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Vegetation change and land tenure in Mexico: A country-wide analysis

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ABSTRACT

There is an ongoing debate on the effect different property regimes have on the use of natural resources and land conversion (i.e., deforestation or reforestation). Much of the discussion has been centered on the two main forms of tenure regime: *common-pool system* and *private property*. Case studies around the world have provided evidence on whether one is more effective at preventing deforestation than the other, but there is not a clear pattern. Part of the problem is that evidence comes from theoretical models or isolated case studies instead of comparative studies across large areas. This paper helps to fill this gap by analyzing the association between land cover change (2001–2010) and land tenure regimes including private and two types of common-pool systems (*communal* and *ejido*) in Mexico at the municipality level. The analyses were conducted for each of the four major biomes (i.e., moist forest, dry forest, coniferous forest, and desert) to control for differences in environmental factors. Municipalities dominated by *communal* land tenure had the largest increase in woody cover (classified as >80% cover) in the moist forest, dry forest, and coniferous forest biomes, and municipalities classified as *private* also had an increase in woody cover, particularly in the desert biome. In contrast, municipalities classified as *ejidos* (common-pool tenure system resulting from the land reform) lost woody cover mostly in moist forest and desert biomes, but gained woody cover in dry forest and coniferous forest biomes. In modeling analyses, environmental variables were the most important variables associated with woody cover change for *private* and most *communal* municipalities, while socioeconomic variables were the most important in *ejido* regimes. These results highlight the importance of land tenure on land cover change, and show that differences in woody cover change between types of common-pool systems can be larger than their differences with private land tenure. During the last 10 years, virtually all deforestation has occurred in areas dominated by *ejidos*; in contrast, *communal* and *private* regimes seem to ameliorate the deforestation process.
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Introduction

Land tenure determines access to land and resources by individuals or groups (FAO, 2002). While there are a large variety of land tenure types, they are generally grouped into two main categories: private or common-pool system – a basic classification assumed to reflect essential differences in the way resources are used. The proportion of these two tenure types vary greatly between countries (e.g., 80% of land in Mozambique is traditional or collectively owned, 72% of land in South Africa is privately owned [U.N., 2003]). Land tenure regimes also varies through time and are strongly related to past politics including decisions made more than a century ago. Historically, land tenure regimes, with the exception of protected areas, have the specific aim to transform natural areas into productive land uses. However, the loss and degradation of natural areas and the negative impact on environmental services have stimulated social and environmental scientists to explore what land tenure regime is more favorable for forest conservation.

The land tenure-conservation debate has historically focused on the dichotomy between private and common-pool system land tenure. Based on empirical evidence of overexploitation of common-pool resources and a well-developed theoretical framework (Hardin, 1968), supporters of the *private* model indicate that the absence of well-defined property rights is a major cause of deforestation, a model supported by studies in agriculture frontier colonies (e.g., Araujo et al., 2008; de Oliveira, 2008; Ferreira, 2004; Nelson et al., 2001; Alston et al., 1999; Deacon, 1999; Angelsen, 1999; Godoy et al., 1998; Jaramillo and Kelly, 1997; Mendelsohn, 1994; Southgate et al., 1991; Southworth and Tucker, 2001; Rudel, 1983). Private property ownership may favor forest conservation because the owners: (i) have higher incentives to use resources

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more efficiently and sustainably; (ii) are able to monopolize many of the long term benefits of sustainable management; and (iii) bear most of the costs of poor management (Tucker, 1999, p. 204). However there are also reasons to expect common-pool systems to be more effective in preventing deforestation given that communities may have a vested interest in preserving forest and resources used by all members (e.g., Perez-Verdin et al., 2009; Bray and Klepeis, 2005; Gibson et al., 2002; Klooster, 1999; Deininger and Minten, 1999; Rudel, 1995; Bromley, 1992; Ostrom, 1990; Berkes et al., 1989). Since users are compelled by social pressure, they prescribe and enforce rules of conduct that could favor forest conservation. Common-pool system users can exclude other potential users and regulate their joint use, thereby reaping the benefits of their own restraint (Berkes et al., 1989). Private owners experience comparatively little social pressure and regulations to preserve the forest whereas communities can make a concerted decision to approve or disapprove deforestation activities. Social control can restrict access to natural resources (Rudel, 1995) through previously established institutions or rules-in-use – the "unwritten laws". Furthermore, communities can act as an antidote to the "profit-maximizer" model of private property (Nelson et al., 2001; Chomitz and Gray, 1996) in which the land owner simply chooses to put the land into its short term most profitable land-use by, for example, converting all forest on their property to agriculture or pasture.

Empirical studies over the last few decades have shown successes and failures in all types of tenure arrangements (Gibson et al., 2005). It has become clear that one model is not necessarily superior as "no single institution generates better outcomes for the resource and for the users under all conditions" (Ostrom and Hess, 2007, p. 1). In addition, not much effort has gone into comparing the general consequences of one model versus the other using empirical research (Ostrom and Hess, 2007, p. 2). Furthermore, few studies have compared the environmental impacts of land tenure systems using a robust experimental design (i.e., a large sample size and controlling for regional differences in the environment). In most cases, studies are conducted at the local level and only include a handful of sample communities. An exception is Killeen et al. (2008) who conducted a thorough and large-scale analysis on land change and drivers in lowland Bolivia, but the focus was on different social groups, not explicitly on tenure systems. Another limitation is that many studies rely on secondary information for land-use and land-cover data such as government or other institutional statistics or household interviews, but this often restricts the analyses to either the national or state level. In addition, previous studies on forest cover change associated with land tenure in tropical regions focus almost exclusively on deforestation, even though forest recovery plays an important role in many regions (Grau and Aide, 2008; Lambin and Mayfroidt, 2010).

Our objective is to evaluate the effect of land tenure on woody vegetation change (both recovery and deforestation) from 2001 to 2010 at the municipality scale in Mexico, a country with contrasting tenure regimes including private and common-pool systems. This research addresses the question: is there an association between the dominant land tenure regime and changes in woody cover at the municipality scale? To address this question, we assess the dominant tenure regime in 2443 municipalities in Mexico and relate this with changes in annual land cover between 2001 and 2010. In addition, we asked what were the social and environmental controls of forest cover change in the different land tenures? This research builds on a previous study (Bonilla-Moheno et al., in press), which showed that between 2001 and 2010 Mexico had a net gain in woody cover, but the patterns varied greatly among biomes; the largest gains in woody cover were in the desert biome while major losses were in the moist forest biome. Furthermore, this study showed that biome was an important variable in predicting woody cover change; therefore, to control for economic and environmental differences among regions in Mexico, all analyses in this study were done separately for the four major biomes (tropical moist forest, tropical dry forest, coniferous forest, and deserts).

Mexico as a study system

Mexico has had a long and rich history of policy reforms that have led to a variety of land property rights, making it a prime example to evaluate the role of land tenure on land cover change. The history of tenure regimes in Mexico was greatly influenced by the colonial period and later by the post-revolutionary era. Although common-use access to resources was a central component of the property rights of indigenous people, the transition to the colonial era represented the emergence of private property where very large extensions of land were distributed among relatively few people, a situation that prevailed after Mexico's independence (SRA, 2010). These inequalities in land distribution associated with poor working conditions were among the main triggers for the revolution of 1910, which set the basis for agrarian reform in the following years and delineated contemporary land property rights. The agrarian reform evolved into Article 27 of the Constitution (1917), which highlighted the importance of public over private institutions, and recognized the need for land redistribution and land title restitution. The land redistribution initiative represented a radical shift in land control and eventually developed into the *ejido* tenure concept – a form of property right based on common-use of resources by rural settlements. The land title restitution involved recognizing the control of lands and resources of original people. According to the Agency of the Agrarian Reform (Secretaria de la Reforma Agraria, SRA), before the revolution of 1910, less than 2000 families owned 87% of the national territory, whereas by the end of the 1980s, 90% of the national territory was in direct control of 5,000,000 *ejidatarios*, *comuneros* and small private owners (SRA, 2010). In 1992, Article 27 was amended to define three major types of land tenure regimes that exist today: social property or agrarian centers (including *ejido* and *communal*), *private* (including *colony*), and *public*. These regimes are described below.

Although the origin of both common-pool systems was different (*ejido* involving land redistribution process and *comunidades* involving land title restitution), in practice there is not a clear distinction between the two systems. In both cases, land is the main ingredient which unifies the presence of *ejidatarios* or *comuneros*, and is divided for three main uses: (1) human settlements; (2) a portion of common-use lands (including forests, water sources and other resources), where the rules regarding access and use are collective; and (3) parceled land for individual exploitation (Téllez, 1993). In addition, the social organization is similar for both, including a decision-making committee (*asamblea*), a representative committee that carries out the resolutions of the decision-making committee (*comisariado*), and vigilance committee (*consejo de vigilancia*). The *asamblea* also regulates the use, management, access and conservation of common-use lands (Téllez, 1993) The differences in the use of natural resources, will reside on the way formal and informal local institutions (set of rules), are implemented or enforced in each tenure system.

Ejido – The *ejido* was conceived by the agrarian reform with the goal of granting property to landless people (SRA, 2007). The land distribution included a portion devoted for human settlements, a portion of common-use lands, and a portion of private parcels for productive activities. Rights to both common-use lands and private parcels, which vary in size and distribution, are passed on to family members. These characteristics are determined at the founding of each individual *ejido*, which varies among communities (Alix-Garcia, 2007). Most forested *ejidos* are collectively owned or farmed, and products are communally marketed (Perez-Verdin et al., 2009). The original legislation was developed to protect the *ejido* land from being sold or rented and promoting, with limitations, production of rural lands (Téllez, 1993). Based on the perceived low productivity of communally owned land as well as the scarcity of productive lands remaining to be distributed among the rural population that continued to grow, in 1991 Article 27 was reformed, modifying some of the original constitutional rights to *ejidos*. The land reform law was passed in 1992 and allowed *ejidatarios* to sell land to people outside the *ejido* community. The main purpose of the reform was to foster tenure security through formal titles and formal transfer registration (SRA, 2010). In addition, after the modification of Article 27 the *asamblea ejidal* could choose whether to devote a land portion for common use (Téllez, 1993). Greater security, in turn, was expected to increase agricultural production through higher incentives and investment opportunities, and through land transfers to more efficient producers (Bouquet, 2009, p. 1390). In 2007, *ejido* tenure represented 44% of the national territory (SRA, 2007).

Communal (Comunidad agraria) – *Communal* tenure has a similar *ejido* decision-making structure and organization, where natural resources can be exploited in a form of common-pool resource. Communal tenure was granted as land title restitution to original groups with ancestral rights to the land and that share traditional practices. In 2007, *communal* tenure represented 9% of the national territory (SRA, 2007).

Private – Unlike the other regimes, land under private tenure is owned by title. This allows the owner(s) – whether an individual or firm (collection of individuals) – to sell, rent, mortgage, transfer, or exchange their property. It allows the owner(s) to exclude others from doing these activities. In 2007, *private* tenure represented 38% of the national territory (SRA, 2007).

Colony – Land assigned under the *colony* tenure was sold to small groups of people, often foreigners (e.g., Mennonites), as part of a colonization effort promoted by the Mexican government during the mid-1900s. Although land is no longer granted under this regime, the *colony* tenure was an important mechanism used to promote population settlement of uninhabited regions such as Sonora state or Baja California peninsula. In 2007, *colony* tenure represented 2% of the national territory (SRA, 2007).

Public – Property rights on public lands reside with the government. In 2007, *public* tenure represented approximately 4% of the national territory (SRA, 2007).

Data description and analysis

Land tenure

The area of each land tenure class for each of the 2443 municipalities in Mexico was obtained from the 2007 *Censo Agricola, Forestal y Ganadero* (INEGI, 2007a,b). Data included only the land that was under some type of productive activity (agriculture, cattle grazing, or forestry); "non-productive" land was not reported and therefore not included in the analyses. According to the census, approximately 112 million ha (∼57% of the Mexican territory) was under some form of production (INEGI, 2007a,b). Using the municipality level to define land tenure classes could suffer from a potential aggregation bias (for a detailed discussion on this, see Deininger and Minten, 1999), for example, where municipalities included multiple property rights regimes. In addition, even if one regime dominates a municipality, the forested area may occur outside of the control of this regime. While it would be preferable to have land tenure information on individual plots, the original Mexican census aggregates land tenure regimes at the municipality level. To overcome these problems in our analyses, we calculated the percent of productive land under each tenure regime and only included those that had at least 80% of the productive land in a single tenure (*Communal*, *Ejido*, or *Private*; Fig. 1) thereby reducing these potential biases. This filter eliminated 60% of the municipalities, but still left us with 965 municipalities distributed across all biomes within Mexico. Only three municipalities were classified as *Colony* or *Public*; therefore, these tenure regimes were excluded from all analyses. Since results from a previous study of land change in Mexico showed that "biome" was the most relevant variable influencing woody cover during the last decade (Bonilla-Moheno et al., in press), analyses in this study were conducted within the biome level. Following the World Wildlife Fund biome classification (Olson et al., 2001), we assigned each municipality to one of the four largest biomes in Mexico: (i) moist forest; (ii) dry forest; (iii) coniferous forest; and (iv) deserts.

Classification of land-use and land-cover

We used the MOD13Q1 MODIS satellite image product and a custom image processing technique to map land-use/land-cover at a 250-m resolution (Clark et al., 2010; Clark and Aide, 2011a,b). The MOD13 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 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 6-month periods, and 3 4-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, 2011a,b). We used 6711 reference samples from eight land-cover classes 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 of the four biomes using the Random Forests (RF) classifier (Breiman, 2001; Liaw and Wiener, 2002) in the R statistical package (R, 2010), 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 average overall classification accuracy from all four biome maps was 78.7% (Table 1); of the classes we analyze in this study, agriculture/herbaceous vegetation had the highest average user's accuracy (80.6%), followed by the woody vegetation class (78.7%), while mixed woody/plantation (hereafter referred to as mixed woody) had the lowest accuracy (64.5%). By biome, woody vegetation user's accuracy was highest in the dry forests (86.7%) and lowest in the deserts (73.6%; Table 1). Woody vegetation in the desert biome corresponds mostly to shrubland cover.

To standardize the change in woody vegetation by municipality from 2001 to 2010, we conducted a linear regression of the area of woody vegetation by year (from 2001 to 2010) for each municipality, and used the Pearson correlation coefficient (R) as the indicator of change (i.e., positive R, gain; negative R, loss).

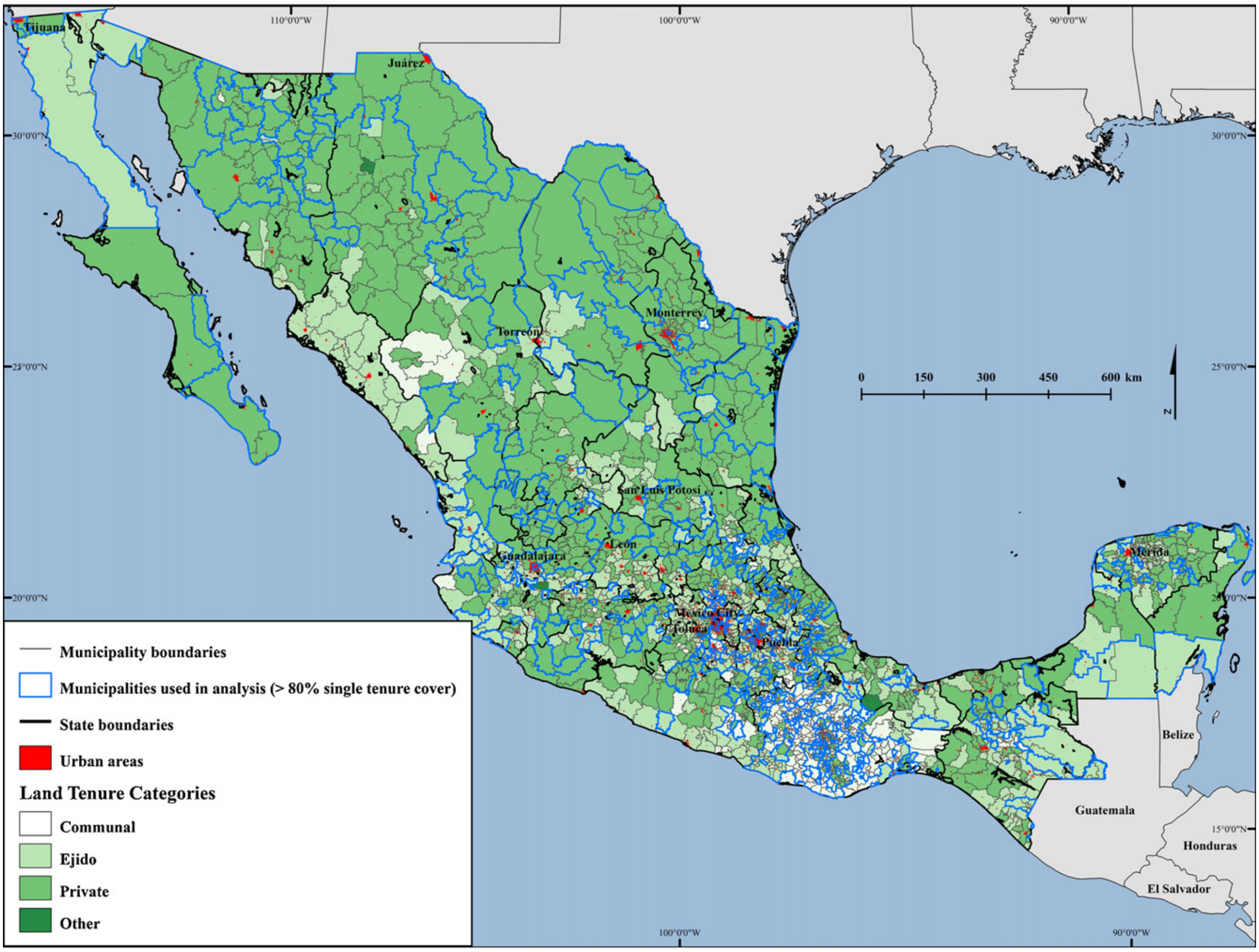

Fig. 1. Map of Mexico showing the dominant land tenure of the productive area in each of the 2243 municipalities.

Data analysis

To evaluate the influence of tenure regime on vegetation change over time, we calculated the mean and standard deviation of the coefficient of correlation (R) for woody and agriculture/herbaceous vegetation from 2001 to 2010 by land tenure category (*ejido*, *private*, and *communal*) for each biome. The direction of the coefficient of correlation would reflect the change in woody cover or agriculture/herbaceous vegetation over time (i.e., a positive R an increase, while a negative R a decrease in woody cover). Using a correlation coefficient instead of change in area from 2001 to 2010, we were able to benefit from three distinct advantages. First, each municipality has equal weight regardless of the municipality's size. This is important since at the national level municipality size in Mexico can vary from 1.26 km^2 to 53,501 km^2. Second, a correlation coefficient reduces the effect of extreme values in either 2001 or 2010. For example, if a municipality experienced steady woody vegetation loss from 2001 to 2009 and then experienced an erroneous jump in woody regeneration in 2010 due to a climate anomaly, the correlation coefficient would minimize the effect of the spurious point. The third advantage is that we are able to take into account all 10 years of the land change analysis, and eliminate years with relatively poor land-cover mapping due to cloud cover and other artifacts, thus minimizing errors introduced by any given year.

To determine which environmental or socioeconomic variables best explained woody vegetation change by tenure regime within a biome, we performed non-linear, non-parametric RF regression using R. We used this approach because we had a complex data set, with non-linear relationships, and this method allowed us to identify the importance of the predictor variables. This approach has been used in other ecological studies with complex data sets where variables are likely to be correlated (Archibald et al., 2009; Cutler et al., 2007; Redo et al., in press). RF regression provides mean squared residuals (MSR), percent of the variance explained

Table 1
Accuracy assessment (by biome and total) of land-cover classification.

	Samples	Overall	Producer's accuracy					User's accuracy				
			Ag/herb	Bare/built	Mixed woody	Water	Woody	Ag/herb	Bare/built	Mixed woody	Water	Woody
Moist forest	1350	79.7	86.2	96.5	56.4	100.0	82.5	77.6	91.7	72.4	94.7	78.4
Dry forest	1573	86.0	76.3	92.6	64.7	100.0	96.4	89.5	85.5	74.1	98.7	86.7
Coniferous forest	1541	76.6	78.7	89.7	44.8	99.0	87.2	79.1	89.7	59.1	97.1	76.2
Desert	2247	72.5	69.5	84.1	42.1	99.1	84.9	76.1	76.4	52.4	94.1	73.6
Total/avg.	6711	78.7	77.7	90.7	52.0	99.5	87.7	80.6	85.8	64.5	96.2	78.7

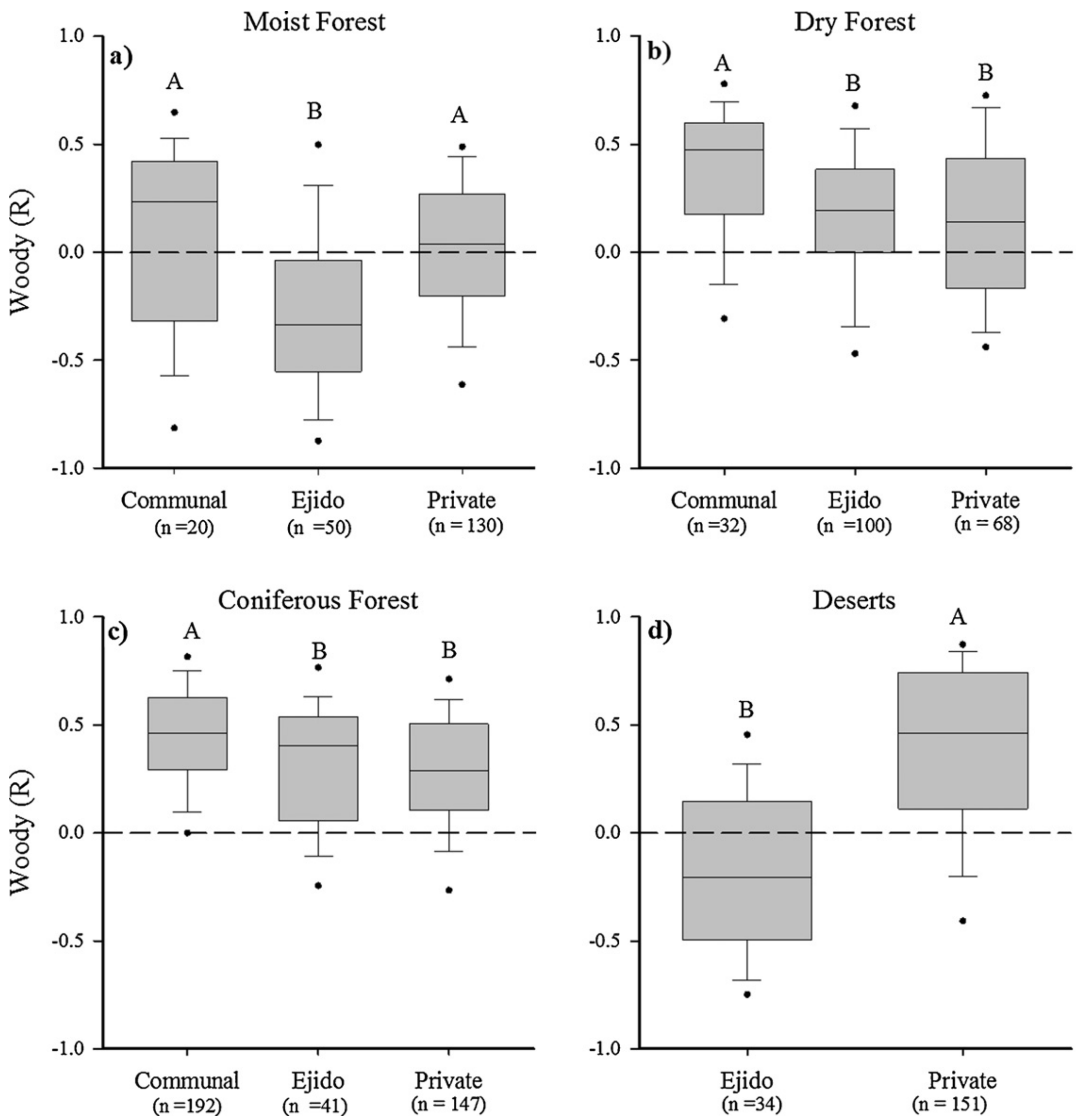

Fig. 2. Woody vegetation change between 2001 and 2010 for the three major land tenure regimes. The graph presents the trend in woody vegetation change over the 10-year period in each municipality for the coefficient of correlation (R). The solid line within the box represents the median, the dotted line the mean, the box includes the 25–75 percentiles of the distribution, and the circles represent the 5–95 percentiles. Means ± standard deviation: (a) moist forest (*communal* = 0.09 ± 0.4; *ejido* = −0.28 ± 0.3; *private* = 0.01 ± 0.3); (b) dry forest (*communal* = 0.38 ± 0.3; *ejido* = 0.15 ± 0.3; *private* = 0.14 ± 0.3); (c) coniferous forest (*communal* = 0.44 ± 0.2; *ejido* = 0.26 ± 0.3; *private* = 0.27 ± 0.2); (d) deserts (*ejido* = −0.18 ± 0.3; *private* = 0.39 ± 0.3). Different letters indicate significant differences with Tukey–Kramer mean comparison among tenure regimes by biome ($p < 0.005$). Number of municipalities by tenure is indicated in parenthesis. The municipalities used in the analyses had more than 80% of their productive area in a single tenure category.

by the model, and the percent mean square error (MSE) for each independent variable. We used the coefficient of correlation (R) for woody vegetation change (2001–2010) as the dependent variable, and environmental and socioeconomic factors as the independent variables. We focused only on the change of woody vegetation because it was the proxy to evaluate forest conservation. Independent variables with the highest predictive power (highest percent MSE) were then compared among biomes and tenure regimes. By controlling for tenure regime and biome, we were able to explore all the potential variables influencing the woody change and identified those that were potential underlying drivers of change. We included environmental and socio-economic variables, as well as municipality area (km^2) as predictive variables. We used partial dependence plots to evaluate the marginal effect the predictive variables on a response, in this case woody cover change (R). Below is an explanation of the environmental and socioeconomic variables used in the regression analysis:

Environmental variables:

i. Mean annual precipitation between 1990 and 2005 (CRU, 2008).
ii. Mean annual temperature between 1990 and 2005 (CRU, 2008).
iii. Mean elevation calculated for each municipality using a 90-m Digital Elevation Model (Jarvis et al., 2008). Mean elevation differentiated highlands and lowland municipalities.
iv. Elevation standard deviation, also calculated for each municipality using a 90-m Digital Elevation Model (Jarvis et al., 2008). Elevation standard deviation was used as an index of a municipality's topographic complexity. Municipalities with large standard deviations represented complex topography (i.e., mountain slopes) while municipalities with small standard deviation represented more level terrain.

Socio-economic variables:

i. Average marginalization index for 1990, 2000 and 2005, which incorporates information from variables that describe social equity and level of development for each municipality (www.conapo.gob.mx); 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, and percentage of population in rural localities (<5000 people). A high index valued represents high marginalization.

ii. Type of income received by landowners (remittances, government incentives, or direct revenue from forestry, cattle ranching or agriculture) (INEGI, 2007a,b); for each municipality we calculated the proportion of landowners of productive lands receiving each type of income.

iii. Absolute and rural population change from 1990 to 2000 and 2000 to 2010. Population change was obtained from national censuses (1990 and 2000) and a national count (2010) (www.inegi.gob.mx). Rural population defined as the population inhabiting localities, within the municipality, with less than 5000 people. This was estimated from the percent population inhabiting rural localities, a variable reported from the marginalization index.

iv. Population density in 1990, 2000 and 2010. Population density was calculated as the number of people per km^2 for each municipality in 1990, 2000 and 2010.

We determined the social makeup of the different tenure regimes, specifically the number of indigenous people associated with each tenure regimes. For each municipality we determined the percentage of people over 5 years of age that spoke an indigenous language using data from the 2000 census (INEGI).

Results

Tenure regime distribution

As of 2007, there were an estimated 31,514 *ejidos* distributed across Mexico. The majority were concentrated in southern Mexico, the Pacific coast and in Sonora. Municipalities with large land areas classified as *communal* were largely concentrated in the states of Oaxaca and Durango. *Private*-dominated municipalities were concentrated in the northern states of Sonora, Chihuahua, Coahuila, Nuevo León and Tamaulipas, but occurred across the country. Two municipalities were classified as *Colony* tenure (Gomez Farias in Chihuahua, and Playa Vicente in Veracruz), and two were classified as *Public* (Chapala in Jalisco, and Totoltepec de Guerrero in Puebla) (Fig. 1). The average area of all municipalities classified by dominant tenure regime varied; *communal*-dominated municipalities had the smallest average area (251.2 km^2), *ejidos*-dominated municipalities were intermediate in *size* (659.7 km^2), and *private*-dominated municipalities were the largest (1007.3 km^2).

The average size municipalities used in the study followed the same pattern as all municipalities: the *communal*-dominated municipalities had the smallest average area (145.9 km^2), followed by the *ejidos*-dominated municipalities (789.4 km^2), and lastly the *private*-dominated municipalities (1010.8 km^2). The distribution of these municipalities illustrates the non-random distribution of the different tenure regimes across the country (Fig. 1). Municipalities in the moist forest and desert biomes were mainly *private* tenure (130 and 151, respectively), while in the dry forest biome municipalities were mainly *ejido* tenure (100), and the conifer forest biome had the highest concentration of *communal* tenure (192). The average percent of people that spoke a native language in the municipalities included for the study varied by tenure regime: 49.9 in *communal* municipalities, 19.3 in *ejido* municipalities and 19.9 in *private* municipalities.

Land use change by tenure regime

Across biomes, mean woody vegetation change (R) varied among land tenure regimes. Within the moist forest biome, the mean R of municipalities classified as *communal* and *private* were positive (increase in woody vegetation, hereafter recovery) while the mean R of municipalities classified as *ejido* was negative (decrease in woody vegetation, hereafter deforestation; Fig. 2a), and this difference was significant ($F_{2,197} = 13.8$, $p < 0.0001$). In general the dry and coniferous forest biomes showed recovery across all land tenures, but municipalities classified as *communal* showed the largest increase in woody cover ($F_{2,197} = 6.6$, $p = 0.001$, $F_{2,377} = 18.9$, $p < 0.0001$, respectively; Fig. 2b and c). In the desert biome, municipalities classified as *private* experienced recovery while those classified as *ejido* showed mean deforestation ($F_{1,183} = 56.1$, $p < 0.0001$; Fig. 2d).

Overall, agriculture and herbaceous vegetation declined among all tenure regimes, but there were differences in the direction of vegetation change among biomes. Within the moist forest and the desert biomes, municipalities classified as *ejido* showed an increase in these cover types, implying agriculture or cattle pasture expansion, while municipalities classified as *private* showed the opposite trend ($F_{2,197} = 12.6$, $p < 0.0001$, $F_{1,183} = 17.9$, $p < 0.0001$, respectively; Fig. 3a and d). In contrast, agriculture and herbaceous vegetation declined in the dry ($F_{2,197} = 1.1$, $p = 0.334$) and coniferous forest ($F_{2,377} = 1.4$, $p = 0.242$) biomes across all tenure regimes (Fig. 3b and c; respectively).

Factors influencing woody vegetation change by tenure regime

Results from the RF regression showed differences among the dominant factors associated with woody vegetation change within land tenure regimes. Although, in general, the models tended to explain a small proportion of the variation in woody vegetation change, municipalities classified as *communal* and *private* were mainly influenced by elevation and topographic complexity (environmental factors), while municipalities classified as *ejido* were mostly influenced by population density and population change (Table 2).

Using partial dependency plots (Appendix A), we found the following trends within biomes (summarized in Table 2):

- Moist forest biome: Woody vegetation change in municipalities classified as *communal* and *private* were mostly influenced by mean elevation, while in *ejido* municipalities woody change was related to mean annual precipitation. The partial dependency plots showed that in municipalities classified as *communal* and *private*, woody vegetation increased slightly at elevations above 1000 m. In municipalities classified as *ejido*, woody vegetation decreased abruptly as precipitation increased from 500 to 1000 mm, and then continued decreasing with higher levels of precipitation.
- Dry forest biome: Change in woody vegetation for *communal* and *ejido* municipalities was best explained by population density; as population density increased (>100 people/km^2), woody vegetation declined. In *private* municipalities, woody vegetation decreased at higher mean elevations (>1500 m).
- Coniferous forest biome: Topographic complexity (standard deviation of elevation) had a marginal effect on the change in woody vegetation in municipalities classified as *communal* and *private*. Municipalities dominated by *communal* tenure showed a slight but continuous decrease in woody vegetation as the topographic complexity increased, while in municipalities dominated by *private* tenure woody vegetation showed a steep increase at low topographic variation (0–100 m) and a stable behavior after this. In municipalities classified as *ejido*, there was a tendency

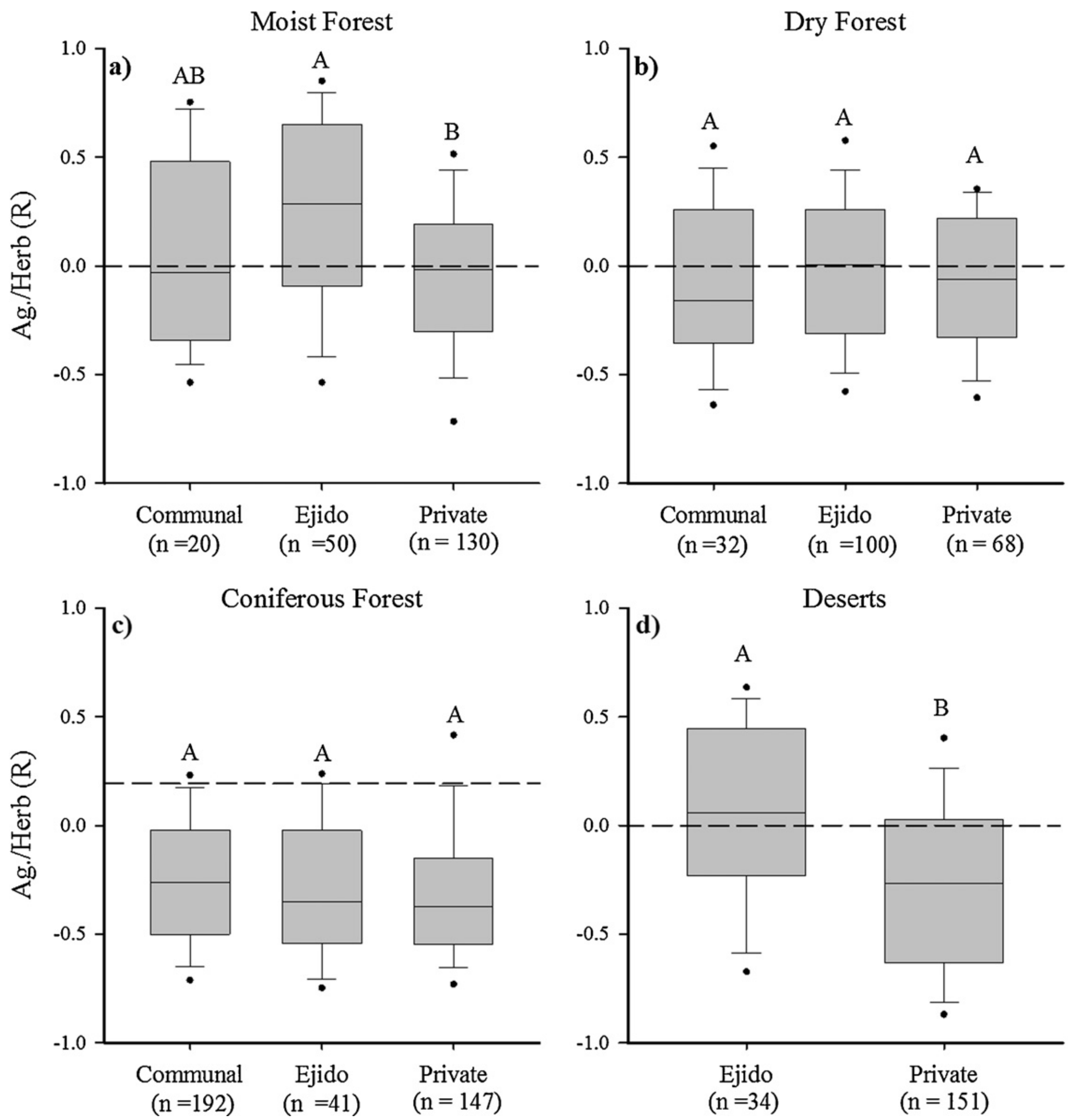

Fig. 3. Agriculture and herbaceous vegetation between 2001 and 2010 for the three major land tenure regimes. The graph presents the trend in agriculture and herbaceous vegetation change over the 10-year period in each municipality for the coefficient of correlation (R). The solid line within the box represents the median, the dotted line the mean, the box includes the 25–75 percentiles of the distribution, and the circles represent the 5–95 percentiles. Means ± standard deviation: (a) moist forest (*communal* = 0.07 ± 0.4; *ejido* = 0.24 ± 0.4; *private* = −0.04 ± 0.3); (b) dry forest (*communal* = −0.08 ± 0.3; *ejido* = −0.008 ± 0.3; *private* = −0.07 ± 0.3); (c) coniferous forest (*communal* = −0.24 ± 0.3; *ejido* = −0.28 ± 0.3; *private* = −0.30 ± 0.3); (d) deserts (*ejido* = 0.04 ± 0.3; *private* = −0.27 ± 0.4). Different letters indicate significant differences with Tukey–Kramer mean comparison among tenure regimes by biome ($p < 0.005$). Number of municipalities by tenure is indicated in parenthesis. Number of municipalities by tenure is indicated in parenthesis. The municipalities used in the analyses had more than 80% of their productive area in a single tenure category.

Table 2
RF regression results for analyses the change in woody vegetation analyzed for each tenure regime within each biome. The results include the percent variation explained by the model, the dominant variable based on percent mean square error (MSE), and the direction of the relation between the dominant variable and woody cover change.

Biome	Tenure regime	% Variation explained	Dominant variable	% Increase in MSE	Trend in woody vegetation change
Moist forest	Communal	13.99	Mean elevation	5.90	Increased as mean elevation increased
	Ejido	47.27	Mean annual precipitation	15.00	Decreased as precipitation increased
	Private	3.58	Mean elevation	8.60	Increases as mean elevation increased
Dry forest	Communal	9.22	Population density (2000)	7.26	Decreased as pop. density increased (>60 people)
	Ejido	7.07	Population density (1990)	9.09	Decreased as pop. density increased (>100 people)
	Private	51.06	Mean elevation	22.70	Decreased at high elevations (>1500 m)
Coniferous forest	Communal	4.58	Topographic complexity	9.98	Steady decreased as elevation increased
	Ejido	15.47	Population density (2000)	8.12	Decreased as pop. density increased (>200 people)
	Private	13	Topographic complexity	16.78	Steady increased as standard deviation increased
Desert	Ejido	−3.97	Population change (2000–2010)	7.83	Increased as population change from lost to gain people
	Private	32.9	Mean annual precipitation	24.14	Decreased at high elevation (>1500 m)

for woody vegetation to rapidly decline as population density increased.

- Desert biome: In municipalities classified as *private* tenure regime the change in woody vegetation was positive across a large range of elevation, but decreased slightly at higher elevation (>1500 m). In municipalities classified as *ejido* the overall trend was a decreases in woody vegetation increased as population change (from 2000 to 2010) went from a reduction (loss of people) to an increase (gain of people).

Discussion

There are many variables that can interact resulting in land change; land tenure is one of them (Geist and Lambin, 2002). It is widely agreed land tenure insecurity promotes land conversion (e.g., Southgate et al., 1991; Deacon, 1999; Ferreira, 2004; Araujo et al., 2008). However, there is no consensus on what type of tenure regime (i.e., private vs. common-pool) will foster more forest conversion. Our study is one of the first country-wide analyses that attempt to quantify the association between forest change (deforestation and recovery) and land tenure regimes.

Even after controlling for spatial autocorrelation and analyzing only those municipalities with the majority of their productive land as a single tenure and dividing them by biomes, it is clear the aggregation of certain regimes is stronger in some regions (for example, communal tenure municipalities in Oaxaca). However, the relevance of the results are highlighted by the robust sample size, its marked geographic patterns of land tenure, and the strong association of its recent socioeconomic changes in relation to globalization. The main emerging pattern from this study is that between 2001 and 2010, Mexican municipalities dominated by *ejidos* showed the greatest decrease in woody vegetation and the greatest increase in agriculture and herbaceous vegetation; *communal* regime had the greatest increase in woody vegetation, while municipalities dominated by *private* tenure had the greatest decrease in agricultural and herbaceous vegetation.

While results from the present study suggest an association between land tenure regime and trends in forest cover, they contradict the general assumption that the main dichotomy in land use effects of property rights is between common-pool and private regimes. In fact, the municipalities dominated by *private* properties showed woody and agriculture/herbaceous vegetation trends similar to those of *communal* tenure; while the two common-pool systems (*ejido* and *communal*) were quite dissimilar.

A similar study (Deininger and Minten, 1999) that evaluated cover change by municipality obtained noteworthy differences compared to our results. They found *ejidos* did not show more deforestation than forest under *private* property. There are a number of reasons that could explain these differences: quality of data sources, number of municipalities included in the studies, number of points in time considered to evaluate forest cover (10 vs. 2 years), and more importantly, *communal*-dominated tenure municipalities (*comunidades agrarias*) were not isolated from the *ejido*-dominated tenure municipalities and results from both tenures could have been confounded. In addition, during the time that the Deininger and Minten study was conducted the reform to article 27 occurred, and during this period Mexico has experienced high levels of urbanization, migration and dependency on international markets (Barnes, 2009), which could have influenced the production activity and therefore the vegetation cover. In fact, this reform could have lead to an increase in urban area and grasslands, and a decrease in native vegetation and agriculture such as the documented case of the Tijuana river watershed in northern Mexico (Farley et al., 2012).

The high heterogeneity of *ejidos* across the country has made them unique in the way they respond to economic and land policies reforms (Barnes, 2009), which will have an effect on the use of resources. However, we found a clear pattern of land change for this tenure regime. Legally there is little difference between the *ejido* and *communal* tenure regimes. In both regimes natural resources are under the same legal protection and the social organization has the same governance structure that regulates land use activities (Téllez, 1993). However, our results indicate that *communal* tenure appears to be more successful in controlling deforestation or, at least, in facilitating the recovery of the forest. In general, *communal* tenure has a longer history and their internal governance has been based in traditional custom (Barnes, 2009). One possible explanation for these results is that formal and informal regulations in the access to natural resources through established institutions or rules-in-use – the “unwritten laws” – seem to be more effectively enforced in *communal* than in *ejidos* regimes.

Previous research on *ejidos* mostly devoted to forestry activities (what many authors call *community-managed forests*) in some southern regions of Mexico (e.g., Bray et al., 2003, 2004, 2008; Bray and Klepeis, 2005; Ellis and Porter-Bolland, 2008) and other countries (Gibson et al., 2002, 2005), highlight community organization and rule enforcement through local institutions as key components to reduced deforestation or encourage higher percent of natural vegetation and species richness (Ortega-Huerta and Kral, 2007). In fact, it is been suggested rules enforced by local organization (whether under *ejido* tenure or not) may be equally as or more successful than rules enforced by protected areas at preventing deforestation across the tropics (Porter-Bolland et al., 2012). While these results highlight the importance of local organization and the presence of institutions to successfully implement conservation rules, they only include specific regional examples and do not compare the use of resources among tenure regimes, only the vegetation trends in time within some *ejido* lands. In addition, these examples may not be representative of other regions of the country, since other studies showed that not all *ejidos* appear to be as efficient at controlling deforestation (Perez-Verdin et al., 2009) even where rules were implemented to protect the forest (Alix-Garcia, 2007). According to our results, at the country level these later examples are more common than the former ones.

Regulation and effective control of resource use and land conversion in common-pool tenure regimes depend on the efficient coordination and cooperation, i.e., “collective action” (Poteete and Ostrom, 2004; Ostrom, 1990), where group origin and membership play a decisive role in land-use change. Therefore, if communities differ significantly in their views on how to use the environment, this can lead to conflict (Klooster, 1999). Group size has been identified as an important predictor of deforestation and land clearing in *ejidos* – land regulations are much easier to enforce in small groups (Alix-Garcia, 2007; Ellis and Porter-Bolland, 2008; Bray et al., 2004), which can affect cooperative action. Origin and cultural practices are also important characteristics that can influence the common use of natural resources (Barsimantov et al., 2011; Deininger and Minten, 1999). Our results support these observations. *Communal* dominated municipalities had the highest percent of people speaking a native language ($\sim$50%) and, on average, a population size an order of magnitude smaller than *ejido* dominated municipalities (4147 vs. 47,150 in 2000). These are all characteristics, which suggest greater similarity within the group. Consistent with this explanation, population change and population density were the most important factors influencing woody cover change in municipalities classified as *ejidos* – as population increased there was a decrease in woody vegetation. By having a common origin, smaller group organization, shared language, and cultural and traditional practices, members of *communal* lands appear to have higher social cohesion and more successful mechanisms for enforcing regulations than members of *ejidos*, and this may partially explain the apparent trend toward a more balanced land use in *communal* tenure.

An alternative explanation on the difference on vegetation change between the two common-pool systems could be related to the interest of *ejido* members in using forest resources rather than a group organization issue. In fact, a study conducted in 450 *ejidos* showed that deforestation was higher in communities engaged in forestry projects, even after properly accounting for self-selection into this activity (Alix-Garcia et al., 2003). In addition, since one of the main goals of the land reform was to promote the intensive agricultural production into the global market economy (Herrera Rodriguez, 2011), is valid to expect the interest of *ejido* members in exploiting their land resources.

Some studies suggest that tenure security given by *private* ownership may encourage deforestation by promoting investments in cattle pasture (Perz, 2002) or simply due to greater profitability of agricultural and ranching activities (Jaramillo and Kelly, 1997). Our results suggest the opposite; across biomes, *private*-dominated municipalities tended to increase or maintain woody cover, while agriculture and herbaceous cover decreased. The greatest reduction in agriculture and herbaceous vegetation in private lands could be due to local land-use intensification or a change in economic activities. Although at the national scale agricultural intensification does not necessarily translate into land sparing (Rudel et al., 2009), it is possible that agriculture adjustment can operate at the regional or property scale. For example, higher investment for agricultural intensification (e.g., irrigation) could explain the increase in woody cover in *private* tenure municipalities within the desert biome. This could be the case for many private municipalities in the desert biome. In the last decade, states such as Tamaulipas and Nuevo Leon increased their agricultural production despite losing cultivation area (SIAP, 2010). In addition, it is possible that some private owners, particularly in northern Mexico, have reduced their agricultural and grazing activities due to an increase in regional violence or climate uncertainly.

Conclusion

Environmental factors such as precipitation, elevation, and temperature play a significant role compared to socioeconomic or demographic factors in Mexico (Bonilla-Moheno et al., in press) and elsewhere in Latin America (Redo et al., in press). However, results from this study shows clear patterns on the dynamics and direction of vegetation change by tenure regime.

Land tenure was associated with changes in woody vegetation trends, but counter to our presupposition, the *private-common-pool* dichotomy was not the dominant explanatory dimension. *Ejido* municipalities tended toward greater deforestation in comparison with *communal* and *private* municipalities. These results suggest that group size and composition, which tend to be smaller and more homogeneous in communal versus *ejidos*, facilitates group decisions and enforcement of rules preventing the loss of woody vegetation. The role of social controls that regulate access to common-pool natural resources (including unwritten and traditional laws and practices), as well as the mechanisms that facilitate agriculture adjustment, emerge as potential explanations and research agendas for explaining forest recovery in *communal* and *private* lands. In contrast, in the *ejidos*, where it seems to be a greater use of resources, the association between deforestation and increasing population density and human marginalization appear to be important factors influencing woody loss.

Acknowledgments

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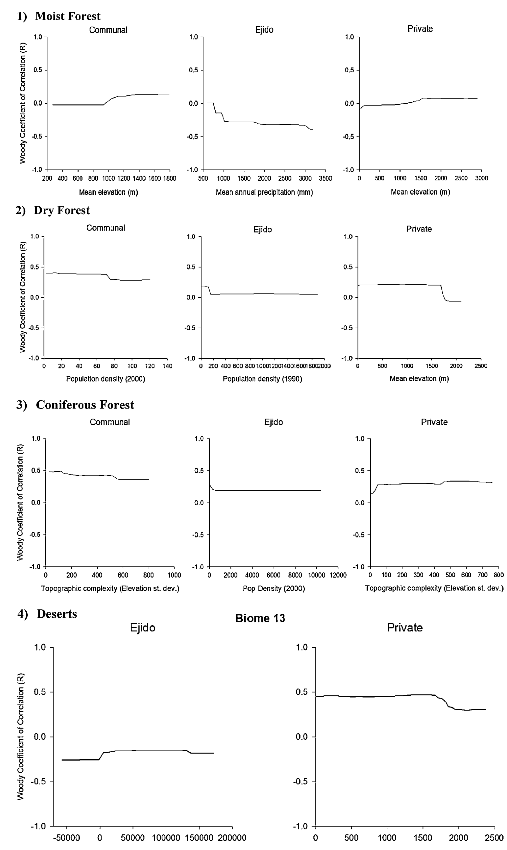
Appendix A.

Partial dependence plots for important variables of woody cover change by tenure regime for (1) moist forest, (2) dry forest, (3) coniferous forest, and (4) desert biomes. Partial dependence plots provide a graphical explanation of the marginal effect of independent variables (in this case the one that explained more variation) on the response (in this case woody cover change).



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