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Research paper

Changing indigenous cultures, economies and landscapes: The case of the Tsimane', Bolivian Amazon

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HIGHLIGHTS

- We assess the link between cultural and economic changes and landscapes.
- Villages along the main road have suffered more cultural changes.
- Economic activities show different spatial distributions and landscape impacts.
- Further contextualization of the education system could reduce landscape degradation.
- We contribute to multidisciplinary research linking people and pixels.

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ABSTRACT

Habitat fragmentation and habitat loss are two of the primary causes of biodiversity loss worldwide. There is abundant literature addressing the factors driving habitat loss and fragmentation in the Amazon basin, yet little is known of how cultural and economic changes may be related to landscape change. In this paper, we present a case study of the Tsimane', an indigenous society native to the Bolivian Amazon, to evaluate the relationship between Tsimane' cultural and economic change and the levels of fragmentation and habitat loss in the landscape surrounding their villages. Socioeconomic and cultural data were collected through household surveys ($n = 778$), and landscape metrics for each village ($n = 59$) were derived from a classified Landsat satellite image. We performed spatial analyses and multivariate regressions to study the associations between social and landscape data. Our results suggest that although habitat fragmentation and habitat loss are relatively low in the studied villages, economic change and, to a lesser extent, cultural change mediate transformations in the landscape. To foster both biocultural conservation and the well-being of indigenous people, economic alternatives to intensive land uses should be promoted, considering the needs and institutional arrangements of the Tsimane'. This article provides a novel approach to further our, understanding of the way cultural and economic changes within an indigenous group can lead to various landscape patterns.

1. Introduction

Indigenous peoples living in small-scale societies have developed a complex body of ecological knowledge for interacting with their surrounding environment (Gadgil, Berkes, & Folke, 1993; Gray, Bilsborrow, Bremner, & Lu, 2008; Wiersum, 1997). They often control highly biodiverse regions and may manage landscapes to maintain a large amount of forest cover, sometimes even enhancing biodiversity levels (Gari, 2001; Posey & Balick, 2006; Schwartzman & Zimmerman, 2005). Nevertheless, as indigenous peoples embrace new cultural values and attitudes influenced by Western societies,

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they also change their worldview, social organization, behaviors, traditional ecological knowledge and attitudes toward nature, all of which may affect the composition and configuration of their surrounding landscape (Rudel, Bates, & Machinguiashi, 2002). Similarly, as indigenous peoples become progressively integrated into the market economy, they often change their traditional livelihoods to more intensive, market-oriented land uses (Huanca, 2008; Peterson, Russell, West, & Brosius, 2010; Rudel et al., 2002), which may result in habitat fragmentation and loss.

Studies of habitat fragmentation and loss have sometimes focused on the historical, political, and economic factors driving such processes (e.g., Geist & Lambin, 2002; Marsik, Stevens, & Southworth, 2011; Merry, Hildebrand, Pattie, & Carter, 2002). However, little attention has been paid to the effects that the current processes of cultural and economic change may have on landscapes (Maurer, Weyand, Fischer, & Stöcklin, 2006; Musacchio, 2011). In general, studies analyzing such effects have focused on the social values attached to the landscapes (Alessa, Kliskey, & Brown, 2008; Bryan, Raymond, Crossman, & Macdonald, 2010) or on how various cultural groups alter the landscape in dissimilar ways (Lu et al., 2010; Rudel et al., 2002). Nevertheless, to our knowledge, no study has assessed the links between cultural and economic change within one cultural group and their landscape patterns. Such an analysis has become of utmost importance because of the rapid increase in the speed and intensity of cultural and economic change among indigenous peoples and given its potential implications for the loss of cultural heritage, including traditional ecological knowledge (Reyes-García et al., 2013), which may in turn affect biodiversity conservation (Maffi, 2005). In this article, we set out to contribute to this significant gap in landscape ecology and advance our understanding of how various levels of cultural and economic change within a society may result in various landscape patterns. Specifically, we explore the associations between various proxies for village-level cultural and economic change and measures of fragmentation and habitat loss among the Tsimane', an indigenous group of Amazonian hunter-gatherers and farmers (Reyes-García, Ledezma, et al., 2012). The Tsimane' represent an ideal case study because they have become progressively acculturated and integrated into the market economy (Godoy, Reyes-García, Byron, Leonard, & Vadez, 2005; Reyes-García, Pascual, Vadez, & Huanca, 2011; Ringhofer, 2010), thus displaying a great variation in the amount of cultural and economic change at the village level (Godoy et al., 2009), which we may expect to have affected their surrounding landscapes.

1.1. Cultural and economic change

By cultural change (also known as acculturation), we mean the changes that occur in the material and symbolic features of a society when its individuals come into continuous contact with individuals from a different society (Berry, 2009; Thomson & Hoffman-Goetz, 2009). Among indigenous peoples, cultural change is often linked to economic change, as both processes are usually driven by the very same forces, although they encompass distinct phenomena (Lu, 2007). Cultural change refers to the broader transformations in the cultural practices, knowledge and values, often including the acquisition of attitudes, social preferences and language skills alien to one's original culture (Schwartz, Unger, Zamboanga, & Szapocznik, 2010). In contrast, economic change refers exclusively to the process of integration into the market economy, i.e., the economic articulation of a subsistence economic system with an economic system based on the exchange of capital, goods and services (Godoy, Reyes-García, & Byron, et al., 2005).

1.2. Habitat fragmentation and loss

Habitat fragmentation and habitat loss are two of the major threats to biodiversity conservation (Broadbent et al., 2008; Geist & Lambin, 2002; Laurance et al., 2011). Fragmentation is primarily an anthropogenic process by which a contiguous habitat is progressively subdivided into smaller patches with higher ratios of edge to area and whose centers are closer to their edges (Broadbent et al., 2008; McGarigal, Cushman, & Ene, 2012). While habitat loss reduces species richness through the removal of natural habitats (Fahrig, 2003), the impacts of fragmentation on biodiversity are directly related to edge effects, a set of mechanisms that create physical and ecological changes that in turn could increase socioeconomic pressures along the transition between two different habitats (Dale, Pearson, Offerman, & O'Neill, 1994; Laurance et al., 2011). Many studies, however, conflate habitat loss and fragmentation effects, as they include the reduction of habitat in fragmentation processes, thus leading to ambiguous conclusions regarding the impacts of fragmentation on biodiversity loss (Fahrig, 2003). Likewise, studies of habitat fragmentation tend to focus just on forests and analyze fragmentation at the patch or class level (Bennett, Radford, & Haslem, 2006; Opdam, 1991). In this work, we differentiate between processes of habitat fragmentation and habitat loss and consider the entire landscape to study the overall effects of fragmentation, thus taking in additional habitats, such as savannas and grasslands. For our case study, we hypothesize that the Tsimane' embrace new values and attitudes as they acculturate and that they will change their livelihood strategies as they become progressively integrated into the market society, all of which will presumably alter the landscape patterns surrounding their villages. We thus expect that the level of cultural and economic change in a village will have a positive association with the degree of fragmentation and habitat loss in its surrounding landscape.

2. The study area and the Tsimane'

2.1. Biophysical setting

Our study area is located southwest of the department of Beni, Bolivia (691123-839863, 8410627-8260686, UTM 19S), and covers an area of approximately 800,000 ha that historically has been occupied by the Tsimane' (Reyes-García, Orta-Martínez, et al., 2012) (Fig. 1). The vegetation consists of lowland tropical forests and wet savannas (Navarro & Maldonado, 2002). The lowland forests cover most of the territory and contain certain deciduous species, owing to a marked seasonality (Guèze et al., 2013). The wet savannas consist of swampy areas subject to periodic flooding due to the flat topography and poorly drained soils, mixed with permanent *terra firme* patches of forest on mounds (Lombardo & Prümers, 2010; Navarro & Maldonado, 2002). The mean annual temperature is 25.8 °C, although it decreases considerably during the dry season with the arrival of cold southern winds (Navarro & Maldonado, 2002). The mean annual rainfall is 1743 mm, but it varies greatly according to topography and seasonality; during the four-month dry season, the rainfall measures less than 100 mm per month (Guèze et al., 2013).

2.2. The Tsimane'

The Tsimane' represent one of the largest indigenous groups in the lowlands of Bolivia, with an estimated population of 8000 people (Censo Indígena, 2001), although recent unofficial estimates elevate the Tsimane' population to approximately 10,000. The Tsimane' are distributed among approximately 125 villages located along riverbanks and logging roads. They have traditionally been

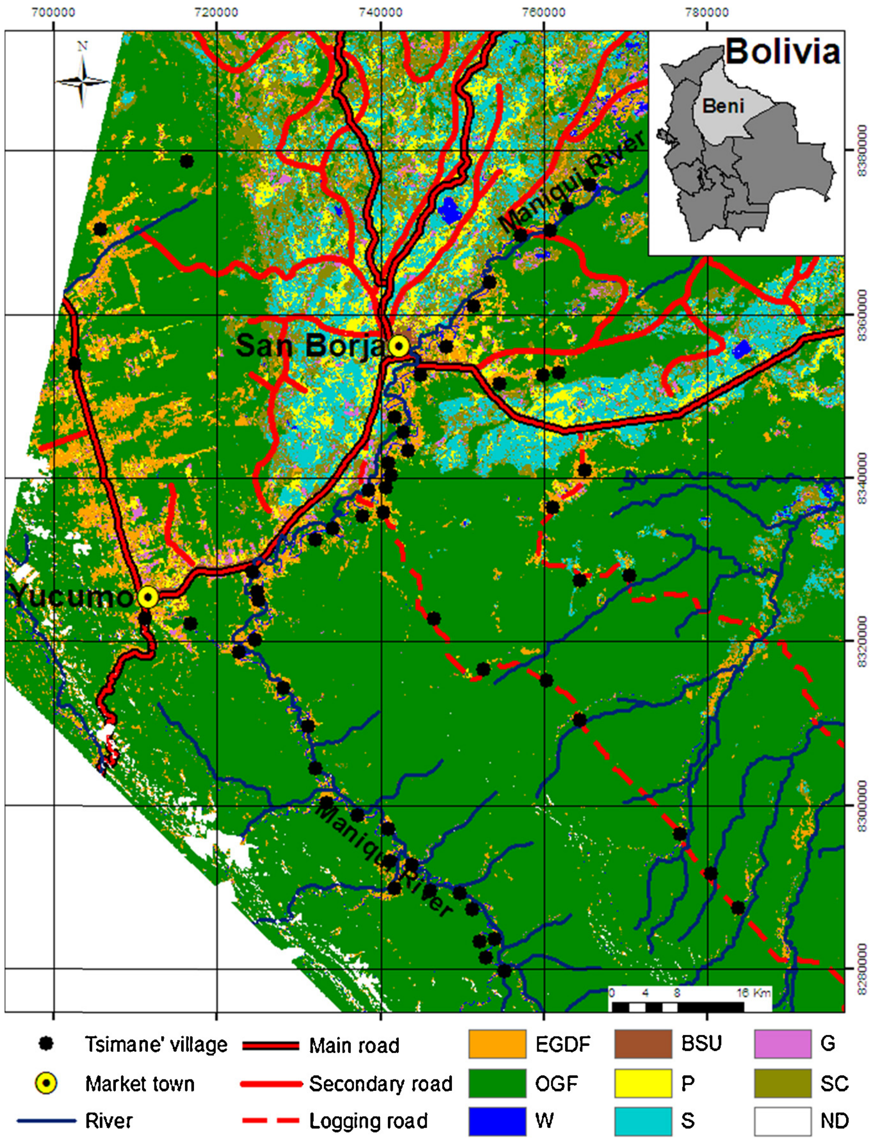

Fig. 1. Classified image used in the present study showing the locations of all of the villages sampled. The image is projected in UTM 19S (WGS84). EGDF = early growth/degraded forest, OGF = old-growth forest, W = water, BSU = bare soil/urban, P = pasture, S = savanna, G = grassland, SC = scrubland, ND = no data.

a semi-nomadic society relying on hunting, fishing, gathering, and slash-and-burn agriculture for subsistence (Vadez, Reyes-García, Huanca, & Leonard, 2008). Until the 19th century, the Tsimane' seem to have avoided contact with outsiders by moving to the less accessible parts of the Maniqui and Apere Rivers, where they remained relatively isolated until the 1950s–1960s, when roads started to be constructed in their territory and part of the land the Tsimane' traditionally occupied was freely distributed to highland colonist farmers (Reyes-García, Ledezma, et al., 2012).

The progressive contact with new people arriving in the area gradually transformed the Tsimane' social and economic systems (Godoy et al., 2005b). Several cultural changes occurred due to the presence of missionaries in the region, who persuaded the Tsimane' to abandon their nomadic practices and polygamous marriages, settle in permanent villages and live as mononuclear families (Reyes-García et al., 2011). Missionaries also built schools in certain of the villages, integrating the Tsimane' into the national system of education (Ringhofer, 2010). The traditionally endogamous and highly egalitarian society (Reyes-García, Ledezma, et al., 2012) has likewise been progressively replaced by more hierarchical structures (Reyes-García et al., 2011). The national government established local representatives in an attempt to create mechanisms of social control among the indigenous villages, while the "New Tribes" missionaries fueled the foundation of the *Gran Consejo Tsimane*', a local political organization that has played an important role in negotiating land rights for the Tsimane' (Reyes-García, Ledezma, et al., 2012).

The arrival of outsiders has also disrupted the traditional subsistence economy of the Tsimane'. New economic activities, such as cash cropping, wage labor on cattle farms and in logging camps, and the commercialization of timber and non-timber forest products have created a wide range of alternative means of subsistence that the Tsimane' have selectively adopted, depending on geographical, historical and social factors (Huanca, 2008; Ringhofer, 2010). Currently, while certain Tsimane' villages remain highly autarkic, others have embraced cattle ranching (Huanca, 2008), cash cropping (Vadez et al., 2008), and small-scale logging (Bottazzi, Cattaneo, Rocha, & Rist, 2013), thus becoming increasingly dependent on selling and wage labor as sources of income. Such variations in cultural and economic behavior within the same indigenous group might cause widely varying impacts on the landscape.

Table 1
Description of the main land use/cover classes present in the study area.

Land use/cover class	Description
Early-growth/degraded forest	Secondary forests that have suffered some kind of perturbation as a consequence of human activities or natural disturbance.
Old-growth forest	Mature forest with complex structure and high diversity of trees, present in areas with little disturbance.
Water	Any kind of water body (i.e., river, lagoon).
Bare soil/urban	Soils lacking vegetation (e.g., river banks, unpaved roads) and urban areas.
Pasture	Areas typically used for cattle ranching, frequently on deforested land.
Savanna	Plains seasonally flooded, creating swamps or marshes.
Semi-natural grassland	Areas with very little or total absence of woody species covered by grasses, mostly across the savanna areas.
Scrubland	Areas dominated by bushes or short trees growing on low quality soils across the savanna areas.

Adapted from "Enhanced land use/cover classification of heterogeneous tropical landscapes using support vector machines and textural homogeneity", Paneque-Gálvez, Mas, Moré, et al., 2013, International Journal of Applied Earth Observation and Geoinformation, 23(0), 372-383.

Table 2
Description of landscape and class metrics used to measure the level of (a) habitat fragmentation and (b) habitat loss.

Metric	Formula	Description
(a) Habitat fragmentation. Landscape metrics (5-km buffer)		
Patch density	PD = $(N/A)(10\,000)(100)$ N = total number of patches in the landscape A = total landscape area (m^2)	Total number of patches per area unit
Edge density	ED = $(E/A)(10\,000)$ E = total length (m) of edge in landscape A = total landscape area (m^2)	Total length of all edges between patches per area unit
Core area index	CAI = $(a_{ij}^c/a_{ij})(100)$ a_{ij}^c = core area (m^2) of patch i from class j a_{ij} = area (m^2) of patch i from class j	Proportion of core area with respect to total landscape area
(b) Habitat loss. Class metrics (3-km buffer).		
Percentage of landscape	PLAND = $P_i(\sum_{j=1}^{n} a_{ij}/A(100))$ Pi = proportion of area occupied by class i a_{ij} = area (m^2) of patch i from class j A = total landscape area (m^2)	Percentage of landscape comprised of the corresponding class (pasture in our case)
Number of patches	NP = n_i n_i = number of patches in the landscape of class i	Number of patches of the corresponding class
Total edge	TE = $\sum_{k=1}^{m} e_{ik}$ e_{ik} = total edge (km) of class i in the whole landscape	Sum of the length of all edge segments of the corresponding class

Adapted from "FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps (Version 4)", McGarigal et al. (2012), University of Massachusetts, Amherst.

3. Materials and methods

3.1. Landscape data

To assess fragmentation and habitat loss, we used a land use/cover classification obtained from a Landsat-5 TM image mosaic (path 233, rows 70 and 71, acquisition date 17/04/2009) (Fig. 1). Such classification was carried out using a support vector machine classifier with reflectance and textural data, and very high accuracies were attained for all of the eight land use/cover classes considered in the study (Paneque-Gálvez, Mas, Moré, et al., 2013); Table 1 provides a brief description of such land use/cover classes.

We studied habitat fragmentation considering all of the land use/cover classes present within a 5-km buffer from the village center (i.e., the school). We selected a 5-km buffer because previous research among the Tsimane' indicates that most of the extractive activities occur within that radius (Cruz-Burga, Reyes-García, Alarcón Novoa, Paneque-Gálvez, & Luz, 2013). We assessed habitat loss using only the metrics developed for the pasture class (i.e., areas used for cattle ranching) because pasture is the only land use/cover class that can be directly and exclusively associated with a non-traditional indigenous activity in the area and because pasture expansion is one of the primary causes of habitat loss in the Amazon basin (Davidson et al., 2012; Geist & Lambin, 2002). Given that the Tsimane' usually farm around their village within a radius of approximately 2 km (Godoy et al., 2009), we chose a conservative distance of 3 km from the village center in our analyses as no pastures were expected farther away. Certain villages, particularly those along the Maniqui River, are so close to one another that parts of their buffers overlap. We allowed buffers to overlap, thus repeating certain information, because such villages actually use the same territories for their extractive activities (Cruz-Burga et al., 2013).

We used patch density, edge density, and the core area index as indicators of fragmentation (Table 2a) because these metrics provide key information regarding the landscape structure (McGarigal et al., 2012). To quantify the habitat loss, we used the percentage of the class (i.e., pasture) relative to the landscape, the number of patches, and the total edges of the pasture class (Table 2b) because these are complementary measures that indicate the extent to which cattle ranching is driving habitat loss around the studied villages.

3.2. Social data

Social data were collected in 2008 and 2009 during visits to 59 Tsimane' villages. We used a recent village census (Reyes-García, Ledezma, et al., 2012) to select villages located various distances from a main road and market-towns. In villages with 10 or fewer households, we surveyed all of the households; in villages with 11 to 40 households, we randomly selected 10 households from a list provided by the highest-ranking authority; and in villages larger than 40 households, we randomly selected 25% of the households for interviews (Reyes-García, Ledezma, et al., 2012).

We collected information on the level of Spanish fluency and schooling as proxies for cultural change, and we collected information on the frequency of visits to the closest market-town and number of days worked for wages as proxies for economic change. Fluency in the national language and level of schooling are standard indicators of cultural change that can be directly observed and quantified (Godoy, Reyes-García, & Byron, et al., 2005; Lu, 2007). Though cultural change is a complex process that cannot be solely reduced to acquiring fluency in the national language, the ability to communicate is a fundamental condition for the exchange of cultural values (Thomson & Hoffman-Goetz, 2009). Because, among indigenous peoples, schooling diverts time from learning the traditional culture and taking part in its activities, the level of schooling is also related to cultural change (Reyes-García et al., 2010; Sternberg et al., 2001). The Spanish fluency of individuals was assessed by the interviewer and was assigned to one of three categories: monolingual in Tsimane', limited knowledge of Spanish, and fluent in Spanish. We measured the level of schooling as the maximum school grade attained by the informant, potentially ranging from 0 to 13.

The frequency of visits to a market-town is directly related to economic change because the Tsimane' travel to the market-town mostly to sell crops or forest products and to acquire commercial goods. Similarly, wage labor is rather new to the Tsimane', as their traditional economic system is primarily based on bartering and labor exchange with family members. To estimate the frequency of visits to market-towns, individuals were asked to recall the number of times they had traveled to the primary market-towns in the area (San Borja and Yucumo) during the 12 months preceding the interview. The importance of wage labor was assessed by asking individuals the number of days they had been employed as laborers for loggers and thatch palm collectors in the three months preceding the interview.

3.3. Data processing and analysis

We first cropped the land use/cover classification based on the buffers constructed around each village and calculated the class and landscape metrics selected using FRAGSTATS 3.3 (McGarigal et al., 2012). Data measuring the cultural and economic change acquired at the household level were aggregated at the village level so that they matched the scale of the landscape analysis (Fig. 2). Specifically, we constructed a village-level variable for Spanish fluency by calculating the proportion of respondents that spoke Spanish fluently in each village and a village-level variable for schooling level by averaging the maximum school grade attained by respondents in a village. We assumed that the larger the proportion of Spanish speakers and the higher the level of education in a village, the more the village had experienced cultural change. We also constructed a village-level variable representing the frequency of visits to market-towns by averaging the information gathered from respondents of the same village and a village-level variable for wage labor by adding the total number of days worked for wages reported in each village. We assumed that the higher the number of visits to the market-town and days working in wage labor, the more the village had experienced economic change. In addition, we created a remoteness index by summing the normalized values of the real distance and the travel cost between the village and the closest market-town.

To visually assess the spatial patterns and possible associations between landscape variables and cultural and economic change, we created maps with pairs of social and landscape variables and displayed the land use/cover classification as a background. Subsequently, we tested the same associations using multivariate analysis. We used our fragmentation and habitat loss indices as outcome variables and our proxies for culture and economic change as explanatory variables. We performed multiple ordinary least square (OLS) regressions with every possible combination. Eq. (1) represents the regression model used:

$$Y_i = \alpha + \beta C_i + \gamma E_i + \delta R_i + \theta X_i + \mu Y_i + \varepsilon_i \quad (1)$$

where Y is the outcome variable, i.e., the level of fragmentation/habitat loss of the landscape surrounding village i; C and E are one of our proxies for cultural and economic change in village i; R is the remoteness index used as a control for the village-to-town distance; X and Y are the standardized geographical coordinates of village i, included in the regressions to control for spatial location; α is the independent term of the equation (intercept); β, γ, δ, θ and μ are the coefficients associated with each variable; and ε is a random error term. We also used the number of households in the village to control for the effects that population density may exert on fragmentation and habitat loss outcomes, but we did not include this variable in our models, as it was not statistically significant in any of the regressions.

Table 3
Descriptive statistics of variables used in multivariate regressions (n = 59).

Variables	Units	Mean	SD	Min	Max
Outcome					
(a) Habitat fragmentation					
Patch density	N/100 ha	13.23	7.74	1.18	31.59
Edge density	m/ha	50.71	29.96	4.80	114.38
Core area index	%	63.10	13.57	42.44	92.07
(b) Habitat loss					
Percentage of landscape	%	3.60	3.88	0.02	17.96
Number of patches	N	84.71	49.11	2	231
Total edge	km	38.19	30.48	0.54	150.36
Explanatory					
(c) Cultural					
Spanish fluency	%	22	24	0	91
Level of schooling	years	1.86	1.22	0	4.63
(d) Economic					
Visits to the market	N/year	18.71	16.11	2.14	99.11
Wage labor	days/3 months	48.63	46.55	0	181.50
Control					
Remoteness index	–	1.90	0.97	0.03	3.66

3.4. Potential limitations of the study

Our analyses may be affected by two primary caveats: spatial autocorrelation of the data and a small sample size. First, certain variables used in the OLS regressions may be spatially autocorrelated (i.e., they may not be truly independent, as their values may be spatially driven by underlying common factors (Griffith, 2009)), and therefore the true significance of our multivariate analyses might be lower than reported. To account for the spatial autocorrelation of variables, we included the standardized coordinates of the villages in the OLS regressions. Second, our sample size was determined by the number of villages (n = 59), not by the number of individuals for which we had social data (n = 778), which was necessary to match with the scale of the landscape data. Our relatively small sample size considerably diminished the statistical power of the regression results, yet this sample represents nearly half of the Tsimane' villages. Conscious of this limitation, we separated the explanatory variables we wanted to test in the various regressions.

4. Results

4.1. Descriptive statistics

On average, we found 13 patches/100 ha, an edge density of 51 m/ha, and a mean core area index of 63% (Table 3). Though there were significant differences among villages, as observed by the minimum and maximum values of these three variables, fragmentation appeared to be relatively low in most of the Tsimane' villages. In addition, we found that most of the villages dedicated very little land to pastures (3.6% on average), although pastures represented as much as 18% in certain villages. The villages had an average of 49 patches of pasture, but there were important differences among the villages. The mean total edge was 38.2 km, although the value of total edge length was lower than this in 35 villages. These figures contrast with the values obtained for the old-growth and early growth/degraded forest classes, which on average occupied a much higher proportion of the landscape (62% and 19%, respectively).

The percentage of respondents who could speak Spanish fluently was very low in most Tsimane' villages: in 17 villages, no

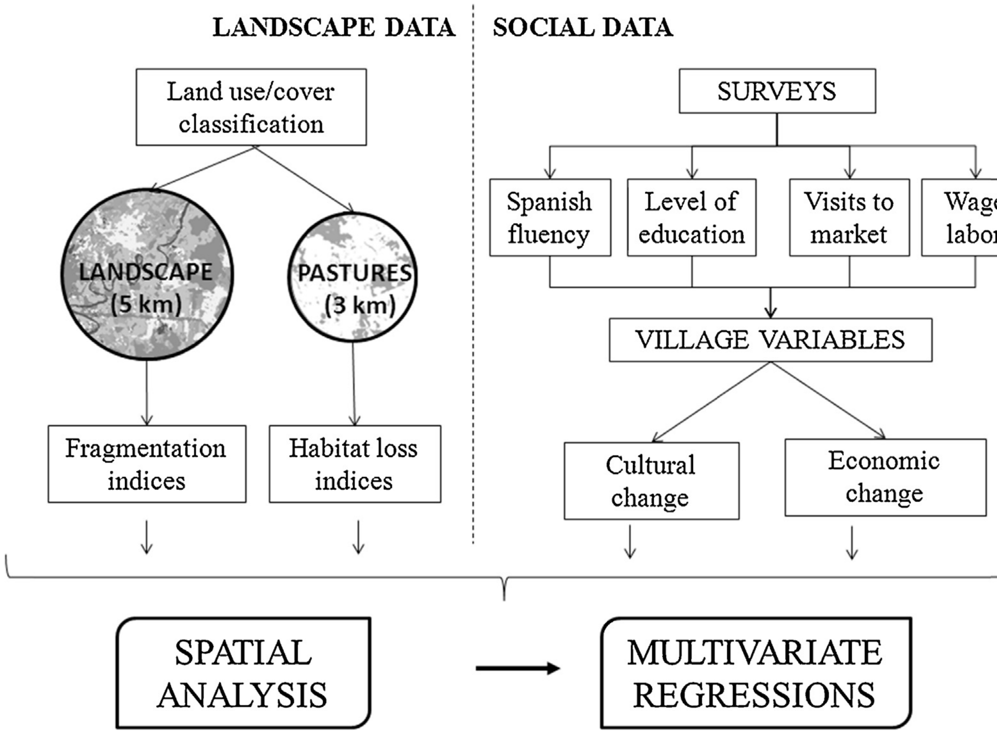

Fig. 2. Flow chart depicting the methodology used.

one could speak Spanish fluently, and in only one village could 90% or more of the respondents speak the language fluently. Similarly, the level of schooling was very low: almost half of the respondents declared that they had no formal education at all, and the village with the highest value had an average of 4.6 years of schooling of a possible maximum of 13. People living in a village close to the town of Yucumo traveled the equivalent of 8 times/month, but the average number of trips to a town among all of the villages sampled was 1.5 times/month (two visits per year being the minimum recorded). The average number of days engaged in wage labor was 47, although in 16 villages none of the respondents had engaged in wage labor during the three months before the interview.

4.2. Spatial patterns of associations

The fragmentation displayed distinctive patterns in relation to our proxies for cultural and economic change along the various communication axes where the Tsimane' villages are located. The patterns of fragmentation vs. Spanish fluency (Fig. 3a) varied inversely to the patterns of fragmentation vs. wage labor (Fig. 3b). In general, the levels of fragmentation and Spanish fluency were higher (and lower for wage labor values) in villages along the main road, particularly near the market-town of San Borja, than in villages along rivers and logging roads. Around the upper logging road, villages had higher levels of fragmentation and Spanish fluency (and lower wage labor values) than did villages around the lower logging road. Along the Maniqui River, these levels lay in between those of villages along the two logging roads.

The spatial patterns of habitat loss vs. level of schooling (Fig. 4a) and vs. frequency of visits to market-towns (Fig. 4b) were similar to the patterns described above. The villages along the main road displayed the highest levels of habitat loss, schooling and (particularly) visits to town, whereas villages far from the main road displayed low values of all of these variables. In villages along the upper logging road, however, the levels of habitat loss, schooling and visits to town were higher than the levels of fragmentation and Spanish fluency.

4.3. Association between cultural/economic change and fragmentation

The results from the multivariate analyses confirmed the association between fragmentation and economic change, i.e., our two proxies for economic change were statistically significant in all of the regressions (Table 4). However, whereas the landscape of villages where people travel more frequently to a market-town was significantly more fragmented than the landscape of villages where people travel less, wage labor was negatively associated with fragmentation. The association between fragmentation and economic change was stronger (higher R^2) and statistically more significant for visits to town (Table 4, odd columns) than for wage labor (Table 4, even-numbered columns). Among our proxies for cultural change, the level of schooling was also significantly associated with all of our fragmentation measures (Table 4, columns 3, 4, 7, 8, 11 and 12). The proportion of fluent Spanish speakers was significantly associated with the edge density and core area indices only in models that used wage labor as an indicator for economic change (Table 4, columns 6 and 10). Regarding our control variables, the remoteness index was statistically significant in all of the regressions, whereas either the standardized latitude or longitude coordinates were significant in many regressions, particularly the core area index regressions.

4.4. Association between cultural/economic change and habitat loss

The spatial variation of variables measuring cultural and economic change and habitat loss suggested the presence of a common trend underlying the three processes (Fig. 4). However, the results of our multivariate analysis indicated that only visits to town were consistently associated with habitat loss (Table 5, odd-numbered columns). Schooling was only associated with two of the three habitat loss measures (Table 5, columns 7, 8, 11 and 12), and neither wage labor (Table 5, even-numbered columns) nor Spanish fluency

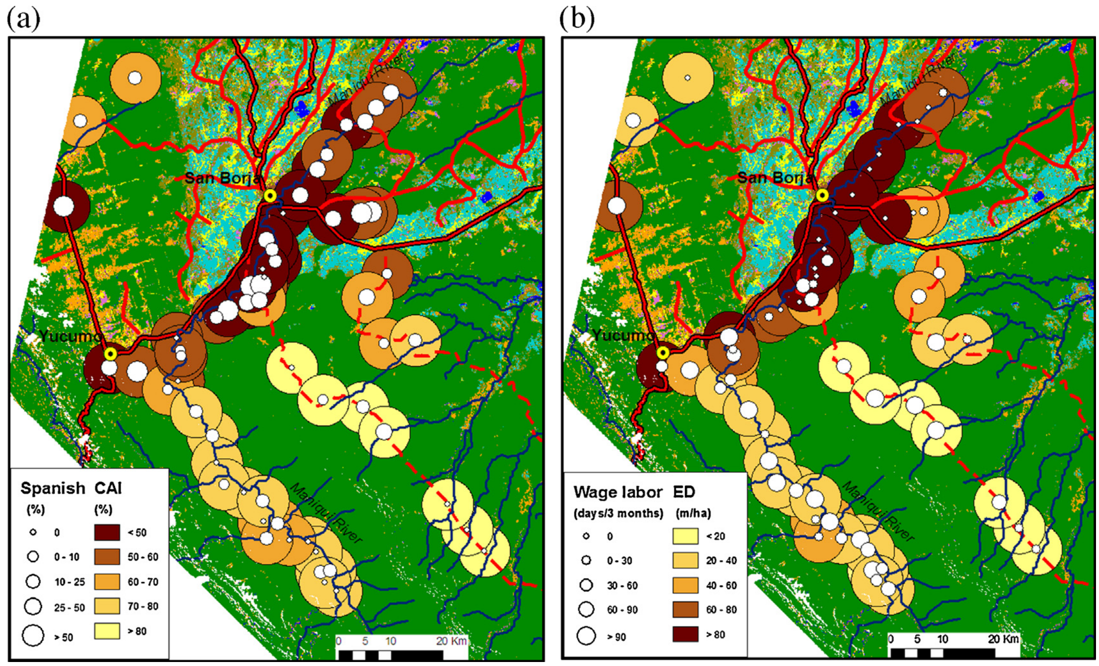

Fig. 3. Spatial representation of (a) cultural change and (b) economic change against habitat fragmentation measured as the core area index (CAI) and edge density (ED), respectively. The white color denotes areas that either fall beyond the limits of the image or are masked out pixels due to the presence of clouds.

was associated with any measure of habitat loss (Table 5, columns 1, 2, 5, 6, 9 and 10). The remoteness index bore a statistically significant association in most regressions, unlike the standardized latitude/longitude coordinates. In general, the associations between the explanatory and outcome variables were weaker with regard to habitat loss than with regard to fragmentation.

5. Discussion

Three primary findings stem from our study. First, fragmentation and habitat loss are still at relatively low levels around the Tsimane' villages that were studied. Second, the two variables that measure economic change display significant but distinct relationships with the level of fragmentation, and only the frequency of visits to a market-town is significantly associated with habitat loss. Third, of our two proxies for cultural change, only the level of schooling is significantly associated with habitat loss and fragmentation. Below, we provide an interpretation of these findings.

Our results indicate that the degrees of fragmentation and habitat loss are not severe in the studied region. A comparison with values obtained in other studies in the Amazon basin suggests that, on average, Tsimane' land use produces less fragmentation than that of other indigenous people and colonists in this and other Amazonian sites (Lu et al., 2010; Paneque-Gálvez, Mas, Guèze, et al.,

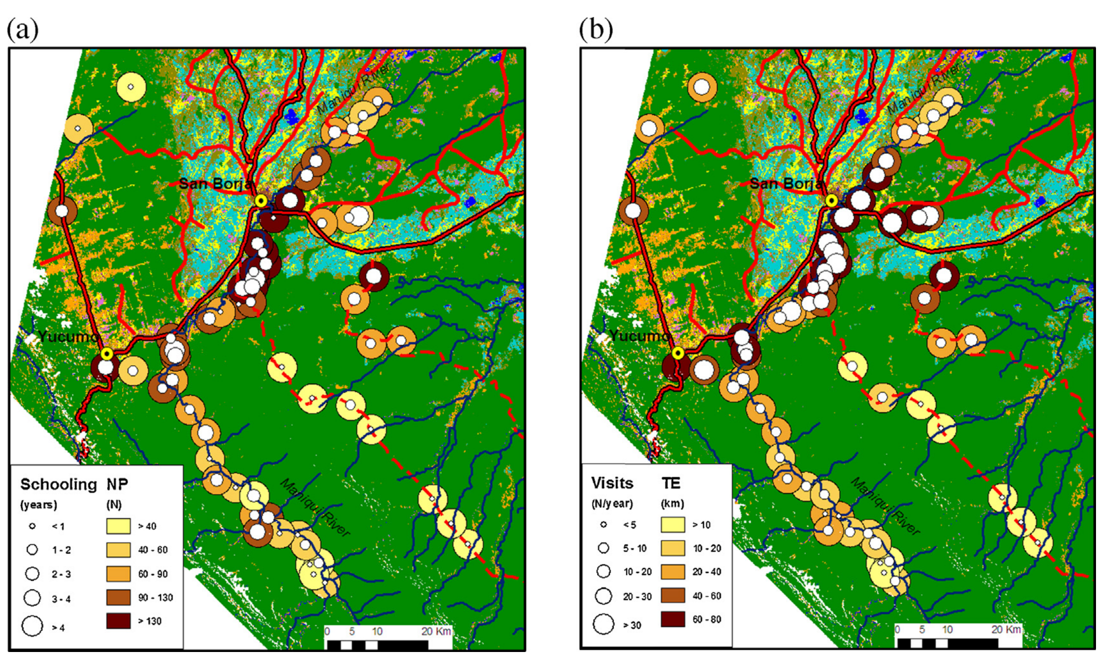

Fig. 4. Spatial representation of (a) cultural change and (b) economic change against habitat loss measured as the number of patches (NP) and total edge (TE), respectively. The white color denotes areas that either fall beyond the limits of the image or are masked out pixels due to the presence of clouds.

Table 4
OLS regression results showing the association between cultural/economic change and habitat fragmentation.

	Outcome: habitat fragmentation											
	Patch density				Edge density				Core area index			
Explanatory	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
Cultural change												
Spanish fluency	1.871	4.770			10.342	19.514*			−6.620	−11.049**		
Level of schooling			1.169**	1.238**			4.492**	4.636**			−2.077**	−2.132**
Economic change												
Visits to the market	0.163***		0.163***		0.482**		0.494***		−0.224**		−0.238***	
Wage labor		−0.036**		−0.031*		−0.141**		−0.122**		0.075**		0.064**
Control												
Remoteness index	−3.640***	−4.282***	−3.287***	−4.032***	−13.194***	−14.721***	−11.830***	−13.840***	3.243**	3.859**	2.609*	3.521**
Longitude	−3.129	−8.383***	−2.134	−7.234**	−7.743	−24.984**	−3.821	−20.735*	11.547**	20.022***	9.677*	18.139***
Latitude	2.776	1.179	2.618	2.299	24.210**	17.030	24.534**	21.848**	−14.699***	−10.717*	−15.393***	−13.720**
Constant	16.991***	25.867***	14.124***	22.776***	57.079***	86.178***	46.009***	74.756***	63.531***	49.234***	68.681***	54.290***
R-squared	0.691	0.661	0.715	0.674	0.700	0.697	0.721	0.706	0.657	0.663	0.675	0.662

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

2013). In a region of the Ecuadorian Amazon, Pan et al. (2004) estimated densities of 27 patches/100 ha and edge densities of 78 m/ha (compared to 13 patches/100 ha and 51 m/ha found in this study). The average proportion of pasture around Tsimane' villages (3.6%) is also low in comparison with findings in other studies. In various regions of the state of Rondônia, Brazil, researchers found that pastures accounted for 15% (Batistella, Brondizio, & Moran, 2000) to as much as 66% (Ferraz, Vettorazzi, Theobald, & Ballester, 2005) of the land. Thus, our findings suggest that the impact of cattle ranching is still limited where the Tsimane' have settled. This finding matches with previous studies of the Tsimane' indicating that the transformation of their economic system has led to the cultivation of cash crops (Vadez et al., 2008) and a higher reliance on wage labor activities (Godoy et al., 2007) rather than expansion of pasture, as the Tsimane' seldom have access to credit for investments in cattle (Paneque-Gálvez, Mas, Guèze, et al., 2013).

Although the Tsimane' have not yet severely transformed their surrounding landscapes, our spatial analysis indicates that certain villages, particularly those closer to the market-towns, display high levels of fragmentation and habitat loss, revealing important internal differences between Tsimane' villages. The heterogeneous landscapes generated by Tsimane' slash-and-burn agriculture, composed of plots at varying stages of maturation interspersed with large patches of natural forest (Huanca, 2008), contrast with intensive new land uses observed along the Yucumo–San Borja Road, which result in bigger and continuous areas of pasture and often smaller and more fragmented patches of forest. Through ethnographic work, we know that these villages, with tighter links to other indigenous and non-indigenous groups, have experienced

Table 5
OLS regression results showing the association between cultural/economic change and habitat loss.

	Outcome: habitat loss											
	Percentage of landscape				Number of patches				Total edge			
Explanatory	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
Cultural change												
Spanish fluency	0.400	2.276			−17.890	−0.849			−9.329	4.546		
Level of schooling			0.502	0.615			13.334***	13.823***			7.073**	7.811**
Economic change												
Visits to the market	0.132***		0.130***		1.047**		0.876**		0.963***		0.873***	
Wage labor		−0.003		−0.001		−0.146		−0.119		−0.033		−0.016
Control												
Remoteness index	−0.706	−1.508**	−0.555	−1.380**	−18.223**	−23.280***	−14.263**	−18.732***	−5.629	−11.365**	−3.528	−8.959**
Latitude	1.352	−1.572	1.766	−0.998	−25.931	−55.23**	−15.778	−40.560	3.801	−18.062	9.191	−9.943
Longitude	1.483	2.083	1.296	2.603	5.864	1.916	−7.539	−6.114	16.771	20.406	9.709	17.775
Constant	0.984	5.948**	−0.239	4.402*	114.364***	163.945***	82.349***	124.293***	23.053	60.154***	6.068	38.225*
R-squared	0.520	0.360	0.539	0.374	0.425	0.374	0.505	0.467	0.469	0.333	0.528	0.409

* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

deeper cultural and economic changes, which takes us to our next two findings.

The variables that measure economic change are inversely associated with fragmentation and habitat loss and display various spatial patterns. Whereas all of the landscape indices display a significant positive association with the frequency of visits to a market-town, their association with wage labor is negative, and only fragmentation is significantly associated with wage labor. We posit that the frequency of visits to a market-town might better capture the land use intensification associated with exchange activities, as most Tsimane' travel to market-towns either to sell agricultural or forest products (e.g., crops, thatch palm, timber) or to acquire commercial goods. The sale of agricultural products exerts a direct impact on the surrounding landscape because cash cropping requires more forest clearance than other traditional Tsimane' subsistence activities (Vadez et al., 2008). Furthermore, in market-towns, the Tsimane' have access to modern technologies, such as chainsaws, used both in clearing plots and extracting timber, which increase their capacity to alter the landscape. We have observed that this pattern is more pronounced in villages closer to market-towns, as many of their inhabitants engage in market-oriented activities. Moreover, we have noted that the Tsimane' living in close contact with cattle ranchers increasingly want to engage in cattle ranching, as it is perceived to be a very lucrative activity. Both Lu and Bilsborrow (2011) and Garland and Painter (1991), studying indigenous communities in the Ecuadorian and the Peruvian parts of the Amazon basin, respectively, found a shift in traditional agriculture toward commercial production in villages with more access to markets, which they attributed to an increasing reliance on bought products (and thus income) to satisfy their basic needs.

In contrast, fragmentation is negatively associated with wage labor, and habitat loss displays no significant association with wage labor. Because people involved in wage labor work primarily for logging companies and cattle ranchers outside their own villages (Godoy et al., 2009), they most likely have reduced their direct interaction with the surrounding landscape. The spatial distribution of the wage labor variable indicates that, in contrast with people living near the market-towns, those living along the lower Maniqui River and logging roads engage more frequently in wage labor, most likely because poor market access restrains them from selling activities. In addition, logging companies operate in more remote areas and have a preference for hiring Tsimane' men to locate precious woods (Gullison, Panfil, Strouse, & Hubbell, 1996). Other studies on deforestation in indigenous territories of Latin America have also concluded that off-farm employment contributes to local landscape conservation, as it reduces the time available for people to invest in clearing the forest from their own village (Carr, 2005; Mena, Bilsborrow, & McClain, 2006).

Our third finding relates to the association between landscape and cultural change. Fragmentation and habitat loss are associated with schooling but not with Spanish fluency. Previous research has found an ambiguous association between education and landscape change; certain studies contend that education decreases deforestation because more educated people enjoy more off-farm employment opportunities or apply their skills to make more efficient use of the forest (Carr, 2005; Godoy, Groff, & O'Neill, 1998). In the case of the Tsimane', the level of schooling does not appear to display any relationship to off-farm employment (certain villages with high levels of wage labor display low levels of schooling and vice versa). As other authors have argued, attending school may equip indigenous people with the necessary skills to sign loans and make deals in the market and increase their material aspirations, potentially leading to more deforestation (Mena et al., 2006; Pichón, 1997). Furthermore, we have observed that educated Tsimane' usually prefer to apply the abilities learned in school to produce crops for the market rather than work for wages, which is a more difficult activity that keeps them away from their homes. Another reason that fragmentation and habitat loss might be related to schooling has to do with a negative association between the formal education of the Tsimane' and traditional ecological knowledge (Reyes-García et al., 2010). The Tsimane' acquire traditional ecological knowledge mostly outside of school by accompanying their elders in their daily tasks. Attending school thus leaves them less time to acquire traditional ecological knowledge (Reyes-García et al., 2010). Individuals with greater traditional ecological knowledge make use of certain practices (e.g., obtaining food and forest products while clearing, leaving patches of forest for uses other than cultivation) that result in more selective and less intensive clearing (Reyes-García et al., 2011). More-educated individuals may be less attached to these traditional practices and customs, thus producing more deforestation.

Regarding Spanish fluency, it is possible that the lack of significant associations with fragmentation and habitat loss may be due to the low proportion of Spanish speakers found among the Tsimane'. As mentioned above, cultural change occurs in multiple dimensions, of which proficiency in the national language is only one. Because schooling was mostly in the Tsimane' language until 2006 (Reyes-García et al., 2010) and because most Tsimane' are not proficient in Spanish, it is possible that this variable does not accurately capture the impact of the entire process of cultural change on the landscape. Similarly, Gray et al. (2008) found no significant effect of Spanish language knowledge on indigenous land use in the Ecuadorian Amazon, though they attributed potential effects through increasing opportunities for wage labor.

6. Conclusions

In this article we have integrated socioeconomic and cultural data (collected through household surveys) with landscape data (derived from satellite imagery), thus contributing to multidisciplinary research linking people and pixels, a key and yet challenging task in the study of complex human-environment systems (Rindfuss, Walsh, Turner, Fox, & Mishra, 2004). Specifically, we have addressed a major gap in the literature by assessing how various levels of cultural and economic change within the same indigenous group might be associated with habitat fragmentation and loss.

Our results suggest that economic changes and, to a lesser extent, cultural changes result in landscape fragmentation and loss. We have also found that while most Tsimane' villages are integrated into the market economy to a certain degree, they have not suffered profound cultural changes, as indicated by the low levels of schooling and Spanish fluency. Although landscape fragmentation and habitat loss are not yet severe, the expected intensification of agriculture and the expansion of cattle ranching in the study area may have important implications for landscape conservation in the near future in this part of the Amazon basin.

Landscape planners and policy makers should take into account the pathways suggested here by which rapid cultural and economic changes among indigenous people can increasingly alter the physical landscape. Various economic activities could be promoted as an alternative to intensive land uses increasingly found in villages closer to market-towns, which have proven to have deleterious effects in terms of fragmentation and loss of natural habitats. To be successful, the proposed activities should be based on the needs and aspirations of the Tsimane' and should take into account their capacities and institutional arrangements. Our results, however, should be read critically. Although wage labor appears to be beneficial for conservation, it has other important implications (the presence of logging companies and colonists encroaching

Tsimane' lands, uprooting, conditions of exploitation, etc.). Similarly, although the level of education is positively associated with fragmentation and habitat loss, this correlation does not mean that schooling unequivocally leads to landscape degradation. Further contextualization of Tsimane' education, holding practical classes outdoors, and training and hiring Tsimane' teachers who combine the values and knowledge of Tsimane' culture with broad aspects of the national curriculum in their classes may all contribute to the conservation of Tsimane' culture and, as a result, discourage fragmentation and habitat loss.

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