deforestation and reforestation patterns and to determine the relative importance of environmental and socioeconomic variables on land-cover change. Although Mexico has a large area of forest cover, its deforestation rate between 1990 and 2000 was one of the highest in the world (FAO 2010). From the mid 1970s to 2000, land change at the national level has been characterized by agriculture, pasture, and to a minor degree, urban expansion at the expense of woody vegetation (Mas et al. 2002, 2004; Velázquez et al. 2002a, b). Regional level studies in Oaxaca and Michoacan states have also identified agriculture and pasture expansion as the main causes of deforestation (Gomez-Mendoza et al. 2006; Ramirez-Ramírez 2001; Velázquez et al. 2003). Work in the Southern Yucatan Peninsula has also shown a decrease in tropical forest by mostly subsistence agriculture, although pastures and extensive agriculture have become a recent form of land pressure (Turner et al. 2001; Vester et al. 2007). A similar scenario was documented in the central region of Veracruz, where between 1990 and 2003 tropical montane forest was converted to pastures and croplands; however, there are other regions in Veracruz where forest are recovering at finer spatial scales (Muñoz-Villers and López-Blanco 2007). A study conducted in the state of Mexico showed agricultural expansion and institutional factors, which varied spatially, were the principal factors promoting local-scale forest-cover change (Pineda Jaimes et al. 2010). Although the overall national trend during the last 40 years has been the conversion of natural areas into agricultural systems, Mexican protected areas, particularly those with higher protection status (i.e., biosphere reserves), have been effective at preventing land conversion (Figueroa and Sanchez-Cordero 2008; Sanchez-Azofeifa et al. 2009).

Coincident with these patterns of land change, since the early 1970s, the Mexican population has shifted from a predominately rural population to a highly urbanized population—today more than 70% of Mexicans live in urban centers. Although there has been an increase in total population, this increase has not been generalized across the country. In fact, between 1990 and 2000, 27% of all municipalities lost people. Population decline was particularly prevalent in the northern states of Durango, Chihuahua, Zacatecas, Tamaulipas, and Sonora, where more than 50% of the municipalities lost people. During the last ten years (2000–2010), population dynamics have continued the same overall trend: population growth in urban areas and population decline in approximately 40% of all municipalities, particularly in the northern states described above, but also in the states of Michoacan and Oaxaca. In addition to the spatial variation in population dynamics, the development index for Mexico, which is above the world's average (UNDP 2010), varies greatly among states and municipalities (Partida and Tuirán 2001), with lower development generally concentrated in the southern states.

Case studies from Mexico have shown that national and international migrations have played a key role in determining patterns of land cover. For example, a study in Oaxaca linked vegetation recovery of sites previously used for agriculture with migration to the United States (Velázquez et al. 2003). This pattern was also described for the Cuitzeo region in the state of Michoacan, where nonproductive lands, particularly on steep areas, were abandoned when people migrated to urban centers in Mexico or left the country (Lopez et al. 2006). But, Mendoza et al. (2011) showed that the patterns of land change are not always easy to predict because environmental and socioeconomic factors can modify the outcomes. For example, migration can directly influence changes in land use through land abandonment, but also indirectly by changing local economies through the effect of remittances (Hecht 2010). In Mexico, remittances provide approximately 3% of the annual GDP (PNUD 2009), suggesting they can have an important influence on local economies and consequently on land cover. This was the case in Michoacan, where the reduction in agriculture was not a direct consequence of migration, but a result of the emergence of alternative economies (e.g., tourism-related activities, and services) encouraged by the influx of cash from abroad (Klooster 2003).

Materials and methods

A database of environmental, socioeconomic, demographic, and land-cover variables was assembled for each of the 2,443 municipalities in Mexico and is described in the sections later.

Environmental variables

Biomes

We followed the World Wildlife Fund biome classification that identifies 14 global biomes (Olson et al. 2001), seven of which are described for Mexico. We grouped municipalities into the four most important biomes (Fig. 1): Tropical and Subtropical Moist Broadleaf forest (i.e., moist forest, $n = 501$), Tropical and Subtropical Dry Broadleaf forest (i.e., dry forest, $n = 614$), Tropical and Subtropical Coniferous forest (i.e., coniferous forest, $n = 858$), and Deserts and Xeric Shrublands (i.e., desert, $n = 470$). These four biomes cover more than 99% of Mexico. Municipalities that occur in more than one biome were assigned to the biome with the greatest area. Municipalities that were surrounded by a biome different than their own were assigned to the surrounding biome.

Precipitation and temperature

Precipitation and temperature variables were based on data from the Climatic Research Unit, University of East Anglia, data sets time series (3.0) (CRU 2008). Data (gridded points at 0.5×0.5 latitude/longitude scale) from 192 months (1990–2005) were clipped to the study area, projected to Interrupted Goode Homolosine, and resampled to a raster with 231.7 m pixel size, the scale of our MODIS imagery (see "Population change and population density"). Monthly precipitation data for each year were summed to produce each year's total precipitation for the years 1990–2005. The average and standard deviation of these data were used to produce a raster of mean annual precipitation and mean annual standard deviation within each municipality's polygon. Annual temperature by municipality was estimated using the average monthly annual temperatures for each year. The average for each municipality was used as mean annual temperature.

Elevation and topography

The mean and standard deviation of elevation within each municipality was calculated using a 90-m Digital Elevation Model (Jarvis et al. 2008). Mean elevation differentiated highlands and lowland municipalities, while the standard deviation of elevation was used as index of topographic complexity within the municipality; municipalities with large standard deviation represented complex topography (i.e., mountains), while municipalities with small standard deviation represented flatter areas.

Socioeconomic variables at the municipality scale

Marginalization

We used the average marginalization index for 1990, 2000, and 2005 (http://www.conapo.gob.mx). This index incorporates information from variables that describe social equality and level of development for each municipality. Variables in the index include: percentage of population with access to elementary education; percentage of households without sewage, bathroom, electricity, and water; overcrowding level; house floor material; percentage of population in rural localities (<5,000 people); and income. Higher values of the index represent relatively more marginalization.

Fig. 1 Distribution of the four major biomes in Mexico. *Lines* represent limits of states (*black*) and municipalities (*gray*)

Type of income

Three types of income received by landowners were used: remittances, government incentives, or direct revenue from productive activities (forestry, cattle ranching, or agriculture). For each municipality, we calculated the proportion of landowners receiving each type of income. Data on income type were obtained from the 2007 *Censo Agricola, Forestal y Ganadero* (INEGI 2007). Income was only reported for owners of productive lands.

Land tenure regime

Land tenure regime was characterized by estimating the percent area of productive land (km^2) within the whole municipality, for five classes: colony, communal, ejido, private, and public. Colony, communal, and ejido lands represent types of collective tenure. Data on land tenure regime by municipality were obtained from the 2007 *Censo Agricola, Forestal y Ganadero* (INEGI 2007).

Population change and population density

Demographic data were obtained from national censuses (1990, 2000, and 2010) available from the *Instituto Nacional de Estadistica y Geografia* (http://www.inegi.gob.mx).

The total number of municipalities varied among censuses (2,403 in 1990; 2,443 in 2000; and 2,456 in 2010). We standardized the number of municipalities to those existing in 2000 as the base for the study, estimating (adding or subtracting people from split municipalities) the population for those municipalities not yet created in 1990 (40) and those that split by 2010 (13). For each municipality, we calculated the total population change, as well as the rural population change between 1990 and 2000 and 2000–2010. Since a lag time was expected between population change (land abandonment) and woody recovery, we included the change in population from the previous decade (1990–2000). Rural population per municipality was considered as the population inhabiting localities with less than 2,500 people. Rural population was obtained from INEGI's censuses historic series (1990 and 2000) and 2010 population census. We defined population change (total and rural) as the gain or loss of at least 100 people in a municipality. Population density was calculated as the number of people per km^2 for each municipality in 1990, 2000, and 2010.

Land-cover classification

Our land-cover mapping methods generally follow those outlined in Clark et al. (2010), with modifications explained in Clark and Aide (2011a) and summarized later. To map classes, we used the MODIS MOD13Q1 (16-day L3 Global 250 m) product. The product is a 16-day composite of the highest-quality pixels from daily images and includes the Enhanced Vegetation Index (EVI), red, near infrared (NIR), and mid-infrared (MIR) reflectance and pixel reliability (Huete et al. 2002). There are 23 samples available per year, with data available from 2001 to present. For each pixel, we calculated the statistics mean, standard deviation, minimum, maximum and range for EVI, and red, NIR and MIR reflectance values from calendar years 2001 to 2010. These statistics were calculated for all 12 months (annual), 2 six-month periods, and 3 four-month periods. The MOD13Q1 pixel reliability layer was used to remove all unreliable samples (value = 3) prior to calculating statistics.

Reference data for classifier training and accuracy assessment were collected with human interpretation of high-resolution imagery in Google Earth (GE, http://earth.google.com) using interpretation criteria discussed in Clark et al. (2010) and automated using a web-based tool (Clark and Aide 2011b). We used 6,711 reference samples from eight land-cover classes (Table 1). Classes were defined by having ≥80% cover of (1) *woody vegetation*, (2) *agriculture* (annual crops), (3) *herbaceous vegetation* (grasslands and pasture), (4) *plantations* (perennial agriculture), (5) *water* (large rivers and lakes), (6) bare areas, (7) *built-up* (man-made or artificial structures), and (8) *mixed woody* (20–80% woody vegetation including herbaceous vegetation, agriculture, or bare ground as a background).

We used a per-pixel land-cover classification for each year (2001–2010) and each biome using the Random Forests (RF) classifier, detailed in Clark et al. (2010). To increase the accuracy of our maps after classification, we combined *agriculture* and *herbaceous vegetation*, *bare and built-up*, and *mixed woody vegetation* and *plantations*, producing a five-class scheme. The overall classification accuracy from all four biome maps was 78.7% (Table 1); of the classes we analyzed, *agriculture/herbaceous* had the highest average user's accuracy (80.6%), followed by *woody vegetation* class (78.7%), while *mixed woody/plantation* had the lowest accuracy (64.5%). By biome, *woody vegetation* user's accuracy was highest in the dry forests (86.1%) and lowest in the deserts (73.6%; Table 1). Note that *woody vegetation* in the desert biome corresponds mostly to shrubland cover.

Country municipality ($n = 2{,}443$) polygons were overlaid on the mosaicked land-cover maps. For each municipality, a linear regression of class area (dependent variable) against time (independent variable, 10 years) was conducted separately for *woody, mixed woody/plantation*, and *agriculture and herbaceous vegetation*. If more than 1% of the total municipality area had pixels mapped as "No Data" for a given year, then the land-cover data for that year were removed from the regression. Note that total municipality area was based on all pixels with a valid class value and "No Data," but not null values that were unvegetated pixels consistently not mapped in the MOD13 product (e.g., coastal areas). For a given class, regression models were only fit for municipalities that had three or more years with valid area data.

We estimated the area (km^2) of change for *woody, mixed woody/plantation*, and *agriculture and herbaceous vegetation* from 2001 to 2010. To minimize errors associated with interannual fluctuations, we used the 2001 and 2010 areas estimated from the regression models for each municipality. For each biome, we used a *t* test to determine whether there was a difference in the size of municipalities that significantly gained or lost *woody vegetation*.

Modeling change in woody vegetation

To assess trends in *woody vegetation* by municipality from 2001 to 2010, we determined the relationship between the area of *woody vegetation* and year (from 2001 to 2010) for each municipality using the Pearson correlation coefficient or *R* (i.e., positive *R*, gain; negative *R*, loss). By using the correlation coefficient, the difference in area among municipality was normalized.

To evaluate the effect of environmental, socioeconomic, and demographic variables on *woody vegetation* trends, we used a Random Forests regression model (Breiman 2001; Liaw and Wiener 2002) using R software (R 2010). RF regression models have proven to be a powerful tool for

Table 1 Accuracy assessment of land-cover classification

	Samples	Overall	Producer's accuracy					User's accuracy				
			Ag/ herb	Bare/ built	Mixed woody/ plant	Water	Woody	Ag/ herb	Bare/ built	Mixed woody/ plant	Water	Woody
Moist forest	1,350	79.7	86.2	96.5	56.4	100.0	82.5	77.6	91.7	72.4	94.7	78.4
Dry forest	1,573	86.0	76.3	92.6	64.7	100.0	96.4	89.5	85.5	74.1	98.7	86.7
Coniferous forest	1,541	76.6	78.7	89.7	44.8	99.0	87.2	79.1	89.7	59.1	97.1	76.2
Desert	2,247	72.5	69.5	84.1	42.1	99.1	84.9	76.1	76.4	52.4	94.1	73.6
Total/avg	6,711	78.7	77.7	90.7	52.0	99.5	87.7	80.6	85.8	64.5	96.2	78.7

understanding multivariate nonlinear patterns, which based on land change literature, are the kind of relationships we expect to find in our data set. In addition, this method has been used for analyzing complex interactions in ecology (Archibald et al. 2009) and predicting the importance of different variables on a specific factor (Cutler et al. 2007). In addition, RF regression provides mean-squared residuals (MSR), percent of the variance explained by the model, and the percent mean-square error (MSE) for each independent variable. All these estimators help to evaluate the relative importance of predictors within the model. We used the trends in *woody vegetation* (R), per municipality, as the dependent variable in our RF models. Independent variables for municipalities included: (1) mean annual precipitation; (2) standard deviation of annual precipitation; (3) mean elevation; (4) standard deviation of elevation (topography); (5) mean annual temperature; (6) percent of productive area under land tenure regime (colony, communal, ejido, private, or public); (7) type of income by landowner (remittances, government incentives, or agroforestry revenue); (8) marginalization index; (9) total population change between 1990 to 2000 and 2000 to 2010; (10) rural population change between 1990 to 2000 and 2000 to 2010; and (11) population density in 1990, 2000, and 2010. This analysis was conducted using all municipalities that showed significant changes in *woody vegetation* across Mexico, as well as within each biome ($R \leq -0.58$ or $R \geq 0.58;$ $P < 0.1$). We used partial dependence plots to visually evaluate the directional effect of the important variables obtained in the RF regression on *woody vegetation*.

Results

Woody vegetation and population change across Mexico

Between 2001 and 2010, 16% (380) of Mexican municipalities significantly gained *woody vegetation*, while 4% (102) significantly lost *woody vegetation*. Although the majority of municipalities (80%; 1,961) did not show a significant change in *woody vegetation* (Table 2), the overall change in *woody vegetation* cover (km^2) for all municipalities, as well as for those with significant change, was positive (Table 3).

The total national population increased from 81,249,645 to 112,336,538 from 1990 to 2010. However, the number of municipalities that lost people remained similar; between 1990 and 2000, 22% (526) of municipalities lost at least 100 people, the same percentage as between 2000 and 2010 (22%; 535 municipalities) (Table 2). As a consequence, the percentage of municipalities that gained population during these periods also remained similar, from 68% (1,673) to 66% (1,622; Table 2). Between 1990 and 2010, the population in rural localities (localities with less than 2,500 people within each municipality) increased ca. 3,300,000 people. However, some states had overall negative growth of rural population between the two periods: 32% and 31% of municipalities lost rural population between 1990 and 2000 and 2000–2010, respectively. The percent of municipalities that gained rural population went from 52 to 51% during these two time periods, respectively (Table 2).

Most municipalities gained people (rural or total) but did not experience a significant change in *woody vegetation* (Table 2). The percentage of municipalities that significantly increased *woody vegetation* and lost population was low: from 1990 to 2000, only 5 and 6% of municipalities gained *woody vegetation* and lost total and rural population, respectively; these percentages were similar for 2000–2010 as well (Table 2). On the other hand, municipalities that significantly decreased *woody vegetation* and gained total population were high: 74% from 1990 to 2000 and 71% from 2000 to 2010. The percent was also high for municipalities that gained rural population: 57% from 1990 to 2000 and 52% from 2000 to 2010. Although we had originally anticipated that population change would be important in explaining deforestation and reforestation patterns, RF variables associated with population change (total and rural, increase and decrease) were not important predictors in the RF model, and these variables explained less than 10% of the model (section "Woody vegetation change across Mexico"). Population density, however, explained ca. 15% of the model.

Woody vegetation change across Mexico

There was no significant difference in the size of municipalities that gained or lost *woody vegetation* at the country level, but there were differences in some biomes (Table 4). At the national scale, biome followed by the annual variation in precipitation (mean annual standard deviation) were the most important predictors of *woody vegetation* change over the last decade, as measured by the correlation coefficient R (Table 5). Once the biome factor was removed from the model, mean annual precipitation and mean elevation—two factors associated with biome characteristics—were the variables that explained most of the variation in *woody vegetation* change (Table 5; Fig. 2). In the partial dependence plots, drier sites showed the greatest increase in *woody vegetation,* while wetter sites had the greatest decrease in *woody vegetation* (Fig. 2). Municipalities with less than 1,000 mm of mean annual precipitation showed a pronounced increase in *woody vegetation*; those between 1,000 and 2,000 mm of mean annual

Table 2 Number of municipalities that showed woody vegetation change from 2001–2010 and total and rural population change (1990–2000 and 2000–2010)

	Municipalities		Total population change						Rural population change					
			1990–2000			2000–2010			1990–2000			2000–2010		
	Total	%	Lost	NC	Gain	Lost	NC	Gain	Lost	NC	Gain	Lost	NC	Gain
Woody vegetation														
Gain	380	15.6	121	52	207	110	62	208	154	67	159	149	86	145
NC	1,961	80.3	381	189	1,391	402	217	1,342	598	306	1,057	584	339	1,038
Lost	102	4.2	24	3	75	23	7	72	27	17	58	33	16	53
Total	2,443		526	244	1,673	535	286	1,622	779	390	1,274	766	441	1,236

Rural population is less than or equal than 2,500 people. A gain or loss in *woody vegetation* was defined as those municipalities that had a significant change in R ($P < 0.1$); A gain or loss of population was defined as those municipalities that changed by more than 100 people. *NC* no change

Table 3 Absolute change in woody area (km^2) by biome

	Woody change (km^2)	
	All municipalities	Significant municipalities
Moist forest	−7,896.4	−4,483.3
Dry forest	12,857.1	4,348.8
Coniferous forest	11,479.4	4,293.0
Desert	79,648.7	57,549.0
Total	96,088.8	61,707.6

Columns show change for all municipalities and only those with significant change in woody vegetation (≤ -0.58 and $R \geq 0.58$)

precipitation showed a more moderate decrease in *woody vegetation*; and those municipalities with over 2,000 mm of mean annual precipitation showed a marked decrease in *woody vegetation* (Fig. 2). In addition, *woody vegetation* tended to increase in municipalities that occurred at elevations greater than 500 m, encompassing approximately the 80% of municipalities that significantly gained wood vegetation (Fig. 2).

Patterns of land-cover change within biomes

Change in land cover varied greatly among biomes (Fig. 3). Between 2001 and 2010, deserts, dry, and coniferous forest showed an increase in *woody vegetation* (79,648, 12,857, and 11,479 km^2, respectively), while the moist forests showed a loss in *woody vegetation* (7,896 km^2; Fig. 3; Table 3). *Mixed woody vegetation/plantations* increased slightly in moist forests (4,907 km^2), but decreased in deserts (56,834 km^2), dry forests (10,288 km^2), and coniferous forests (896 km^2). *Agriculture and herbaceous vegetation* increased in moist forests (1,654 km^2) and decreased in coniferous forest (6,538 km^2), deserts (4,206 km^2), and dry forests (397 km^2) (Fig. 3).

Once municipalities were analyzed by biome, thereby avoiding the effect of the broad-scale climatic conditions, we found that environmental variables were still important predictors of deforestation and reforestation, although population density also played a relevant role.

Moist forests Between 2001 and 2010, 63 municipalities showed significant *woody vegetation* change in moist forests: 51 lost forest cover and 12 gained forest cover. The

Table 4 Average size of municipalities by biome

	Average size of municipalities (km^2)			
	All municipalities	Significant municipalities		
		Woody loss	Woody gain	P value
Moist forest	620.7	1,034.5 (± 278.8)	512.7 (± 574.9)	0.048
Dry forest	617.6	639.4 (± 184.1)	734.3 (± 119.2)	0.449
Coniferous forest	459.5	72.2 (± 190.0)	200.8 (± 25.5)	0.254
Desert	1,881.1	1,689.6 (± 935.6)	2,760.8 (± 342.3)	<0.0001
Total	805.8	995.3 (± 247.2)	1,170.1 (± 128.1)	0.694

Columns show average size of all municipalities and those with significant change in woody vegetation (≤ -0.58 and $R \geq 0.58$). P values show differences in means municipality area (±SE; t test on normalized data) between municipalities that lost and gained woody vegetation

Table 5 Percent increase of mean-square error (MSE) for the three most important predictors using RF regression for all municipalities with significant change in woody vegetation (≤ -0.58 and $R \geq 0.58$) and divided by biome

Models	Two most important variables	% Inc MSE
All municipalities	Biome	40.71
% Var: 60.8; MSR: 0.13	Precipitation variation (annual SD)	20.74
All municipalities (w/o Biome)	Mean precipitation (annual)	32.66
% Var: 46.6; MSR: 0.17	Elevation (mean)	17.32
Moist forest	Elevation (mean)	14.78
% Var: 29.0; MSR: 0.20	Temperature (mean annual)	10.87
Dry forest	Elevation (mean)	17.52
% Var: 64.7; MSR: 0.14	Population density 2010	14.73
Coniferous forest	Population density 2010	4.71
% Var: −8.54; MSR: 0.04	Population density 2000	4.66
Deserts	Temperature (mean annual)	14.98
% Var: 56.19; MSR: 0.09	Elevation (mean)	12.46

Each models shows the percent variation explained (% Var) and mean of squared residuals (MSR)

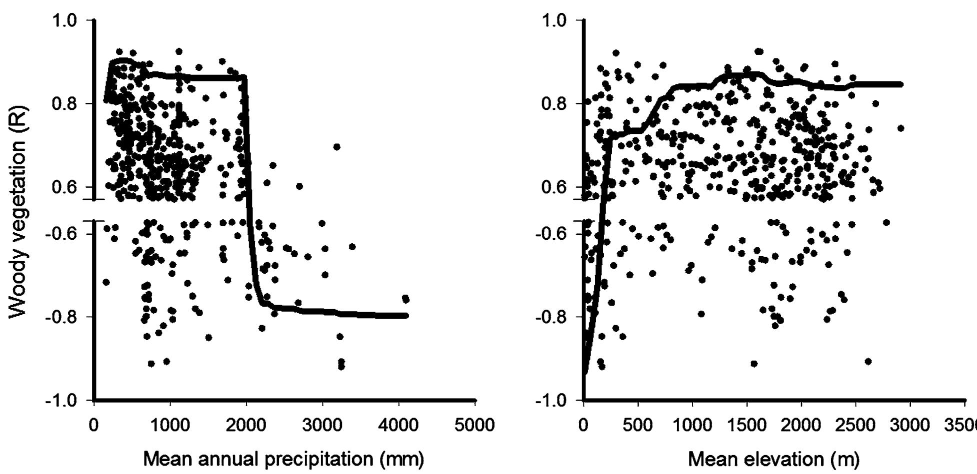


Fig. 2 Partial dependence plots of the two most important variables explaining woody change for municipalities with significant woody change. Note break on *Y* axis; only shows values from −1.0 to −0.58 and from 0.58 to 1.0, the scale representative of municipalities (*dots*) that experienced significant woody vegetation changes. The *line* indicates the marginal effect of the independent variable on woody vegetation change

average size of the municipalities with a negative or positive trend varied, 1,034.5 and 512.7 km^2, respectively, and this difference was significant (Table 4). Mean elevation explained most of the variation in *woody vegetation* change (Table 5). Deforestation mainly occurred in municipalities in the lowlands (<1,500 m elevation) (Fig. 4). The municipalities with a significant loss of *woody vegetation* were mainly located in southern Mexico, in Veracruz, Oaxaca, and Chiapas (Fig. 5).

Dry forests From 2001 to 2010, 74 municipalities in the dry forests biome experienced a positive trend in woody vegetation, while 31 underwent a negative trend in *woody vegetation*. Municipalities that gained forest were slightly larger in average size than those that lost forest, but this difference was not significant (734.3 and 639.4 km^2, respectively; Table 4). Municipalities in lowlands (<1,000 m elevation) and with low population density in 2010 showed a reforestation trend and were mostly located in the states of Oaxaca, Sonora, and Yucatan (Table 5; Fig. 4).

Coniferous forest From 2001 to 2010, 170 municipalities showed a significant trend of *woody vegetation* change: 167 experienced reforestation and only 3 had deforestation. This difference was reflected in the average size of the municipalities that showed a significant change: average of 200.8 km^2 for those that reforested and average of 72.2 km^2 for those that had deforestation. This difference, however, was not significant (Table 4). Municipalities that experienced reforestation were associated with low population densities in 2010 and 2000 (<500 people/Km^2) (Table 5; Fig. 4) and were mostly concentrated in Oaxaca state, but also in Puebla and Michoacan (Fig. 5). The variation explained by this biome's model, as well as the population density variables, however, was very low.

Deserts Most municipalities (144) that showed significant change in *woody vegetation* were located in the desert

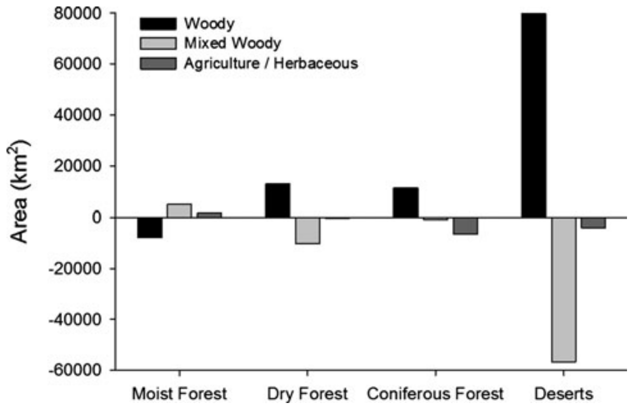


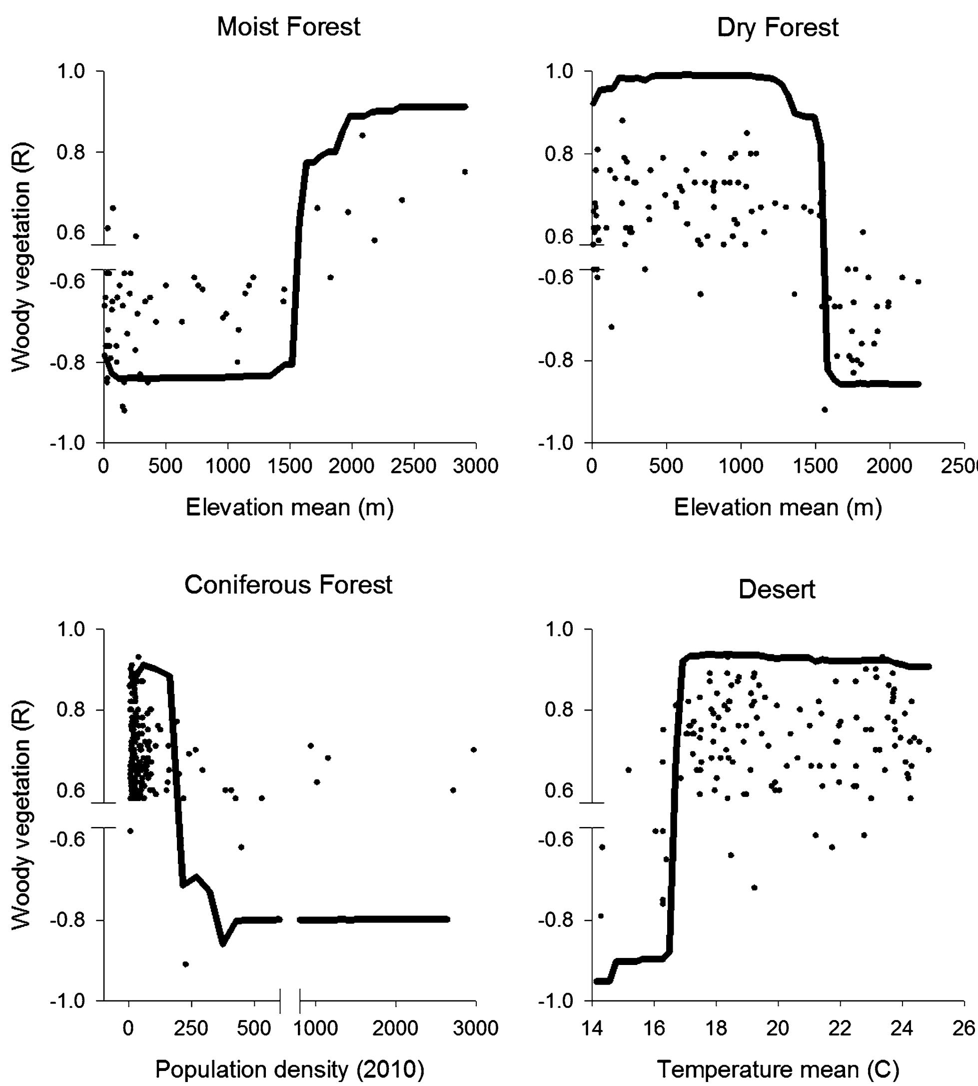
Fig. 3 Fitted area of change (2001–2010) for woody, mixed woody/plantation, and agriculture/herbaceous by biome

biome. Within this biome, 127 municipalities (88%) experienced a positive trend and only 17 (12%) a negative trend in *woody vegetation* change from 2001 to 2010. The average size of the municipalities that had an increase in woody vegetation was significantly larger (2,760.8 km^2) than the average size of the municipalities that lost woody vegetation (1,689.6 km^2; Table 4). The most important variables explaining trends in *woody vegetation* were mean annual temperature followed by mean elevation (Table 5). In this biome, municipalities with low mean annual temperature (14–16°C) showed "deforestation" (i.e., loss of shrubs scattered trees), while those with intermediate temperature (16–18°C) experienced a rapid increase in *woody vegetation* change (Fig. 4). Municipalities that showed a gain in *woody vegetation* were mostly located in the states of Chihuahua, Nuevo Leon, and San Luis Potosi (Fig. 5).

Discussion

This paper showed that during the last decade (2001–2010), Mexico as a whole experienced a net gain in

Fig. 4 Partial dependence plots of the most important variable explaining woody change by biome. Note that the *Y* axis only shows values from −1.0 to −0.58 and from 0.58 to 1.0, which represents municipalities with significant woody vegetation changes. The *line* indicates the marginal effect of the independent variable on woody vegetation change



woody vegetation due to reforestation and woody encroachment. In addition, the total number of municipalities that had significant reforestation outnumbered those with deforestation. Analyses at the biome scale showed that land conversion patterns varied among biomes—*woody vegetation* decreased in moist forests and increased in the deserts coniferous and dry forests. Our RF regression models revealed that environmental conditions, rather than demographic or socioeconomic factors, were the most important variables explaining patterns of deforestation and reforestation at the national scale, but variable importance varied at the biome scale.

Land-cover and population change

Many studies have shown a positive correlation between population growth and deforestation at broad spatial scales (see Carr 2004); however, for municipalities across Mexico, our results did not support this observation, nor was there a correlation between population loss (total or rural) and forest recovery. These results coincide with those reported for the humid tropics, where deforestation was not related to rural population growth (DeFries et al. 2010). At the national scale, neither rural nor total population changes were important predictors of *woody vegetation* change. For example, municipalities in the desert biome, in particular the Chihuahuan desert (part of Chuihuahua, Coahuila, and Durango states), the meseta central matorral (part of Zacatecas, San Luis Potosi, and Nuevo Leon states), and the Tamaulipan mezquital ecoregions (located in the north of Tamaulipas, Nuevo Leon, and Coahuila states), gained woody vegetation, yet total and rural population increased and decreased in a similar proportion, regardless of land-cover dynamics.

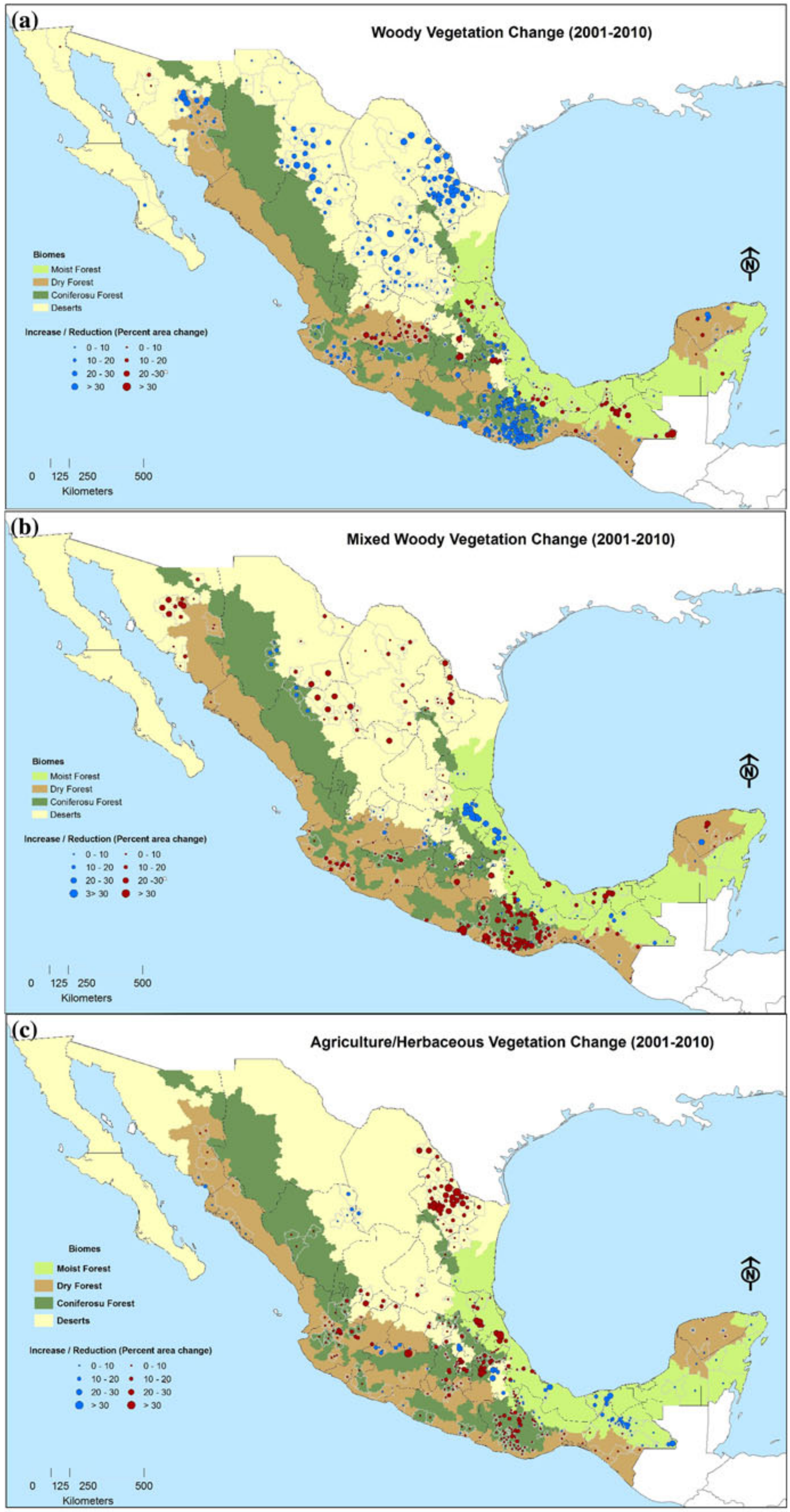
While forest recovery in municipalities that lost population is an expected effect of land abandonment, the increase in woody cover in municipalities that gained population might be the result of urbanization, changes in rural productivity, or new economic activities that intensify land use in one area, yet allow woody recovery in other areas (e.g., Aide and Grau 2004; Baptista and Rudel 2006; Baptista 2008; Grau et al. 2003, 2008; Hecht et al. 2006; Meyfroidt and Lambin 2008; Rudel et al. 2005). Urbanization and subsequent economic development can affect both local land use (e.g., transitioning from producers to consumers) and regional land use (e.g., creating nonfarm jobs that attract people from nearby areas). The regional aggregation pattern of reforestation deserves more detailed analysis; however, we speculate that forest recovery in Mexico is a regional dynamic mostly constrained by environmental conditions that facilitate or impede the expansion of productive activities.

Deforestation

Mexico's moist forest biome had the most net deforestation. Within this biome, the lowlands experienced the greatest amount of overall land conversion, while municipalities at higher elevations showed forest recovery. These results coincide with data from central Veracruz, which documented reforestation occurring at higher elevations (>2,700 m; Muñoz-Villers and López-Blanco 2007). In addition, the area of *agriculture and herbaceous vegetation* in this biome increased, suggesting forests within this biome were mostly converted into cropland and pasturelands, a trend that coincides with previous estimates for Mexico (García-Barrios et al. 2009), Latin America (Eva et al. 2004; Wassenaar et al. 2007) and worldwide (Achard et al. 2002; Gibbs et al. 2010; Mayaux et al. 2005; Sala et al. 2000; Skole and Tucker 1993). In the Mexican tropical region, extensive agriculture and pasturelands are more common than small-scale subsistence agriculture (Garcia-Romero et al. 2005). Our results show that regions with the most extensive area of deforestation occurred in the Peten-Veracruz ecoregion, specifically along the border between Oaxaca and Veracruz and along the border with Guatemala, and the Veracruz moist forest ecoregion, specifically in the north of Veracruz, south of Tamaulipas, and east of San Luis Potosi (Fig. 5). Deforestation in both ecoregions was mostly observed in large municipalities.

The expansion of mechanized agriculture for human food, animal feed, and biofuel production, as well as extensive cattle ranching, is representative of sites losing forest and people—as small-scale agriculture is replaced with intensified production and larger land holdings, less labor is needed. In this case, local demographic factors are not the main cause of deforestation, but rather changes in regional and global product-specific demands (Barbier et al. 2010; Carr 2009). In fact, the global demand for oil palm is beginning to affect land use in Mexico. In only 6 years (2003–2009), the area of oil palm plantation in the state of Veracruz increased from 2,023 to 6,417 ha, while in Chiapas, it increased from 1,300 ha to 22,700 ha between 1985 and 2009 (SIAP 2010a). In addition, most of the municipalities that significantly lost *woody vegetation* have increased livestock production (SIAP 2010b). Although at the national scale, agricultural intensification does not necessarily translate into land sparing (Rudel et al. 2009), the low number of municipalities that lost woody vegetation and gained people suggests that small-scale agriculture is declining, while large-scale commercial agriculture is expanding, a pattern that has also been described in other countries (Butler and Laurance 2008; DeFries et al. 2010; Rudel et al. 2009).

Fig. 5 Municipalities that had a significant change in woody (**a**), mixed woody (**b**), or agriculture and herbaceous (**c**) cover in Mexico between 2001 and 2010. The size of the *circles* represents the regression-fitted area (km^2) of vegetation change. The color of the circles represent the direction of vegetation change (printed version: *white*-increase, *black*-decrease; online version: *blue*-increase, *red*-decrease)



Reforestation

Reforestation was highly associated with those regional environmental conditions not optimal for productive agriculture activities—so-called "marginal" areas, such as arid regions (e.g., deserts and dry forests) and areas at high elevations. Contrary to the trend found for moist forests, in the deserts, the greatest increase in *woody vegetation* occurred in large municipalities (Table 4). Low precipitation and high elevation, the two factors associated with reforestation, support the idea that agricultural and grazing activities in regions with harsh environmental conditions are vulnerable to competition from other countries or more productive agricultural areas within a country, and this can lead to abandonment and woody recovery (Aide and Grau 2004).

Population density, a factor directly related to the effect of human pressure on natural resources, was also a relevant factor explaining reforestation. According to our results, sites with very low population densities had a higher tendency to increase *woody vegetation*, a result that concurs with Carr (2004), who suggested that sites with high population density will be accompanied by agricultural expansion at regional scales. This was the case for the coniferous forest; however, since the variation explained by the conifer forests RF model was lower compared to the rest of biomes, these trends should be further explored.

The dramatic increase in *woody vegetation* in the desert biome, particularly in the area of mesquite-grasslands in the Tamaulipan mezquital ecoregion, coincides with research that suggests that shrublands are now the major land cover in Mexico (Giri and Jenkins 2005). In fact, desert municipalities with high temperature at middle elevations seem to be the places with the greatest increase in *woody vegetation*. The increase in *woody vegetation* in desert grasslands and savannas is a process well documented for arid regions in North America (e.g., Archer et al. 1988; Briggs et al. 2002, 2007; Skole and Tucker 1993; Van Auken 2000), particularly in areas where the frequency of fire and grazing has been reduced (Briggs et al. 2005; Brown and Archer 1999; Kupfer and Miller 2005). An important change that could partially explain the increase in woody vegetation was the increase in precipitation. Four of the northern states of Mexico, which occur in the desert biome, had a significant increase in annual precipitation in the last decade (2001–2009) in comparison with the average of the previous 50 years (Comision Nacional del Agua). Another important factor could be a change in economic activities that has occurred over that last decades. In the past, important economic activities in the northern states of Mexico included extensive grazing and dryland agriculture, but there has been a shift to manufacturing industry, particularly the rise of the *maquila* industry near the United States border following the signing of the North American Free Trade Agreement (NAFTA), which has created new economic opportunities for local and regional population and thereby promoted rural–urban migration to cities near the border (Currit and Easterling 2009). These results highlight the potential consequences of climate coupled with broader-scale economic processes (e.g., multinational integration) for *woody vegetation* cover in desert areas.

Mapping land change over large national scales

There are two potential caveats in our study. The first one is related to the accurate detection of dryland vegetation. Climatic fluctuations, in particular precipitation variation, have been identified as a source of uncertainty for estimating the extent of vegetation cover in arid areas (Lambin 1999; Lambin et al. 2003; Serneels et al. 2007; Vanacker et al. 2005). We believe that our analytical approach, (1) aggregating cover class area at the municipality scale; (2) calculating the cover class in each of the 10 years; (3) determining the 10 year trend of change; and (4) analyzing only the municipalities with a significant change during this period ($P < 0.1$), will capture real trends in vegetation change without a bias in a particular direction.

The second caveat is related to the area of change that can be detected with our data and analytical process. A MODIS pixel of 250 × 250 m, or 6.25 ha, will detect large-scale changes (10–100 ha), such as cattle ranching or agriculture, but small-scale (1–10 ha) agriculture or reforestation would be difficult to detect in a single pixel. By aggregating all pixels within a municipality, we could analyze change based on the linear trend of hundreds of pixels over 10 years. This approach minimizes the effects of interannual climate variation and accumulative changes due to small-scale deforestation should be captured by the analysis. We acknowledge that our analysis is more sensitive to sustained, accumulated change over many pixels within the municipality. Higher resolution satellite imagery, such as from Landsat, would certainly help detect small-scale changes in vegetation that last only a few years; however, due to cloud cover and other factors, available national data are from different years and seasons, and land-cover maps based on these data would also introduce error when comparing broad regions. With the temporally-composited MODIS data used in our study, we could produce recent, annual, and spatially consistent land-cover maps across Mexico (e.g., "wall-to-wall") and minimize our mapping error by analyzing aggregated trends over 10 years, an approach which greatly facilitates national-scale analysis of land change.

Conclusions

During the last decade, three of the four major biomes in Mexico have experienced a net gain in wood vegetation. Forest gain in the dry forest biome is encouraging given that this biome has been one of the most threatened habitats in Mexico (Trejo and Dirzo 2000) and the neotropics (Janzen 1988; Portillo-Quintero and Sánchez-Azofeifa 2010). The increase in *woody vegetation* in the desert biome was mainly a change from a mixed herbaceous/shrubland cover to mostly shrubland cover. This has important implications for conservation. On the one hand, woody encroachment in dry areas has been identified as a serious threat to native grassland systems (Briggs et al. 2005). On the other hand, the accumulation of *woody vegetation* represents a substantial increase in total biomass, and so this trend may indicate a growing regional carbon sink with implications for global climate change and carbon emission agreements. These results are particularly important because, compared to wet forests, the identification of land-use change in arid areas has been less studied (Hüttich et al. 2011; Lambin et al. 2003).

Although there were some regions of reforestation in the tropical moist forest biome, the net change has been deforestation. Population change (rural or total) was a poor predictor of *woody vegetation* change. Although in the past, small-scale slash-and-burn agriculture was an important cause of deforestation, the expansion of large-scale agriculture, cattle pasture, and oil palm plantations are becoming the most important causes of deforestation in Mexico. The increasing food demands of a growing human population, particularly the urban population, in Mexico and around the world are driving this agricultural expansion; thus, it is critical to develop effective methods of production that can satisfy the growing demand without replacing more natural systems (Foley et al. 2005), by agricultural diversification (Perz 2004), increasing yield production (Ewers et al. 2009), or encouraging new strategies for development and agriculture (García-Barrios et al. 2009).

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