Land **2014**, *3*, 1-x manuscripts; doi:10.3390/land30x000x

OPEN ACCESS

land

ISSN 2073-445X

www.mdpi.com/journal/land/

Article

Integrating forest cover change with census data: from a meso-scale approach to a typology of social-ecological systems applied to Bolivia and the Lao PDR

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Received: / Accepted: / Published:

Abstract: Integrating remotely sensed data on land cover with socio-economic data is a key challenge of land change science. This paper has the objective to explore possible links between forest cover change and characteristics of social-ecological systems at regional scale based mainly on census data. We assessed relationships between population, poverty, ethnicity, accessibility, land tenure, concessions, protected areas and forest cover change in the last decade for four regions of Bolivia and the Lao PDR, thanks to the calculation of influence areas of communities based on travel time. We found that population density, poverty, ethnicity, accessibility, land tenure and forest cover change are usually interdependent, but do not follow a straightforward model of increasing forest loss with population and poverty. These dependencies were used to elaborate a typology of social-ecological systems in the study areas, identifying three challenging contexts: 1) cash crop expansion areas with high forest loss, less poverty and dominant ethnic groups; 2) smallholder areas with both forest loss and gain, high ethnic diversity and a gradient of market integration, and 3) remote areas near national borders, with low population and surprisingly high forest loss.

Keywords: forest cover change; deforestation; integrative land change science; social-ecological systems; meso-scale; Bolivia; Laos

1. Introduction

The integration of remotely sensed data on land cover with data related with decisions of land managers has been identified as a key challenge of land change science [1]. Furthermore, the institutional factors that influence land use change, including property-rights regimes, environmental policies and decision making systems are being increasingly considered [2]. Theory and practice related with land use and land cover change (LULC) as well as with natural resources governance have long evolved in parallel. In both cases, they have sought to overcome traditional oversimplifications and build new approaches to address the complexity of human-environment relationships at multiple scales.

Several challenges have been identified as being inherent to the integration of social, natural and geographical information sciences: the aggregation and inference of data, the link between land users and remotely sensed information, data quality and validation, spatial-temporal mismatch, use of ancillary information, spatial autocorrelation and accuracy assessment [1]. On the other hand, governance theory has developed a social-ecological framework, which seeks to address multiple levels of variables so ordered to enable diagnosing social-ecological systems and look for patterns across large numbers of cases [3]. The framework faces however the challenge of the cost and difficulty of assessing key variables beyond the local scale for large samples.

This paper has the objective of exploring possible links between land cover change and characteristics of social-ecological systems that can be derived from data available for a relatively large number of cases in a defined region. We focus on forest cover change in four sub-national regions of two developing countries, the Plurinational State of Bolivia and the Lao PDR. In these countries, a relatively good corpus of case studies exist, but there area relatively little data at broader (sub-national and national) scales. At broader scales, census data represent the main source of socio-economic information and relatively few land cover datasets are available. In this context, we explore what kind of relationships can reasonably made visible at sub-national scale using census data, simple land cover assessments and simple statistics. Contrary to most studies on land change that are based on pixels, we chose local communities as main observation units, using a village polygon-based approach developed by [4]. We discuss then the obtained results in light of existing case studies within the regions chosen.

1.1. Causes of forest cover change: a summary

Land change science has been defined as the “interdisciplinary field [that] seeks to understand the dynamics of land cover and land use as a coupled human-environment system” [5] 20666). According to these authors, it includes four main fields of research: 1) the observation and monitoring of land changes, 2) the proper understanding of these changes as a coupled human–environment system, 3) the modelling of land change and 4) the assessment of system outcomes. In this study, we focus specifically on the understanding of land cover change as a coupled human–environment system.

In the past, the causes of land use and land cover change (LULC) have often been misinterpreted and oversimplified in relation with a single factor, like population, technology or socio-economic inequalities [6]. It is now widely acknowledged that the causes of LULC are complex and result from the interaction between social, political, economic, demographic, technological, cultural and biophysical variables [7]. According to [2], identifying the causes of land-use change requires an understanding of how people make land-use decisions and distinguish between proximate causes, which are the direct human actions that operate at the local level and physically affect land cover, and underlying causes, which rely on a more complex array of social, political, economic, demographic, technological, cultural and biophysical variables. Underlying causes alter proximate causes; they often originate at higher levels of organizations, from regional to global, and local communities have little control over them [2,8].

Deforestation has been defined as the conversion of forest to another land cover type, or the fall of tree canopy below a defined threshold [2]. In their meta-analysis of 152 case studies within the tropics, [7] have identified infrastructure extension, agricultural expansion and wood extraction as the main proximate causes of deforestation, and biophysical, economic/technological, demographic, institutional and cultural factors as underlying causes of forest conversion. Biophysical factors include mainly forest-pasture conversion and drought induced forest fires in the Amazon basin. Economic factors embrace the general expansion of cash economy and expanding markets, and agrotechnological changes that were observed to tend to encourage more deforestation. Institutional factors include incentives for land based activities, infrastructure expansion (especially roads), and also legalization of land titles. Demographic factors are usually linked with in-migration and colonization, but rarely with fertility rates. Cultural factors have been shown to underlie economic and political forces, as for example in the cultural preference for cattle ranching found in some regions of Latin America. An important finding of this overall meta-analysis is that the identified factors usually do not operate alone. In most cases, multiple causal factors and their interaction have led to deforestation.

1.2. Integrative land change science: challenges and opportunities

[1] have summarized the challenges met at integrating social, natural and geographic information in the context of land change science. A key challenge to establish empirical linkages between land use change and these causes is the ability to obtain and match socio-economic, environmental and remotely sensed data by scale [1,5].

Firstly, the level of aggregation in measuring data needs to fit the level of aggregation of the tested hypothesis. This is made especially difficult when census data are only available for large geographic units like districts. On the other hand, collecting data at individual or household level for large areas is costly and challenging. A second issue arises when land users have to be linked to remotely observed land parcels and pixels. These land units might not been directly controlled by the people who settle nearby, and inversely, local people might control more remotely located lands. Studies must therefore clearly state whether they take people or parcel as the starting point. Besides data quality, accuracy assessment and validation issues, [1] also mention the difficulty of matching land cover and socio-economic data in space and time. For example, the spatial resolution of a sensor might be coarser than land parcel size. [5] also mention the existing trade-off between single-sector analyses, which focus on general causes, and place-bases analyses which miss linkages to the general picture.

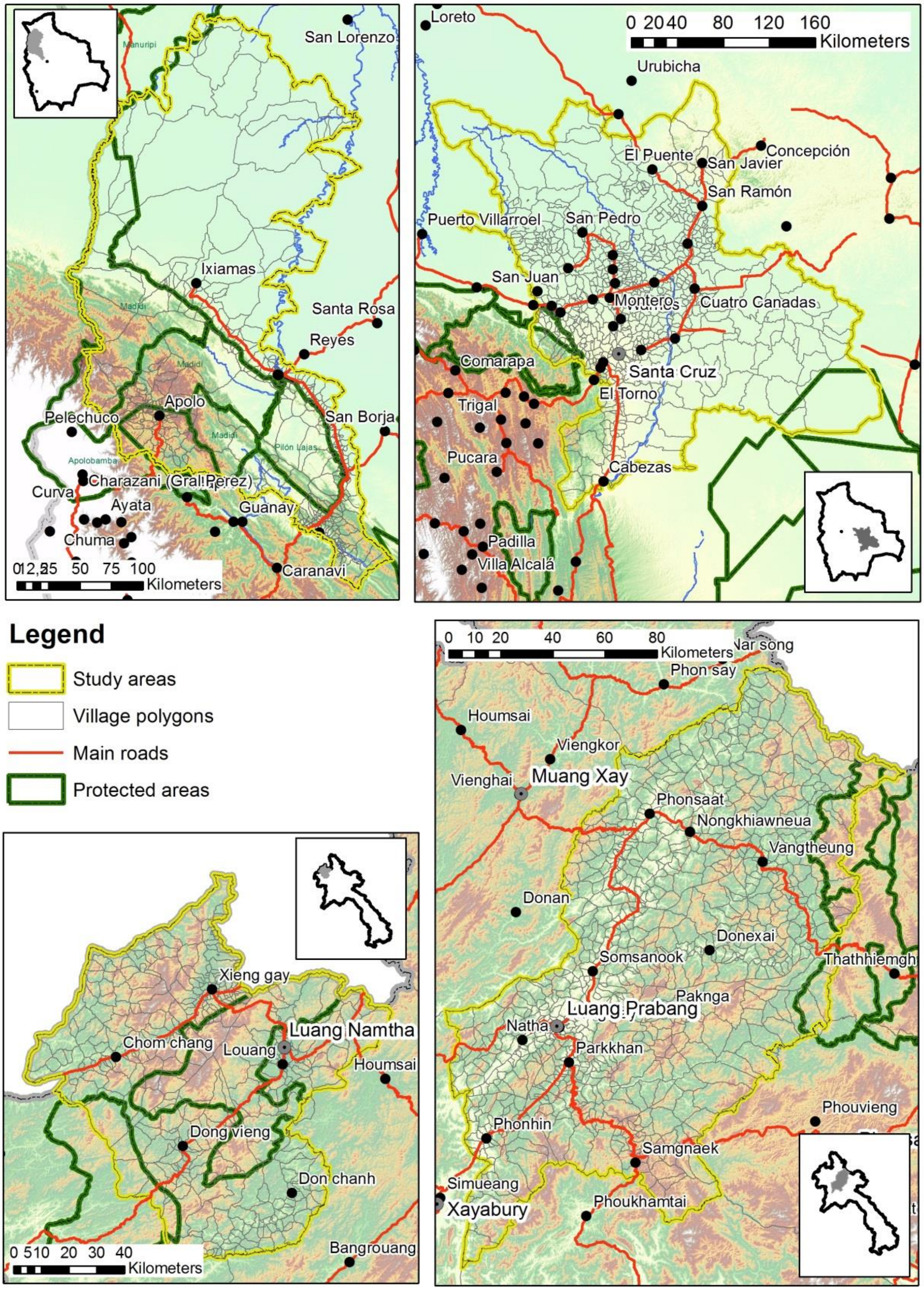
The further development of natural resources governance theory faces similar challenges. Natural resources governance, defined as "the broader arena in which institutions operate and the various management-related concepts take place" [9] 491), has also faced the challenge of overcoming traditional simplifications. These include especially "panaceas", which "predict optimal performance if specific institutional arrangements are in place" [3] 451). Nowadays, it is widely acknowledged that social-ecological systems are characterized by multivariable, non-linear and cross-scale processes [10]. [3] have developed a diagnostic approach for the analysis of social-ecological systems based on a series of variables meant to be unpacked until the analyst has found the disturbance that may affect a SES. These authors set up an agenda for future work that includes the accumulation of empirical data on social and ecological variables at multiple levels of aggregation. They require the performance of a large number of case studies, their meta-analysis and the search for patterns across cases using descriptive and inferential statistics. As they state [3]460), comparisons should allow building typological theories, that "specify independent variables, delineates them into the categories to be measured, and provide hypotheses and generalizations" [11] Can land change science already perform contributions to the research agenda of elaborating typologies of social-ecological systems? Without replacing the need for in-depth field studies, we argue that using land cover change data in combination with census data can help to identify different social-ecological contexts and give useful orientations for both research and policy making.

1.3. Area of study

Bolivia and the Lao PDR were chosen because, while at the same time inserted in very different continental contexts, they share some characteristics. Both countries are "hard" landlocked developing countries in the sense that they do not have any fluvial ports to the sea, which has represented an important barrier to their economic integration [12,13]. As a matter of fact, both Bolivia and the Lao PDR have among the lowest GDP and development level in their respective regions. However, they also have lower population densities than their neighbors, highly uneven distributed populations, high ethnic diversity with 45 languages spoken in Bolivia and 84 in Laos, [14], and the highest per capita forest cover in their respective regions. In this sense, Bolivia and the Lao PDR can be considered countries with low economic but high natural capital in the sense of [15].

Both countries are also undergoing rapid changes including sustained economic growth and increased integration with their BRIC neighbors, Brazil and China, respectively, which enhances infrastructure development and cash crop expansion. In 2011, both countries were losing about 0,5 % of their forest cover per year [16], and Bolivia has been mentioned as one of the current emerging deforestation hotspot [17]. On the other hand, both countries have recently enacted several reforms on environment, land and forest governing policies. These also include decentralization reforms which recognized local communities as legal entities and partly handed over natural resources governance to them, making these communities pertinent as units of observation.

Figure 1. The four study areas



In Bolivia, land redistribution and economic development policies have had a strong influence on forest conversion to cropland in the Eastern lowlands, where roads were opened and land was distributed to Andean and foreign colonists since the 1960s [18,19]. Since 1996, a process of land title regularization was launched, which recognizes indigenous territories (called Tierras Comunitarias de Origen TCO), small properties as well as medium and large landholdings. During the 1990s, large forested areas of the lowlands were also declared protected. In 2006, the "Law of agrarian reform renewal" was enacted by pro-indigenous and pro-peasant president Evo Morales. The normative led to an acceleration of the title formalization process led by the State and its emancipation from international cooperation [20], as well as the application of a clause of "socio-economic function of land" which foresees the verification of economic activities in large landholdings, and their expropriation to the State and ultimately smallholder communities in case of it could not be established [21].

Due to the successive and partly overlapping colonization, distribution and conservation policies, the Bolivian lowlands are characterized by a high diversity of economic rural actors that are also partly linked to ethnic groups. Mestizo and foreign settlers practice medium to large scale mechanized cultivation or extensive cattle ranching, Andean settlers (most of indigenous Quechua and Aymara origin) are small to medium semi-mechanized producers oriented at the national market, typically farming between 10 and 20 hectares of land, and lowland indigenous peoples (more than 30 different groups) are mainly subsistence farmers practicing shifting cultivation and NTFP collection [18].

The two lowland regions chosen represent different combination of this diversity (Fig. 1). The North of La Paz forest landscape (NLP) in mainly inhabited by lowland indigenous peoples as well as by Andean colonists who concentrate their settlements along roads opened mainly during the 1980s. The area is part of the "Tambopata-Madidi greater landscape" and includes a network of protected areas and indigenous territories aimed at conserving one of the most biologically diverse area in the world, shared between Bolivia and Peru. The Santa Cruz agroindustrial area (SCA), also called "Santa Cruz integrated North" has been a pole of national economic development since the 1970s. Highly mechanized cultivation aimed at export markets, especially soybeans, have been constantly expanding around the city of Santa Cruz, encroaching into forested areas and co-existing with areas of Andean colonization along the roads to Cochabamba and to Trinidad.

Since the foundation of the Lao PDR in 1975, all land in Laos formally belongs to the State, but after the transition to market economy since 1986, citizens have rights to market their land ownership and use rights. Land reforms were then enacted with the objectives of increasing land tenure security and eliminate slash-and-burn agriculture, meant to be destructive to upland ecosystems [22,23]. From 1993 onwards, a land allocation policy was enacted, including a land zoning system to be implemented at the village scale. Zoning plans had the effect to separate farmland from forest land, removed large area of the villages from the slash-and-burn cycle, and reduced the agricultural land per capita. [22,23]. On the other hand, a resettlement policy, already starting 1975 and officialized later, consists in relocating most remote populations near roads and towns to "benefit from rural development policies" [24]quoted by Lestrelin 2010). Finally, a network of National Protected Areas was created after 1993 as well [23]. According to the same author, these policies had a much larger impact in the upland areas, for which they were mainly meant: lowland paddy fields were not affected by the allocation process. Finally, more recently, a large number of land concessions have been granted by the Lao government to foreign companies, aimed at developing cash crops [25].

Laos is an ethnically very diverse country, with about the half of the population belonging to the ethnic Lao, and the rest to 48 officially recognized minorities. Ethnic Lao occupy most lowland areas, have had a dominant position and have often disregarded highland groups [26]. In their first years at power, the revolutionary government used a tripartite system classifying ethnies by altitude: Lao Loum (lowlanders), Lao Theung (midlanders) and Lao Suung (highlanders) [27]. Though no more officially used, this classification correspond roughly to the main ethnolinguistic families of Laos: Lao Loum belong mainly to the Tai language family, Lao Theung to the Austroasiatic family and Lao Suung to the Miao-Yao and Tibeto-Burman linguistic families [28]. Though agricultural practices vary considerably from one village to another among the same ethnic group [29], most middle-land and highland ethnic minorities practice slash-and-brun agriculture, while rural lowlanders practice permanent, irrigated cultivation.

Two lao provinces with large communities of ethnic minorities were chosen to carry out the study. The province of Luang Prabang (LPP), topographically and ethnically highly diverse, was one of the first areas where the land allocation policy was implemented [30]. There, the majority of currently existing villages have been resettled and/or have gone through the land allocation procedure [31]. The province of Luang Namtha (LNP) has a high proportion of Tibeto-Burman and Austroasiatic minorities, and has witnessed a rapid expansion of cash crops [32], particularly rubber, along the road linking the province to the Chinese border [33].

1.4. Approach and methodology

Our approach builds on the methodology developed by [34] to describe human-environment interactions beyond the local context at national scale in the Lao PDR. Their study represent an important innovation to link land cover with land use and socio-economic information at a "meso"-level of spatial scale, which they understand as corresponding to the district to the national level. Two innovations were used to match land cover with socio-economic data: first, land cover information (available for a single point in time) was aggregated into land cover mosaics before it was interpreted as a land use categories, thus allowing to interpret landscape mosaics like slash-and-burn cultivation and permanent agriculture in relation with socio-economic data. Second, they used the calculation of village polygons based on equidistance of travel time to represent and analyze socio-economic data at the highest possible resolution. The village polygon approach stems from the fact that in the Lao PDR, villages have no available official boundaries and are represented as points with attached Population and Housing Census information.

In this study, we chose to perform an assessment of land cover at three points in time in the study areas, thus privileging indicators of change over indicators of landscape mosaics. We took the village polygons as main units of observations, aggregating land cover change data as well as census data and other variables to each village or community. The four study areas sum a total of 1991 communities (North of La Paz: 259; Santa Cruz agroindustrial: 626; Luang Prabang: 765; Luang Namtha: 341).

1.4.1. *Socio-economic and socio-cultural variables*

For the Lao cases, we used the village polygons with census data from the Population and Housing Census 2005 calculated and processed by [4], and available on Lao Decide Info data portal (www.decide.la). For the Bolivian cases, we calculated "influence areas" for each locality registered by the Censo Nacional de Poblacion y Vivienda 2001, and represented as georeferenced points. To do so, we built an accessibility model that ascribes a travel cost value for each 90x90m raster cell in a Geographical Information System (GIS) environment. Travel cost was estimated through a decision tree involving land cover, slope, roads, navigable and non-navigable rivers [35]. Equidistant lines of travel time were calculated around locality points, and then aggregated by community level, which correspond roughly to the legally recognized rural communities by the Bolivian government.

For both countries, we first calculated **population density** by community, dividing the total population registered in the last censuses by the village polygon area. Percentages of population belonging to **three aggregated ethnic groups** were then calculated. Data on ethnic groups in Laos, obtained from the census of 2005, were aggregated as percentage of population of the village belonging to the Tai, Austroasiatic, Miao-Yao and Tibeto-Burman ethnolinguistic families, the last two being merged as a "highlander" category, as usually done in Laos [28]. In Bolivia, we used the "self-identification" with an indigenous group of people aged 15 and more variable, as registered in the Census 2001, and aggregated the data as percentage of population of each community who identifies itself as 1) not being indigenous (mestizo and foreign settlers), 2) belonging to an Andean indigenous group (Quechua, Aymara or Uru) or 3) belonging to a lowland indigenous group (all others). Due to the fact that Bolivian lowland indigenous groups have low levels of native language fidelity [36], the self-identification measure appears more robust for these groups.

Poverty incidence in each community was calculated using the data provided by [37]. for Laos. For Bolivia, the percentage of people living 1) in poverty and 2) in extreme poverty was calculated as the percentage of people belonging to the three, respectively two lowest categories of "satisfaction of basic needs" calculated for Bolivia by UDAPE (2001) on the base of 2001 census data. The method takes into account housing, access to health and education services, and income.

Distance to local and provincial urban centres of each village in Laos were calculated as the mean value of all cells from the accessibility model elaborated by [4] within a village polygon. The same exercise was repeated for Bolivia, adding the mean distance to the main roads as an additional variable.

Protected areas were taken into account calculating the percentage of each community covered by a national protected area. We used the data provided by the IUCN world database on protected areas (WDPA, 2012).

Land tenure data at regional scale were only available for Bolivia. We used the data from the Instituto Nacional de Reforma Agraria (INRA) who has been carrying out a land title clearing process (*saneamiento*) that began in 1996, and had covered 61% of the whole national territory by end of 2012 [20,38]. Existing types of properties were aggregated into five main categories: indigenous territories, communal lands, small private landholdings, medium and large private landholdings, and State lands. Areas with formalization "in process" were merged with not yet formalized areas. The proportion of area cleared under each type of property was then calculated for each community polygon.

Concessions data were also only available for Bolivia. Forest concession (2006) and mining concession (2005) data were obtained from the Bolivian Ministry of Planification, and hydrocarbon (gas and oil) concessions (2008) were obtained from the Bolivian Hydrocarbon Agency. Similarly to protected areas, we calculated the percentage of each community covered by a concession type.

1.4.2. Land cover change data

Land cover and land cover change is a difficult and costly process to assess, which often relies on expensive imagery that cannot be purchased for large areas, and even with more difficulty for developing countries. For the study areas, existing data on land cover were not directly comparable at two or more different points in time. In the case of Bolivia, national land cover map were elaborated in 2001 (Superintendencia Agraria) and 2010 (Unidad Técnica Nacional de Información de la Tierra) with a spatial resolution of 30 m and 50 to 60 land cover classes. However, because of the technology accessible in 2001, the methods used at that time were not as accurate as the ones used in 2010. In the case of Laos, the only dataset covering the study areas was the national land cover map of 2002 (Ministry of Agriculture and Forestry). For these reasons, we decided to produce our own land cover datasets for the four study areas. We used exclusively freely available imagery, taking into account that the reproducibility of our approach in developing country contexts would strongly depend on its cost. In spite of its limitations, the classification of Landsat images has been the most popular method to assess land cover change up to now, and Landsat imagery currently represent the highest available spatial resolution available for free (30 m).

In Bolivia, we performed supervised classification of Landsat 5 images for the years 2001, 2005 and 2010 in both study areas, using cloudless images taken between June and August (dry season). The images were classified on a pixel base using their 6-band spectral signature of the images as well as the derived Normalized Difference Vegetation Index (NDVI). A first classification in seven classes (forest, shrub, grassland, cropland, water, rock, urban) was then aggregated into forest and non-forest classes. The ascription of land cover classes to the classes obtained from the images was based on expert knowledge and performed by people who knew the study area (Y. Sandoval and his students). Field-based verification and accuracy assessment was not possible due to the extension and difficult access of the area assessed, and the fact that the classification was performed in 2013 (three years after the last studied scene).

In Laos, a preliminary dataset from the ongoing national land cover change assessment, performed by S. Thongmanivong, was used. The dataset was produced for the years 2005 and 2010 on the base of Landsat 5 images, using supervised and object-based classification based on expert knowledge at a resolution of 30 m for the whole country. An additional dataset was produced by the same author for the year 2000 in the two study areas. For the three time points, the images were classified in 17 land cover types including different types of forests, then aggregated to 9 classes and finally to forest and non-forest.

Three variables derived from land cover were calculated for each village and community polygon: a) the forest cover change (TDEF) using the formula proposed by [39], b) the total forest loss relative to baseline forest cover in t0 (DEFR), and c) the total gained forest relative to the polygon area (REGR). In the Bolivian lowlands TDEF, DEFR and REGR were calculated using only pixels which have experienced change between forest and non-forest categories such as shrub, pasture, cropland and urban land. The dynamics between forest and water bodies as well as bare soil (in this case river banks) were considered non-anthropogenic and not taken into account.

1.4.3. Assessing relationships between land cover and socio-economic data

We used simple inferential statistics to assess existing relationships between land cover and socio-economic data, but also within socio-economic variables. In each study area, we excluded the 5% most densely populated communities, considered urban. Pearson's correlations and their significance below p-values of 0,05 and 0,01 were calculated two-by-two within socio-economic variables, as well as between these variables and forest cover change.

The typology of communities for each study area was performed through k-means cluster analysis, sorting all communities into 4 to 6 classes. We used 10 to 17 variables that appeared to be related as a basis for the analysis, and then calculated the modified centroids (median values) of these variables for each class.

2. Results and Discussion

2.1. Relations between socio-economic and cultural variables

The two Bolivian and two Lao sub-national cases as well as the national scale show existing relationships between spatial patterns of population density, poverty, accessibility and ethnicity, showing that these variables cannot be considered as independent. Especially, the proportion of poverty appears related to ethnicity and distance from urban centers.

In Laos (Table 1a), poverty is negatively correlated with population density, and positively with distances from districts capital (D_distr) and province capitals (D_prov). It is also positively correlated with the presence of minority ethnic groups belonging to the Austroasiatic language families, and negatively with the proportion of ethnic Lao. All these trends appear more marked in LPP than in LNP. At national scale, poverty also appears related to distance and to the Austroasiatic ethnic groups.

In Bolivia (Table 1b), poverty does not appear related with distance from roads or towns, but with the presence of Andean (Quechua and Aymara) ethnic groups and high rural population density. This trend is visible at national scale as well. Protected areas appear located at longer distances from urban centers, but more specifically further away from roads in the cases of NLP and SCA.

Table 1a. Pearson correlations between main socio-economic variables in Laos

Luang Prabang province

	Popdens	Poverty	D_distr	D_prov	P_Tai	P_Aust	P_MY_TB
Popdens	1						
Poverty	**-,335****	1					
D_distr	**-,454****	**,449****	1				
D_prov	**-,426****	**,480****	**,937****	1			
P_Tai	**,201****	**-,700****	**-,215****	**-,244****	1		
P_Aust	-,122**	**,478****	,172**	**,210****	**-,652****	1	
P_MY_TB	-,066	,157**	,016	-,001	**-,268****	**-,555****	1
P_AP	-,160**	,094*	,229**	,236**	,003	,011	-,016

Luang Namtha province

	Popdens	Poverty	D_distr	D_prov	P_Tai	P_Aust	P_MY_TB
Popdens	1						
Poverty	**-,289****	1					
D_distr	**-,291****	**,337****	1				
D_prov	**-,260****	**,330****	**,980****	1			
P_Tai	**,222****	**-,630****	-,183**	-,165**	1		
P_Aust	-,082	**,353****	,160**	,164**	**-,241****	1	
P_MY_TB	-,079	,118*	-,018	-,033	**-,482****	**-,733****	1
P_AP	-,242**	,081	,083	,003	-,105	-,013	,080

Whole Laos

	Popdens	Poverty	D_distr	D_prov	P_Tai	P_Aust	P_MY_TB
Popdens	1						
Poverty	-,172**	1					
D_distr	-,112**	**,360****	1				
D_prov	-,138**	**,417****	,936**	1			
P_Tai	,120**	**-,580****	**-,342****	**-,362****	1		
P_Aust	-,092**	**,554****	**,194****	**,229****	-,721**	1	
P_MY_TB	-,051**	,091**	**,229****	**,213****	-,452**	-,282**	1
P_AP	-,051**	,140**	,197**	,196**	-,035**	,028**	,008

Popdens = population density; Poverty = proportion of poor people; D_dist = travel time to district capital; D_prov = travel time to province capital; P_Tai = proportion of people from Lao-Tai ethnolinguistic group; P_Aust = proportion of people from Austroasiatic ethnolinguistic group; P_MY_TB = proportion of people from Miao-Yao or Tibeto-Burman ethnolinguistic group; P_AP = proportion of area within a protected area. *indicate significance of correlation at p<0,05 and ** at p<0,01 level.

Table 1b. Pearson correlations between main socio-economic variables in Laos

North of La Paz forest landscape

	Popdens	Poverty	Extrpov	Droad	Dmun	Ddep	Pand	Plind	Pnoni
Popdens	1								
Poverty	-,009	1							
Extrpoverty	,017	**,746****	1						
Droad	**-,498****	,176**	,133*	1					
Dmun	-,133*	-,131*	-,100	**-,254****	1				
Ddep	**,352****	**-,484****	**-,395****	**-,477****	-,139*	1			
Pand	**,205****	**,354****	**,311****	**-,239****	,007	,112	1		
Plind	-,084	**-,222****	**-,188****	,122*	-,020	-,047	**-,672****	1	
Pnoni	**-,200****	**-,274****	**-,248****	,211**	,010	-,109	**-,733****	-,010	1
P_AP	-,172**	,160*	,302**	,407**	,047	-,348**	,008	,010	-,020

Santa Cruz agroindustrial area

	Popdens	Poverty	Extrpov	Droad	Dmun	Ddep	Pand	Plind	Pnoni
Popdens	1								
Poverty	-,170**	1							
Extrpoverty	-,054	**,723****	1						
Droad	**-,298****	,022	-,105**	1					
Dmun	**-,349****	,064	-,124**	**,379****	1				
Ddep	**-,360****	**,361****	,172**	,187**	**,720****	1			
Pand	-,019	**,320****	**,306****	,062	,038	**,208****	1		
Plind	-,042	,032	-,005	,011	,033	,129**	**-,315****	1	
Pnoni	,056	**-,313****	**-,279****	-,065	-,055	**-,287****	**-,746****	**-,370****	1
P_AP	-,064	-,101*	-,074	,405**	,064	-,014	,205**	-,111**	-,121**

Whole Bolivia

	Popdens	Poverty	Extrpov	Droad	Dmun	Ddep	Pand	Plind	Pnoni
Popdens	1								
Poverty	-,030**	1							
Extrpoverty	-,022**	,701**	1						
Droad	-,017*	,120**	,095**	1					
Dmun	-,018*	,087**	,047**	,980**	1				
Ddep	-,022**	,112**	,039**	,903**	,903**	1			
Pand	,006	,212**	,259**	-,103**	-,128**	-,255**	1		
Plind	-,006	-,079**	-,141**	,103**	,124**	,248**	-,545**	1	
Pnoni	-,004	-,202**	-,220**	,058**	,075**	,149**	-,850**	,022**	1
P_AP	-,005	-,073**	-,037**	,216**	,240**	,210**	-,016	,009	,013

Popdens = population density; Poverty = proportion of poor people; Extrpoverty = proportion of people in extreme poverty; Droad = travel time to main roads; Dmun = travel time to municipal capital; Ddep = travel time to department capital; Pand = proportion of people self-identified with Andean indigenous groups; Plind = proportion of people self-identified with lowland indigenous groups; Pnoni = proportion of people who do not identify themselves with any indigenous group. *indicate significance of correlation at p<0,05 and ** at p<0,01 level.

The four cases and the national scale also show negative correlations between the proportion of an ethnic group and the other, showing that there is relatively little ethnic mix within communities.

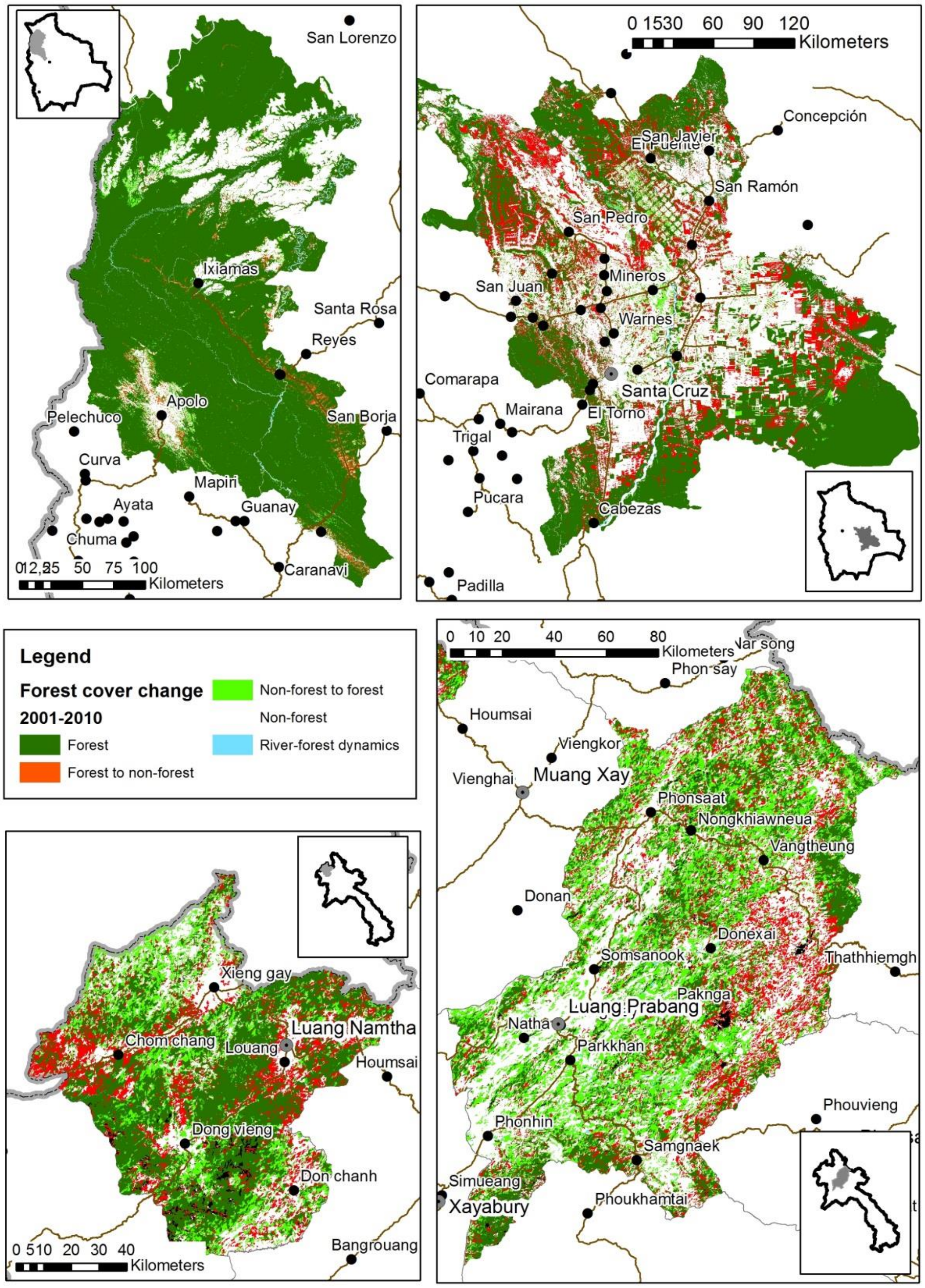
2.2. Forest cover change patterns

Fig. 2 shows the main forest conversion patterns in the four study areas between 2001 and 2010 in Bolivia and 2000 and 2010 in Laos (note that the scale of maps are different). In the NLP case (Fig. 2a), forest conversion to cropland along the main road is clearly visible, showing a fishbone pattern around the road. Two additional areas of forest conversion are visible: in the North, forest is converted into pasture by the action of fire which can be anthropogenic or natural. However, an important regeneration of pastures to forest is also visible in the North-West, which should be confirmed by field observations difficult to get in this extremely remote area. Another pole of dynamic between forest and non-forest is the Apolo region, where forest is mainly converted to shrub, and might be linked with the presence of illicit coca cultivation in that area [40].

The SCA case (Fig. 2b) shows a large ring-like forest conversion area around the city of Santa Cruz towards the East. Two patterns of forest conversion are visible: to the North, an area inhabited by Andean colonists, we observe fishbone-like deforestation similar to the NLP case; to the East, the main area of agroindustrial farming, forest conversion occurs in a mosaic of large plots. Regeneration is visible in both areas, mainly around the Rio Grande, suggesting that cultivation might be limited there by the occurrence of periodic floods.

The LPP case (Fig. 2c) shows a mosaic of small and larger deforested patches, which might represent slash-and-burn cultivation, on the one hand, and industrial cropping on land concessions on the other. An intriguing result is the high area of regenerated forest, which should be interpreted with caution. In this mountainous area, it is often difficult to distinguish between shrub and secondary forest because of the strong influence of topography (shadows and semi-shadows) on spectral signature. Moreover, the spatial resolution of 30 m does not allow to capture most small-scale cultivation plots. In the LNP case (Fig. 2d), converted patches appear larger and mainly concentrated along the road which connects China to Myanmar and around the urban centers of Luang Namtha and Vieng Poukha. Smaller forest conversion patches can be observed together with regeneration areas in the far North and South of the province, probably corresponding to slash-and-burn cultivation areas.

Figure 2. Forest cover change (2001-2010 and 2000-2010) in the four study areas.



2.3. Forest cover change in relation with socio-economic variables

In both Bolivian cases, a pattern of increasing relative forest loss with population density, accessibility, and, to a lesser extent, extreme poverty is visible (Table 2a). In general, the trend is stronger in the NLP than in the SCA case. Relative forest loss correlates stronger with socio-economic indicators than forest cover change rate, which is sensitive to both forest loss and gain. In both cases, forest loss correlates with road accessibility, but with urban centers accessibility only in the case of SCA. An interesting observation is that, in the case of NLP, areas with strong forest loss, high poverty and easy access to roads are also related with high forest gain, but not in the case of SCA. Ethnic groups show higher relations to forest cover change in NLP than in SCA; there, the presence of Andean settlers is clearly linked with both forest loss and gain. Surprisingly, the presence of mestizo people has a stronger negative correlation with both loss and gain than lowland indigenous people. This trend is also visible in SCA, but with much weaker correlations. No clear trends are seen in the relation between territory under protection and forest cover change in NLP; but in SCA, protected areas appear to be less deforested. Finally, there are little differences in the found correlations for forest cover change between 2001-2005 and 2005-2010, with the exception of extreme poverty in SCA, which was related with forest loss between 2001 and 2005 but not any more for 2005-2010.

Table 2a. Pearson correlations between forest cover change and socio-economic variables in the two Bolivian cases

North of La Paz area

	Forest cover change rate			Relative deforestation			Relative regeneration		
	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010
Popdens	-,012	**-,314****	**-,274****	**,369****	**,468****	**,448****	**,378****	**,211****	**,246****
Pand	-,106	-,086	-,126*	**,314****	**,270****	**,247****	**,308****	**,209****	**,264****
Plind	,090	,029	,069	**-,172****	-,131*	-,113	-,148*	-,142*	-,151*
Pnoni	,060	,090	,107	**-,265****	**-,245****	**-,231****	**-,281****	-,152*	**-,217****
Poverty	,010	-,132*	-,108	,352**	,324**	,273**	,368**	,109	,290**
Extrop	-,047	**-,192****	**-,188****	**,452****	**,419****	**,395****	**,290****	,054	**,209****
Droad	,076	**,168****	**,181****	**-,338****	**-,363****	**-,369****	**-,330****	**-,224****	**-,246****
Dmun	-,040	,114	,078	-,084	-,142*	-,113	-,136*	-,087	-,110
Ddep	-,091	,053	,001	-,003	-,020	,026	,058	,215**	,088
P_AP	-,150*	-,004	-,078	,067	-,006	,028	-,092	-,136*	-,076

Santa Cruz Agroindustrial area

	Forest cover change rate			Relative deforestation			Relative regeneration		
	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010
Popdens	-,038	,091*	,076	**,286****	**,313****	**,300****	,093*	,116**	,128**
Pand	**-,153****	-,052	**-,202****	,170**	,074	,148**	-,020	,060	-,027
Plind	,040	,069	,121**	-,041	-,032	-,043	,064	,008	,081*
Pnoni	**,123****	,012	**,126****	**-,136****	-,050	**-,114****	-,025	-,061	-,020
Poverty	**-,112****	-,074	-,191**	,069	-,050	,018	,000	,041	-,001
Extrop	**-,234****	,067	-,127**	**,205****	,021	,167**	**-,158****	,121**	-,005
Droad	,087*	-,007	,069	**-,341****	**-,362****	**-,398****	-,086*	-,145**	-,149**
Dmun	,044	-,029	,003	**-,317****	**-,308****	**-,308****	-,090*	-,121**	-,127**
Ddep	,001	-,092*	-,113**	**-,206****	**-,229****	**-,201****	-,019	-,095*	-,082*
P_AP	,071	,007	,073	**-,207****	**-,214****	**-,244****	-,049	-,057	-,103**

Popdens = population density; Poverty = proportion of poor people; Extrpoverty = proportion of people in extreme poverty; Droad = travel time to main roads; Dmun = travel time to municipal capital; Ddep = travel time to department capital; Pand = proportion of people self-identified with Andean indigenous groups; Plind = proportion of people self-identified with lowland indigenous groups; Pnoni = proportion of people who do not identify themselves with any indigenous group. *indicate significance of correlation at $p<0{,}05$ and ** at $p<0{,}01$ level.

The two Lao cases (Table 2b) show generally weaker relationships and very different ones in both study areas. In LNP, forest loss correlates negatively with distance to urban centers as expected, and, to a smaller extent, positively with population density. The trend is only visible over the 10-years period. Forest gain is more strongly related to distance as well as to poverty and lower population density. Among ethnic groups, ethnic Lao show a negative correlation with forest gain as well as a tiny positive relationship to forest loss. Highlanders also show a tiny positive relation with regeneration. No clear trend is visible among communities dominated by Austroasiatic ethnic groups. The case of LPP shows partly contrary trends to the LNP one: deforestation tends to occur in more remote, sparsely populated and poorer areas. On the other hand, regeneration also tends to occur in these areas. Ethnicity variables show a relation, though also relatively weak, between deforestation, regeneration and Austroasiatic population, which might be related to slash-and-burn practices. Inversely, both forest loss and gain tend to be negatively linked with the presence of ethnic Lao. Finally, the presence of highlanders shows a tiny reversing trend from deforestation from 2000 to 2005 to regeneration from 2005 to 2010. Protected areas show no clear relationships with forest cover change in LPP, probably because they cover small areas in this province. However, we can observe that in LNP, the area under protection (mostly the Nam Ha Biodiversity Conservation area) correlates negatively with forest conversion.

Table 2b. Pearson correlations between forest cover change and socio-economic variables in the two Lao cases

Luang Prabang province

	Forest cover change rate			Relative deforestation			Relative regeneration		
	2000-2005	2005-2010	2000-2010	2000-2005	2005-2010	2000-2010	2000-2005	2005-2010	2000-2010
Popdens	**,145****	**-,130****	,088*	-,076*	**,251****	,006	-,086*	**-,179****	**-,213****
Poverty	-,073*	-,004	**-,110****	,059	-,098**	**,125****	**,187****	**,119****	**,182****
D_distr	-,151**	-,032	**-,232****	,028	-,100**	**,128****	**,173****	,067	,101**
D_prov	-,143**	-,061	**-,263****	,064	-,045	**,203****	**,224****	,059	,092*
P_Tai	,042	-,037	,033	-,115**	,048	**-,127****	**-,153****	**-,153****	**-,183****
P_Aust	,049	-,055	-,031	,032	,043	**,130****	**,204****	,010	,099**
P_MY_TB	**-,112****	**,115****	,004	,087*	-,107**	-,029	-,101**	,157**	,071
P_ap	-,054	-,042	-,101**	-,032	-,016	,024	-,032	-,030	-,093*

Luang Namtha province

	Forest cover change rate			Relative deforestation			Relative regeneration		
	2000-2005	2005-2010	2000-2010	2000-2005	2005-2010	2000-2010	2000-2005	2005-2010	2000-2010
Popdens	-,116*	-,048	**-,204****	,119*	,085	**,330****	**-,155****	**-,337****	**-,233****
Poverty	,010	,064	**,146****	,090	-,021	**-,136***	,094	**,330****	**,245****
D_distr	-,070	**,166****	**,173****	,057	-,093	**-,209****	,092	**,413****	**,361****
D_prov	-,086	**,174****	**,167****	,092	-,055	**-,173****	,111*	**,404****	**,377****
P_Tai	-,037	-,035	-,121*	,031	,035	**,144****	**-,189****	**-,258****	**-,236****

P_Aust	-,094	,095	-,054	,173**	,055	,031	-,096	,111*	,005
P_MY_TB	,110*	-,059	,134*	-,175**	-,074	-,127*	**,220****	,080	,162**
P_ap	,147**	-,121*	,017	**-,294****	**-,249****	**-,309****	,021	,091	-,108*

Popdens = population density; Poverty = proportion of poor people; D_dist = travel time to district capital; D_prov = travel time to province capital; P_Tai = proportion of people from Lao-Tai ethnolinguistic group; P_Aust = proportion of people from Austroasiatic ethnolinguistic group; P_MY_TB = proportion of people from Miao-Yao or Tibeto-Burman ethnolinguistic group; P_AP = proportion of area within a protected area. *indicate significance of correlation at $p<0,05$ and ** at $p<0,01$ level.

2.4. Land tenure, socio-economic variables and forest cover change in Bolivia

In Bolivia, land tenure categories also appear to be related to socio-economic and ethnicity variables (Table 3). As expected, indigenous territories overlap with the presence of lowland indigenous groups, but the trend is much stronger in NLP than in SCA. They also increase with lower population density and road distance. Inversely, small properties are related to Andean colonists, with a stronger relation in SCA, and with a negative relation with road distance in NLP. Is it noteworthy to observe that small properties correlate positively with poverty in SCA but negatively in NLP. Medium and large properties as well as communal properties show no clear trend, and surprisingly no relation with non-indigenous population in SCA. State lands clearly appear to be located in most remote areas in both cases. Non-formalized areas show very distinct patterns in both study areas: in the case of NLP, these areas are strongly linked with poverty, remoteness and Andean indigenous peoples. In SCA, they area negatively related with poverty but positively with non-indigenous people. These trends might be linked to different challenges met by the title formalization process: on the one hand, remote and at the same time extremely fragmented lands are difficult to survey. On the other hand, land titling may meet resistance from agro-industrialists who try to delay or avoid formalization because of its links with the verification of "socio-economic functions" and possibility of expropriation, thus also explaining the lack of relation between this group and formalized medium/large landholdings.
Table 3: Pearson correlations between the proportion of community area under different land tenure types and socio-economic variables in the two Bolivian cases.

Table 3. Pearson correlations between the proportion of community area under different land tenure types and socio-economic variables in the two Bolivian cases.

North of La Paz forest landscape

	Community	Indigenous terr.	Small private	State	Medium and large private	In process /not form.
Popdens	-,157*	-,211**	1	-,339**	-,062	,144*
Pand	,094	-,472**	,252**	-,215**	-,094	,222**
Plind	-,068	,404**	-,247**	,046	,006	-,075
Pnoni	-,064	,266**	-,114	,248**	,121	-,231**
Poverty	-,030	-,350**	-,248**	-,013	-,145*	,533**
Extrpov	,024	-,349**	-,394**	-,173**	-,155*	,730**
Droad	,149*	,161**	-,434**	,512**	-,115	-,110
Dmun	,102	,191**	-,159*	-,038	,105	-,055
Ddep	-,035	-,253**	,661**	-,222**	,054	-,253**

Santa Cruz agroindustrial area

	Community	Indigenous terr.	Small private	State	Medium and large private	In process /not form.
Popdens	-,072	-,122**	,018	-,143**	-,225**	,165**

Pand	,058	-,125**	,404**	,124**	-,116**	-,331**
Plind	,127**	,112**	-,127**	-,071	,143**	,019
Pnoni	-,140**	,047	-,313**	-,070	,021	,311**
Poverty	,193**	,049	,345**	,031	,169**	-,437**
Extrpov	,136**	-,055	,323**	,021	,158**	-,380**
Droad	,084*	,265**	-,055	,655**	-,030	-,207**
Dmun	,144**	,181**	-,004	,135**	,090*	-,142**
Ddep	,205**	,115**	,196**	,069	,151**	-,325**

Popdens = population density; Poverty = proportion of poor people; Extrpoverty = proportion of people in extreme poverty; Droad = travel time to main roads; Dmun = travel time to municipal capital; Ddep = travel time to department capital; Pand = proportion of people self-identified with Andean indigenous groups; Plind = proportion of people self-identified with lowland indigenous groups; Pnoni = proportion of people who do not identify themselves with any indigenous group. *indicate significance of correlation at p<0,05 and ** at p<0,01 level.

Table 4 shows the relationships between land tenure types and forest cover change for both areas of study from 2001 to 2005 and 2010. Trends are much more visible in the NLP case. There, indigenous territories and state lands – which are also more remote [41] – experience less forest cover change dynamics in general. This is also the case in SCA, but only for deforestation. In NLP, small properties appear to experience more forest regeneration, probably linked with fallow secondary forests or plantations. Inversely, non-formalized lands experience higher relative deforestation, suggesting that tenure insecurity in the contexts of "socio-economic function" might lead to more forest clearance. Finally, the case of SCA shows that small properties had a relation with deforestation between 2001 and 2005, but not any more between 2005 and 2010, and the inverse occurs with non-formalized properties.

Table 4. Pearson correlations between land tenure types and forest cover change in the two Bolivian cases.

North of La Paz forest landscape

	Forest cover change rate			Relative deforestation			Relative regeneration		
	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010
pcom	-,020	,108	,082	-,095	-,135*	-,107	-,231**	-,099	-,166**
ptco	,084	,084	,113	-,323**	-,273**	-,282**	-,301**	-,245**	-,269**
ppeq	-,054	,072	,035	,033	-,001	,018	,263**	,350**	,277**
pfisc	,098	,112	,144*	-,335**	-,306**	-,326**	-,301**	-,208**	-,237**
pmedemp	,002	,100	,086	-,071	-,142*	-,131*	-,072	,120	,046
pprocno	-,063	-,272**	-,264**	,481**	,491**	,475**	,318**	,037	,187**

Santa Cruz agroindustrial area

	Forest cover change rate			Relative deforestation			Relative regeneration		
	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010
pcom	-,059	,029	-,019	-,031	-,154**	-,100*	-,054	,110**	-,052
ptco	,044	,005	,045	-,147**	-,181**	-,187**	-,051	-,076	-,076
ppeq	-,120**	-,097*	-,228**	,114**	,041	,124**	-,026	,007	-,035
pfisc	,045	,050	,104**	-,169**	-,214**	-,228**	-,066	-,050	-,041
pmedemp	,017	-,042	-,036	-,071	-,114**	-,074	-,059	-,030	-,027
pprocno	,090*	,077	,176**	,016	,148**	,051	,090*	,005	,079*

pcom = proportion of area under communal property; ptco = proportion of area within indigenous territory; ppeq = proportion of area under small private property; pfisc = proportion of area under fiscal property; pmdeemp = proportion of area under medium and large private property; pprocno = proportion of non-formalized area or in process; *indicate significance of correlation at p<0,05 and ** at p<0,01 level.

2.5. Concessions, socio-economic variables and forest cover change in Bolivia

Few trends are visible while correlating the area covered by a hydrocarbon, mining of forest concessions and socio-economic characteristics of communities (Table 5). In NLP, one can observe a general trend of more concessions in communities populated by lowland indigenous people and less in Andean settlers' areas. This could be due to the fact that lowland indigenous people occupy larger areas, but no clear trend is visible with population density. In SCA, we observe that forest concessions tend to occur in more remote communities, which is a general trend at national level as well.

There are no hydrocarbon concessions in the NLP area (Table 6). In that case, forest and mining concessions show no clear relationship with forest cover change. In SCA, there is a tiny trend of a negative relationship between forest loss and forest and mining concessions, which could be linked with remoteness in the case of forest concessions. The reason why, despite not appearing more remote, areas with mining concessions would be less deforested is not clear.

Table 5. Pearson correlations between concession area and socio-economic variables in Bolivia

North of La Paz forest landscape

	Popdens	Poverty	Extrpov	Droad	Dmun	Ddep	Pand	Plind	Pnoni
P_hydr	.^{c}	.^{c}	.^{c}	.^{c}	.^{c}	.^{c}	.^{c}	.^{c}	.^{c}
P_for	-,081	-,149*	-,120	-,010	**,167****	,027	**-,183****	**,153***	,107
P_min	**,200****	-,074	-,072	-,030	-,059	,118	**-,136***	**,167****	,031
P_conc	-,010	-,156*	-,129*	-,015	,128*	,062	**-,210****	**,199****	,101

Santa Cruz agroindustrial area

	Popdens	Poverty	Extrpov	Droad	Dmun	Ddep	Pand	Plind	Pnoni
P_hydr	,053	-,212**	-,090*	-,049	-,028	-,107**	-,065	-,056	,095*
P_for	-,112**	,070	-,030	**,159****	**,218****	**,190****	,018	,009	-,022
P_min	,081*	-,031	-,055	-,043	-,055	-,052	-,090*	,068	,043
P_conc	,087*	-,144**	-,125**	-,012	,024	-,041	-,047	-,044	,073

Whole Bolivia

	Popdens	Poverty	Extrpov	Droad	Dmun	Ddep	Pand	Plind	Pnoni
P_hydr	-,002	-,059**	-,084**	-,048**	-,038**	-,012	-,062**	,026**	,058**
P_for	-,003	-,006	-,039**	**,132****	**,139****	**,142****	-,163**	,107**	,127**
P_min	,016*	-,034**	,025**	-,055**	-,063**	-,074**	,081**	-,044**	-,069**
P_conc	,007	-,073**	-,049**	-,035**	-,033**	-,031**	-,023**	,009	,022**

Popdens = population density; Poverty = proportion of poor people; Extrpoverty = proportion of people in extreme poverty; Droad = travel time to main roads; Dmun = travel time to municipal capital; Ddep = travel time to department capital; Pand = proportion of people self-identified with Andean indigenous groups; Plind = proportion of people self-identified with lowland indigenous groups; Pnoni = proportion of people who do not identify themselves with any indigenous group; P_hydr= proportion of community area within a hydrocarbon concession; P_for= proportion of community area within a forest concession; P_min= proportion of community area within a mining concession; P_conc= proportion of community area within any type of concession. *indicate significance of correlation at p<0,05 and ** at p<0,01 level.

Table 6. Pearson correlations between concession area and forest cover change in the two study areas in Bolivia

North of La Paz forest landscape

	Forest cover change rate			Relative deforestation			Relative regeneration		
	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010
P_hydr	nn	nn	nn	nn	nn	nn	nn	nn	nn
P_for	-,003	,006	,004	-,094	-,063	-,050	-,145*	-,104	-,127*
P_min	-,072	,044	,002	,053	-,002	,023	-,051	,086	-,031
P_conc	-,026	,020	,004	-,070	-,057	-,037	-,150*	-,068	-,127*

Santa Cruz agroindustrial area

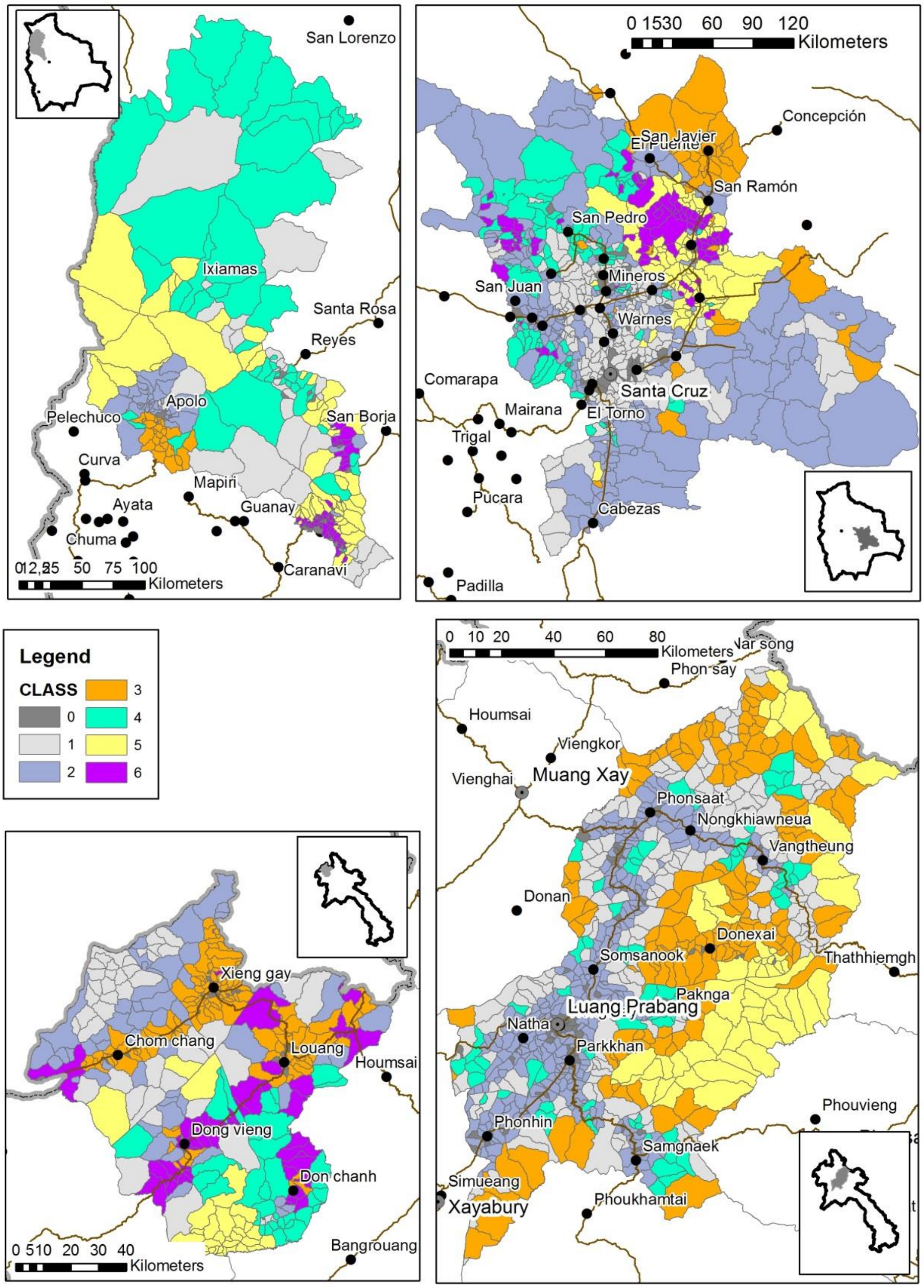
	Forest cover change rate			Relative deforestation			Relative regeneration		
	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010	2001-2005	2005-2010	2001-2010
P_hydr	,025	-,005	,017	-,089*	-,090*	-,075	-,052	-,044	-,057
P_for	,028	,007	,036	**-,102***	**-,113****	**-,105****	-,056	-,071	-,070
P_min	,098*	-,077	-,004	**-,174****	**-,101***	**-,144****	,101*	-,098*	-,062
P_conc	,048	-,050	-,016	**-,165****	**-,137****	**-,133****	-,019	-,123**	-,102*

P_hydr= proportion of community area within a hydrocarbon concession; P_for= proportion of community area within a forest concession; P_min= proportion of community area within a mining concession; P_conc= proportion of community area within any type of concession. *indicate significance of correlation at $p<0,05$ and ** at $p<0,01$ level.

2.6. Towards a regional typology of social-ecological systems?

According to [8] and [34], a key challenge of land change science is understanding complexity beyond stating that "everything is related with everything". Complex systems are also characterized by clustered and chained drivers and processes, and their arrangements in levels [34,42].

Figure 3. A typology of related variables for the four case studies



Our findings show that the relationships between variables that are captured by census data as well as with remotely sensed data on land cover are not random. We found significant dependencies between some key variables like population density, poverty, ethnicity, accessibility, land tenure and forest cover change, while the presence of protected areas or concession had less clear relationships. The dependencies found do not necessarily follow the same direction: poverty and accessibility can be positively or negatively related with forest cover loss depending on the case.

Table 7a. Median value of the used variables for the typologized classes in Bolivia

North of La Paz forest landscape

Class	1	2	3	4	5	6
Popdens	5,0	8,7	7,0	2,9	3,3	10,7
Pand	12,5	**91,7**	**87,7**	17,5	**83,3**	**83,9**
Plind	**69,6**	0,7	8,3	9,9	3,8	2,3
Pnoni	17,9	7,7	4,1	**72,6**	12,8	13,8
Extrpoverty	35,2	**80,8**	**86,5**	41,5	**37,7**	**35,8**
Droad	8,9	6,5	3,6	10,1	**9,6**	**1,6**
pcom	11,5	19,6	1,0	13,2	**28,5**	4,5
ptco	**49,1**	0,5	0,0	27,4	15,0	2,1
ppeq	3,9	1,5	0,0	9,1	11,3	**74,7**
pfisc	9,6	0,8	0,0	**24,1**	25,4	3,4
pproc	16,3	**72,8**	1,5	11,5	14,2	11,2
pnosan	8,3	4,6	**97,4**	11,5	4,0	1,0
tdef	-0,01	-0,05	-0,02	-0,01	-0,01	-0,01
defr	0,10	**0,40**	**0,31**	0,07	0,06	0,18
regr	0,02	0,07	0,08	0,02	0,02	0,08

Santa Cruz agroindustrial area

Class	1	2	3	4	5	6
Popdens	12,9	9,0	5,9	8,5	8,2	10,1
Pand	14,6	14,7	3,5	**69,4**	33,7	**69,9**
Plind	12,0	11,4	**81,8**	5,1	9,9	6,6
Pnoni	**72,8**	**73,8**	14,7	24,3	**56,5**	23,6
Extrpoverty	**28,8**	25,1	**44,8**	**29,4**	**92,0**	**72,7**
Droad	1,1	1,9	2,8	2,5	0,9	1,7
Ddep	1,9	3,0	4,7	3,4	3,4	4,2
pcom	0,4	2,1	7,6	3,0	3,1	3,5
ptco	0,1	1,4	3,7	0,1	0,0	0,0
ppeq	5,0	**22,1**	15,2	23,0	24,0	**69,6**
pmedemp	2,2	9,5	14,6	4,2	**19,3**	3,8
pfisc	0,1	2,6	0,4	5,7	1,1	2,6
pproc	8,3	40,7	44,8	28,8	42,1	15,9
pnosan	**84,0**	21,5	13,5	35,2	10,5	4,7
tdef	0,00	-0,03	0,00	-0,05	-0,05	-0,07
defr	**0,55**	**0,44**	0,40	**0,51**	**0,59**	**0,63**
regr	0,07	0,05	0,07	0,05	0,06	0,05

Popdens = population density; Poverty = proportion of poor people; Extrpoverty = proportion of people in extreme poverty; Droad = travel time to main roads; Dmun = travel time to municipal capital; Ddep = travel time to department capital; Pand = proportion of people self-identified with Andean indigenous groups; Plind = proportion of people self-identified with lowland indigenous groups; Pnoni = proportion of people who do not identify themselves with any indigenous group. pcom = proportion of area under communal property; ptco = proportion of area within indigenous territory; ppeq = proportion of area under small private property; pfisc = proportion of area under fiscal property; pmdeemp = proportion of area under medium and large private property; pprocno = proportion of non-formalized area or in process; tdef= forest cover change rate 2001-2010; defr=relative forest loss 2001-2010; regr=relative forest gain 2001-2010

The relationships found between these key variables calls for the recognition of "clustered chained drivers and processes" within the different areas of study, and use them to produce a typology of communities within the area on the base of these variables.
Fig. 3 shows the obtained typologies taking into account population density, poverty, ethnicity, accessibility and forest cover change in the Lao cases, and the same variables plus land tenure in the Bolivian cases, using k-means clustering into 4 to 6 classes. In the four cases, the class 0 represent the urban areas excluded from the analysis. Table 7 a and b show the median values (centroids) for the different variables of each class. The regional cases can now be further interpreted on the light of these typologies.

Table 7b. Median value of the used variables for the typologized classes in Laos

Luang Prabang province

Class	1	2	3	4	5
Popdens	19,5	**38,0**	16,1	21,6	10,7
P_Tai	19,5	**42,8**	14,5	2,7	15,5
P_Aust	**77,0**	**48,6**	**68,4**	8,8	**69,4**
P_MY_TB	2,9	7,8	16,3	**87,6**	14,1
D_prov	246,1	104,6	443,2	219,3	**707,1**
D_distr	181,7	73,7	334,8	159,4	**581,7**
Poverty	48,9	**35,4**	52,8	**51,2**	**58,1**
tdef	0,032	0,076	0,028	0,047	-0,017
defr	0,339	0,300	0,339	0,378	**0,505**
regr	0,251	0,200	0,273	0,270	0,208

Luang Namtha province

Class	1	2	3	4	5	6
Popdens	13,2	12,1	**44,3**	16,1	24,8	28,7
P_Tai	12,8	12,5	**26,5**	2,3	11,0	14,0
P_Aust	1,3	6,4	3,9	**94,7**	38,2	**81,2**
P_MY_TB	**84,6**	**80,2**	**68,9**	1,9	50,0	3,8
D_prov	358,2	233,5	**105,5**	347,5	619,3	**144,3**
D_distr	285,6	163,5	**59,3**	275,0	529,2	**90,7**
Poverty	44,7	42,2	**35,4**	57,2	46,4	40,8
tdef	0,031	0,008	-0,044	0,018	-0,013	-0,041
defr	0,274	0,347	**0,572**	0,373	0,450	0,463
regr	0,236	0,184	0,095	0,212	0,224	0,126

Popdens = population density; Poverty = proportion of poor people; D_dist = travel time to district capital; D_prov = travel time to province capital; P_Tai = proportion of people from Lao-Tai ethnolinguistic group; P_Aust = proportion of people from Austroasiatic ethnolinguistic group; P_MY_TB = proportion of people from Miao-Yao or Tibeto-Burman ethnolinguistic group; tdef= forest cover change rate 2000-2010; defr=relative forest loss 2000-2010; regr=relative forest gain 2000-2010

2.6.1. The North of La Paz forest landscape

One class (1) is represented by communities dominated by lowland indigenous peoples (median = 69%) with difficult access, indigenous territories and little forest conversion. The areas dominated by non-indigenous people (class 4) is also remote, dominated by State land and has little forest dynamics. The four other classes represent different levels of poverty, accessibility and land tenure types of Andean settler communities. Classes 2 and 3 are concentrated in the Apolo area, a little researched sector with difficult access, high poverty, and little State intervention in land titling. Forest conversion (mainly forest to crops and shrubs) appear to be higher among these two classes, and might be linked with the expansion of coca cultivation. Classes 5 and 6 represent Andean settler communities located along the main roads, with more private land titles and forest loss near the road, and more collective titles and less forest loss further away.

2.6.1. The Santa Cruz agroindustrial area

Classes 1 and 2 include communities with mostly non-indigenous or mestizo population (median > 70%) and high relative forest loss rates. Class 1 includes communities near the city of Santa Cruz but with a very high proportion of non-formalized titles. This might be linked to the high density of small properties difficult to register. But it could also be linked with passive resistance against the titling process in this region dominated by political opposition to the current government, especially because, since 2006, the land titling process includes the verification of socio-economic function and the possibility of expropriation. Class 2 represents areas slightly further away where titling under private regime is more advanced. In the region, the lowest forest conversion rate is found with areas occupied by lowland indigenous peoples, who also have the lowest population density (class 3). Classes 4 and 6 are areas dominated by Andean settlers, but with different degrees of poverty. Class 6 represent poorer communities with higher population density and small private titles. A particular case is represented by class 5: extreme poverty is extremely high (92%), but ethnic composition is mixed and there is the highest proportion of forest loss and medium and large landholdings. This area appears to bear high socio-economic inequality which might be reflected in land access as well.2.6.1. The Santa Cruz agroindustrial area.

2.6.1. The province of Luang Prabang

Three classes (1, 3, and 5) appear dominated by Autroasiatic peoples with increasing degrees of remoteness and poverty. Forest dynamics (both loss and gain) are high in the three cases but only the last one, the most remote, has a negative forest change balance. The reason why deforestation would be higher in remote areas remains unclear. Moreover, no land concessions and lease have been reported in that area (Schönweger et al., 2012). Class 2 is concentrated along roads and around urban centers. It has the highest population density, lowest poverty level, and the highest proportion of ethnic Lao, though still overcome by the Autroasiatic people. Class 4 is distinguished from the other mainly by ethnicity and the high proportion of Miao-Yao people (Hmong). However, in this class, other variables like accessibility, poverty and forest cover change do not differ from the other groups but rather represents a middle ground.

2.6.1. The province of Luang Namtha

Classes 1 and 2, dominated by Tibeto-Burman peoples, hardly differ among themselves, with class 1 representing somewhat more remote communities with less forest cover change, but without difference in population density. Class 3, the most densely populated and with the highest (though still minority) proportion of ethnic Lao, also shows the highest forest loss and easiest access. These communities are probably linked with the establishment of rubber plantations under contact schemes with Chinese enterprises, who can easily export their products to the nearby Chinese border, as observed by Guntern, (2013). In the south of the province, there are poorer communities dominated by Autroasiatic peoples (class 4), but with high regeneration rates, thus probably linked with slash-and-burn practices. Easier accessible communities with similar backgrounds (class 6) show higher forest loss and lower gain. Finally, class 5 represent ethnically mixed, more remotely located communities in the extreme South of the province, which also show both forest loss and gain.

3. Conclusions

What drives forest cover change in the study areas?

In the Bolivian cases, several forms of tenure insecurity can be identified: the fulfillment of socio-economic function in agroindustrial areas, and deforestation in remote and poorer areas without land formalization might drive forest cover change. At the contrary, common lands experience less deforestation and cannot be considered a more insecure land tenure type. The question of knowing whether commons are less deforested because they are more remote **[41]** merits further investigation. Nevertheless, in the Bolivian cases, deforestation appears more linked to a “tragedy of enclosures” than a “tragedy of the commons”. Roads are linked with relatively recent settlements (planned and spontaneous colonization) but usually precede them and respond to a national integration need by linking the country’s regions. On the other hand, colonization areas also show forest regeneration, which can be secondary fallow forest but also tree crops and plantations set up by the older settlers.

In the Lao cases, forest loss is often associated with forest gain, probably linked with slash-and-brun cycles. The balance between gain and loss varies in relation with accessibility, as observed in Luang Namtha. In this last case, the most accessible communities along the road to China represent another driving force for forest cover change: the establishment of rubber plantations, which appear as deforested areas when they are young. Poverty does not seem to be a driver of deforestation but rather cash crop opportunities and accessibility.

Three critical social-ecological contexts linked with high forest cover change emerge from the typological analysis:

1. Cash crops expansion areas, mainly rubber in Laos and soybean in Bolivia, usually show high forest loss and insignificant gain. These are the areas where global markets directly influence land cover. They occur in fishbone-like areas along roads and ring-like areas around urban centers. They typically show lower poverty rates, good accessibility, and are inhabited by culturally and economically

dominant ethnic groups. Within these areas, there are cases with high ethnic mix and high poverty but good accessibility, suggesting the emergence of high socio-economic inequalities.

2. Smallholder areas typically feature both forest cover loss and gain. They form a gradient between subsistence economy and market integration, with decreasing remoteness, increasing private property and increasing forest loss. The gradient includes lowland indigenous people areas in Bolivia, slash-and-burn cultivation areas in Laos dominated by ethnic minorities, and easily accessible Andean settlements along roads in Bolivia.

3. Some remote areas found with low population, high poverty and high deforestation (found in LPP and NLP) appear intriguing and are difficult to interpret in absence of field information. Both areas are located near national borders. Press reports **[40]** on a possible expansion of coca cultivation in a remote sector of the NLP area near the Peruvian border might be an element of explanation.

Poverty and population, often cited as causes of deforestation, appear not to have straightforward relationship with it. Poverty cannot be considered a driver of forest cover change, except in some remote areas for which little field data are available. Accessibility is what comes first. In Bolivia, infrastructure development often precedes settlements, but this might also be the case in Laos for resettled villages. Road accessibility drives a gradient from cash crop areas to smallholders and less integrated communities. This gradient sometimes corresponds to along population density (NLP), but sometimes not (LNP).

Are these findings generalizable to other contexts? Bolivia and Laos are sparsely populated and have a high forest cover, making these processes visible. When large areas become converted to cropland and have few forest patches, relative forest cover change rates might be quickly affected by small changes and the general picture become more blurred.

Assessing social-ecological systems at meso-scale: strengths and weaknesses

What could be captured using a meso-scale approach and what could not be? Coming back to the challenges posed by **[1]**, we can observe that the criterion of aggregating the data at fitting scales was fulfilled. Other challenges were however more difficult to overcome. First, the link between land cover change and people was determined by residence during censuses and travel time, which might mask more external actors that have influence on land use decisions. Secondly, the Landsat resolution of 30 m might poorly capture very small-scale cultivation, as it seems to be the case in the LPP area, thus underestimating slash-and-burn cultivation and misinterpreting fallows as secondary forest. The space-time match remains acceptable in Laos with census data at the middle of the assessed cover change period, but more problematic in Bolivia when census data were only available at the beginning of the study period. This is however somewhat compensated by the availability of more actual land tenure data.

Can census and land cover variables contribute to a diagnostic approach of social-ecological systems? As stated above, some key challenging configurations could be identified, such as market integration and tenure insecurity. Yet a meso-scale study cannot capture the way local organizations cope with change. Rather, it informs on the possible extent of contexts which should then be further characterized with studies at finer scales.

It seems noteworthy to formulate a last remark on the use of ethnicity as a relevant variable to land cover and the characteristics of social-ecological systems. Though ethnicity has been deemed an important variables in the first "people-to-pixel" approaches **[43]**, they are subject to the essentialist critique. As shown by **[29]** in Nothern Laos and **[44]** in the Bolivian Andes, very diverse land use practices can exist within an ethnic group. Cultural aspects should rather be considered as a pool of use options considered acceptable by a group, which are then modeled by socio-economic contexts. In this sense, ethnicity also appears as a cluster of converging socio-economic characteristics inherited by the history of groups that partly determine their location, settlement schemes, and access to land resources and to investment capital.

Acknowledgments

The research presented in this paper was financed by the Swiss Network for International Studies (www.snis.ch)

Author Contributions

Main text paragraph.

Conflicts of Interest

The authors declare no conflict of interest.

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