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Land tenure and forest cover change. The case of southwestern Beni, Bolivian Amazon, 1986–2009

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A B S T R A C T

As land use change continues to increase throughout the Amazon basin, there is a pressing need to accurately map, quantify and assess the effects of different factors on forest cover change (FCC). Land tenure may sometimes have important effects on forest cover, yet such effects remain poorly understood in Amazonia, particularly outside Brazil. In this paper we assess whether significant differences in trends of FCC can be partially explained by different land tenure arrangements, using a case study in southwestern Beni (Bolivian Amazon). We examine spatio-temporal dynamics of FCC across four land tenure systems (indigenous titled territory, protected area, logging concession, and private land) by classifying forests using a time-series of Landsat satellite imagery consisting of four dates (1986, 1996, 2001, 2009). Specifically, we unravel (1) trends in early growth and old-growth forest extent, including changes in total cover area, annual change rates, and spatial change dynamics, and (2) trends in old-growth forest fragmentation. To better understand the association between land tenure and FCC, we qualitatively assess the potential role that other underlying and proximate drivers may have had in FCC over the study period. We found that private lands underwent, by far, the largest FCC, that indigenous territories and the protected area had little FCC, and that logging concessions were responsible for the lowest FCC. Our findings suggest that land tenure played a key role in FCC except in private areas, where many other drivers had operated. Our study sheds light into the potential role of land tenure in FCC and has important implications for public policies aimed at socioeconomic development and environmental conservation in the Amazon. We give some policy recommendations drawn from a biocultural conservation perspective that could contribute to implement more inclusive conservation policies in the region.

Introduction

Amazonian tropical forests are home to an incredible wealth of biological, cultural and linguistic diversity (Maffi, 2005). These forests have long been inhabited and managed by indigenous groups (Heckenberger, Russell, Toney, & Schmidt, 2007; Lombardo, Canal-Beeby, Fehr, & Veit, 2011; Mann, 2008), and in more recent times, they have attracted a myriad of outsiders seeking fortune by extracting commodities such as rubber, gold, and timber (Hetch & Cockburn, 2011). In the second half of the 20th century, population growth, slash-and-burn agriculture, and the severe intensification of market-oriented economic activities (e.g., cattle ranching, industrial farming, logging, and mining) have resulted in the loss, fragmentation, and degradation of many old-growth forests in the region (Geist & Lambin, 2001; Rudel & Roper, 1997). Such forest cover change (FCC) has significant implications for local livelihoods (Sunderlin et al., 2008), biocultural conservation (Gorenflo, Romaine, Mittermeier, & Walker-Painemilla, 2012), and global climate (Luyssaert et al., 2008). As land use change continues to increase throughout the Amazon basin (Davidson et al., 2012; Hecht, 2005), there is a pressing need to map, quantify, and

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identify the main drivers of FCC so that effective biodiversity conservation programs, climate change mitigation schemes and rural development policies can be designed and implemented.

Many studies have sought to map, quantify and/or identify the spatial dynamics and patterns of FCC in the Amazon (e.g., Lorena & Lambin, 2009; Sierra, 2000), the main factors associated with forest loss and fragmentation (e.g., Fearnside, 2005; Laurance, Albernaz, et al., 2002; Steininger, Tucker, Ersts, et al., 2001) and, less often, with forest degradation or regrowth (e.g., Perz & Skole, 2003; Walsh, Shao, Mena, & McCleary, 2008). In this context, several studies have recently aimed at documenting and explaining FCC in the Bolivian Amazon (e.g., Bottazzi & Dao, 2013; Kaimowitz, 1997; Killeen et al., 2007; Killeen et al., 2008; Marsik, Stevens, & Southworth, 2011; Müller, Müller, Schierhorn, Gerold, & Pacheco, 2012; Pacheco, 2002, 2006; Steininger, Tucker, Townshend, et al., 2001). Though FCC has been partly explained by direct factors such as the expansion of soybean cultivation (Hecht, 2005; Müller, Müller, Schierhorn, Gerold, & Pacheco, 2012), there are important underlying factors such as the 1974 forestry law, the agrarian and forestry reforms enacted in 1996, and the more recent agrarian reform of 2006 that have triggered significant forest clearance, fragmentation and degradation across the eastern lowlands of Bolivia (Pacheco, 2006; Redo, Millington, & Hindery, 2011). Such reforms have led to a specific configuration of land tenure systems, each one characterized by the allocation of specific land uses and property rights. For example, across the Bolivian Amazon, some state (public) lands were declared protected areas for biodiversity conservation in the 1980s, while others were granted to companies as logging concessions for timber extraction; in the early 1990s, other lands were declared indigenous territories to acknowledge the rights of indigenous populations to part of their ancestral lands. In addition, different colonization projects have given state lands to a variety of colonists, including, for instance, Andean peasants and miners who became unemployed when the mining industry collapsed in the mid-1980s (Killeen et al., 2008; Pacheco, 2006).

The association between land tenure (or property rights) and FCC has been found to be significant in some case studies in the Amazon (e.g., Araujo, Bonjean, Combes, Motel, & Reis, 2009; Fearnside, 1993; Messina, Walsh, Mena, & Delamater, 2006) because land tenure and tenure insecurity affect the migration of populations and landholders' decisions related to land use, labor, and capital investment (Fearnside, 2001). However, the association between land tenure and FCC has not been sufficiently explored in the Bolivian Amazon; furthermore, because different land tenure systems are legally restricted to specific land use types (Reyes-García, Ledezma, et al., 2012), we contend that land tenure (and therefore property rights and land use allocation, two factors closely related to land tenure) may have had important effects on FCC in the region. Thus, the main goal of this paper was to assess whether significant differences in FCC trends can be partially explained by different land tenure systems using a case study in southwestern Beni. We examined the spatio-temporal dynamics of FCC across four land tenure systems (indigenous titled territory, protected area, logging concession, private land) and hypothesized that both indigenous territories and the protected area underwent less FCC than private lands and logging concessions. Specifically, we assessed the association between land tenure and FCC by mapping and quantifying (1) the trends in extent, annual change rates, and spatial dynamics of both old-growth and early growth forests, and (2) the trends in old-growth forest fragmentation patterns. In addition, to improving the understanding of the association between land tenure and FCC, we qualitatively assessed the potential effects that other underlying and proximate drivers may have had on FCC over the study period.

Our FCC assessment is more comprehensive than that of previous studies covering this area of the Amazon (e.g., Bottazzi & Dao, 2013; Killeen et al., 2007) because it adopts an enhanced land use/cover classification approach (Paneque-Gálvez et al., 2013) and discriminates between early growth and old-growth forests, which is important to address not only deforestation but also forest degradation and regrowth; furthermore, our study uses reliable and easy-to-interpret fragmentation indexes. We conducted our study from 1986 to 2009 because (1) most FCC in the Bolivian lowlands has occurred since the mid-1980s following the structural adjustment reforms undertaken by the Bolivian government (Killeen et al., 2008; Pacheco, 2006), and (2) the current configuration of land tenure systems started to be implemented in the mid-1980s.

Case study

Biophysical setting

The study area was located southwest of the Beni department, in northeastern Bolivia (Fig. 1). This region has a high diversity of habitats that can be broadly grouped into montane tropical forests, lowland tropical forests, and wet savanna areas. Here we focus on lowland tropical forests, as they occupy approximately 80–90% of the different land tenure systems examined, most of which are old-growth *terra firme* forests,[1] although *bajío* forests also thrive in seasonally or permanently flooded areas (Guèze et al., 2013). In addition, degraded forests can be found in selectively logged areas (Gullison, Panfil, Strouse, & Hubbell, 1996), and early growth forests[2] surround both indigenous and non-indigenous settlements where swidden-fallow agroforestry systems are commonplace (Huanca, 1999). Lowland forests across the study area contain semi-deciduous tree species due to the existence of contrasting dry and wet seasons (four months with <100 mm of precipitation) (Guèze et al., 2013). The mean annual temperature of the region is approximately 26 °C (Navarro & Maldonado, 2002) and the mean annual rainfall is approximately 1750 mm (Guèze et al., 2013). Most soils are quaternary alluvial sediments of fluvial origin, particularly acrisols and ferrasols (Navarro & Maldonado, 2002).

Land tenure systems

There are four land tenure systems in the study area: titled indigenous territories (TCOs, the acronym for the Spanish *Tierra Comunitaria de Origen*), protected areas, logging concessions, and private lands. In this study, we analyzed FCC in each land tenure system using five areas (Fig. 1, Table 1). TCOs are indigenous titled territories with communal property rights where land cannot be sold. We considered two TCOs in our analyses: Tsimane' and Multiethnic TCOs, both of which were initially recognized in 1990 and accounted for approximately 400,000 ha each. However, since the 1996 agrarian reform, both TCOs have lost much land as a result of an ongoing land tenure regularization process (nationally known as *saneamiento*) that gives land to third parties who can demonstrate (1) land occupancy before the TCOs were established and (2) the land's socioeconomic function as defined in the reform (Reyes-

[1] We define old-growth forests as forested areas with low levels of disturbance that consist of mature trees forming a dense and structurally complex canopy with few gaps and a typical height range of 10–40 m.

[2] We define early growth forests as forested areas with varying degrees of disturbance due to human activities (e.g., typically slash-and-burn agriculture or logging) or natural dynamics (e.g., flooding regimes). These forests are typically composed of regenerating trees, dead trees and logs, crops such as rice, manioc and bananas, sometimes with large scattered old trees. The canopy is rather open, structurally simple, and the average tree height ranges from 3 to 10 m.

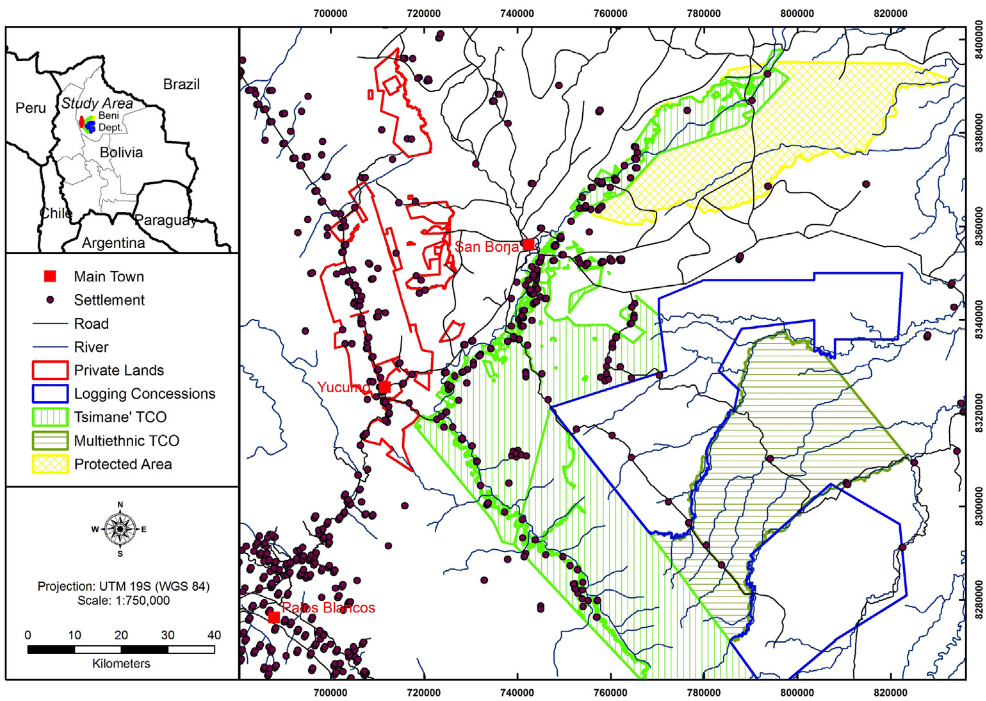


Fig. 1. Study area showing the five areas used to analyze the association between land tenure and forest cover change. Settlements within the Multiethnic TCO (approximately 20) are not shown due to the lack of GIS data.

García et al., submitted for publication), i.e., evidence of current land use. Thus, at present, the Tsimane' TCO accounts for some 330,000 ha while the Multiethnic TCO has some 358,000 ha (Chumacero, 2011).

The Tsimane' TCO is inhabited by Tsimane' indigenous people, though the presence of abutters encroaching onto the land is commonplace (Reyes-García, Ledezma, et al., 2012). The Multiethnic TCO is inhabited by four native indigenous groups: Moxeño, Yuracaré, Tsimane', and Movima. Additionally, mestizo cattle ranchers have settled in the Multiethnic TCO in recent decades. In fact, because the land-use plan for the Beni department (approved in 2002 by Law DS No. 26732) recommends grazing as the primary activity across part of the Multiethnic TCO, this law could have incentivized and somehow legitimized the settlement of cattle ranchers, as indigenous peoples seldom have access to credit and therefore cannot invest in cattle. Within the Multiethnic TCO, mestizo cattle ranchers are found both in savanna patches (including cultivated pastures, semi-natural grasslands, and scrublands) and in previously forested areas that have been converted to pastures. Land uses of native indigenous peoples in both TCOs include subsistence slash-and-burn agriculture (mostly rice, plantain, cassava and fruits), limited cash cropping (mostly rice), fishing, hunting, and gathering of wild fruits and non-timber forest products such as thatch palm (*Genoma deversa*) that is sold or bartered. Selective logging is allowed in TCOs for non-commercial purposes and, under approved management plans, for trade (though the Tsimane' TCO still did not have a forestry management plan in 2012) (Reyes-García, Ledezma, et al., 2012; Reyes-García et al., submitted for publication). Cattle ranching is rare among indigenous peoples in both TCOs, particularly in settlements far from Yucumo and San Borja.

We analyzed one protected area, the Beni Biological Station (EBB, the Spanish acronym for *Estación Biológica del Beni*), created in 1982 and declared a UNESCO Biosphere Reserve in 1987. This protected area comprises approximately 135,000 ha of state land, 35,000 (approximately 30%) of which was declared to also belong to the Tsimane' TCO in 1990; as a result, that part of the EBB has a dual status (i.e., indigenous land and protected area). The main land use of the EBB is biological conservation and indigenous people living within the EBB have similar rights to use land and resources as they do in TCOs; however, commercial logging and intensive land uses are prohibited (Reyes-García, Ledezma, et al., 2012). To avoid confusion, in this study we considered the overlapping area as part of the Tsimane' TCO and the non-overlapping area, which is almost completely uninhabited, as the protected area.

We also examined six of the seven logging concessions that were granted in this area to logging companies at the end of 1986 (Gullison et al., 1996; Lehm, 1994). Such logging concessions are located on state lands between the Tsimane' and the Multiethnic TCOs, thus overlapping the traditional territories of several indigenous groups (Reyes-García et al., submitted for publication). Some indigenous settlements are found within these logging concessions and, aside from commercial forestry, indigenous peoples have the same rights to use natural resources as indigenous people in communities settled in TCOs and protected areas. The main land use in logging concessions is industrial timber extraction.

Finally, we examined private lands corresponding to approximately 100 settlements located around the Rurrenabaque-Yucumo road and further northwest. While the latter settlements were more recently established and not yet well connected to infrastructure and markets, the former settlements are the result of the Rurrenabaque-Sécure colonization project. This project brought a mass of Andean colonists to the area between 1975 and 1986, a process that intensified after 1979 once the road was finished, and then after 1987, when the Rurrenabaque-Yucumo-San Borja road was improved and many Andean miners migrated to this colonization area as a consequence of the tin mining collapse of the mid-1980s (Bottazzi, 2008). The main land uses of colonists in these private lands include slash-and-burn agriculture for self-subsistence or more commonly for rice production (and to a lesser extent for other cash crops such as cacao, coffee, corn and fruits) and cattle ranching. Mechanized agriculture is still rare and only present on some large farms (Bottazzi and Dao, 2013).

Table 1
Key information about the five areas studied. Population data taken from Chumacero (2011), Bottazzi (2008) and our own field data.

Name	Land property rights	Land tenure	Main social group(s)	Settlements/total population	Main land use(s)	Creation (date, law)	Area analyzed (ha)
Tsimane' Indigenous Territory	Communal	Indigenous Lands (TCO)	Tsimane'	~55/~7,000	Slash & burn agriculture for self-subsistence, hunting, fishing, foraging	1990, Law No. 23611	~280,000
Multiethnic Indigenous Territory	Communal	Indigenous Lands (TCO)	Tsimane', Yuracarés, Moxeños, Movimas, Mestizo Cattle ranchers	~20/~3,500	Slash & burn agriculture for self-subsistence, hunting, fishing, foraging, selective logging, cattle ranching	1990, Law No. 23611	~146,000
Beni Biological Station	State	Protected Area	Tsimane'	Almost uninhabited	Biological conservation	1982, Law No.19191	~105,000
Logging Concessions	State, but leased to logging companies	Logging Concessions	Mestizo and colonist laborers, Tsimane'	~6 Tsimane'/~700	Industrial timber extraction, Indigenous self-subsistence activities	1986, Forestry Law No. 11686	~250,000
Private Lands	Private	Private lands	Andean colonists	~100/~40 families per settlement	Slash & burn agriculture for rice, corn and fruits for national markets (and to less extent cacao, coffee and tea for export), cattle ranching	Mostly since the mid-1980s, Colonization Law No. 107765	~86,000

Material and methods

Satellite imagery and GIS data

We analyzed FCC by employing the standard procedure of classifying a time-series of satellite imagery (Lu, Mausel, Brondízio, & Moran, 2004) and used Landsat-5 TM and Landsat-7 ETM+ satellite imagery to construct a four-date time-series. To cover the study area, we acquired six images from three dates (27/10/1986, 18/07/1996, 25/08/2001) from the United States Geological Service (USGS) and two images (17/04/2009) from the Brazilian National Institute for Space Research (INPE), corresponding to path 233, rows 70, 71. We used the ASTER's Global Digital Elevation Model (GDEM) v.1 to perform geometric and radiometric corrections on Landsat imagery. We carried out fieldwork campaigns in 2009 and 2010 to collect GIS data. Specifically, to assist in the process of imagery geometric correction, we collected GPS points at road crossings and other human-made features on the ground and GPS tracks along the main roads and rivers. In addition, we collected GPS points to gather information on land use/cover, which were used to classify the imagery. To map and quantify FCC according to land tenure, we used a GIS database created by Bolivia's National Institute for Agrarian Reform (INRA) in 2007 from which the five study areas described in the previous section were retrieved as independent GIS layers. Unfortunately, INRA's geodatabase did not contain any information on population, ethnicity or land use types, which would have been useful to improve our analyses.

Multi-temporal forest cover classification

We pre-processed and classified the time-series of Landsat satellite imagery. Pre-processing steps consisted of geometric and radiometric corrections, image mosaicking, cloud and cloud-shadow masking, and cropping to the borders of the study area. We then carried out four independent forest classifications corresponding to the four imagery dates, following an approach previously devised to classify land use/cover in the area; this approach consisted in using support vector machines (SVM) with the radial basis function kernel to classify Landsat reflectance along with textural homogeneity (Paneque-Gálvez et al., 2013). When the time-series forest classification was completed, we performed Card's correction (Card, 1982) on each classification. We then constructed confusion matrices to estimate the overall accuracy of forest classifications and both producer's and user's accuracies for each thematic class. Specifically, our four forest classifications included three thematic classes: early growth/degraded forest (hereafter early growth forest), old-growth forest, and non-forest. Prior to carrying out FCC analyses, we constructed a mask that contained any pixel that had not been allocated to a specific thematic class in a classification. We then applied this mask to each forest classification so that all four classifications contained exactly the same amount of pixels corresponding to forest/non-forest data.

Forest cover change analyses by land tenure system

To examine general trends across the study area, we used the entire forest classifications. In addition, to assess potential differences in forest trends according to different land tenure systems, we cropped each forest classification to the extent of the five analyzed areas (see Fig. 1).

Trends in forest extent

To examine trends in forest extent, we retrieved forest cover areas for both early growth and old-growth forests and estimated their net area change at three study periods (1986–1996, 1996–2001, 2001–2009). We considered forest extent in the oldest classification (1986) as the baseline level representing 100% of the original forest cover area. Then, to facilitate comparisons across the three study periods, we calculated the net annual rates of change in both early growth and old-growth forests following the method described by Puyravaud (2003). In addition, we calculated the percentage of gains, losses and swap[3] to better understand the dynamics of land use/cover change (Pontius, Shusas, & McEachern, 2004), for both forest types during the three study periods. Finally, to detect the spatial distribution of persistent vs. dynamic forest areas, we mapped the total number of forest changes during the three study periods and quantified the extent of each type of area (i.e., areas with no FCC vs. areas with one, two and three forest changes).

Trends in forest fragmentation

To unravel trends in forest fragmentation, we restricted the analysis to old-growth forests because of their greater ecological importance (Gibson et al., 2011) and coverage across the study area. We conducted morphological spatial pattern analysis over the multi-temporal forest classifications using GUIDOS software (Vogt et al., 2007). Here we focus on two morphological classes (edge and core), as they are the most intuitive and best suited to evaluating forest fragmentation. We selected an edge width of 10 pixels (i.e., 300 m in Landsat imagery) to perform the fragmentation analysis because most ecological effects occur within this edge width (Broadbent et al., 2008; Harper et al., 2005) and because we have observed that land uses in the study areas do not usually create wider edges in old-growth forests. Thus, we define core forest as old-growth forest patches with edges no larger than 300 m inside and bounded by edges larger than 300 m.

Assessment of the main drivers of forest cover change

To better understand the strength of the association between land tenure and FCC in the five study areas, we carried out a qualitative assessment that included all of the broad categories of underlying and proximate drivers identified by Geist and Lambin (2002). Within such categories of drivers, we first identified the drivers that could have affected any of our five study areas during the whole study period (e.g., influence of population density and immigration dynamics under demographic underlying drivers, or the influence of road accessibility under proximate drivers). Subsequently, we qualitatively assessed the impact of each driver on FCC within each of the five study areas based on a literature review of previous studies concerned with FCC in this and other Amazonian regions, and based on extensive knowledge gathered over years working in these areas. For each study area, we coded each potential driver of FCC as 1, 2 or 3 depending on whether it was deemed to have had small, medium or large effects on FCC, respectively; intermediate values (i.e., 1–2, 2–3) were also allowed.

Limitations of the study

We acknowledge the complex nature of land use/cover change in tropical areas and the synergistic effects of different underlying driving factors and proximate causes on FCC (Lambin, Geist, & Lepers, 2003). Therefore, although we investigated the association between land tenure and FCC, it is admittedly difficult to elucidate the real magnitude of such an association because land tenure has operated in combination with other factors that could only be characterized qualitatively due to the lack of sufficient, reliable quantitative data. Moreover, while land tenure may have had significant effects on FCC, FCC may have also had important effects on land tenure (i.e., deforestation and degradation may have triggered changes in land tenure, for example from state land to private land). In addition, we acknowledge that some land tenure systems were not in place at the beginning of the study periods (1986) and that their exact limits have changed slightly over time. We have not been able to account for such changes due to the lack of historical GIS data; however, because the extent of the assessed study areas have not substantially changed during the three study periods and because the main actors operating within the study areas have remained relatively stable, we believe that our findings are not significantly affected. Finally, we realize that some confusion exists in our multi-temporal forest classification regarding our early growth forest class, as *bajío* forests were erroneously classified as early growth forests due to their spectral similarity. However, *bajío* forests are only found in seasonally or permanently inundated areas that occur marginally in the northern region of our study area. To address this forest classification problem and to adequately interpret FCC in areas potentially affected by misclassification, we relied on our botanical knowledge acquired from extensive work in the area (e.g., Guèze et al., 2013) and on the utilization of Google Earth.

Results

Multi-temporal forest cover classification

The classification approach selected returned overall accuracies greater than 90% for the four forest cover classifications (Table 2). We obtained extremely accurate classification results for old-growth forests but were less successful in mapping early growth forests, most likely because of their high heterogeneity in composition and structure. Nevertheless, we were able to map early growth forests with producer's accuracies ranging from 86% to 95% and user's accuracies ranging from 77% to 88%. Fig. 2 shows the four forest cover classifications along with the relative extent of forests and non-forests for the entire study area. From 1986 to 2009, the total relative cover of early growth forests increased from 3.5% to nearly 7% (approximately 48,500 ha), while the relative cover of old-growth forests decreased from 72% to 66%, (approximately 64,000 ha). Therefore, multi-temporal forest classification results show a general trend toward old-growth forest clearance and early growth forest spread across the entire study area.

Spatio-temporal patterns of forest cover change by land tenure system

Trends in forest extent

The total area of old-growth forests decreased by 4.5% across the entire study area from 1986 to 2009. We found important

Table 2
Summary of multi-temporal classification accuracy assessments. OA, overall accuracy; PA, producer's accuracy; UA, user's accuracy; EGF, early growth forest; OGF, old-growth forest.

Landsat Imagery	OA	PA OGF	UA OGF	PA EGF	UA EGF
1986	95.52	98.50	98.41	86.00	77.41
1996	90.54	97.00	98.95	87.50	88.17
2001	97.53	98.50	99.44	90.00	82.97
2009	94.77	96.00	99.65	95.00	81.20

[3] Swap is defined as the difference between the absolute total change (gains + |losses|) and the absolute net change (gains − |losses|). Thus, for example, if over a given period and for a specific land tenure, 10% of old-growth forests were cleared in one location, but 10% were recovered through regrowth in another location, the net change would be 0%, yet swap would amount to 20%.

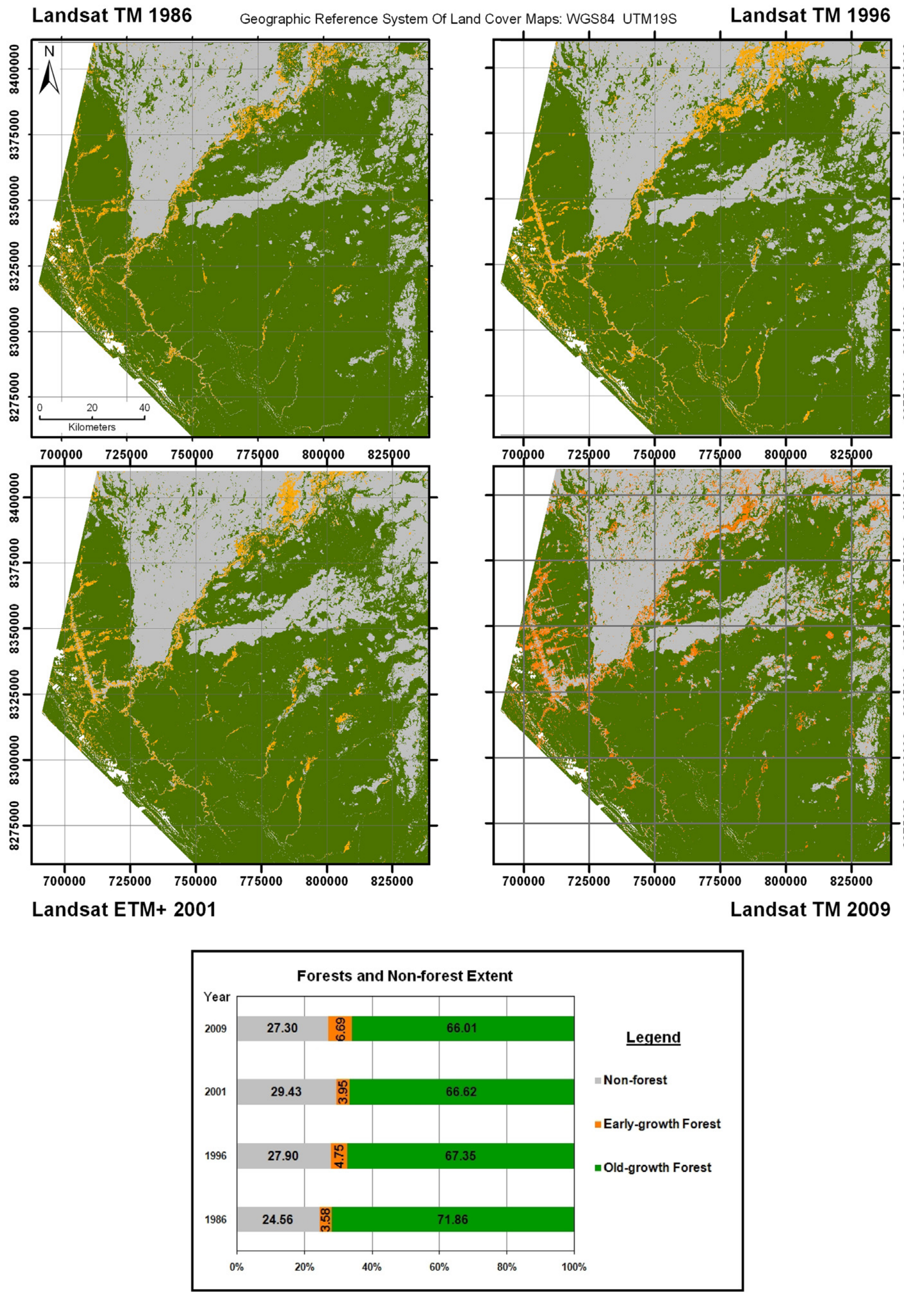


Fig. 2. Multi-temporal forest cover classifications showing the relative extent of forests and non-forest cover for each date.

differences among land tenure systems; however, in terms of the change in percentage of old-growth forest relative to the baseline levels of 1986, differences appeared to be subtle (aside from on private lands) due to the large extent of old-growth forests within each land tenure system (Fig. 3). By far, the biggest loss of old-growth forest by 2009 had occurred on private lands (approximately 22,000 ha or ~25% of their total area in this study) (Table 3). Logging concessions lost nearly 4000 ha (which was only ~1.5% of their total extent). The two TCOs followed inverse trends over the second and third study periods; besides, by 2009 the Multiethnic TCO lost approximately 5100 ha (3.5% of its total area), while the Tsimane' TCO only lost approximately 700 ha of old-growth forest (representing barely 0.25% of its extent). Finally, the protected area also showed little old-growth forest loss by 2009 (~1050 ha, ~1% of its extent).

During the same period, the total extent of early growth forests increased by 77% across the entire area, with important differences among land tenure systems (Fig. 3). Relative to the levels of 1986 and in terms of percentage, by 2009 the largest increase was found in logging concessions, where the area of early growth forests had increased 3.5 times. However, this increase only represented ~1% (2600 ha) of the total area of logging concessions (Table 3). Conversely, the lowest increase was found in the Tsimane' TCO (approximately 0.3%, 800 ha). In the Multiethnic TCO, even though the area occupied by early growth forests had doubled by 2009, it only represented a net gain of some 2000 ha (1.3%). In the protected area, the extent of early growth forests was 85% higher in 2009 than in 1986 but it only represented an increase of ~1600 ha (1.5% of its total area). Finally, by 2009 early growth forests had nearly tripled on private lands, representing the largest increase in absolute and

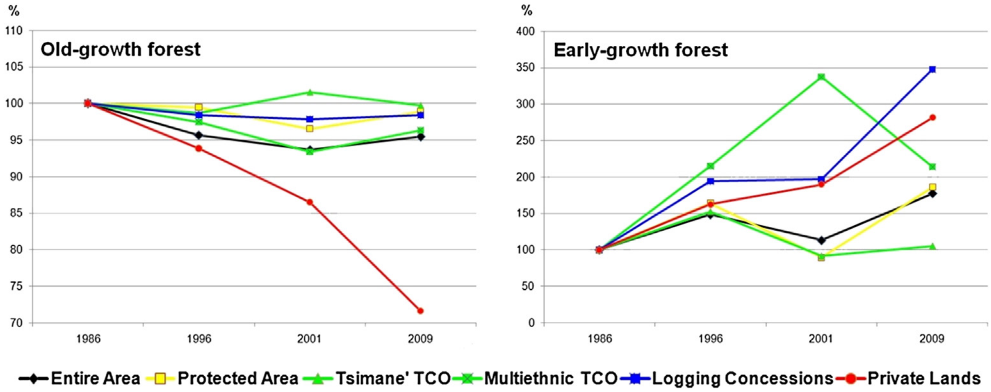


Fig. 3. Trends in the extent of old-growth and early growth forests in relation to their 1986 baseline level (%). Trends are derived from multi-temporal forest cover classifications.

relative terms (~12,000 ha and ~14% of their total extent, respectively).

Annual forest change rates

During the two first study periods (1986–1996, 1996–2001), we encountered net annual old-growth forest losses in all land tenure systems except the Tsimane' TCO during the second period (Fig. 4) where an annual net recovery rate of approximately 0.6% was observed (i.e., a gain of approximately 7000 ha over the entire period, Table 3). Annual old-growth forest loss rates increased during the second period in the protected area, in the Multiethnic TCO and especially on private lands (1.6%). During the third period (2001–2009), we observed a net recovery of old-growth forests everywhere except in the Tsimane' TCO (where moderate annual net losses occurred) and on private lands (where significant annual losses (2.4%) occurred). The smallest variations in old-growth forest change rates occurred on logging concessions.

During the first period, we found annual early growth forest change rates greater than 4% in all areas (Fig. 4); rates of change were highest in the logging concessions and in the Multiethnic TCO (+6.6% and +7.6%, respectively). From 1996 to 2001, annual early growth forest change rates were significantly different from those of the previous period only in the Multiethnic TCO (+9%), on private lands (+3%), and in the protected area and the Tsimane' TCO (−10%). Finally, from 2001 to 2009, rates of annual early growth forest change followed similar patterns as those of the first period, with the exception of a 5.7% decrease in the Multiethnic TCO.

Spatial distribution and intensity of forest cover changes

We also found important differences in gains, losses and swap of both old-growth and early growth forests among land tenure systems (Fig. 5). Again, private lands experienced far more changes than the other land tenure types from 1986 to 2009, having (1) 3–5 times more old-growth forest losses than gains, (2) more early growth forest gains than losses, and (3) an early growth swap of ~3%, i.e., 3–4 times higher than in the rest of the land tenures, which indicates a much higher land use intensity in forested areas. The protected area, both indigenous TCOs and the six logging concessions had low levels of gains, losses and swap for both early growth and old-growth forests. Fig. 5 shows unambiguously how these three tenure systems are much more effective at preventing FCC than private lands.

Additionally, we found that old-growth and early growth forests on private lands were by far the least persistent (74%), and that private lands were the only study area where three changes occurred in more than 1% of its extent (Fig. 6). Forest persistency was much lower on private lands close to the Yucumo-Rurrenabaque road than on private lands further north, where little FCC occurred. Forested lands under the three other tenures were highly persistent, especially on the logging concessions (99%) and in the protected area (97%). Forests in the Tsimane' TCO were 4% less persistent than in the Multiethnic TCO (91% vs. 95%), and, in both cases, we observed that the majority of forest changes occurred in the vicinity of savanna areas.

Fragmentation trends in old-growth forests

The percentages of core old-growth forest areas relative to the total extent of old-growth forest within each study area were far higher in indigenous TCOs, on logging concessions, and in the protected area (ranging between 76% and 86% in 2009) than on private lands (Table 4). From 1986 to 2009, the only land tenure

Table 3
Trends in the extent of old-growth and early growth forests. Top figures refer to the total area covered by each forest type (in hectares), while bottom figures (within brackets) refer to the area covered by each forest type relative to the extent of each study area (in percentage).

Land tenure system	Old-growth forest				Early growth forest			
	1986	1996	2001	2009	1986	1996	2001	2009
Entire area	1,401,194	1,340,832	1,312,655	1,337,408	62,942	93,364	71,078	111,598
	(71,79)	(68,70)	(67,26)	(68,52)	(3,22)	(4,78)	(3,64)	(5,72)
Protected area	93,008	92,543	89,782	91,951	1875	3078	1688	3482
	(88,58)	(88,14)	(85,51)	(87,57)	(1,79)	(2,93)	(1,61)	(3,32)
Tsimane' TCO	253,110	249,809	257,048	252,426	14,645	22,336	13,449	15,445
	(90,40)	(89,22)	(91,80)	(90,15)	(5,23)	(7,98)	(4,80)	(5,52)
Multiethnic TCO	139,822	136,298	130,592	134,704	1730	3719	5829	3693
	(95,77)	(93,35)	(89,45)	(92,26)	(1,19)	(2,55)	(3,99)	(2,53)
Logging concessions	242,846	238,922	237,671	238,947	1051	2035	2064	3649
	(97,14)	(95,57)	(95,07)	(95,58)	(0,42)	(0,81)	(0,83)	(1,46)
Private lands	76,447	71,740	66,103	54,742	6531	10,609	12,385	18,376
	(88,89)	(83,42)	(76,86)	(63,65)	(7,59)	(12,34)	(14,40)	(21,37)

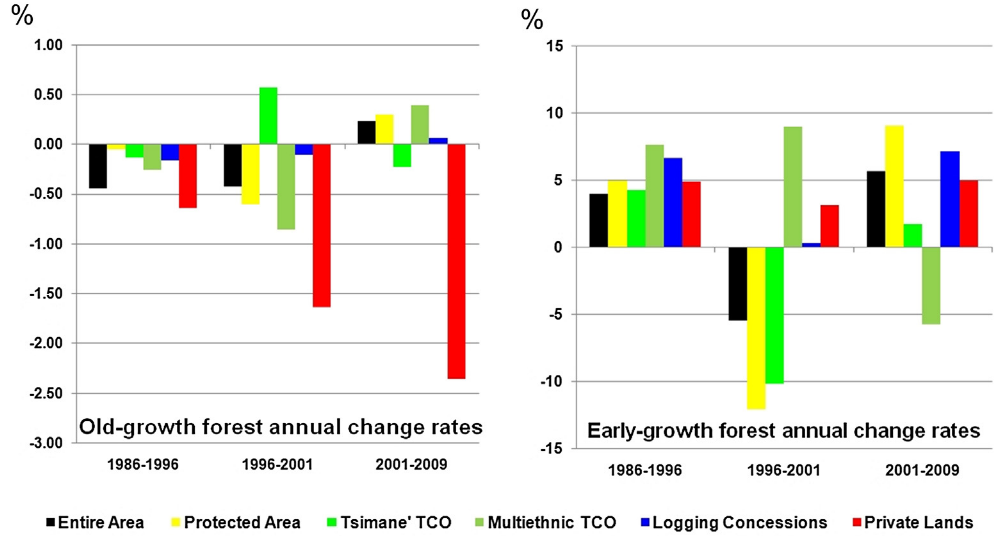


Fig. 4. Annual change rates of old-growth and early growth forests. Negative rates for old-growth forests refer to net deforestation and positive rates to net regrowth. For early growth forests, while negative rates refer to net deforestation, positive rates refer to a combination of net degradation (from old-growth forests) and net regrowth (from non-forest covers).

system where there was an increase in core old-growth forest was the protected area (5%), while the Tsimane' and the Multiethnic TCOs lost 2.5%, and the logging concessions lost 4% of their core old-growth forest area. On private lands, the core area of old-growth forest fell from 67% in 1986 to 44% in 2009. In parallel, from 1986 to 2009, old-growth forest edge increased to almost 15% in private areas; in the other land tenure systems, the proportion of old-growth forest edge did not increase during the three study periods and remained low (2–3%), with logging concessions showing slightly lower levels of edge.

Main drivers of forest cover change

We found that land tenure, property rights and tenure insecurity coupled with land use policies were the major underlying drivers of FCC in all of the study areas (Table 5). In fact, such policy and institutional drivers (along with remoteness) were possibly the most important drivers in the protected area, the two indigenous territories, and the six logging concessions. In four such areas, very few other factors drove an increase or decrease in FCC. Thus, flood susceptibility was the only other identifiable driver in the protected area; few other drivers operated in both indigenous territories, which were affected by similar pressures from indigenous peoples (e.g., subsistence agriculture, loss of traditional ecological knowledge, floods) and to a greater extent from encroachers (e.g., illegal logging, cattle ranching, and farming); whilst in logging concessions there were a few more drivers of FCC, both indirect (i.e., underlying, such as timber markets) and direct (i.e., proximate, such as road accessibility and logging operations). In contrast, we identified many more direct and indirect factors with a significant impact on FCC on private lands than in the rest of land tenure systems. For instance, high population density and immigration have been key FCC drivers on private lands but not in other areas, while many other factors have played a much more important role in explaining FCC on private lands than elsewhere (e.g., road accessibility, logging, commercial agriculture and cattle ranching). Interestingly, private lands are not better suited for commercial agriculture and livestock than the rest of our study areas, as many are located in the Andean foothills, and therefore have higher slopes, rainfall and flood risk.

Discussion

Our results indicate that very different spatio-temporal patterns of FCC exist for different land tenure systems, and that, aside from land use/tenure issues, few other factors have driven FCC in any of the study areas except private lands. These findings suggest that land tenure is strongly associated with the fate of forests in the Bolivian Amazon. Specifically, we observed that (1) private lands underwent, by far, the largest FCC of all of the land tenure systems analyzed, (2) both indigenous TCOs and the protected area had relatively little FCC but their trends differed somewhat, and (3) logging concessions experienced the lowest FCC. Therefore, our initial hypothesis was not fully supported, as logging concessions underwent less FCC than both indigenous territories and the protected area. We do not believe that these findings are biased by the methodology used, as very high accuracies were obtained in our multi-temporal forest classification. We discuss these findings and conclude the section by highlighting their implications for forest conservation and the well-being of forest inhabitants.

Land tenure and spatio-temporal patterns of forest cover change

The results of the FCC analysis confirm that private lands have a remarkable impact on forests in the Amazon (Fearnside, 2008; Killeen et al., 2008; Lu et al., 2010; Rudel, Bates, & Machinguiasli, 2002). FCC in private lands greatly increased during the last two study periods (1996–2001, 2001–2009), most likely due to an increase in population density and the intensification of commercial agriculture and cattle ranching in response to national/international market stimuli. Additionally, a potential key factor underlying such trends in FCC has been the increasing need to demonstrate the socioeconomic function of land (given the increasing population growth across colonization areas) as a way of securing private property rights. This factor triggered extensive old-growth forest clearance in colonization areas after the 1996 and 2006 agrarian reforms (Bottazzi & Dao, 2013) that converted state lands (mostly forest-land) into private property for rural and indigenous communities as long as they demonstrated the socioeconomic function of the land (Redo, Millington, & Hindery, 2011).

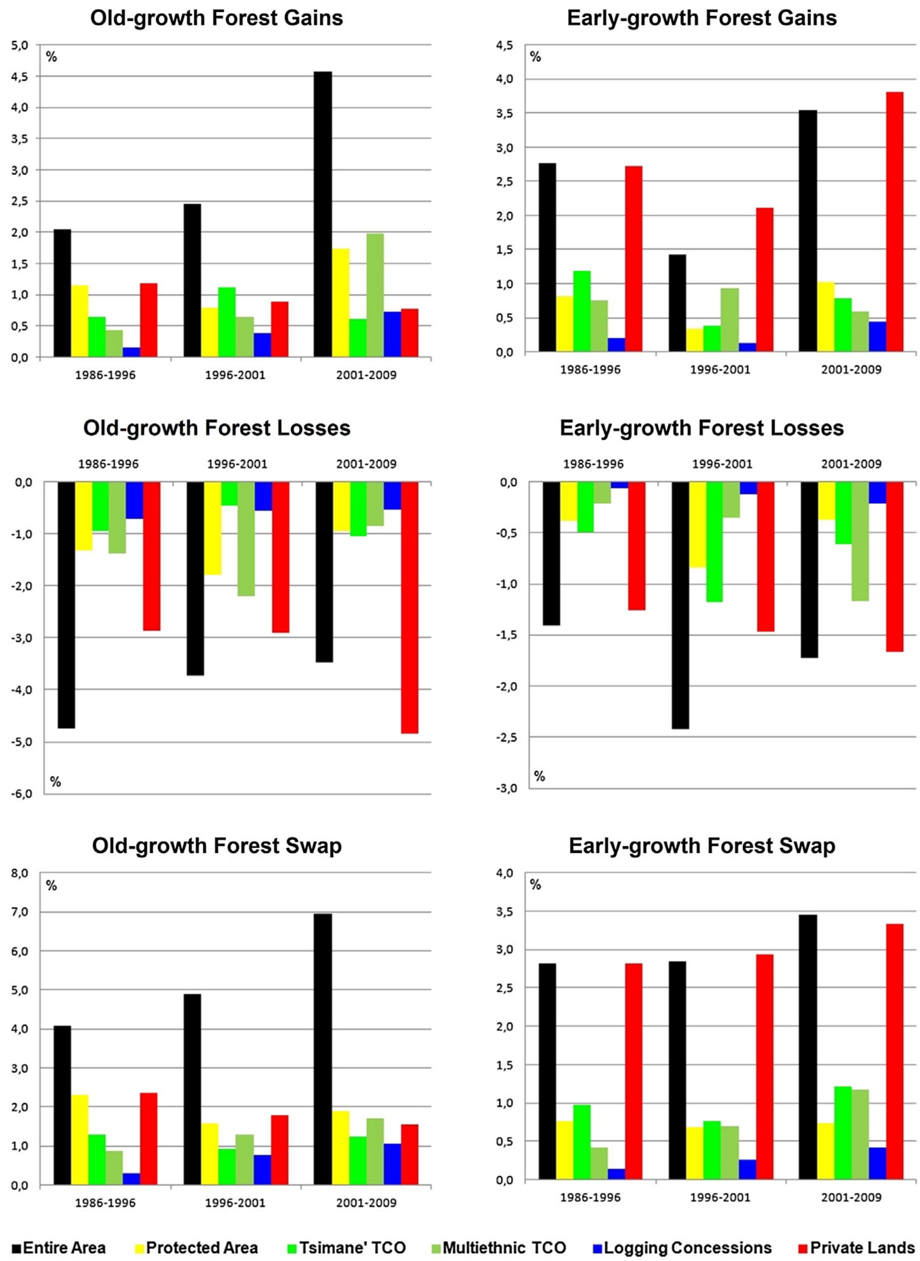
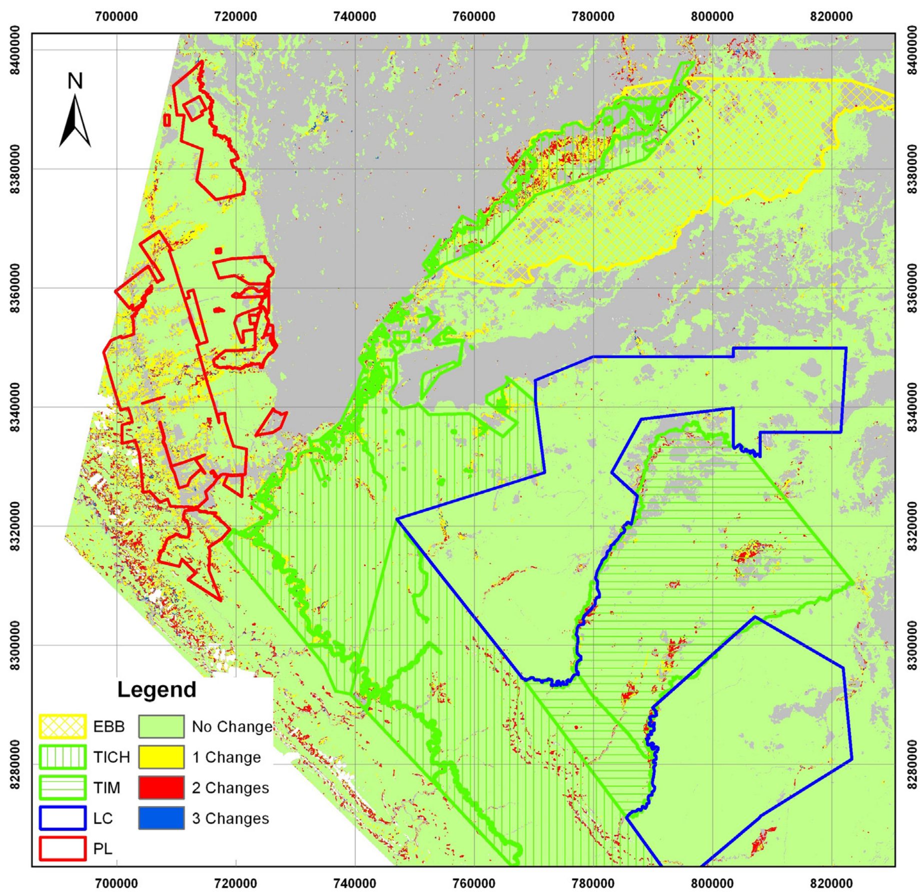


Fig. 5. Gains, losses and swap in old-growth and early growth forests (as a percentage relative to the total extent of each study area).

Nevertheless, there are many other factors associated with the trends of FCC observed on private lands, some of which have had significant influence (e.g., road accessibility). In this context, Bottazzi and Dao (2013) highlighted the importance of historical political processes defined by multiple stakeholders that have led to the establishment of private property rights in this area. We posit that, even if private land tenure has not been pivotal in FCC across private lands, colonists have caused much FCC to obtain permanent private property rights.

Trends in FCC in the protected area and in the two indigenous TCOs are not as clear as on private lands and logging concessions. Forests in the protected area were extremely persistent, and the clearance and fragmentation of old-growth forests occurred at very low rates during all three periods. Although we found an important increase in early growth forests, we believe that the increase was mostly due to (1) confusion with *bajío* forests (as explained in Section 3.5) and, to a much greater extent, to (2) flooding regimes that are typical of this protected area during the rainy season (when the imagery was taken) rather than to extractive or productive activities (e.g., timber extraction, cattle ranching), which are illegal in the biological reserve. Therefore, we believe that the apparent increase in early growth forests within the protected area is mostly due to recent flood dynamics.

Forests in the Tsimane' TCO were very persistent, but not as much as those in the protected area; we also found that old-growth forests underwent very little deforestation and fragmentation during the three study periods. Net gains in early growth forest cover were only significant during the first period, most likely because of the encroachment of logging companies, illegal loggers and other actors on Tsimane' lands before the Tsimane' TCO was established (Godoy et al., 1998; Reyes-García et al., submitted for publication). Most FCC occurred in areas adjacent to savanna areas (which we believe was mostly the result of flood dynamics) and in areas close to the market town of San Borja, where most



	Persistence	1 Change	2 Changes	3 Changes	Total
Entire Area	92.08 (1,184,503)	4.93 (63,359)	2.59 (33,351)	0.41 (5,239)	100 (1,286,452)
Protected Area	97.21 (84,317)	1.65 (1,435)	1.02 (884)	0.12 (101)	100 (86,737)
Tsimane' TCO	90.92 (234,575)	5.53 (14,257)	3.14 (8,094)	0.41 (1,066)	100 (257,992)
Multiethnic TCO	95.06 (125,138)	2.10 (2,765)	2.72 (3,579)	0.12 (161)	100 (131,643)
Logging Concessions	98.69 (231,570)	0.74 (1,746)	0.52 (1,220)	0.05 (113)	100 (234,649)
Private Lands	73.61 (50,671)	21.58 (14,856)	3.68 (2,530)	1.14 (783)	100 (68,840)

Fig. 6. Map showing unchanged (i.e., persistent) forest areas vs. forested areas that underwent 1, 2, and 3 changes. Figures in the table refer to the percentage and extent (in hectares) of persistent vs. dynamic forest areas relative to the total coverage of forest (i.e., both early growth and old-growth forests) within each study area. Gray areas correspond to persistent non-forest covers.

Tsimane' market-oriented activities and conflicts between cattle ranchers and colonists (who encroach upon Tsimane' lands and clear forest to later claim property rights through the *saneamiento* process) take place. This *saneamiento* process, which has yet to conclude and is a cornerstone of the 1996 agrarian reform to allegedly solve conflicts over land, has given private property to land claimants who could "demonstrate" settlement in the area prior to the creation of the Tsimane' TCO (Reyes-García et al., submitted for publication). In this TCO, most FCC caused by the Tsimane' themselves occurred along the Maniqui River as a result of their settlement pattern.

In the Multiethnic TCO, we found that despite the high persistence of forests, during the first and second periods old-growth forests underwent moderate fragmentation and deforestation coupled with a significant increase in the area of early growth forest, which occurred at even higher rates than on private lands and logging concessions. However, we found an opposite trend during the third period when significant net forest regrowth occurred. Most FCC was observed around small, rather isolated savanna patches. Based on our work in this TCO, we believe that such trends can be mostly explained by the long-term presence of cattle ranchers rather than by flood dynamics. In fact, given the natural occurrence of patches of savanna and semi-natural grasslands suitable for grazing, cattle ranching has been a major land-use activity as recommended by the land-use plan of Beni. We believe that many cattle ranchers must have claimed legal rights to the land they occupied through the *saneamiento* process during the

Table 4
Trends in old-growth forest fragmentation. All figures refer to the percentage of old-growth forest cover.

Land tenure system	1986		1996		2001		2009	
	Core	Edge	Core	Edge	Core	Edge	Core	Edge
Entire area	70.31	4.15	70.30	5.23	64.63	3.90	66.06	4.78
Protected area	73.39	2.99	79.08	2.71	62.38	3.48	78.34	2.94
Tsimane' TCO	77.92	2.91	77.55	4.72	77.20	2.70	75.71	2.90
Multiethnic TCO	84.30	1.83	82.24	3.03	75.07	3.04	80.94	2.47
Logging concessions	90.41	1.83	84.87	2.48	81.78	2.44	86.39	2.66
Private lands	67.25	8.18	70.41	11.86	53.72	9.90	44.12	14.64

Table 5
Qualitative assessment of the effects that the main potential underlying and proximate drivers have had on increasing forest cover change in our five study areas over the whole study period (1986–2009). Notation: 1=Low, 2=Medium, 3=High. Intermediate values (i.e., 1–2, 2–3) are also allowed.

	Protected area	Tsimane' TCO	Multiethnic TCO	Logging concessions	Private lands
Underlying drivers					
Demographic					
Population density	1	1	1	1	3
Immigration	1	1	1	1	3
Economic					
National markets for cash crops, meat/dairy, timber	1	1	1–2	2	3
Technological					
Agricultural and forestry mechanization	1	1	1	1–2	1–2
Policy & Institutional					
Land tenure and property rights[a]	3	2–3	2–3	3	1
Land use policies[a]	3	2	2	2	1
Land socioeconomic function to secure tenure[b]	1	1–2	1–2	1–2	3
Institutional power of main social group	1	1	1	2	3
Cultural					
Unconcerned about forest	1	1	1	2	3
Acculturation and loss of traditional ecological knowledge	1	2	2	1	1
Proximate drivers					
Infrastructure extension					
Road accessibility	1	1	1	2	3
Agricultural expansion					
Commercial agriculture	1	1	1	1	3
Subsistence agriculture[c]	1	2–3	2–3	1–2	1
Cattle ranching[b]	1	1–2	2–3	1	3
Colonization[c]	1	1	1	1–2	3
Wood extraction					
Legal logging	1	1	1	2	3
Illegal logging[b]	1–2	2	2	1	1
Other factors					
Land susceptibility for agriculture and livestock	1–2	1–2	2	1–2	1–2
Flood susceptibility	2–3	2–3	2–3	2–3	2–3
River accessibility	1	2	1–2	1	1
Remoteness[a]	3	2–3	2–3	2	1–2
Illegal land encroachment to claim land in property[c]	1	2–3	2–3	1–2	1

[a] These drivers refer to the opposite, i.e., their potential effects on decreasing FCC.
[b] Regarding TCOs, values for these drivers greatly refer to abutters encroaching upon indigenous lands.
[c] For logging concessions, values for these drivers greatly refer to abutters encroaching upon over the period 2001–2009.

second study period; as a result, because they would have needed to show evidence of the socioeconomic function of the land, high rates of old-growth forest loss and early growth forest gains could have occurred. The contrasting FCC trends observed during the third period could be the result of the fact that most cattle ranchers had already settled with land property rights and perhaps because encroachment onto new land was limited by increasing indigenous governance; this could have also reduced the leakage effect that likely occurred in the Multiethnic TCO during the first two periods, as this area is virtually surrounded by logging concessions.

We posit that FCC trends found in the two TCOs reveal the fragility of this land tenure system. The asymmetric power divide between indigenous organizations and those representing other social groups such as colonists and mestizo cattle ranchers has resulted in land development policies that favor intensive land uses and concede less accessible (and often less productive) land and the lowest priority regarding land rights to indigenous peoples (Assies, 2006; Bottazzi & Dao, 2013). As a result, indigenous TCOs have lost much of their ancestral lands over the past decades as outsiders have moved in and claimed land on private property (Reyes-García et al., submitted for publication). Riester (1993) raised concerns about this issue and, more recently, researchers have documented the encroachment of abutters onto indigenous lands to steal timber or to clear forest and farm and/or raise cattle with the goal of claiming land property rights, thus leading to conflicts with indigenous peoples (Godoy et al., 1998; Reyes-García, Ledezma, et al., 2012; Reyes-García, Orta-Martínez, et al., 2012). Land encroachment has been facilitated by a relatively late political awakening of indigenous peoples (Reyes-García, Vadez, Aragon, Huanca, & Jagger, 2010) and the fragmentation of their institutions (Reyes-García et al., submitted for publication). In the case of the Multiethnic TCO, we argue that governance may have been more difficult due to the co-existence of four indigenous groups and the adjacency of logging concessions.

Results for logging concessions reveal that this land tenure system can be very effective in protecting old-growth forests from clear-cutting; this finding coincides with findings of Oliveira et al. (2007) in the Peruvian Amazon but contradicts observations of Asner et al. (2006) in logged forests in the Brazilian Amazon. In addition, we found that old-growth forest fragmentation in logging concessions has been very low and that forests are extremely persistent across these areas. These facts could be explained by the fact that the companies have only extracted abundant precious woods such as mahogany and cedar, which represent a low proportion of the total forest cover (Gullison et al., 1996), and because companies have stopped outsiders from using "their" forests.

We observed that early growth forest notably increased during the first and third study period, most likely due to the two forestry reforms undertaken by the Bolivian government. The first reform was issued in 1974 and, in 1986, seven logging concessions were granted in the area until 2011, thus explaining the rapid increase in selective logging from 1986. However, a second forestry law issued in 1996 was not as beneficial to logging companies as the previous one because royalties were then based on area rather than on volume harvested (Pacheco, 2002); as a result, the companies were able to avoid paying royalties by declaring lower harvests. The resultant conflicts between companies and forestry authorities may have triggered a relative decrease in logging activities, most likely exacerbated by a severe decline in the stocks of precious woods after at least two decades of intense timber extraction (Gullison et al., 1996). The rapid increase in the amount and change rates of early growth forest observed during the third period can be explained by the end of the logging grants in 2011, which may have previously boosted timber harvesting to unsustainable levels. Furthermore, logging concessions were expected to become part of TCOs or to be given to colonists (Reyes-García et al., submitted for publication), which may have prompted colonists to move in during the last few years to claim land property rights once logging concessions expired; indeed, a high number of conflicts between colonists and abutters was recently reported by Tsimane' villagers living within logging concessions (Reyes-García, Ledezma, et al., 2012).

Land tenure, forest conservation, and livelihoods

Overall, our results are in agreement with those of other studies that assessed how FCC across the Amazon basin is affected by land tenure systems and land use allocation (e.g., Killeen et al., 2008; Lu, et al., 2010; Nepstad et al., 2006; Oliveira et al., 2007; Soares-Filho et al., 2010). From a biocultural conservation perspective, our results suggest that future conservation policies in Bolivia should emphasize the potential key role of native Amazonians in effectively protecting old-growth forests and expand the existing network of indigenous TCOs accordingly. Previous studies corroborate the importance of taking into account indigenous peoples in conservation policy (Alcorn, 1993; Colchester, 2004; Gadgil, Berkes, & Folke, 1993) and of establishing alliances or partnerships to promote conservation (Schwartzman & Zimmerman, 2005; Vermeulen & Sheil, 2007).

Nevertheless, indigenous governance systems need to be strengthened to avoid the negative consequences of the FCC caused by the encroachment of abutters onto TCO lands; these problems are due to the fragility of the indigenous land tenure system (Assies, 2006) and to the increasing fragmentation of indigenous institutions (Reyes-García et al., submitted for publication). In fact, the legitimacy of indigenous institutions and their systems of authority and power could be more important for forest conservation and the improvement of indigenous livelihoods than the indigenous land tenure itself (Ostrom & Nagendra, 2006; Robbins, 1998). Though we have not conducted in-depth research on the forest governance institutions of the indigenous populations living in the Tsimane' and the Multiethnic TCOs, previous studies have shown that the Tsimane' are increasingly acculturated and integrated into the market economy (Godoy, Reyes-Garcia, Byron, Leonard, & Vadez, 2005); as a result, the Tsimane' are rapidly losing their traditional ecological knowledge (Reyes-García et al., 2013) and facing a weakening of their traditional institutions (Huanca, 2006), which is likely to compromise forest conservation.

Since the area previously granted to logging concessions could now be potentially annexed to TCOs, community-based forest management could be encouraged by the authorities. Community forestry has proven very effective for protecting forest cover while enhancing indigenous livelihoods (Berkes, 2007) and is often more effective for conservation than the establishment of protected areas (Porter-Bolland et al., 2012). However, even though community forestry has been promoted in Bolivia since the 1996 forestry reform and particularly since Morales came to office in 2006 (Pacheco, de Jong, & Johnson, 2010), it has nonetheless proved difficult to achieve because rural elites have hampered its implementation to retain their privileges (de Jong, Ruiz, & Becker, 2006) and because it has often been difficult to carry out among indigenous populations (e.g., León, Uberhuaga, Benavides, & Andersson, 2012; Pacheco, 2012).

In addition, our findings suggest that both protected areas and logging concessions with sustainable timber extraction levels can be very effective at protecting forest cover from clear-cutting. Therefore, these land tenure systems could be promoted on state lands with small rural populations (whether indigenous or not) as long as their customary rights are respected. Furthermore, we suggest that sustainable logging concessions should be promoted in areas where rural and indigenous communities are well suited to manage forests and should be regarded as a key component of the current network of protected areas and indigenous TCOs to curtail the high levels of FCC observed in private areas. Expanding such a network could (1) foster biocultural conservation, (2) improve the land rights and livelihoods of rural and indigenous populations, and (3) generate new economic opportunities for rural and indigenous populations in the forestry sector.

Finally, given the commodity frontier expansion and the high levels of FCC associated with private lands documented in this study, we argue that some conservation incentives (e.g., subsidies for sustainable agroforestry systems) are needed on private lands to effectively address climate change mitigation strategies (Soares-Filho et al., 2006) and to maintain at least some biodiversity refuges and corridors to diminish the pervasive effects of fragmentation in Amazonian old-growth forests (Laurance, Lovejoy, et al., 2002). Moreover, as recent research has shown that levels of human development follow a boost-and-bust pattern as deforestation takes place in Amazonian frontier settings (Rodrigues et al., 2009), financial incentives and policies that promote more sustainable development scenarios should be promoted. Further research is needed to assess the effects of the drivers of land use/cover change operating within the study areas, especially of those associated with household land-use decision-making along the agricultural frontier, so that effective conservation measures can be implemented while ensuring the well-being of local populations.

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