


Mapping, quantifying and assessing the effects of different social factors underlying recent trends in tropical forest cover change and biocultural conservation

A case study on the ancestral lands of Tsimane' Amerindians (Bolivian Amazon)

Jaime Paneque-Gálvez

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Mapping, quantifying and assessing the effects of different social factors underlying recent trends in tropical forest cover change and biocultural conservation.
A case study on the ancestral lands of Tsimane' Amerindians (Bolivian Amazon)

Tesis presentada por Jaime Paneque Gálvez para optar al grado de Doctor (PhD) por la Universitat Autònoma de Barcelona

Con la aprobación de los directores de la tesis doctoral

Dra. Victoria Reyes García   Dr. Jean-François Mas

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A la memoria de mi abuelo Fernando,
que me inculcó las ganas por aprender y la importancia del pensamiento crítico,
y que viaja conmigo a donde quiera que voy,

y a su inseparable compañera de viaje, mi abuela Lola,
con inmensa gratitud por su amor incondicional

A mis padres y hermanas,
por estar siempre ahí a pesar de la distancia y las diferencias

A Antonio Conejo,
por su amistad incondicional y por ser como un hermano para mí

A todas las personas que de una u otra forma
han hecho posible esta tesis doctoral, y muy especialmente a Viki, Ana y Alev

A Noelia, por todo su amor y su apoyo

Y a todas las personas que trabajan cada día en pro
de la justicia social y ambiental,
y de los derechos humanos

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Esta tesis doctoral constituye el final de un largo camino académico que se inició como estudiante en la facultad de Biología de la Universidad de Sevilla dada mi pasión por la naturaleza, y en particular por las aves y la conservación biológica. Convertirme en biólogo y conocer a varios de mis mejores amigos, compañeros de viajes y entusiastas naturalistas como yo, empezó a perfilar mi interés profesional. Le estoy particularmente agradecido a Antonio Conejo y Puri, a Leónidas, Raúl y Pedro, a Ana Verde, Bibi, Manu y Ana Yanes, todos ellos compañeros pajareros inseparables, y también a Ana de Santiago, Patri y Rorro. Posteriormente me licencié en ciencias ambientales en la facultad de Ciencias de la Universidad de Córdoba, con el objetivo de integrar aspectos geográficos, ambientales, y sociales a mi formación en ecología y conservación, lo cual despertó un profundo interés por la teledetección y los sistemas de información geográfica. Dicho interés motivó que hiciese un máster en ambas disciplinas, en el departamento de Geografía y Ciencias de la Tierra de la Universidad de Gales, Aberystwyth (Reino Unido). Conocer al que fuese mi supervisor en el máster, el Dr. Richard M. Lucas, ejerció una enorme influencia en mis intereses profesionales, contagiándome de su pasión por la teledetección ambiental y apoyándome para realizar mi investigación en un bosque tropical nublado de los Andes Ecuatorianos. A él le debo en buena medida haber obtenido unos buenos resultados en el máster, y haber decidido realizar un doctorado sobre bosques tropicales.

Después de vivir varios años en el Reino Unido y de trabajar durante un tiempo como técnico de SIG en una consultora ambiental en Inglaterra, llegar al Institut de Ciència i Tecnologia Ambientals de la Universitat Autònoma de Barcelona fue una experiencia tremendamente refrescante. Me siento muy privilegiado por haber conocido a tanta gente interesante y haber vivido en un ambiente académico tan enriquecedor. Asimismo, me siento extremadamente afortunado por haber tenido la oportunidad de trabajar bajo la dirección de Viki, que ha sido una fuente incesante de inspiración y aprendizaje. Su dedicación y calidad académica, además de su trato a nivel personal, son algo muy difícil de encontrar, como un tesoro. A ella le debo en buena medida mi creciente interés por el mundo académico, el mundo indígena, y la investigación social, y espero poder seguir trabajando juntos en la nueva etapa que se abre ahora ante mí. Además, me siento muy afortunado de haber compartido tesis, trabajo de campo, y múltiples aventuras urbanas y campestres con Ana Catarina Luz y Max Guèze. No puedo imaginar a compañeros mejores durante estos años y deseo de corazón que encontremos la manera de seguir trabajando juntos, estemos donde estemos. Me resulta imposible expresar con palabras el agradecimiento que siento hacia Alev, mi compañera y guía durante casi toda la tesis, con la que viví tantos buenos momentos a pesar de las dificultades que afronté durante la tesis: teşekkürler ederim aşkım, seni çok seviyorum. Me siento asimismo feliz de haber hecho grandes amigos en el ICTA. A Pablo, Francisco, Isa, Martí, Jovanka, Laura, y al resto de compañeros del Laboratorio de Etnoecología; a Arnim, Sara, Gonzalo, Pere, Tarik, y al resto de gente del Grupo de Análisis de Sistemas Rurales; a María Heras, Marina, Zora, Christian, Almudena, Ethem, Hyerim, Cris, Irene, y a todos los que sin duda me olvido con las prisas de última hora, os doy las gracias por haberme hecho disfrutar y aprender tanto con vosotros. Especiales gracias a Marina y Ana por las gestiones burocráticas relativas al depósito de la tesis, por lo que les estoy tremendamente agradecido. En Barcelona también a Caro y a Fer, por haber compartido piso, sueños y tantos momentos bonitos juntos en Barcelona.

De mi estancia en Bolivia tengo sinceras palabras de agradecimiento para nuestros amigos Tsimane', Evaristo Tayo, Paulino Pache, Fernando Saravia, y Marco Lero, sin cuya ayuda no hubiéramos podido hacer nada. Al pueblo Tsimane' en general, por su enorme paciencia, generosidad, y por permitirnos compartir con ellos esta preciosa experiencia. Ojalá que puedan disfrutar de sus increíbles cielos estrellados por siempre, que no se extingan los amos del bosque, y que sus niños, los más felices que vi jamás, no pierdan la sonrisa y las ganas de jugar. Agradezco los consejos y el entusiasmo científico de Ricardo Godoy, y el apoyo logístico de Tomás Huanca, Esther Conde y Milenka Aguilar, quien me ayudó además a muestrear las zonas de sabana junto con Evaristo. Y sobre todo gracias a Ana y a Max por haberme acompañado en esta experiencia amazónica; sin ellos, ni la cocina de Doña Sandra ni la vida en nuestro particular Macondo hubieran sido tan divertidas a pesar de las largas jornadas de trabajo.

Mi primera estancia en el Centro de Investigaciones en Geografía Ambiental, de la Universidad Nacional Autónoma de México (Morelia, Michoacán, México), llevada a cabo en 2011, me permitió iniciar una fructífera colaboración con Jean-François, al que había conocido poco antes en un congreso internacional de ecología del paisaje en Portugal, y que hizo que se convirtiera en mi co-director de tesis. Posteriormente realicé dos estancias más en 2012, donde escribí buena parte de esta tesis. Empezar a trabajar con Jean fue clave para terminar de solucionar diversas dudas que tenía con respecto a cuestiones metodológicas de teledetección, y para entender bien las diversas metodologías que podía emplear para hacer el análisis de cambios forestales. Su trato personal fue asimismo encomiable, y le estoy muy agradecido por todo su apoyo. Además, quisiera agradecer los buenos momentos compartidos con todos los amigos del CIGA, especialmente a Iván (el padre espiritual del Franch), Carlos, Caro, Pedro, Raquel, Gabi, Frida, Maluca, Ale, Miriam, Daniela. También agradecer a los amigos que hice fuera del CIGA durante este tiempo y que hicieron mis estancias más agradables, especialmente a Daniela, Érika, Alicia, Gabi, y a la gente del Foro4 y Cotacum.

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List of Main Acronyms

LULC: Land use - land cover

FCC: Forest cover change

LC: Land use/cover

TEK: Traditional ecological knowledge

EGDF: Early-growth / degraded forest

OGF: Old-growth forest

TM: Thematic Mapper

ETM+: Enhanced Thematic Mapper

ML: Maximum likelihood

KNN: *k*-nearest neighbors

SVM: Support vector machines

RBF: Radial basis function

MMHC: MiraMon's software hybrid classifier

GLCM: Gray-level co-occurrence matrix

HI: Homogeneity Index

OA: Overall accuracy

PA: Producer's accuracy

UA: User's accuracy

CM: Confusion matrix

TCO: Tierra Comunitaria de Origen

PLAND: Percentage of landscape

ED: Edge density

CPLAND: Core area percent of landscape

PAFRAC: Perimeter-area fractal dimension

OLS: Ordinary least square [regression]

Abstract

Tropical forests play a key role in biodiversity conservation, hydrological regulation, regional and global climate, and are vital to support the livelihoods of their dwellers. Nevertheless, the current extent and intensity of land use/cover change in tropical forests is driving their loss, fragmentation, and degradation at alarming rates. Therefore, it is a matter of the utmost importance to understand the underlying driving forces of loss and impoverishment of tropical forests so that more effective conservation policies can be enacted. In this PhD thesis I carry out a case study on the ancestral lands of Tsimane' Amerindians, an indigenous society of hunter-gatherers and farmers native to the Bolivian Amazon, with the primary goals of mapping, quantifying and assessing the effects of different social factors underlying recent trends in forest cover change and levels of biological and cultural conservation. Specifically, I devote the first research chapter to devise an efficient remote sensing classification approach to accurately map broad land cover classes, including both early-growth and old-growth forests, as a basis for the assessments of trends in forest cover change and of forest conservation. In the second research chapter I assess the effects of different land tenure systems on forest cover change, while in the third one I evaluate the potential role of indigenous traditional ecological knowledge in old-growth forest conservation at a time such knowledge is being lost due to a rapid acculturation process. Although land tenure and cultural change may underlie tropical forest cover change and thus forest conservation, to date their effects have not been adequately examined, and this PhD thesis aims to contribute to previous research on such topics. The Tsimane' constitute an excellent case study to accomplish the goals of this thesis because their settlements are currently scattered across different land tenure systems, and because they display the largest variation amongst native Bolivian Amazonians regarding market integration, which also reflects on a great variation regarding traditional ecological knowledge and acculturation. Also, because they have been extensively studied in the last 15 years and there are historical studies about them, so I can draw on previous data and results to better interpret my findings.

My results contribute to improving methods for mapping and quantifying land use/cover change in tropical heterogeneous landscapes, which is challenging and nevertheless critical to enhance carbon mapping, biodiversity assessments, natural resource management, and territorial planning. In addition, I use a novel approach to integrate and analyze data derived from remote sensing imagery with data obtained from social surveys, which remains a challenging task in land change science. At a theoretical level, my findings provide new insights into the effects of land tenure and indigenous knowledge on tropical forest conservation, which are factors still poorly understood in the Amazon basin and elsewhere. My results have significant implications for public policies aimed at socioeconomic development and environmental conservation in the Amazon and I give some policy recommendations drawn from a biocultural conservation perspective. For instance, my results on the effects of land tenure on forest cover change show that indigenous territories may be as effective as protected areas for forest conservation, which suggests the benefits of expanding the number and/or size of indigenous territories and the need of strengthening indigenous governance. Results also show that logging concessions may be very effective to prevent forest from clear-cutting, and that conservation incentives are needed in private lands to curtail their high and increasing levels of deforestation and forest degradation. As regards the role of indigenous traditional ecological knowledge in forest conservation, I find both their levels are significantly associated, and that there is a very significant spatial overlap, something that had not been assessed at the local scale, and that suggests the existence of a functional connection between both cultural and biological diversity. This finding implies that forest conservation policies should proceed hand in hand with the protection of indigenous knowledge, which has important implications for indigenous rights to land and natural resources management.

Key words: land change science; land use; land cover; land use/cover change; tropical deforestation and degradation; forest fragmentation; remote sensing; thematic classification; land tenure; protected area; logging concession; private land; indigenous territory; indigenous knowledge; cultural change; biocultural conservation; Tsimane'; Amazon; Bolivia

Resumen

Los bosques tropicales juegan un papel clave en la conservación de la biodiversidad, la regulación hidrológica, el clima regional y global, y son vitales para el sustento de sus habitantes. Sin embargo, la extensión actual y la intensidad de los cambios de usos del suelo y de cobertura en los bosques tropicales están propiciando su pérdida, fragmentación y degradación a un ritmo alarmante. Por lo tanto, comprender los factores subyacentes a la pérdida y al empobrecimiento de los bosques tropicales es un asunto de enorme importancia para que se puedan implementar políticas de conservación más eficaces. En esta tesis doctoral llevo a cabo un estudio de caso sobre las tierras ancestrales de indígenas Tsimane', una sociedad indígena de cazadores-recolectores y agricultores nativos de la Amazonía boliviana, con los objetivos principales de cartografiar, cuantificar y evaluar los efectos de diferentes factores sociales que subyacen a las tendencias recientes en el cambio de la cubierta forestal y los niveles de conservación biológica y cultural. En concreto, dedico el primer capítulo de investigación a elaborar un enfoque eficaz para mapear con precisión clases generales de usos del suelo/cobertura, que incluyen tanto los bosques en regeneración como los maduros, como base para la evaluación de las tendencias en el cambio de la cubierta forestal y del grado de conservación forestal. En el segundo capítulo de investigación evalúo el efecto de diferentes sistemas de tenencia de la tierra en el cambio de la cubierta forestal, mientras que en el tercero investigo el papel potencial del conocimiento ecológico tradicional indígena en la conservación de los bosques maduros, en un momento en que el conocimiento se está perdiendo debido a un proceso de aculturación rápida. Aunque la tenencia de la tierra y el cambio cultural pueden ser factores subyacentes a los cambios en la cobertura forestal, y por tanto determinantes de su grado de conservación, hasta la fecha sus efectos no han sido adecuadamente examinados, por lo que esta tesis doctoral tiene como objetivo contribuir a la escasa investigación existente sobre estos temas. Los Tsimane' constituyen un excelente caso de estudio para lograr los objetivos de esta tesis porque sus asentamientos están dispersos en diferentes sistemas de tenencia de la tierra, y porque muestran la mayor variación entre los nativos amazónicos bolivianos con respecto a la integración del mercado, lo que también se refleja en una gran variación en cuanto a conocimientos ecológicos tradicionales y aculturación. Además, debido a que han sido ampliamente estudiados en los últimos 15 años y a que hay estudios históricos acerca de ellos, puedo recurrir a los datos y resultados existentes para interpretar mejor mis resultados.

Mis resultados contribuyen a mejorar los métodos existentes para mapear y cuantificar los cambios de usos del suelo y de cubiertas en paisajes tropicales heterogéneos, lo cual es difícil y sin embargo fundamental para mejorar las estimaciones de carbono en bosques, las evaluaciones sobre biodiversidad, la gestión de los recursos naturales, y la planificación territorial. Además, uso un enfoque novedoso para integrar y analizar los datos derivados de las imágenes de satélite con datos obtenidos encuestas sociales, lo cual continúa siendo una tarea complicada en la ciencia del cambio de usos del suelo y de cubiertas. A nivel teórico, mis resultados proporcionan nuevos conocimientos sobre los efectos de la tenencia de la tierra y el conocimiento indígena en la conservación de los bosques tropicales, que son factores todavía poco conocidos tanto en la cuenca del Amazonas como otros lugares. Mis resultados tienen implicaciones importantes para las políticas públicas para el desarrollo socioeconómico y la conservación del medio ambiente en la Amazonía y doy algunas recomendaciones en materia de políticas públicas, desde una perspectiva de conservación biocultural. Por ejemplo, mis resultados sobre los efectos de la tenencia de la tierra sobre los cambios en la cubierta forestal demuestran que los territorios indígenas puede ser tan eficaces como las áreas protegidas para la conservación forestal, lo que sugiere los beneficios de ampliar el número y/o tamaño de los territorios indígenas, y la necesidad de fortalecer la gobernanza indígena. Los resultados también muestran que las concesiones madereras pueden ser muy eficaces para prevenir los bosques de la deforestación, y que algún incentivo de conservación es necesario en terrenos privados para reducir sus altos niveles (y crecientes) de la deforestación y la degradación forestal. En cuanto al papel del conocimiento ecológico tradicional de los pueblos indígenas en la conservación forestal, mis resultados muestran que los niveles de ambos están significativamente asociados, y que existe entre ellos una superposición espacial muy importante, algo que no había sido evaluado con rigor a escala local, y que puede sugerir la existencia de un conexión funcional entre la diversidad cultural y biológica. Este hallazgo implica que las políticas de conservación forestal deben buscar también la protección del conocimiento indígena, lo cual tiene importantes implicaciones para los derechos indígenas sobre la tierra y los recursos naturales.

Palabras clave: ciencia de cambios de usos del suelo y cubiertas; cambio de usos del suelo; cambio de cubiertas; deforestación y degradación tropical; fragmentación forestal; teledetección; clasificación temática; tenencia de la tierra; áreas protegidas; concesiones madereras; tierras privadas; territorios indígenas; conocimiento indígena; cambio cultural; conservación biocultural; Tsimane '; Amazonas; Bolivia

Chapter 1

Introduction

In Gaia we are just another species, neither the owners nor the stewards of the planet. Our future depends much more upon a right relationship with Gaia than with the never ending drama of human interest

(James Lovelock)

1. Research Problem: forest cover change in the Bolivian Amazon

Land use and land cover (LULC) change have become one of the main global environmental problems of our time owing to the significant disruption they cause to the functioning of ecosystems and the services they provide (Foley *et al.*, 2005) as well as to their effects on climate change (Pielke, 2005). LULC change is particularly worrying across tropical regions and, more specifically, in tropical forests, given their critical importance for biological conservation, hydrological and climatic regulation, and for biogeochemical cycles (Nepstad *et al.*, 2008; Rodrigues *et al.*, 2009), and given the high rates of conversion of tropical forests into anthropogenic LULC types (e.g., farmland, pasture, urban) (Lambin, 1997; Turner, 2003; Gibbs *et al.*, 2010; Lambin and Meyfroidt, 2011). Therefore, the loss, fragmentation and degradation (i.e., forest impoverishment caused by human-induced factors such as fire, logging and climate change) of tropical forests have been at the center stage of the environmental debate for several decades. Furthermore, tropical forests play a vital role in supporting people's livelihoods (Pimentel *et al.*, 1997; Agrawal *et al.*, 2008), alleviating poverty (Sunderlin *et al.*, 2008), and ameliorating the spread of infectious disease (Foley *et al.*, 2007) such as malaria (Vittor *et al.*, 2009). Thereby, owing to its pervasive consequences for human-environment systems, it is critical to develop effective systems to monitor and systematically assess tropical forest condition over time, as well as to assess the effects of geographical, environmental and social factors that may influence or bring about changes in forest cover.

Land change science has emerged over the last decade in growing recognition of the key role that LULC change plays into global environmental change and its implications for sustainability science (Rindfuss *et al.*, 2004). This new scientific field acknowledges the need for integrative approaches that combine methods and theories from geographic, natural, and social sciences, as traditional studies based on single disciplines are not well suited to elucidate the complex patterns and processes of coupled human and natural systems (Liu *et al.*, 2007). Land change science has four major components, namely: 1) observation, monitoring and land characterization to assess land changes underway throughout the world, 2) analysis of the causes, impacts and consequences of land change in human-environment systems, 3) spatially-explicit modeling of land change, and 4) assessment of system outcomes as a result of change (Turner *et al.*, 2007). Given the high complexity of proximate causes and underlying driving forces of FCC in tropical regions (Geist and Lambin, 2002), this new science is to play a critical role in finding solutions in the quest for sustainability.

To date, much of the public and scientific concern about the fate of tropical forests has been raised with respect to the rainforests of the Amazon basin, and particularly those within Brazil due to their extent and relative importance: two thirds of Amazonian forests, ~40% of remaining rainforests worldwide (Laurance *et al.*, 2001), and key for global biodiversity conservation (Brooks *et al.*, 2006). Yet, in spite of the many studies focusing on specific underlying driving factors and proximate causes of forest cover change (FCC) in the Brazilian Amazon, some of them are understudied and therefore poorly understood. This would be the case, for instance, of studies assessing the role of policy and institutional factors such as land tenure, or of cultural factors such as traditional ecological knowledge and cultural change, in FCC. Therefore, we are still far from attaining a clear picture of what the factors of Amazonian FCC are, and how the interact with each other. In addition, the study of FCC dynamics across the non-Brazilian Amazon basin is paramount to effectively protect the full range of Amazonian biodiversity and ecosystem services, as well as the many people who depend on them (Sierra, 2000). In effect, in comparison with studies focusing on FCC across parts or even the whole Brazilian Amazon, relatively few studies have attempted to map, quantify and/or identify the main determinants of FCC in other Amazonian areas.

Regarding the Bolivian Amazon, there have been several studies with that pursue (e.g., Kaimowitz, 1997; Pacheco, 1998; Steininger *et al.*, 2001a; Steininger *et al.*, 2001b; Pacheco, 2002; Mertens *et al.*, 2004; Pacheco, 2006; Killeen *et al.*, 2007; Killeen *et al.*, 2008; Marsik *et al.*, 2011; Müller *et al.*, 2011; Redo *et al.*, 2011; Southworth *et al.*, 2011; Müller *et al.*, 2013). Critically, even though some of those studies are very comprehensive and have led to an enhanced understanding of the spatio-temporal dynamics of FCC and their underlying driving forces and/or proximate causes, most have relied on secondary data and made little or no use of primary social information at the household and regional levels. In addition, the spatial scale of remotely-sensed data has frequently been too coarse to derive accurate FCC estimates, and/or the extent of the study area too large as to adequately explain the plausible drivers of FCC. Lastly, most studies on FCC in the Bolivian Amazon have focused on the Santa Cruz Department owing to its economic importance and the high rates of forest conversion that have taken place there over the last few decades. Yet, we do not have much information about trends in FCC for other areas of the Bolivian Amazon, nor do we have information on the main drivers of such trends at local scales. In this PhD thesis I aim to contribute to filling up those methodological and theoretical gaps.

1.1. Rationale and main contributions of this PhD thesis

Previous researchers have suggested that, in order to inform the design and implementation of effective policies for slowing down FCC to sustainable levels, detailed studies at the local scale are particularly needed (e.g., Kaimowitz and Angelsen, 1998). In my PhD I have carried out a case study on FCC focusing on the ancestral lands of Tsimane' Amerindians, an indigenous group of hunter-gatherers and farmers native to the Bolivian Amazon. The Tsimane' constitute an excellent case study to undertake a FCC assessment for five main reasons: 1) they have been extensively studied over the last decade in relation to different socioeconomic, political, cultural and environmental issues, by means of both panel and cross-sectional surveys (www.tsimane.org), 2) here are historical studies on the Tsimane' that may help understand trends in FCC (e.g., Reyes-Garcia *et al.*, in review-c), 3) the Tsimane' display a large variation regarding their level of integration to the market at the household and the village levels, which leads to economic differences among them but also to differences regarding their use of natural resources, traditional ecological knowledge, acculturation, health, and well-being (Godoy *et al.*, 2005; Godoy *et al.*, 2009b), all of which have potential implications for FCC, 4) Tsimane' settlements are nowadays scattered across an array of land tenure systems, each one with specific legal restrictions on land use and natural resource management (Reyes-García *et al.*, 2012), which also poses important implications for FCC, and 5) even though some studies have attempted to estimate the potential association between different socioeconomic and cultural factors and both old-growth and fallow forest clearance (Reyes-Garcia *et al.*, 2007b; Vadez *et al.*, 2008; Godoy *et al.*, 2009c; Reyes-Garcia *et al.*, 2011), they have done so by using self-reported estimates of the area deforested for agriculture over the previous farming cycle (Vadez *et al.*, 2003), and thus their conclusions may be flawed because they have not made use of spatial data nor have they accounted for temporal dynamics longer than a year.

Therefore, the Tsimane' case study provides a unique opportunity as regards the analysis of FCC because there is already abundant baseline data, much of which has already been analyzed and published, yet there is plenty of room for improvement through the use of spatial data analyses. Indeed, the use of spatial data provides a robust means of assessing not only the spatial dimension of FCC, but its temporal one too, which may be linked to underlying factors such as land development policies (e.g., land tenure reforms undertaken in Bolivia over the last few decades), or the ongoing processes of Tsimane' acculturation and integration into the market economy. Nonetheless, detailed LULC maps of sufficient spatial resolution have not been produced for the Tsimane' territory. Similarly, accurate assessments of FCC have only been carried out in regard to old-growth forest loss (Killeen *et al.*, 2007), but not as regards early-growth forest dynamics (whether deforestation or regrowth) nor in regard to other important factors for conservation such as forest fragmentation and degradation.

Acknowledging those limitations, my first goal within the scope of this PhD thesis is to devise a remotely-sensed data classification approach to produce accurate LULC maps for the Tsimane' territory and its adjacent areas (i.e., roughly the Tsimane' ancestral lands). Accomplishing this task is paramount to satisfy the remaining goals of this thesis as it constitutes the basis upon which I carry out the subsequent FCC analyses. To achieve this first goal, I devise an approach that seems very well suited for classifying complex, heterogeneous tropical landscapes. Given the current challenges of mapping LULC in tropical regions, the development of such approach bears significant implications for the many applications that require accurate LULC maps over tropical areas (e.g., biodiversity assessments, carbon mapping, landscape planning, or LULC change assessments). The second goal of the dissertation is to assess the effects of different land tenure systems on the spatio-temporal dynamics of FCC. To do that, I first apply the LULC classification approach previously devised to a time-series of Landsat satellite data consisting of four dates (1986, 1996, 2001, 2009). Then, I derive 1) trends in early-growth and old-growth forest extent, and 2) trends in old-growth forest fragmentation, both in accordance with areas under four different land tenure systems throughout the periods 1986-1996, 1996-2001, and 2001-2009. This analysis sheds light into the extent up to which different land tenure systems may drive or influence the fate of forests in the Amazon, a policy factor whose importance regarding FCC has been acknowledged in different studies but remains poorly assessed as aforementioned. My last goal is to evaluate whether there exist a significant association and a spatial overlap between Tsimane' traditional ecological knowledge and the conservation state of old-growth forests surrounding their villages. This analysis is important because 1) it contributes to further our little understanding of the associations between cultural and biological diversity and 2) it might provide the first attempt to accurately assess the spatial overlap of cultural and biological conservation at a local scale. Results from the last two analysis have significant implications for public policies aimed at socioeconomic development and environmental conservation in the Amazon. Thus, the assessment of the effects of land tenure on FCC may guide the future allocation of land use activities in this and other regions of the Amazon, and provided that traditional ecological knowledge and old-growth forest conservation are significantly associated, biological conservation policies in the region should be reformulated so they protect cultural diversity as well.

2. <u>Background</u>

This PhD thesis presents a case study that addresses the first two land change science components outlined above, and serves as a baseline to carry out further research focusing on the other two components. The first component is of fundamental importance as it sets the stage for analyses regarding each of the other components. Thus, characterizing land into different LULC types is a first critical step if, for example, one wants to estimate land change in a specific location, or wants to assess the factors underlying such land change, or model future changes based on a set of plausible scenarios. Such a characterization is done using remote sensing data, whether air-borne or space-borne, most frequently applying classification techniques that produce LULC maps. Land change, such as FCC, can then be derived following post-classification analyses, which is a relatively straightforward technique to detect change (Mas, 1999; Lu *et al.*, 2004). However, classifying LULC in tropical areas, particularly those that have different ecosystems (i.e., different types of natural and disturbed forests, savannas, agricultural areas, grasslands, marshlands) remains a very challenging task. This, in turn, affects our ability to accurately detect and quantify certain land changes over tropical regions. The next subsection focuses on giving a brief explanation in this respect as my first goal of this dissertation tackles this methodological limitation. The following two subsections provide an overview of two factors that are known to underlie tropical FCC on occasions: land tenure, a policy factor, and traditional ecological knowledge and its loss (i.e., acculturation), a cultural factor (Geist and Lambin, 2002). The effects and potential role of both factors remain poorly understood given a relative scarcity of assessments carried out to study them, including a total lack of this kind of studies for the Bolivian Amazon.

2.1. Challenges in mapping Amazonian LULC and quantifying forest cover change

Mapping tropical LULC at adequate spatial scales through the use of satellite imagery continues to be a very challenging task. Even though the latest improvements in the spatial, spectral, and temporal resolution of space-born imagery have somewhat eased such a task, there are several important constraints that are yet to be overcome. For instance, new satellite sensors of very high-spatial resolution (i.e., <1m panchromatic, <3-4m multispectral) are now available (e.g., QuickBird, IKONOS, GeoEye-1), but the footprint of their images is very small (e.g., 16.5km x 16.5km for QuickBird), their cost is extremely high (several thousand US dollars per scene), and their spectral resolution may not suffice for tropical habitat discrimination (typically 1 panchromatic band and only 3-4 multispectral bands in the visible and near infrared). Likewise, space-born hyperspectral imagery now exist (EO-1 Hyperion) at a relatively high spatial resolution (30m), which would potentially make possible to discriminate forest communities (Chambers *et al.*, 2007). However, these images are narrow strips of ~36km x 7.5km so it is very unlikely that they are able to provide full coverage of one's area of interest; thereby their usefulness remains very limited at operational levels. Air-borne hyperspectral imagery could resolve that problem, while increasing our ability to discriminate vegetation formations and even single tree species at high-spatial resolutions (Clark and Roberts, 2012), but the cost of deploying a mission may be too high for most studies. Something similar happens with the use of LiDAR data, which are promising for mapping tropical forest species and communities when used in combination with hyperspectral or multispectral data

(Asner *et al.*, 2008). Yet, space-born LiDAR systems do not provide high-spatial resolution (Lefsky, 2010) and air-borne LiDAR missions are very expensive and thereby most studies cannot afford the cost unless they need to cover small areas. And the same can be said about radar imagery, which may only provide sufficiently detailed LULC information when data are gathered with different polarizations at very high-spatial resolution, which needs the commission of aircraft flights and hence results in high economic cost and the consequent limitation to cover large areas.

Additionally, all the aforementioned imagery types may not provide adequate temporal resolution, an issue that may be problematic to study LULC change in very dynamic areas such as agricultural frontiers. Coarse-resolution (>250m) multispectral sensors such as MODIS, which provide much higher temporal resolutions (1-2 days), may seem a potential solution, but their spatial resolution may not be enough. Moreover, coarse-resolution satellite data are particularly affected by mixed pixels, i.e., by the fact that a single pixel does not represent a single LULC type, but a mixture of two or more types (as a direct consequence of the big size of pixels), which severely affects our capacity to derive accurate LULC classifications from these sensors, even after appropriate techniques such as linear spectral unmixing are employed prior to data classification. Importantly, both multispectral and hyperspectral systems are affected by cloudiness, a persistent feature over the Amazon (Asner, 2001), which severely limits our ability to gather cloud-free data from which to classify LULC. The problem is more acute when more than one image within a single year is needed to derive an accurate classification owing to strong seasonal differences in cover (e.g., agricultural areas, deciduous forests) or illumination (e.g., high-relief areas). Cloudiness can also severely hamper the construction of a time-series using the same periods of the year (e.g., always during the dry season) so as to minimize spectral differences as a result of phenological changes. As to date, Landsat TM/ETM+ imagery has provided the best compromise in most studies seeking to classify LULC and/or to assess LULC changes (Townshend *et al.*, 2012) and hence the pivotal role of Landsat sensors in ecological studies (Cohen and Goward, 2004).

In addition to the inherent limitations of remote sensing systems available for Amazonian LULC mapping, there are limitations in the techniques at our disposal. Thus, although conventional classification approaches have been relatively successful in mapping distinct LULC types (e.g., old-growth forest cover, pasture, large-scale agriculture, water bodies) and distinct LULC changes (e.g., deforestation), such approaches have failed to accurately map different stages of growth in regenerating and degraded forests owing to their spectral complexity and dynamism (Vieira *et al.*, 2003). This fact has had significant implications for the reliability of estimations of carbon stocks and emissions (Asner *et al.*, 2010), and for biodiversity assessments in tropical forests (Peres *et al.*, 2006). Even though significant progress has been made in these fronts since the late 1990s (Nepstad *et al.*, 1999; Lucas *et al.*, 2000; Vieira *et al.*, 2003; Asner *et al.*, 2005; Souza *et al.*, 2005; Matricardi *et al.*, 2010), mapping early-growth and degraded forests from remotely-sensed data such as Landsat continues to be a challenging enterprise plagued with difficulties at an operational level. Indeed, no single method has proven to be fully valid in every location and for every acquisition condition. And yet, different mapping approaches may yield significantly different results, as I have verified for this study area. As a consequence, the reliability of LULC change assessments and, in particular, of FCC studies (other than deforestation) conducted over large areas of Amazonia, remains probably low. Hence the need to improve remote sensing classification approaches from which to derive FCC assessments.

2.2. Effects of land tenure systems on Amazonian forest cover change

Land tenure may seriously affect FCC dynamics and thus forest conservation because it usually regulates land use types and their intensities. Yet, in spite of their potential importance and that calls for such assessments have long been made (e.g., Thiesenhusen, 1991), few comprehensive empirical assessments have been carried out to account for the effects of land tenure systems (and tenure insecurity) on FCC in Amazonia. Fearnside (1993) observed that, for the Brazilian Amazon, private land tenure had significant effects on deforestation. Specifically, he found that medium- (100-1000ha) and large-sized (>1000ha) properties were responsible for ~70% of the total extent of deforestation, whereas small farmers accounted for the remaining 30% (though deforestation was more intense as a result of higher population densities). Nowadays the same trend persists in the Brazilian Amazon as shown by Pacheco (2012). Further, Fearnside (2001) showed how deforestation was a primary form of claiming land ownership among landless migrants as well as a way to increase tenure security among landholders in the State of Pará (Brazilian Amazon). This land use strategy has been shown to be a typical mechanism in other parts of the Amazon basin such as Ecuador (Pichon, 1997; Messina *et al.*, 2006), Peru (Pinedo-Vasquez *et al.*, 1992) and Bolivia (Godoy *et al.*, 1998; Bottazzi and Dao, 2013), particularly in frontier settings where access to land and markets is favored by governmental policies and facilitated by the development of infrastructure, which attracts landless migrants (Pacheco, 2009).

Among the few assessments found in the scientific literature regarding the effects of different land tenure systems (and thus of land use allocation) in the Amazon basin, it is worth mentioning the work carried out by Nepstad *et al.* (2006). In their seminal work, which included all the Brazilian Amazon, they demonstrated that indigenous titled lands were very effective in inhibiting both deforestation and fire in old-growth forests, particularly as they often impeded the advancement of colonization frontiers. This situation differed from that of protected areas (parks and biological reserves), whose effectiveness in preventing deforestation was better explained by their remoteness and isolation. Nepstad *et al.* (2006) argued that, owing to the sheer extent of indigenous reserves in the Brazilian Amazon (one fifth of its total extent), indigenous lands were vital for biological conservation and that their governance should be strengthened with a broad base of political support. In a similar vein, Oliveira *et al.* (2007) found that over 1999-2005 and throughout the Peruvian Amazon, protected areas and indigenous territories were very effective in protecting old-growth forest from deforestation and degradation, while recent logging concessions were very effective in preventing forest from being clear-cut but not from being degraded. Similarly, the implications of protected areas and indigenous lands in the current context of climate mitigation schemes have also been highlighted (Ricketts *et al.*, 2010; Soares-Filho *et al.*, 2010) as the most effective way to reduce the emissions caused by tropical deforestation and degradation. Conversely, several studies have highlighted the high rates of forest clearance, fragmentation and degradation encountered in colonist settings across the Amazon (e.g., Sierra, 2000; Pacheco, 2002; Rudel *et al.*, 2002; Messina *et al.*, 2006; Nepstad *et al.*, 2006; Fearnside, 2008; Killeen *et al.*, 2008; Lu *et al.*, 2010; Pacheco, 2012). This is worrisome trend because, as LULC change continues to expand across the Amazon basin (Davidson *et al.*, 2012) and the ecosystem goods and services they provide to us are increasingly degraded (Foley *et al.*, 2007), some assessments claim that the current network of protected areas (biological reserves, indigenous lands, and sustainable use lands -e.g., low intensity logging concessions) will not be enough for maintaining adequate levels of ecosystem services and therefore, some forms of conservation will also be needed in private lands (Soares-Filho *et al.*, 2006).

In the specific case of Bolivia, the effects of land tenure systems have been analyzed mostly from a social justice perspective, i.e., the rights of indigenous peoples over their ancestral lands and natural resources (Assies, 2006; Reyes-Garcia *et al.*, in review-c), and from an economic point of view, i.e., their implications for economic development (INRA, 2008). Several studies on forest tenure systems have also been published in relation to different forestry policies (de Jong *et al.*, 2006; Cronkleton *et al.*, 2009; Pacheco *et al.*, 2010), particularly emphasizing the effects of decentralization policies on the forest sector and the economic pathways that those forestry policies open for indigenous and rural inhabitants' forest management (Pacheco, 2004). Nevertheless, to date there has not been any attempt at mapping and quantifying the effects of land tenure systems in the Bolivian Amazon in spite of the important changes regarding land tenure that have taken place in the region from the 1950s and, particularly, from the mid-1980s . Such changes will be summarized in the third section, dedicated to give an overview of the Tsimane' case study.

2.3. Indigenous traditional ecological knowledge and conservation of Amazonian old-growth forests

Geist and Lambin (2002) discriminated five broad types of underlying driving forces of tropical deforestation, namely: demographic, economic, technological, policy and institutional, and cultural factors. Among them, cultural factors have received comparatively little attention and so literature addressing the association of cultural change affecting individual/household behavior on FCC is scarce. Agent-based models have recently gained momentum in studies of deforestation to address the latter issue, i.e., to understand individual/household decision-making as regards FCC (Deadman *et al.*, 2004; Robinson *et al.*, 2007). Yet, the potential role of culture and cultural change (or acculturation as it is also referred to) in FCC remains understudied. There is a growing body of literature concerned with indigenous' and traditional societies' cultures and their role in protecting biodiversity, particularly as regards traditional ecological knowledge (TEK). This increasing interest has crystallized into a new scientific field that is concerned with the study of biocultural diversity (Maffi, 2005), which stems from the relatively recent recognition of two facts. First, the global spatial overlap between biological diversity and indigenous' and traditional societies' cultural diversity (often proxied by language diversity), which suggests the existence of a functional connection between both types of diversity (Gorenflo *et al.*, 2012). And second, the fact that not only biodiversity, but also cultural diversity, are severely threatened worldwide (Reyes-Garcia *et al.*, in review-a), often by the very same forces (Sutherland, 2003).

Most studies focused on TEK have documented indigenous knowledge regarding plants (Reyes-Garcia *et al.*, 2006; Turner and Turner, 2008; Moreno-Calles *et al.*, 2012) animals (Dowsley, 2009), soils (Barrera-Bassols and Zinck, 2003), climate (Peloquin and Berkes, 2009) or indigenous' full understanding of their coupled human-environment system including their skills to use that knowledge and the beliefs to regulate the use and management of natural resources (Posey, 2002; Huanca, 2006; Alarcón-Cháires, 2009). Such studies have usually suggested the importance of TEK for biological conservation, some of them providing empirical assessments to support that claim (e.g., the existence of higher floristic diversity in areas with higher TEK). But all too often such studies have been carried out in just one community, or in very few, which makes difficult the extrapolation of results beyond those few locations. In addition, those studies have frequently failed to provide sound quantitative information about forest conservation (i.e., extent and condition), particularly using spatially-explicit data to account for spatial variations within a given population. Moreover, most biocultural studies highlighting the co-occurrence of biological and cultural (or linguistic) diversities have been undertaken at global (Gorenflo *et al.*, 2012) or continental scales (Moore *et al.*, 2002). Yet, and because the high co-occurrence of biological and cultural diversity at global or regional scales may disappear when examining data at a finer scale (Manne, 2003), we also need assessments of such a co-occurrence at local and regional scales so as to better assess the alleged existence of some form of functional connection between both types of diversity (Zent, 2009). Importantly, local studies on this topic may unravel that the association between biological and cultural diversity (if any) may be best explained by historical settlement patterns rather than by functional links. Whatever the case, this type of assessments at the local scale are better suited to understand the role of local knowledge, management practices, and informal institutions and beliefs regulating resource use, in forest conservation.

The debate over the role of indigenous ecological knowledge in forest conservation over tropical regions such as Amazonia matters because if higher indigenous knowledge tends to be associated with higher old-growth forest conservation levels (and therefore with higher biodiversity), the finding would have important policy implications. Indeed, this finding could support governmental policies aiming to protect indigenous knowledge by recognizing the rights of indigenous peoples to their ancestral lands and to their natural-resource base, their traditional forms of livelihood, their political autonomy, and so on. Yet, there is much controversy around this issue and different authors have stressed that high conservation levels across indigenous territories may be the incidental result of low population densities, lack of modern technologies, and remoteness, rather than of real conservation attitudes and behaviors (Smith and Wishnie, 2000; Raymond, 2007). I argue in this doctoral dissertation that, given the potential key role that indigenous peoples (Alcorn, 1993; Gadgil *et al.*, 1993) and indigenous lands may have in biological conservation and climate change mitigation (Nepstad *et al.*, 2006; Soares-Filho *et al.*, 2010) in the Amazon, and given the commodity-frontiers are expanding at ever-higher rates across the whole Amazon basin (Finer *et al.*, 2008), shedding light into this specific issue is of critical importance. Therefore, empirical assessments showing positive associations between indigenous knowledge and forest conservation would be important to give scientific support to conservation approaches based on the creation of indigenous reserves, and on establishing partnerships between indigenous organizations and conservation sectors such as governments, academia, NGOs (Schwartzman and Zimmerman, 2005; Vermeulen and Sheil, 2007) or even companies (Morsello, 2006), while strengthening indigenous governance and securing their land rights. In such a scientific pursue, it is important to measure the potential role of indigenous people in forest conservation, but also to attempt at understanding the mechanisms underpinning such a role.

3. <u>The Tsimane' and their context</u>

The Tsimane' Amerindians are an indigenous society native to the Bolivian Amazon, mostly settled in the southwest of the Department of Beni. The last official census estimated their population at ~8,000 people (Censo-Indígena, 2001), but current informal estimates situate their population at ~15,000 people (Reyes-Garcia *et al.*, in review-c). living in ~125 villages. Tsimane' villages are located along the river banks of the Maniqui (~50), Quiquibey (~16), and Sécure (~3), along the road Yucumo-Rurrenabaque or nearby (~25), and along logging concession roads or close to them (~27) (Reyes-Garcia *et al.*, in review-c). The Tsimane' economy centers on hunting, fishing, plant foraging and on slash-and-burn farming (Godoy *et al.*, 2009c) for subsistence, though some Tsimane', particularly those living in villages closer to the main market towns (San Borja, Yucumo and Rurrenabaque), are increasingly engaged in market-oriented activities such as cash cropping and wage labor (Vadez *et al.*, 2004). In fact, amongst Bolivian Amazonians, the Tsimane' display the largest variation as regards their level of integration into the market economy, from unacculturated groups living in semi-nomadic settlements far from the main market towns, who do not speak Spanish (the national language), maintain high levels of TEK , and rely on forest products for their subsistence, to other groups that are sedentary, have received formal education, speak

Spanish fluently, and earn most of their income through wages as laborers or selling cash crops (Godoy *et al.*, 1998).

Historical accounts of the Tsimane' show that they refrained from being settled in missions even though there were successive attempts from the early seventeenth century (Reyes-Garcia *et al.*, in review-c). Ethnographic works among the Tsimane' have described them as a highly mobile society with semi-nomadic and dispersed settlement patterns (Ellis, 1996), that has traditionally lacked of centralized social and political organizations (Daillant, 2003), which may explain why missionaries did never succeed in settling the Tsimane'. The same reasoning probably apply for explaining why they remained relatively isolated avoiding contact with outsiders until the late nineteenth century, barely participating in the new economic activities brought by outsiders (Nordenskiold, 1924). Though during the early twentieth century they started to pan gold, extract quinine, tap rubber, sell rice, and work as laborers for loggers and cattle ranchers (Chicchón, 1992), the majority of the Tsimane' society remained self-sufficient, living as forest dwellers with little or no contact with outsiders. This isolation ended after the national revolution of Bolivia (1952), when different laws boosted the colonization of several parts of the Bolivian Amazon and the economic development of the region, which resulted in the opening of new roads, land tenure reforms and whatever means needed for an increase in market integration, which put the Tsimane' in contact with other segments of the Bolivian society (Reyes-García *et al.*, 2012). To a great extent, these processes transformed Tsimane' ancestral lands, their communal land tenure system, and their land use activities (Godoy, 2001).

Tsimane' settlements are nowadays scattered across an array of land tenure systems (Figure 1.1) as a result of different policies deployed in successive laws after the national revolution, aimed at colonization, agrarian and forestry reforms, sparing land for biological conservation, and giving indigenous peoples communal property-rights over part of their ancestral lands (Reyes-Garcia *et al.*, in review-c). As a consequence, Tsimane' villages are now settled within three protected areas (Beni Biological Station, Pilón-Lajas, and Isiboro-Sécure), within several logging concessions, within four indigenous titled territories (TCOs for the Spanish acronym referred to *Tierras Comunitarias de Origen*), namely Tsimane' TCO, Multiethnic TCO, Pilón-Lajas TCO, and Isiboro-Sécure TCO, and also in private lands that include but are not limited to colonization areas (Reyes-Garcia *et al.*, in review-c). This issue matters in studies concerned with trends in FCC and with forest conservation because different land tenure systems have legal restrictions on land use and natural resource management (Reyes-García *et al.*, 2012), and therefore it is necessary to understand the evolution of policies that have resulted in land tenure and property-rights reforms. In the case of the Tsimane', they are currently allowed to hunt, fish, clear land to farm, and extract timber and non-timber forest products for their own consumption in TCOs, protected areas, and logging concessions. Besides, in TCOs Tsimane' can clear forest for cash crops and cattle ranching, and extract timber for commercial purposes under approved forest management plans, while in private lands they can intensify land use as desired as land is held under private tenure and conservation is not an intended outcome of land use (as it may be expected [by governmental authorities] in TCOs, and in biological reserves and parks) (Reyes-García *et al.*, 2012).

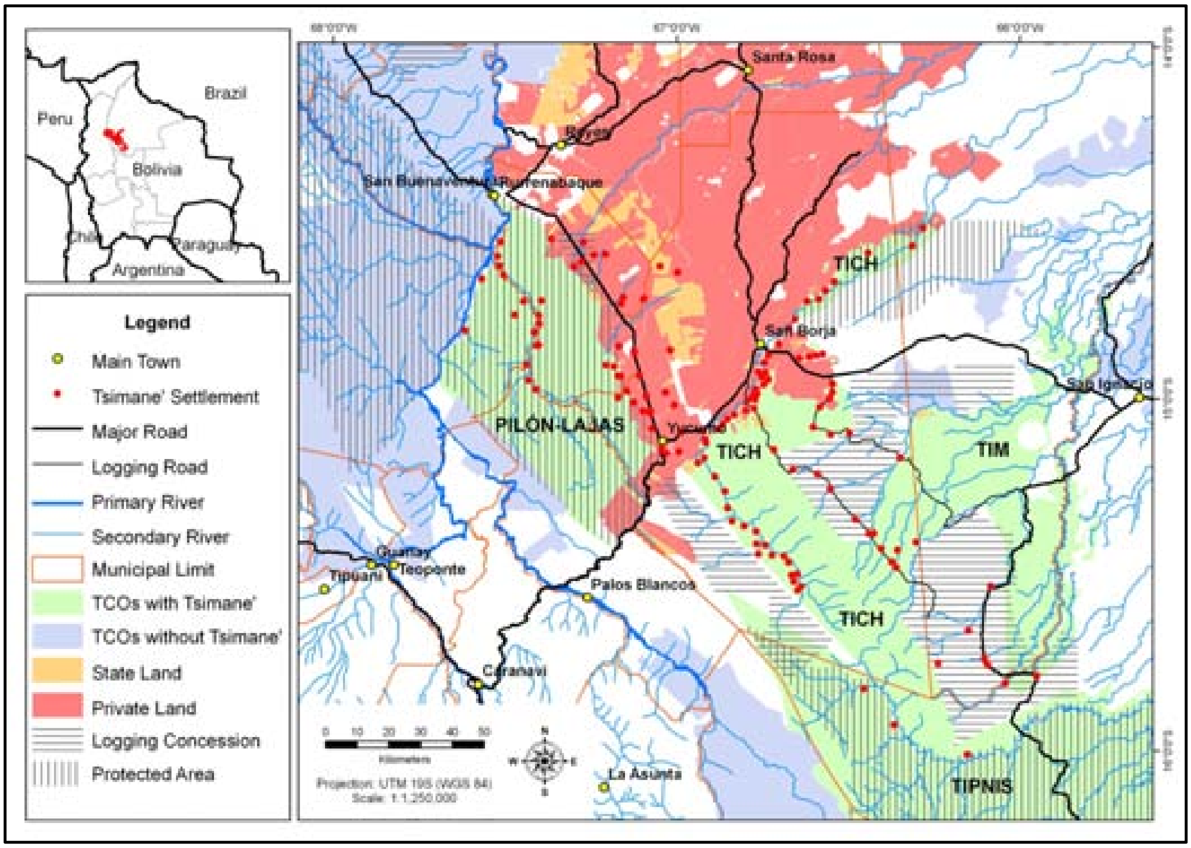

Figure 1.1. Tsimane' settlements showing the different land tenure systems that contain them.

3.1. Historical overview of land reforms configuring current land tenure systems in the ancestral lands of the Tsimane'

The first agrarian reform in Bolivia was put forward in 1953 following the 1952 national revolution so as to achieve a more equitable land distribution and an increase in agricultural production. That reform promoted the conversion of large tracts of forests to agricultural land tailored to medium and large landowners' interests, who focused on commodities production (e.g., sugar, cotton, soy, beef), particularly in what is now the Santa Cruz Department (Mertens *et al.*, 2004). In addition, the state promoted various colonization projects across the eastern lowland forested areas, where large tracts of state land were given to colonists as private property (Pacheco, 2002), a phenomenon that brought to the Bolivian lowlands successive waves of colonists, particularly from the 1980s (Reyes-Garcia *et al.*, in review-c). Colonization projects mainly benefited Andean indigenous peoples who moved to the lowlands and became small colonist farmers provoking severe deforestation in their settlement areas (Pacheco, 1998). A first forestry law appeared in 1974 and attempted to regulate and improve timber extraction in Bolivia, as so far logging companies and individual loggers had been operating in the country without much control from the state (Pacheco *et al.*, 2010). To a large extent, native Amazonian indigenous peoples were neglected in these economic development policies. Moreover, the arrival of new actors (mostly colonists and loggers) competing for lowland indigenous peoples' traditional lands and resources further boosted their discontent and conflicts arose as a consequence. Those conflicts culminated in the first "march for dignity and territory" in 1990, in which various ethnic groups from the lowlands claimed for legal recognition of part of their ancestral territories as a means of securing communal property rights over land and natural resources (Reyes-Garcia *et al.*, in review-c).

The second agrarian reform in Bolivia was deployed in 1996 and brought formal recognition to indigenous tenure systems (TCOs). Yet, non-indigenous actors had priority regarding claims for land property rights where disputes existed, so long they could demonstrate land occupancy before the TCOs were decreed (Assies, 2006), which had to be resolved by a slow governmental process of land demarcation (known as *saneamiento*). Although this process is yet to conclude, it has already resulted in the loss of part of TCOs' lands to different non-indigenous claimants. A second forestry law was launched in 1996. This law had the aim of improving the regulation of timber extraction activities and of increasing royalties from logging companies, changing from payments based on volume harvested to a scheme based on the area leased to companies for their operations (Pacheco *et al.*, 2010). The third agrarian reform, issued in 2006 by the newly elected indigenous government of president Evo Morales, set out to speed up the *saneamiento* of lands in TCOs and to give away new state lands (often forestland) to highland indigenous peoples and small farmers. Nonetheless, the formal recognition of indigenous land rights has not ceased land conflicts in the Bolivian lowlands as indigenous land rights have seldom guaranteed tenure security for indigenous societies (Chumacero, 2011). In fact, as TCOs are virtually surrounded by a myriad of different land tenure regimes and social groups, encroachment upon their land is not rare. This situation has led to the existence of frequent conflicts between the Tsimane' and other actors who visit their communities (Reyes-García *et al.*, 2012), as such actors are perceived as people who may encroach upon or extract natural resources from Tsimane' ancestral lands. This may bear important consequences for FCC, as previous research in the area has documented a positive association between tenure insecurity and deforestation (owing to the need of proving the socioeconomic function of the land (Bottazzi and Dao, 2013)), and the existence of frequent conflicts with abutters encroaching upon communal Tsimane' land (Godoy *et al.*, 1998).

3.2. Tsimane' Traditional Ecological knowledge

Tsimane' TEK has been extensively studied in the last ~10 years using ethnobotanical knowledge and skills as a proxy. Specifically, several studies have been carried out with the aims 1) of establishing the correlates between Tsimane' TEK specific social and environmental variables, and 2) of assessing whether TEK is being lost amongst the Tsimane' in the face of increasing market integration and formal education, both of which may bring about increasing acculturation. As regards the former, recent research has shown that individual levels of Tsimane' TEK are positively associated with effective habitat management proxied by the conservation of crop diversity (Reyes-Garcia *et al.*, 2008b) and with a decrease in the area cleared for agriculture in old-growth forest (Reyes-Garcia *et al.*, 2007b). In addition, a positive association has been observed between Tsimane' individual TEK and individual's nutritional status (Reyes-Garcia *et al.*, 2008a) and between parental TEK and child health (McDade *et al.*, 2007). As for assessments of the potential ongoing loss of TEK among the Tsimane', recent research suggests that, overall, TEK is being lost at an alarming rate (Reyes-Garcia *et al.*, in review-a), which nonetheless depends on the cultural domain of analysis (Reyes-Garcia *et al.*, in review-b). Therefore, secular trends of loss of TEK vary across domains and results suggest that the Tsimane' are losing TEK related to canoe-building and firewood, and to a lesser extent (non-significant results) related to medicinal and edible plants. Conversely, the Tsimane' seem to be acquiring knowledge of plants that are useful for house-building (Reyes-Garcia *et al.*, in review-b).

As the loss of TEK may be partially attributed to the processes of market integration and formal education attainment, some studies have been focused specifically on those associations. For instance, Reyes-Garcia *et al.* (2005) found that distance with the main market town (San Borja) is correlated with higher levels of TEK; however, when controlling for distance Reyes-Garcia *et al.* (2005) found that other factors that may be used to estimate the level of market integration, specifically, cash earnings and wealth, bore no consistent, significant correlation with TEK. Later on, Reyes-Garcia *et al.* (2007a) found that the only market-related activities that are seemingly associated with the loss of Tsimane' TEK are those that take them off their environment (e.g., wage labor). As for the potential effects of formal education (i.e., schooling) on the loss of Tsimane' TEK, Reyes-García *et al.* (2010) observed that the magnitude and negative association between education and TEK is rather low, something the authors interpreted as a consequence of the partially contextualized school curriculum that protestant missionaries introduced a few decades ago (i.e., learning through Tsimane' language, with Tsimane' teachers, and with a partial focus on the Tsimane' environment). Therefore, to date research on the potential loss of TEK amongst the Tsimane' owing to their increasing market and formal education exposure suggest that both factors are not mediating the loss of TEK in a unambiguous manner. What seems likely is that TEK is not significantly lost when the Tsimane' continue to depend on their forests for their livelihoods, as it is usually the case (Godoy *et al.*, 2009a).

4. Thesis structure and main objectives

This PhD thesis is a hybrid between a classic dissertation and a compilation of scientific papers in the sense that it has a general introduction and a final chapter with the main conclusions, but includes three research chapters in a paper-like format that are either already submitted to international journals (the first one) or are about to be sent (the second and third). The thesis presents a case study that addresses the first two land change science components (i.e., land characterization and change detection, and analysis of causes, impacts and consequences of land change). The work presented also serves as a baseline to carry out further research focusing on the other two components (i.e., modeling future land change, and assessment of system outcomes). The thesis revolves around three main objectives that relate to the three research chapters, which are briefly outlined below.

In the first research chapter I seek to devise a classification approach that enables me to derive accurate maps of LULC for the study area, a challenging enterprise owing to the high spatial and temporal heterogeneity of LULC types. To accomplish this task I compare different remote sensing image classification algorithms with and without the use of ancillary data. As a result, I develop a highly-accurate classification approach, which serves for the remaining spatial analyses undertaken throughout the second and the third research components of the thesis. The approach seems very well suited for classifying complex, heterogeneous tropical landscapes in the Bolivian Amazon and elsewhere. Consequently, the approach may be utilized for the many applications that require accurate LULC maps over tropical areas (e.g., biodiversity assessments, carbon mapping projects, landscape planning, LULC change assessments). This appears to be a significant contribution given the current challenges of mapping LULC in tropical regions. This chapter is accepted upon revision in the *International Journal of Applied Earth Observation and Geoinformation* (Elsevier).

In the second research chapter I employ the classification approach previously devised and produce four high-accuracy LULC maps corresponding to a time-series of Landsat satellite imagery that consists of four dates (1986, 1996, 2001, 2009). My primary goal here is to assess the effects of the four main land tenure systems found in the study area (protected area, indigenous titled territory, private land, and logging concession) on FCC. To carry out such an assessment I unravel trends in the extent of old-growth and early-growth forests, and trends in fragmentation of old-growth forests, over three study periods (1986-1996, 1996-2001, 2001-2009). I then compared trends across land tenure systems. This analysis contributes to clarify the role of land tenure as a policy factor that, despite of being known to be potentially important as a driver of FCC, has rarely been adequately examined in the Amazon. As a matter of fact, to my knowledge, this assessment is the first comprehensive one carried out for the Bolivian Amazon. This chapter will be sent for revision to *Applied Geography* (Elsevier) in October-November 2012.

Finally, in the third research chapter, my main objective is to evaluate the potential association of Tsimane' traditional ecological knowledge and the extent and the level of fragmentation of old-growth forests surrounding their villages, and thus on the present conservation state of their forests. Moreover, I assess the potential overlap between their traditional ecological knowledge and forest conservation state so as to elucidate whether their spatial patterns overlap. This study is of significant importance because assessments of the co-occurrence between cultural (or linguistic) and biological diversities have been conducted at global and continental scales, but we lack of empirical assessments at local and regional scales, which hampers our understanding of the connections between these forms of diversities. I discuss the implications of my results for policies aiming at conserving biodiversity and ecosystem services and goods, which in my view and based on my results, should proceed hand in hand with cultural conservation. This chapter will be sent for revision to *Human Ecology* (Springer) in October-November 2012.

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Chapter 2

Enhanced land use/cover classification of heterogeneous tropical landscapes using support vector machines and textural homogeneity

For every complex problem there is an answer that is clear, simple, and wrong

(attributed to H. L. Mencken)

Abstract

Land use/cover classification is a key research field in remote sensing and land change science as thematic maps derived from remotely sensed data have become the basis for analyzing many socio-ecological issues. However, land use/cover classification remains a difficult task and it is especially challenging in heterogeneous tropical landscapes where nonetheless such maps are of great importance. The present study aims to establish an efficient classification approach to accurately map all broad land use/cover classes in a large, heterogeneous tropical area of Bolivia, as a basis for further studies (e.g., land use/cover change, carbon mapping). Specifically, I compare the performance of parametric (maximum likelihood), non-parametric (*k*-nearest neighbor and support vector machines - SVM, with four different kernels), and hybrid (unsupervised-supervised) classifiers, using both hard and soft (fuzzy) accuracy assessments. In addition, I test whether the inclusion of textural information in the classifications improves the performance of the classifiers tested. I classified Landsat imagery for two dates corresponding to dry and wet seasons and found that non-parametric (particularly SVM) classifiers outperformed both parametric and hybrid classifiers. I also found that the use of some textural indexes, but particularly homogeneity and entropy, can significantly improve classifications at the 30m spatial resolution of Landsat imagery. I focused on the use of the homogeneity index, which has so far been neglected in land cover classification efforts, and found that this index along with reflectance bands significantly increased the overall accuracy of all the classifiers, but particularly of SVM. I observed that improvements in producer's and user's accuracies through the inclusion of the homogeneity index were different depending on land use/cover classes. Early-growth/degraded forests, pastures, grasslands and savanna were the classes most improved, especially with the SVM radial basis function and SVM sigmoid classifiers, though with both classifiers all land cover classes were mapped with producer's and user's accuracies of ~90%. My classification approach seems very well suited to accurately map land use/cover in tropical regions, thus having great potential to contribute to climate change mitigation schemes such as REDD+, conservation initiatives, and the design of natural resources management plans and rural development policies.

Key words: remote sensing; thematic classification comparison; SVM; *k*-nearest neighbor; hybrid classification; texture; Bolivian Amazon

1. Introduction

Land use/cover (land cover hereafter, LC) classification is a key research field in remote sensing (Lu and Weng, 2007) and a fundamental component of land change science as LC maps derived from remotely-sensed data are vital to analyze environmental change (Turner *et al.*, 2007). LC maps are critically needed in regions where few or no other maps exist at local and landscape scales, which is a common situation in tropical areas worldwide. Yet, LC classification remains a challenging task in highly heterogeneous tropical areas for several reasons. A major problem lies in the difficulty of acquiring cloud-free multispectral imagery (Asner, 2001), which may be partly overcome through the use of radar imagery (Saatchi *et al.*, 1997; Freitas *et al.*, 2008). However, radar imagery interpretation is not straightforward in tropical areas (Almeida-Filho et al., 2007). Another major drawback is related to the limitations (in terms of cost, time, and accessibility) for carrying out fieldwork to collect sufficient information on LC classes, which hampers the training and validation stages of supervised and hybrid LC classification approaches. Other constraints for accurate LC mapping in tropical regions are the usual lack of aerial photography and videography, of previous LC maps, and of ancillary data (e.g., digital elevation model – DEM, geological maps) that may be used to improve classification results. Given all these limitations, in tropical regions it is essential to deploy an efficient LC classification scheme.

A fundamental issue is the selection of the classifier in that respect. Although object-based classifiers have been successfully applied in tropical regions (e.g., Alphan *et al.* (2009)), per-pixel classifiers continue to dominate such LC classification endeavors. Among the latter, the use of machine learning algorithms have gained momentum in recent years and some assessments of their relative performance compared to other classifiers have been conducted in the Amazon region (Lu *et al.*, 2004; Carreiras *et al.*, 2006a). Specifically, support vector machines (SVM) have been shown to attain high accuracies in LC mapping and outperform other algorithms (Huang *et al.*, 2002; Foody and Mathur, 2004a; Pal and Mather, 2005; Kavzoglu and Colkesen, 2009; Mountrakis *et al.*, 2011; Szuster *et al.*, 2011).

SVM have two significant advantages for LC mapping. First, since SVM classifiers seek to separate LC classes by finding a plane in the multidimensional feature space that maximizes their separation, rather than by characterizing such classes with statistics, they do not need a large training set. Foody and Mathur (2004b) found that SVM classifiers only require the training samples that are support vectors, which lie on part of the edge of the class distribution in feature space, as all the others do not provide useful information to them. Thus, for SVM classifiers Foody and Mathur (2006) suggested to use small training sets composed of purposely selected mixed pixels containing the support vectors, as this approach does not compromise classification accuracies and may save considerable time. Second, SVM algorithms are independent of data dimensionality (Negrón-Juárez *et al.*, 2011), which is a key feature when using many spectral bands such in hyperspectral imagery (Haack, 1982) or when ancillary data are included in the classification process; contrarily, for classifiers that depend on dimensionality (e.g., artificial neural networks), training sets must exponentially increase in size to maintain classifier performance (Dixon and Candade, 2008). Hence, SVM have been recently portrayed as "an ultimate classifier that may possibly provide the best classification performance" (Chen and Ho, 2008).

Another fundamental issue to enhance LC classification is the adequate selection of input variables, which some authors suggest that may have the same impact as the selection of the classifier (Heinl *et al.*, 2009). Nevertheless, I argue that the combination of an allegedly superior classifier such as SVM with appropriate ancillary data should improve results, as observed by Watanachaturaporn *et al.* (2008) using multisource classification with SVM. Different textural measures are a potential source of ancillary data, whose benefits for LC classification have been highlighted in studies using different techniques and classifiers (Berberoglu *et al.*, 2000; Chica-Olmo and Abarca-Hernández, 2000; Maillard, 2003; Tsaneva *et al.*, 2010). The incorporation of textural data for mapping forest age, forest types, detecting forest cover change, and characterizing canopy structure has also been widely examined (Palubinskas *et al.*, 1995; Franklin *et al.*, 2000; Franklin *et al.*, 2001; Coburn and Roberts, 2004; Zhang *et al.*, 2004; Kayitakire *et al.*, 2006; Malhi and Román-Cuesta, 2008) and it has proved particularly useful with high-spatial resolution imagery (Ota et al., 2011). A significant advantage of using texture to enhance image classification in tropical regions, where other ancillary data sources may not exist, is that textural data can be extracted from the image itself. Thus, for example, the gray-level co-occurrence matrix method can be used to extract textural indexes that can be included as data bands in the classification process (Gong et al., 1992).

There have been few attempts to provide LC classifications for the Bolivian Amazon, which are needed to undertake socio-ecological studies and design management plans and policies. The most comprehensive study was carried out by Killeen et al. (2007) and served as the basis for a historical land use change analysis of all Bolivian territory below 3,000m of altitude (Killeen et al., 2008). However, owing to the large spatial extent of their analysis, Killeen et al. (2007) used very broad LC classes and validated their results through videography. Thereby, both their classification approach and results may be of limited usefulness for studies that need to analyze LC or LC change at local or landscape scales. Moreover, Killeen et al. (2007) did not discriminate between old-growth, early-growth and degraded forests, a mandatory issue for REDD+ projects despite its complexity. To address such issues, the main goal of this study was to establish an appropriate classification approach to accurately map all LC classes considered in my study area in the Bolivian Amazon. My specific objectives were: 1) to test if the use of SVM classifiers improved LC classification with regard to parametric, non-parametric, and hybrid classifiers; and 2) to assess whether the inclusion of textural measures could improve classification results at the moderate spatial scale of Landsat imagery (30m).

2. Study Area, field surveys, and map legend definition

2.1. Study area

The study area is located in the department of Beni, Bolivia (Figure 2.1). I selected this large area because its landscapes are highly heterogeneous as a transition across three biogeographic areas: 1) montane tropical forests covering the foothills of the Andes to the west, 2) lowland tropical forests to the south and centre of the study area, and 3) wet savannas to the north and east (Navarro and Maldonado, 2002). Montane tropical forests are possibly the most plant diverse area of Bolivia (Ibisch and Mérida, 2004) and in my study area are found over 400m. Lowland forests are located below 400m and form a rolling landscape. These Amazonian forests contain some deciduous species owing to a marked seasonality (dry and wet seasons) and are not as species-rich as montane tropical forests or typical Amazonian rainforests (further north and east), though they are very similar in species composition and structure to the latter ones (Killeen et al., 1993). In wet savannas vegetation is controlled by small variations in ground elevation and relief, which in turn are shaped by river dynamics and periodic flooding. They consist of swampy areas and lagoons with aquatic vegetation in the lowest areas; scrublands, semi-natural grasslands and pastures in areas less prone to be flooded; and patches of forests on mounds that do not get seasonally flooded and are seemingly the result of past civilizations (Lombardo and Prümers, 2010). The vegetation formations of the study area are also shaped by the land use type and intensity of its different inhabitants, who range from Andean indigenous peoples in montane forests, to local peasants, cattle ranchers, and different native and colonist indigenous peoples in lowland forests and savanna areas.

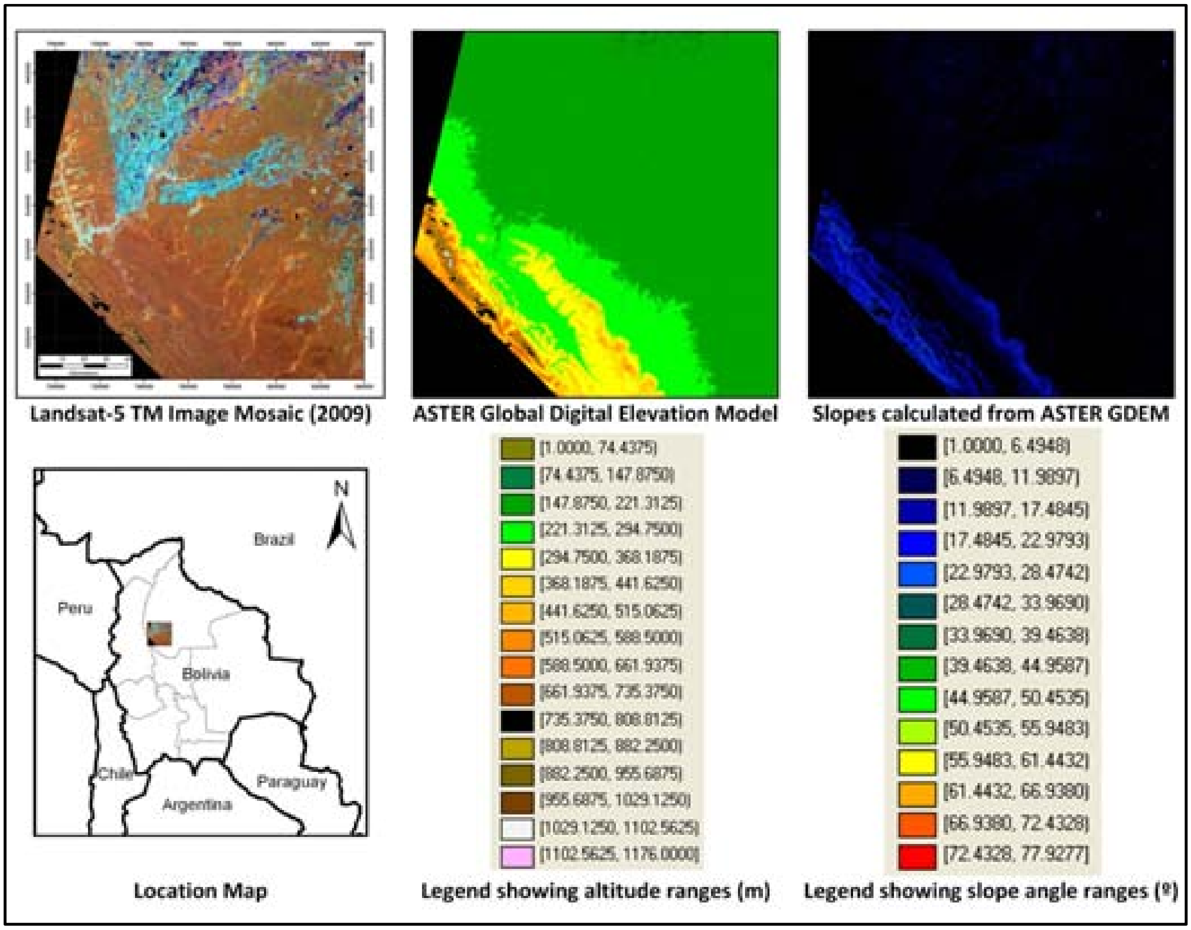

Figure 2.1. Study area showing the most recent Landsat image mosaic (RGB: 4-5-3) and the GDEM used in the study.

2.2. Field surveys

Two field surveys were undertaken across the study area to collect LC data in support of the classification process. The first focused on forested areas (old-growth, early-growth, and degraded forests), water, bare soil, and infrastructure/urban categories, and was carried out in June-August 2009 (dry season). The second one took place in April-May 2010 (end of the wet season) and was conducted on the large savanna areas that are present across the study area, which mix with patches of pastures, semi-natural grasslands, and scrublands. Planning the acquisition of ground-truth data was done upon preliminary analyses of the most recent Landsat-5 Thematic Mapper (TM) scenes (April 2009). Ground data were acquired with handheld GPS units, with typical mean positioning errors of 2-4m in open areas and 4-6m in forested areas. Along with each GPS reading, I recorded information on land use/cover, and on ecological and geomorphological features (e.g., main plant species, average vegetation height and diameter at breast height, canopy fraction, soil type, drainage). Additionally, to assist in the processes of geometric correction and geometric accuracy assessment, I collected GPS points at road crossings and other human-made features on the ground, and GPS tracks along the major roads and rivers across the study area.

2.3. Map legend definition

The definition of broad LC classes was carried out prior to the field surveys based on previous knowledge of the area and initial remotely sensed data exploration. This exploration consisted in 1) carrying out several unsupervised ISODATA classifications on the most recent Landsat imagery I had, and 2) checking the classification obtained by Killeen et al. (2007) for my study area. Nevertheless, the definition of LC classes was modified according to my field observations and thorough examination of the spectral signatures extracted from my field data. Finally, I considered eight broad LC classes (Table 2.1). Agriculture was not defined as a specific class because nearly all the agricultural plots in this area consist in subsistence slash and burn agriculture. Such plots, that account for a small percentage of the study area, are small (<0.5 ha), have usually great abundance of non-photosynthetic biomass (dead trees and logs) lying on the ground, include banana and other tree crops, and are mixed with pioneer tree species (e.g., Cecropia spp.). In addition, they do not usually have a clear spatial distribution pattern and are highly dynamic, rapidly evolving into young regenerating forests. As a consequence, these agricultural plots exhibit in Landsat imagery a very similar spectral response to older regenerating forests (Chan et al., 2001; Vieira et al., 2003), which makes it very hard to accurately identify this LC class. Therefore, I deemed preferable to include agriculture within the early-growth forest class. Likewise, I included the infrastructure/urban class within the bare soil class owing to the lack of paved roads and streets in the area. Moreover, the spectral response of these linear features was relatively similar to that of roofs in urban settlements and, to a lesser extent, to that of sand banks along the main rivers. The spectral similarity of agriculture to early-growth forests and of urban areas to bare soil was tested by the Jeffries-Matusita transformed divergence index, which confirmed that in both instances they could be grouped under a single LC class.

Table 2.1. Definition of LC classes included in the study.

LC Class	Definition
Early-growth / degraded forest (EGDF)	Forested areas with varying degrees of disturbance due to human activities (e.g., typically slash and burn agriculture or logging) or natural dynamics (e.g., flooding regimes). Typically composed of regenerating trees, dead trees and logs, crops such as rice, manioc and bananas, sometimes with scattered old big trees. The canopy is rather open, structurally simple, and the average tree height is 3-10 m
Old-growth forest (OGF)	Forested areas with low levels of disturbance that consist of mature trees forming a dense and structurally complex canopy with few gaps and a typical height range of 15-40 m

Water (W)	Water bodies such as creeks, rivers, shallow lakes, and deep lakes
Bare soil / urban (BSU)	Sand banks along rivers, urban areas including towns, unpaved streets and roads
Pasture (P)	Areas typically used for cattle ranching, both in deforested and savanna areas. In deforested areas, pasture species are frequently sown, while in savanna areas pastures are usually not sown. In both instances it is common to have varying amounts of bare soil
Savanna (S)	Low relief savanna areas that are seasonally inundated and may form swamps or marshes
Semi-natural grassland (G)	Grassland patches that occur mostly across the savanna areas, with very little or total absence of woody species
Scrubland (SC)	Open canopy areas dominated by bushes or short trees, commonly present across the savanna areas, growing on dry ground of low quality; sometimes in the fringe or vicinity of forested areas

3. Materials and methods

3.1. Satellite data and pre-processing

LC classifications were carried out on Landsat satellite mosaics composed of two scenes (path 233, rows 70, 71). I used two dates (25/08/2001 and 17/04/2009, corresponding to the dry and the end of the wet periods, respectively) so as to account for differences in phenology, illumination, and reflectance, and hence strengthen the classification comparison among different algorithms. I chose Landsat data because of the large extent I needed to cover, and because Landsat is arguably the world's most commonly used satellite to undertake ecological studies in tropical landscapes, including LC classifications (Cohen and Goward, 2004), which renders my results more comparable to other studies than if I had used data from a less conventional sensor. In addition, to carry out topographic and illumination corrections I used the ASTER Global Digital Elevation Model v.1 (Figure 2.1; http://www.gdem.aster.ersdac.or.jp/). This DEM was released on June 29, 2009 and has 30m horizontal and 20m vertical accuracies. Thus, GDEM provides more accurate results for Bolivia than the older DEM provided by the Shuttle Radar Topography Mission (SRTM; http://www2.jpl.nasa.gov/srtm/).

The two 25/08/2001 Landsat-7 Enhanced Thematic Mapper (ETM+) scenes were acquired through the United States Geological Survey (USGS) and their geometric accuracy was assessed through the ground control points and GPS tracks I had collected in the field. Geometric accuracy was high (misalignments ~0.5 pixels) in both cases, which was deemed appropriate for the objectives of the study. The two 17/04/2009 Landsat-5 TM scenes were acquired from the Brazilian National Institute for Space Research (INPE) and required geometric and topographic corrections, which were carried out with MiraMon software (Pons, 2000) using the procedure developed by Palà and Pons (1995). The Landsat-7 ETM+ scenes were used as reference images and the geometric errors obtained for both Landsat-5 TM images after the corrections were consistent with those of the reference scenes (~0.5 pixels). Subsequently, each pair of images corresponding to the same date was mosaicked and radiometric corrections were performed using MiraMon, which implements a radiometric correction model that includes atmospheric and illumination corrections. The atmospheric correction is done in terms of additive and multiplicative factors that account for solar irradiance, atmospheric effects, and sensor calibration, operating on an image-wide basis. The illumination correction is carried out on a pixel by pixel basis using a DEM, and minimizes the effects of differential illumination conditions due to sun location and relief, as well as atmospheric conditions (Pons and Solé-Sugrañes, 1994). Upon radiometric correction completion, the two mosaics were cropped to the extent of the area of interest. Finally, a cloud and cloud-shadow mask was manually built through visual interpretation and applied to each image mosaic, being thus ready for classification analysis.

3.2. Training data

Training data were retrieved for each mosaic starting with the most recent one (2009). I carefully examined both field data and spectral signatures across the image to select the training sets from the images. In most cases training data consisted of small polygons, though there were few instances in which single pixels were chosen in narrow areas (e.g., roads, sand banks and rivers). Much care was taken to scatter training areas across the image to ensure they were representative of the entire mosaic, and to retrieve as many training areas for each class so as to satisfy previously suggested criteria to establish an appropriate minimum sample size (Mather, 2004; Congalton and Green, 2009; Foody, 2009). Table 2.2 shows the size of training samples selected for each mosaic. To enhance the comparability of results between the classifications of both dates I tried to use the same training areas as much as possible (i.e., when no change had occurred). The Jeffries-Matusita transformed divergence index was used to assess the separability of training data for both dates. I confirmed that separability was rather high for water, bare soil/urban and old-growth forest, but much lower for the other LC classes.

Table 2.2. Size of training samples (# pixels) collected for each classification.

LC Class	2009	2001
EGDF	10,025	5,008
OGF	10,035	5,003
W	2,506	2,000
BSU	1,000	600
P	5,000	1,000
S	5,000	1,508
G	2,005	1,000
SC	1,352	1,008

3.3. Classification algorithms

I used a parametric classifier (maximum likelihood – ML), non-parametric classifiers (*k*-nearest neighbor – KNN, and four different support vector machines – SVM: linear, polynomial, radial basis function, and sigmoid), and a hybrid classifier (unsupervised-supervised, contained in MiraMon software – MMHC). I do not explain here how the ML, KNN and SVM algorithms work since detailed descriptions abound in remote sensing and pattern recognition textbooks (e.g., Richards and Jia, 2006; Tso and Mather, 2009; Adger *et al*., 2011). However, I provide a very brief explanation of MMHC as it is not a conventional classification method. MMHC classification approach involves the use of an unsupervised ISODATA algorithm (IsoMM) based on the methodology proposed by Duda and Hart (1973) to retrieve spectral classes, and a subsequent supervised classification (ClsMx) performed on the ISODATA results using training areas to obtain thematic classes (see Serra *et al.* (2003) for further details). MMHC has been successfully used to classify Mediterranean environments (Serra et al., 2003; Serra et al., 2005) and has also been used in tropical dry areas of Nicaragua to classify vegetation (García-Millán and Moré, 2008). To my knowledge this is the first time MMHC has been used to classify tropical forests and savannas.

3.4. Textural data

I explored the use of texture to assess whether classification results could be improved. I extracted textural measures from the gray-level co-occurrence matrix (GLCM), which is often employed to extract textural information from remote sensing images (Haralick et al., 1973). Specifically, I calculated eight textural indexes from six Landsat reflectance bands (1-5, 7): mean, variance, homogeneity, contrast, dissimilarity, entropy, second moment and correlation. I used moving windows of two different sizes (3x3 and 7x7 pixels), hence obtaining 12 textural data bands for each index (6 from 3x3- and 6 from 7x7-pixel windows). I then used the 6 textural bands calculated for each index and moving window size, along with the six Landsat spectral bands, to carry out a maximum likelihood classification. I assessed the potential usefulness of each index based on the overall accuracies obtained for each classification and the producer's and user's accuracies attained for the two forested classes. I performed all calculations for both image mosaics.

3.5. Classification post-processing and accuracy assessment

I applied a 3x3-pixel majority filter to all the classifications to eliminate the salt and pepper effect prior to their accuracy assessment. Reference data retrieval for accuracy assessment was based on a stratified random sample selection, with sample units taken at a minimum distance of 2km to avoid the potential effects of spatial autocorrelation (Congalton, 1988). Reference data were ground-truthed by expert-knowledge from the images themselves (I did not use data collected in the field as they had not been randomly selected due to logistic reasons). Sample units lying on the fringe of two or more LC classes were not discarded so as not to affect the randomness principle of accuracy assessment. For practical reasons I used points rather than clusters of 3x3 pixels (using such clusters has been suggested by Congalton and Green (2009) as appropriate sample units for accuracy assessment of Landsat-derived classifications). However, since I performed a 3x3-pixel majority filter on every classification prior to their accuracy assessment, each reference point represents not the thematic class of a single pixel, but the most common class classified within the 3x3-pixel window centered on the reference point. I used the rule of thumb proposed by Congalton and Green (2009) regarding the minimum reference dataset size required for accuracy assessment, whereby 75-100 testing sample units per thematic class should suffice for large areas and less than 12 thematic classes.

I carried out both hard and soft (also known as fuzzy) classification accuracy assessments. The soft classification assessment may enable a better evaluation of the behavior of a classifier, particularly regarding points that are challenging because they lie on transition or mixed zones (Woodcock and Gopal, 2000), being thus well suited to compare classifiers. For the soft assessment I assigned by expert-knowledge two possible LC classes to each reference point: a primary class, which coincided with that used in the hard classification assessment and that was supposed to represent the ground *truth*, and a secondary class, which was specific to the soft assessment and was considered to be right too because it represented a *good* or *acceptable answer* given the location of the reference point. However, whenever a reference point was located in a homogeneous area and its LC class was deemed clear, I assigned the same LC class to both primary and secondary classes. For both types of accuracy assessment and for each classification obtained I generated a confusion matrix (CM – also known as error matrix), which is the most standard method for remote sensing classification accuracy assessment (Congalton and Green, 2009). Through the construction of CM, for each assessment I retrieved the classification overall accuracy (OA) as a global measure of classification accuracy, and the producer's and user's accuracies (PA and UA, respectively) as specific accuracy measures to each of the eight thematic classes considered in this study. I did not retrieve the kappa coefficient as some authors reported this measure of global map accuracy is problematic (Gordon, 1980; Stehman, 1997; Foody, 2004) since it does not have a probabilistic interpretation (unlike OA, PA or UA). Moreover, the kappa coefficient has been shown not to be an appropriate map accuracy measure for comparing the accuracy of thematic maps, particularly when (as in this study) the reference data used have always been the same (Foody, 2004).

3.6. Classification overall accuracy comparison

I used the McNemar test to assess the statistical significance of the difference in OA between each pair of classifications because I had used identical reference data to generate the CM and thus obtain the proportion of correctly allocated cases (Agresti, 1996; Foody, 2004). This test is based on a 2x2 matrix and analyzes the level of agreement with respect to correct and incorrect allocations between two classifications based on the following formula:

$$Z = \frac{f_{12} - f_{21}}{\sqrt{f_{12} + f_{21}}}$$

where f_{ij} indicates the frequency of allocations lying in element *i,j* of the 2x2 matrix. This test compares the frequencies of cases correctly allocated in one classification but misclassified in the other. Two classifications are considered to be significantly different at the 95% level of confidence if $Z > |1.96|$ (de Leeuw et al., 2006; Foody, 2006). In this study I carried out McNemar tests to evaluate the statistical significance of differences in classification OA observed 1) among the seven classifications without texture (i.e., 21 tests), 2) between each of the seven classifiers with and without texture (7 tests), and 3) among the seven classifications with texture (21 tests).

4. Results

4.1. Improvements in overall LC classification results using SVM

I find that, for both imagery dates (2001 and 2009) and types of accuracy assessment (hard and soft), all four SVM classifications attain the highest OA and only KNN for 2001 imagery is comparable to them (Table 2.3). On the contrary, MMHC attains the lowest OA for both dates and assessments, though these are similar to ML and KNN for 2009 imagery. ML results are significantly worse than those of SVM for both dates and assessments, whereas KNN results appear somehow contradictory as they are similar to SVM for 2001 and to MMHC and ML for 2009, irrespective of the type of accuracy assessment. I used the McNemar test to evaluate differences only in OA of hard accuracy assessments as the differences in OA of soft assessments were very similar (see Table 2.3). McNemar results are shown in Table 2.4 and a few things are worth noting. First, the statistical significance of the differences between any SVM and MMHC is always maximum regardless of the date, whereas that between any SVM and ML ranges from significant to extremely significant for 2001 and is always extremely significant for 2009. Second, KNN shows no statistically significant differences with the least accurate classifiers (ML and MMHC) for 2009 imagery (although its OA is slightly higher than theirs) and extremely significant differences with all SVM classifiers. However, for 2001 imagery KNN shows no statistically significant differences with the most accurate SVM classifiers and a significant difference with SVM linear, attaining in fact the highest OA of all the classifiers. Third, the relative performance of the different SVM algorithms is very similar. There are no statistically significant differences among them for 2009 and minor differences for 2001 imagery, being perhaps in the latter case the SVM polynomial of 6th grade the best one though this classifier is no significantly better than the SVM RBF and SVM sigmoid.

Table 2.3. Hard versus soft overall accuracy classification results obtained for 2009 and 2001 imagery using only reflectance bands. OA=Overall accuracy; ML=Maximum Likelihood; SVM=Support Vector Machine; KNN=*k*-nearest neighbor; MMHC=Hybrid classification.

Hard vs. Soft Assessment	17/04/2009		25/08/2001	
Classifier	**Hard OA**	**Soft OA**	**Hard OA**	**Soft OA**
ML	71.50	80.50	70.25	70.88
SVM Linear	79.25	86.75	73.25	76.63
SVM Polynomial (6th grade)	79.25	86.63	74.50	74.88
SVM Radial Basis Function	79.38	87.00	73.88	74.25
SVM Sigmoid	80.13	87.75	75.25	75.63
KNN	72.63	80.50	75.75	76.75
MMHC	70.75	79.75	64.13	67.88

Table 2.4. McNemar tests showing the statistical significance of the differences in overall accuracy from a hard assessment among classifiers, for both 2009 and 2001 imagery and using only reflectance bands. Codes are referred to statistical significance: 0 – No significant (p>0.05), 1 – Hardly significant (p~0.5), 2 – Significant (0.5<p≤0.01), 3 – Very significant (p≤0.001), 4 – Extremely significant (p≤0.0001). Left values refer to 2009 and right values to 2001 classifications. Positive values indicate better performance of the row classifier whereas negative values indicate better performance of the column classifier.

17/04/2009 | 25/08/2001	SVM Linear	SVM Polynomial	SVM RBF	SVM Sigmoid	KNN	MMHC
ML	-4 | -2	-4 | -3	-4 | -2	-4 | -3	0 | -4	0 | 3
SVM Linear		0 | -2	0 | 0	0 | -1	4 | -1	4 | 4
SVM Polynomial			0 | 0	0 | 0	4 | 0	4 | 4
SVM RBF				0 | 0	4 | 0	4 | 4
SVM Sigmoid					4 | 0	4 | 4
KNN						0 | 4

4.2. Using textural indexes to improve LC classification results

The potential usefulness of texture for classifying LC is shown in Table 2.5 (only results from indexes extracted with 7x7-pixel moving windows are shown as they led to higher accuracies than indexes extracted from 3x3-pixel windows). I distinguish among three groups of indexes ranked in accordance with their potential usefulness: 1) homogeneity and entropy, which provide significant improvements, 2) mean, dissimilarity, and second moment, that lead to moderate improvements, and 3) variance, contrast, and correlation, which actually decrease classification accuracies when compared with baseline maximum likelihood classifications (i.e., those without texture). Based on these results I focus hereafter on the use of homogeneity (as extracted from a 7x7-pixel moving window), thus discarding the use of other textural indexes. I decided not to use entropy along with homogeneity so as not to increase data dimensionality, and because I tried different combinations of entropy and homogeneity bands that did not increase the accuracies obtained using just homogeneity (results not shown).

Table 2.5. Comparative assessment of the usefulness of textural indices extracted from the gray-level co-occurrence matrix and used in combination with spectral bands, carried out using the maximum likelihood classifier. No maximum likelihood classification could be obtained using the correlation index extracted from 2001 imagery.

Textural indices	17/04/2009			25/08/2001		
	OA	**PA EGDF**	**UA EGDF**	**OA**	**PA EGDF**	**UA EGDF**
Without texture	81.64	75.56	97.84	81.67	85.78	97.23
With a textural Index						
Mean	84.17	88.89	98.52	82.74	94.67	74.35
Variance	76.88	73.22	89.30	77.21	83.89	74.46
Homogeneity	85.54	89.67	97.46	86.21	90.11	86.18
Contrast	78.90	73.89	89.38	81.63	87.78	80.94
Dissimilarity	84.03	88.44	94.54	82.85	91.22	87.43
Entropy	84.92	88.33	96.95	85.21	90.33	83.64
Second Moment	82.20	81.67	97.35	84.76	85.56	86.03
Correlation	76.55	82.67	86.61	-	-	-

4.3. Improvements in overall LC classification results using the homogeneity index

The use of the homogeneity index (HI) greatly improves the results obtained by any classifier regardless of the imagery date and the type of accuracy assessment (Table 2.6). Even though the differences in OA attained by each classifier with and without HI are striking, they too have been evaluated with the McNemar test albeit only for hard assessments as the differences in OA for soft assessments follow the same pattern. I find that the differences in OA are extremely significant for all the classifiers, with the sole exception of the MMHC classification for 2009 imagery, which is not statistically significant. Yet, even in that case, the OA increases 1.25% with the inclusion of HI. Looking carefully at the magnitude of the improvements achieved in the classifications with the inclusion of HI (Table 2.6), I find that there is a gradient from small to moderate improvements in MMHC (1.25% & 7.12%), moderate to large improvements in ML (7.38% & 9.13%) and KNN (7.12% & 11.00%), and large to very large improvements in the four SVM classifiers (ranging from around 11% to 13% for 2009 imagery to around 16% and up to 22% for 2001 imagery). Figure 2.2 illustrates classification results showing examples of ML, KNN and SVM RBF with the use of HI.

I applied McNemar tests to evaluate whether there was statistical significance regarding the differences obtained in map (hard) accuracy by all the classifiers when incorporating HI in the classification process (Table 2.7). The main finding is that with HI all four SVM algorithms outperform even further all the other algorithms. For instance, it is remarkable that without HI and for 2001 imagery, KNN shows no significant difference with any SVM and actually performs a bit better than SVM linear (Table 2.4), whereas with HI the statistical significance of the superiority of SVM algorithms over KNN ranges from significant to extremely significant (Table 2.7). Similarly, the superiority of all SVM over ML classifiers increases for 2001 imagery with the inclusion of HI, as evidenced by the increase in the statistical significance of their differences (see Tables 2.4 and 2.7).

Therefore, all four SVM classifiers optimize the use of HI compared to KNN, ML and MMHC. Looking at the differences in performance among the four SVM algorithms it is worth mentioning that, with HI, SVM sigmoid and particularly SVM RBF obtained the best results for both imagery dates, thus maximizing the usefulness of HI (recall that without HI all SVM performed similarly well).

Table 2.6. Hard classification results obtained for the images of 2009 and 2001 using both reflectance and the homogeneity index (HI)bands. IOA=Improvement in Overall Accuracy owing to the inclusion of HI in the classification.

Hard vs. Soft Assessment	**17/04/2009**				**25/08/2001**			
Classifier	**Hard OA**	**Hard IOA**	**Soft OA**	**Soft IOA**	**Hard OA**	**Hard IOA**	**Soft OA**	**Soft IOA**
ML	78.88	7.38	85.25	4.75	79.38	9.13	81.50	10.62
SVM Linear	90.50	11.25	93.88	7.13	90.38	17.13	90.50	16.87
SVM Polynomial (6^{th} grade)	89.13	9.88	92.25	5.62	89.88	15.38	90.13	15.25
SVM RBF	92.63	13.25	95.63	8.63	96.13	22.25	96.25	22.00
SVM Sigmoid	92.75	12.62	95.50	7.75	90.63	15.38	92.00	16.37
KNN	79.75	7.12	86.25	5.75	86.75	11.00	88.63	11.88
MMHC	72.00	1.25	81.38	1.63	71.25	7.12	75.38	7.50

Table 2.7. McNemar tests showing the statistical significance of the differences in overall accuracy from a hard assessment among classifiers, using HI and for both 2009 and 2001 imagery. Notation as in Table 2.4.

17/04/2009 | 25/08/2001	**SVM Linear + HI**	**SVM Polynomial + HI**	**SVM RBF + HI**	**SVM Sigmoid + HI**	**KNN + HI**	**MMHC + HI**
ML + HI	-4 | -4	-4 | -4	-4 | -4	-4 | -4	0 | -4	4 | 4
SVM Linear + HI		0 | 0	-4 | -4	-3 | 0	4 | 3	4 | 4
SVM Polynomial + HI			-4 | -4	-4 | 0	4 | 2	4 | 4
SVM RBF + HI				0 | 4	4 | 4	4 | 4
SVM Sigmoid + HI					4 | 3	4 | 4
KNN + HI						4 | 4

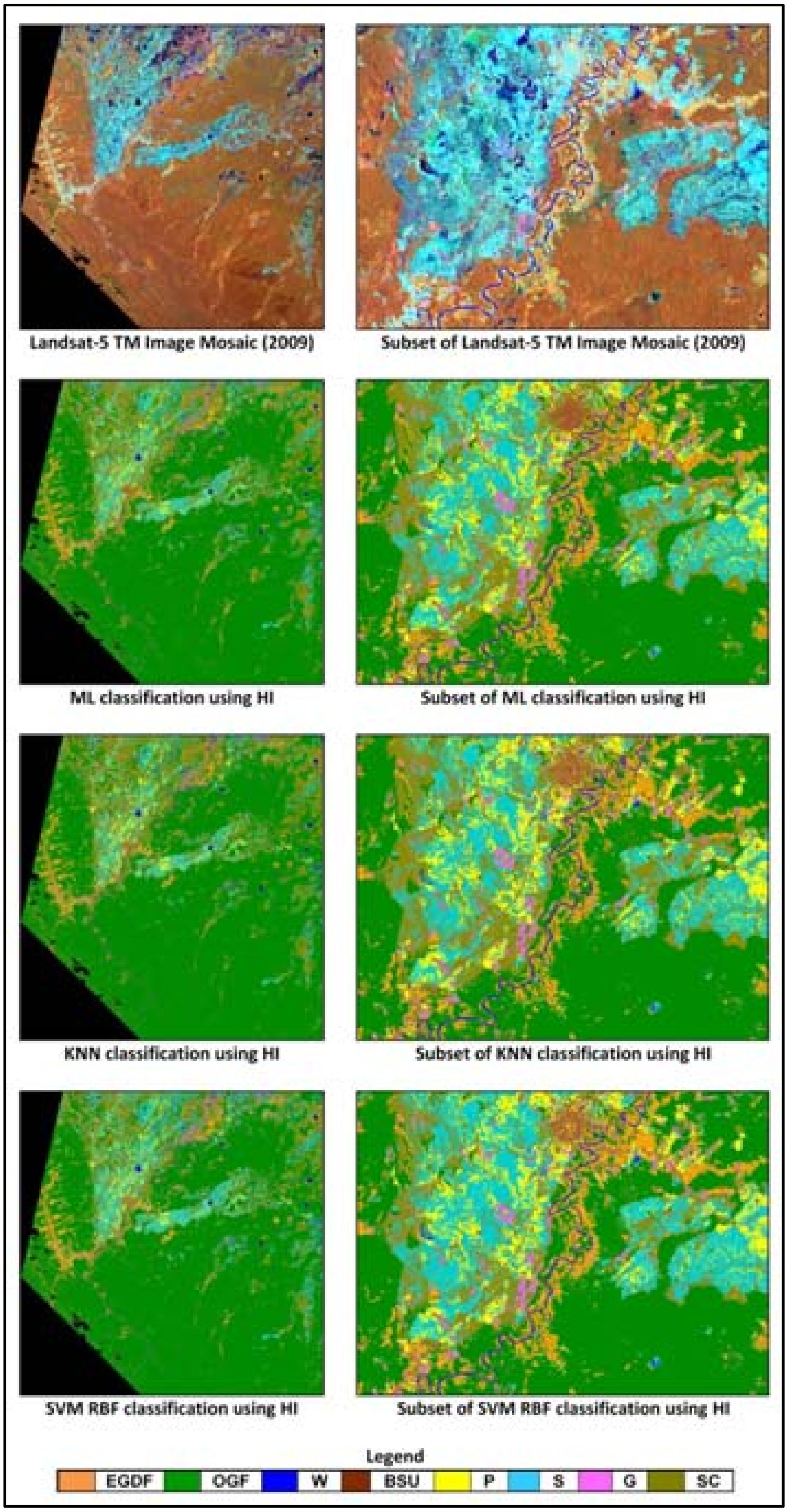

Figure 2.2. ML, KNN and SVM RBF classifications using reflectance bands along with HI. Left column shows classifications for the entire image mosaic and right column shows a subset of 1280 x 944 pixels from the center of the mosaic. EGDF=Early-Growth/Degraded Forest, OGF=Old-Growth Forest, W=Water, BSU=Bare Soil/Urban, P=Pasture, S=Savanna, G=Grassland, SC=Scrubland.

4.4. Improvements in classification results by LC classes using the homogeneity index

To assess what LC classes benefit more with the inclusion of HI, I present here the confusion matrices (CM) of ML, KNN and SVM RBF classifications. I do not show CM of other SVM as overall SVM RBF appears to be the best SVM classification when HI is included. Neither do I show CM of MMHC because its improvement with HI for 2009 is not significant, only moderate for 2001, and the OA attained with this classifier for either date is not satisfactory compared to the rest of classifiers tested here. I focus on hard accuracy assessments and show CM just for 2009 classifications.

Table 2.8 shows the CM of ML without and with HI respectively. Regarding PA there are very large improvements in early-growth/degraded forest (20%) and pasture (17%), and a moderate improvement in grassland (7%) when HI is included. Both savanna and scrubland remain with the same PA and old-growth forest slightly decreases (4%) but still has a 90% PA. Regarding UA there are moderate improvements in grassland (7.14%) and scrubland (6.39%), and larger ones in old-growth forest (11.32%) and savanna (15.13%). Both early-growth/degraded forest and pasture remain with the same UA. The results from the CM from 2001 imagery are similar. The main differences in relation to PA are higher increases in pasture and grassland (48% and 23%, respectively) while savanna and scrubland decrease 8% and 7% respectively, whereas for UA the main differences relate to greater improvements in savanna and scrubland (28.47% and 19.53%), and a significant decrease in early-growth/degraded forest (14.74%). Table 2.9 shows the CM of KNN. Remarkably, these CM are very similar both in values and trends to those of ML. The main differences with what has been shown for ML are that, for KNN, savanna's PA is improved in one date and that early-growth/degraded forest's UA is not affected in either date.

Table 2.10 shows the CM of SVM RBF. With respect to PA everything improves except old-growth forest, which decreases to 93%. PA gains are most remarkable for early-growth/degraded forest (31%) and pasture (20%), but notable for savanna (10%), grassland (13%), and scrubland (11%). UA improvements are very large for old-growth forest (21.57%), savanna (25.33%), and scrubland (18.07%), and moderate for pasture (8.34%), grassland (6.06%), and early-growth/degraded forest (4.10%). Results from the 2001 classification are very similar. Again, neither PA nor UA decrease with HI and, in fact, improvements with HI are even higher for 2001 imagery: pasture's and grassland's PA increase by 62% and 41% respectively whereas savanna's, grassland's, and scrubland's UA enhance by 36.32%, 32.40% and 34.54% respectively. Therefore, SVM RBF maximizes the use of HI as it boosts both PA and UA. Furthermore, it does so for all eight LC classes (not just for some as ML and KNN do) and up to very high levels of PA and UA (almost always >90%, unlike ML and KNN that did only achieve similar accuracies for old-growth forest). Lastly, it is to be highlighted that even though the other 3 SVM classifiers did not perform as well as SVM RBF, they show very similar PA and UA values (usually >85-90%) and trends of improvement by LC class with the inclusion of HI.

Table 2.8. Hard assessment confusion matrices for the maximum likelihood classifications of Landsat data (17/04/2009). Left values refer to the classification without HI and right values to the classification with HI. Notation as in Figure 2.2.

Classification Data	Reference Data																			
	EGDF		**OGF**		**W**		**BSU**		**P**		**S**		**G**		**SC**		**Total**		**UA**	
EGDF	57	77	0	1	0	0	0	0	0	0	0	0	0	0	1	3	58	81	98,3	95,1
OGF	15	3	94	90	1	0	0	0	0	0	0	0	0	0	0	0	110	93	85,4	96,8
W	0	0	0	0	57	66	0	0	0	0	0	0	0	0	0	0	57	66	100,0	100,0
BSU	0	0	0	1	11	14	88	96	6	8	0	1	9	5	0	0	114	125	77,2	76,8
P	0	0	0	0	0	0	5	4	67	84	7	9	0	0	1	1	80	98	83,7	85,7
S	0	0	1	1	30	20	0	0	13	0	65	66	0	1	9	6	118	94	55,1	70,2
G	4	1	1	0	1	0	1	0	1	0	0	2	60	67	5	5	73	75	82,2	89,3
SC	24	19	4	7	0	0	6	0	13	8	28	22	31	27	84	85	190	168	44,2	50,6
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	800	800	78,3	83,1
PA	57,0	77,0	94,0	90,0	57,0	66,0	88,0	96,0	67,0	84,0	65,0	66,0	60,0	67,0	84,0	85,0	71,5	78,9		

Table 2.9. Hard assessment confusion matrices for *k*-nearest neighbor classifications of Landsat data (17/04/2009). Left values refer to the classification without HI and right values to the classification with HI. Notation as in Figure 2.2.

Classification Data	Reference Data																			
	EGDF		**OGF**		**W**		**BSU**		**P**		**S**		**G**		**SC**		**Total**		**UA**	
EGDF	45	63	0	0	0	0	0	0	0	0	0	0	0	1	1	1	46	65	97,8	96,9
OGF	27	14	94	93	5	10	0	0	0	0	0	2	0	0	1	1	127	120	74,0	77,5
W	0	0	0	0	78	81	0	0	0	0	0	0	0	0	0	1	78	82	100,0	98,8
BSU	0	0	0	0	0	1	85	87	3	2	0	0	4	1	0	0	92	91	92,4	95,6
P	0	0	0	0	0	1	9	10	68	87	5	6	0	0	0	0	82	104	82,9	83,6
S	0	0	0	0	10	1	0	0	11	3	50	62	0	0	5	4	76	70	65,8	88,6
G	2	1	1	1	5	3	2	1	2	0	0	1	73	78	5	6	90	91	81,1	85,7
SC	26	22	5	6	2	3	4	2	16	8	45	29	23	20	88	87	209	177	42,1	49,1
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	800	800	79,5	84,5
PA	45,0	63,0	94,0	93,0	78,0	81,0	85,0	87,0	68,0	87,0	50,0	62,0	73,0	78,0	88,0	87,0	72,6	79,7		

Table 2.10. Hard assessment confusion matrices for SVM radial basis function classifications of Landsat data (17/04/2009). Left values refer to the classification without HI and right values to the classification with HI. Notation as in Figure 2.2.

Classification Data	Reference Data																			
	EGDF		OGF		W		BSU		P		S		G		SC		Total		UA	
EGDF	60	91	0	0	0	0	1	0	0	0	0	0	2	0	1	2	64	93	93,7	97,8
OGF	28	6	95	93	2	0	0	0	0	0	0	0	0	0	8	1	133	100	71,4	93,0
W	0	0	0	0	79	98	0	0	0	0	0	1	0	0	0	1	79	100	100,0	98,0
BSU	0	0	0	0	0	0	88	92	2	1	0	0	3	0	0	0	93	93	94,6	98,9
P	0	0	0	0	0	0	7	5	71	91	5	2	0	0	1	0	84	98	84,5	92,9
S	0	0	1	1	15	0	0	0	14	2	84	94	0	0	10	4	124	101	67,7	93,1
G	1	0	1	0	4	1	3	3	2	1	0	0	80	93	2	3	93	101	86,0	92,1
SC	11	3	3	6	0	1	1	0	11	5	11	3	15	7	78	89	130	114	60,0	78,1
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	800	800	82,3	93,0
PA	60,0	91,0	95,0	93,0	79,0	98,0	88,0	92,0	71,0	91,0	84,0	94,0	80,0	93,0	78,0	89,0	79,4	92,6		

5. <u>Discussion</u>

5.1. Comparative performance among classifiers

In this study I have found that SVM classifiers outperform parametric (ML), non-parametric (KNN), and hybrid (MMHC) classifiers. This finding is consistent with research that has shown the superiority of other non-parametric machine learning algorithms for LC mapping in the Amazon basin (Lu *et al*., 2004; Carreiras *et al*., 2006a) and demonstrates the usefulness of SVM for LC classifications of tropical landscapes, something seldom explored to date (e.g., Wijaya and Gloaguen (2007)).

Several major advantages have been highlighted regarding the use of SVM (and other non-parametric classifiers) for LC mapping, which may make them achieve better results than parametric or hybrid classifiers. One substantial advantage relates to the fact that there is no need to assume any particular data distribution, which is more appropriate (particularly when some LC classes are highly heterogeneous as in this study) and facilitates the use of ancillary data in the classification process (Lu and Weng, 2007). I have verified some of my training data do not follow a normal distribution (Figure 2.3), which may partly explain why in my study SVM have significantly outperformed the rest of classifiers. This fact may also explain the poor performance of ML even for the case of soft assessments, as this algorithm requires that training data be normally distributed. Yet, possibly the main reason underlying the superiority of SVM may be related to the training sets I have used and the occurrence of mixed pixels within them. As Foody and Mathur (2006) demonstrated, SVM use mixed pixels to obtain the support vectors they need for classifying data, whereas the rest of classifiers cannot deal properly with mixed pixels as they derive LC class statistics from training samples to characterize such classes.

I do not have a clear explanation with regard to the contrasting performance of KNN for 2001 and 2009 imagery irrespective of the type of accuracy assessment. As aforementioned, I used the Jeffries-Matusita transformed divergence index to test the separability of all pairs of LC classes for both imagery dates and found that, unlike for 2001 imagery (dry season), some of them were hardly separable for 2009 imagery (wet season), which may suggest that under challenging conditions KNN cannot perform too well. Finally, although MMHC has been successfully used in Mediterranean environments (Serra et al., 2003; Serra et al., 2005), in my study area its performance is very poor for both dates and assessments compared to all SVM classifiers. I believe MMHC may not be appropriate for classifying tropical areas as they are typically too complex spectrally and, therefore, a very large training set may be needed to derive an accurate supervised classification from the many spectral classes obtained with the ISODATA classification. This finding is consistent with that of García-Millán and Moré (2008) for LC classification of a tropical dry area in Nicaragua, as they obtained 0% of PA for several LC classes and of UA for one class.

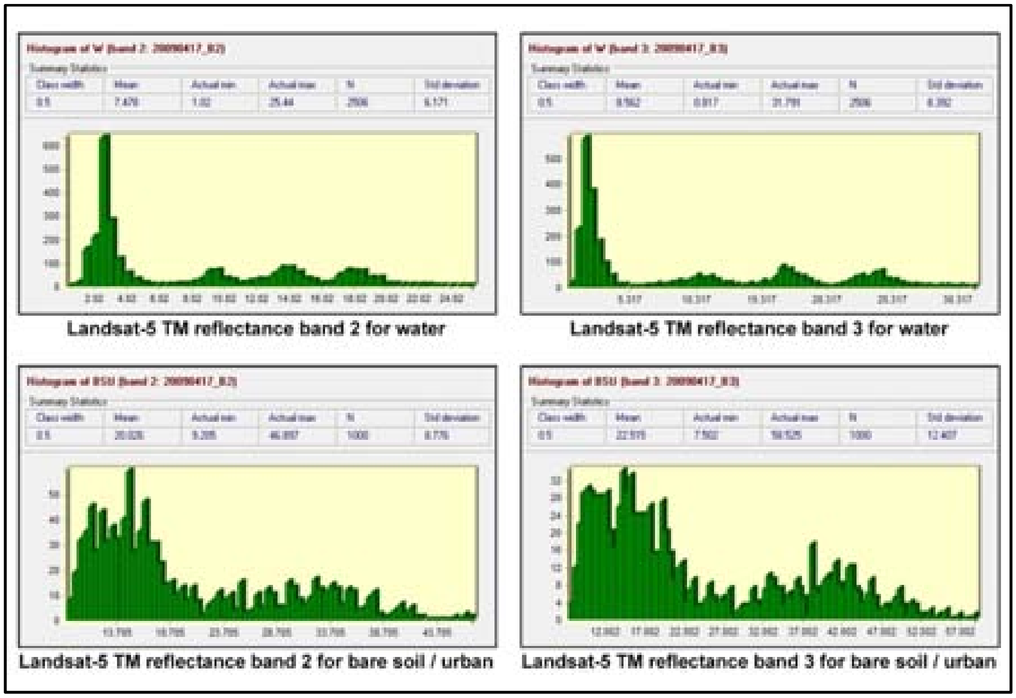

Figure 2.3. Examples of non-Gaussian distributions in training data (histograms shown refer to reflectance bands of water and bare soil/urban classes; frequencies are shown in Y axis and reflectance in X axis).

5.2. Taking advantage of textural information: the case of the homogeneity index

My results show the potential usefulness of including textural measures to enhance the classification of LC in heterogeneous areas. This finding is consistent with other studies that have sought to evaluate whether improvements in OA can be attained when using spectral-textural classification approaches rather than approaches based solely on spectral features (Gong *et al.*, 1992; Franklin *et al.*, 2000; Haack and Bechdol, 2000; Zhang *et al.*, 2004; Ota *et al.*, 2011), including studies in tropical forest areas (Riou and Seyler, 1997; Chan et al., 2001; Chan et al., 2003). Furthermore, my results suggest that HI and entropy may be the most appropriate indexes for LC classification endeavors. While both textural indexes have been shown to describe nearly all the textural information contained in sonar imagery (Huvenne *et al.*, 2002; Blondel and Gómez Sichi, 2009), they have seldom been used to classify LC from multispectral imagery (especially HI). Among the few examples found in the literature, Chan et al. (2001) and Chan et al. (2003) used HI together with other seven textural indices extracted from the GLCM and four indices derived from the gray-level difference vector for forest classification with Landsat TM imagery in Peru and the Congo Republic respectively, but apparently did not find HI useful as they did not include it in their final classifications, though this fact was not discussed. Chehade et al. (2009) explored the use of HI together with other three conventional textural indices (energy, contrast and entropy) and NDVI, for classifying vegetation types from an aerial color infrared image with SVM algorithms, obtaining accurate results. I have not found, however, any LC classification study that exploits HI on its own together with spectral bands. In fact, studies comparing the performance of different textural indices for image classification have not regarded HI as one of the most useful ones (Haralick *et al.*, 1973; Gong *et al.*, 1992; Baraldi and Parmiggiani, 1995).

Nonetheless, my study suggests that HI may be a very powerful textural index for LC mapping as the improvements in OA of both hard and soft accuracy assessments for 2001 and 2009 classifications are extremely significant irrespective of the classifier employed (with the sole exception of MMHC for 2009 imagery). I believe the improvements I have obtained may be explained by two main reasons. First, based on the fact that the combination of entropy and HI has not improved the results attained in preliminary classifications with respect to those attained using just HI, it seems that HI by itself may be able to characterize most textural variability found in the imagery, thus improving classification results. Second, as illustrated in Figure 2.4, I have observed that the inclusion of HI has often enabled the classifier to correctly allocate ambiguous reference points, i.e., points located in the transition between different covers (mixed pixels) or corresponding to transition covers not considered specifically in the classification scheme. For instance, for 2009 imagery, when HI was used the SVM RBF algorithm correctly classified 31 reference points more for the early-growth/degraded forest class. I verified that 28 out of those 31 points lied in between two or more LC classes (normally either old-growth forest or scrubland), and only 3 points were located within homogeneous areas. Similarly, 20 reference points more for the pasture class were correctly classified by using HI, from which 17 were ambiguous. This trend is followed by other LC classes and explains the improvements obtained using soft accuracy assessments. Therefore, the inclusion of HI alleviates the classification problem posed by spectrally mixed pixels.

Additionally, I have found two facts in conflict with previous research. First, contrary to what was suggested by Augusteijn et al. (1995), small window sizes (7x7-pixel in my study) seem to accurately characterize GLCM textural information as related to LC classes. I believe this responds to the relatively small size of patches of some LC classes such as early-growth/degraded forest, pasture and grassland, which therefore makes texture to change over small areas in many instances. Second, contrary to the findings of Ota et al. (2011), my classification accuracies improve with the inclusion of textural information at 30m spatial resolution, including PA and UA of forest types. This is important as demonstrates the potential usefulness of using texture with Landsat imagery and not just with very high spatial resolution images such as IKONOS or QuickBird, which are frequently too expensive for operational use in tropical areas and inappropriate when large areas are to be mapped.

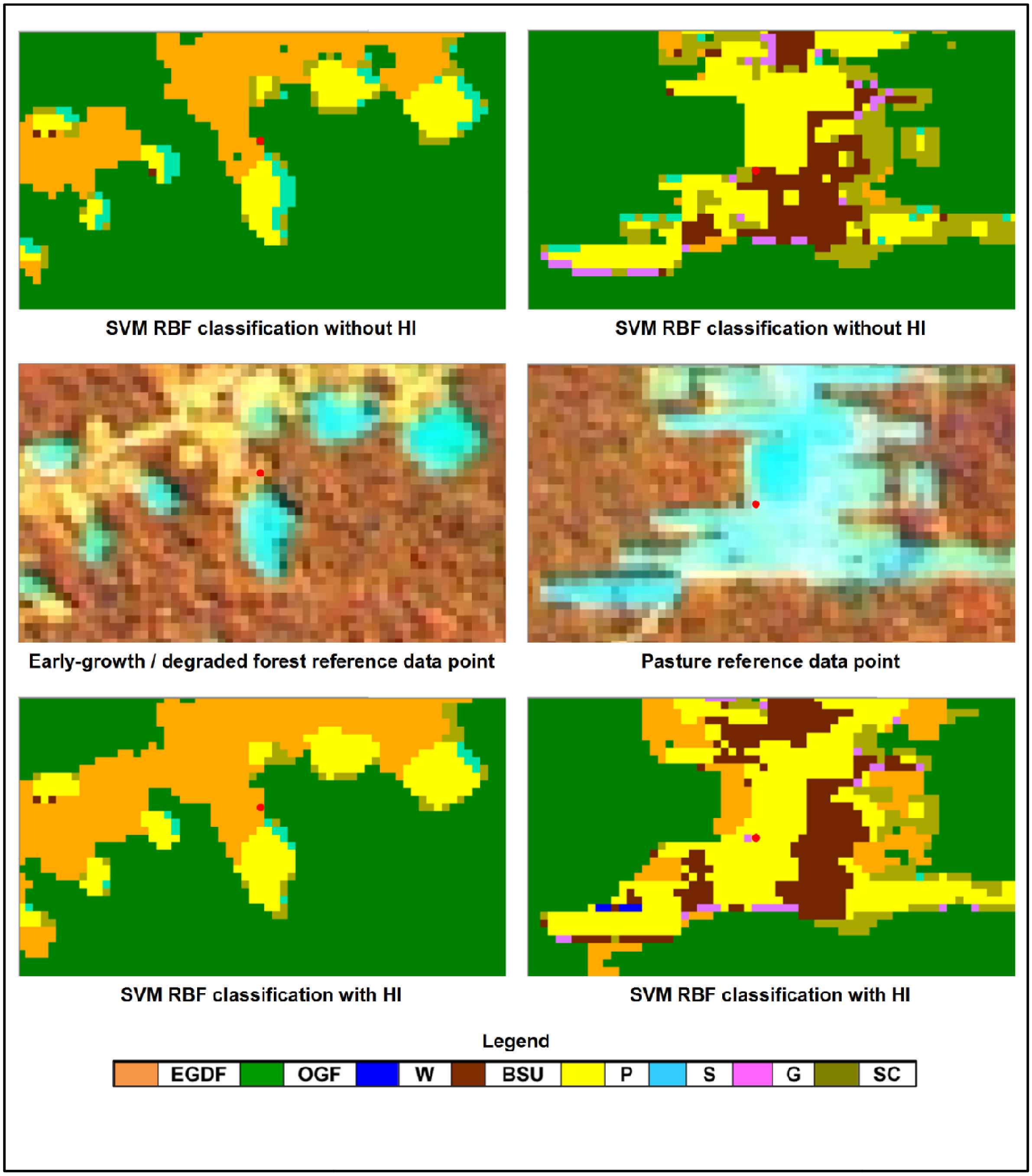

Figure 2.4. Examples show misclassification (top row) and accurate classification (bottom row) of reference data points (in red at the center of subsets) lying on the fringe of different LC classes. The inclusion of HI significantly improves the classification of these points in the case of SVM classifiers, particularly for EGDF (left column) and P (right column) classes. Notation as in Figure 2.2.

Regarding the improvements achieved by different classifiers through the use of HI alongside spectral data, it is clear that SVM classifiers take further advantage of HI. One possible explanation for this improvement is that SVM classifiers are independent of data dimensionality (Dixon and

Candade, 2008) unlike the rest of the classifiers tested in this study. Since I did not increase the size of the training set after including the 6 HI bands in the classification, the improvements in performance of SVM classifiers may have been more significant than those of the rest, as dimensionality-dependent classifiers would have required bigger training datasets to increase their performance. In addition, I have verified that some training data extracted from the 6 HI data bands calculated for each Landsat mosaic do not follow a normal distribution (Figure 2.5), which may explain why non-parametric algorithms deal with the inclusion of HI in the classification in a better way. This fact may also explain why certain classes show large improvements in PA and/or UA while others are not seemingly affected or may even slightly decrease their accuracies.

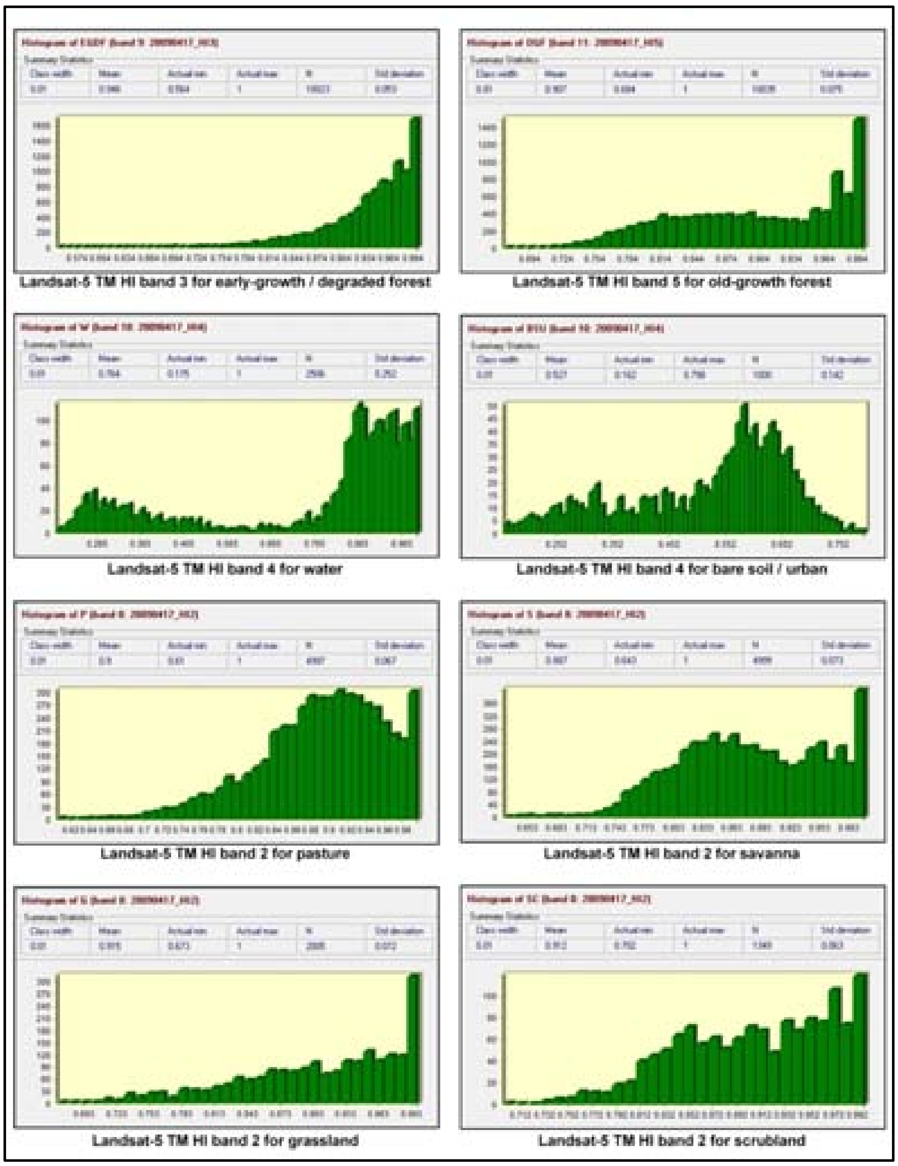

Figure 2.5. Examples of non-Gaussian data distributions in training data (histograms refer to HI bands and one example is given per LC class; frequencies are shown in Y axis and HI values in X axis).

5.3. Accurate mapping of all LC classes using SVM and the homogeneity index

I have found that the combination of HI and spectral bands is particularly useful when using SVM classifiers (particularly SVM RBF and SVM sigmoid) as all the LC classes considered could be accurately mapped both in terms of their PA and UA. This is important as many studies need to attain reasonably high accuracies for all LC classes considered, for instance studies aiming to monitor LC change trajectories (Schulz et al., 2010) or to model future LC changes (Guerrero et al., 2008). Similarly, in studies that seek to quantify a specific LC class or just a few, attaining high accuracies for such classes is of critical importance. This is common for many studies focusing on mapping forests to assess deforestation, forest degradation and/or forest regrowth (Lambin, 1999; Lucas *et al.*, 2000; Lu *et al.*, 2003; Porter-Bolland *et al.*, 2007; Díaz-Gallegos *et al.*, 2010), which sometimes barely go beyond the forest/non-forest legend (Messina *et al.*, 2006; Marsik *et al.*, 2011), as well as for studies concerned with mapping some other typical LC such as agriculture, grassland, pasture, savanna (Carreiras *et al.*, 2006b; Baldi and Paruelo, 2008; Brannstrom and Filippi, 2008).

In my study I needed to develop an approach that enabled me to obtain high accuracies for all LC classes as a first step to assess LC change and landscape dynamics. Though I found that HI significantly increased the OA regardless of the classifier used, I observed that for non-SVM classifiers (i.e., KNN, ML, MMHC), improvements in PA and UA were highly dependent on LC class as some classes were largely improved (early-growth/degraded forest, pasture, and grassland for PA, and savanna for UA), while others did not appear to improve or even worsened (scrubland for PA). However, SVM classifiers improved all LC classes both in terms of their PA and UA, with the only exception of old-growth forest (its PA slightly decreased though it always retained an extremely high value). I believe the main reasons underpinning this finding are very similar to what has been explained in the previous subsection, i.e., the optimal use of HI by SVM classifiers compared to the rest (as our training set was not enlarged and non-SVM classifiers would exponentially need more training samples to keep up their performance as data dimensionality increases), and the no normality found in the training samples for some HI bands, which is dependent on LC class and may explain why improvements are not evenly spread among LC classes. Further research should address this issue more in-depth and analyze differences in misclassification errors among LC classes.

6. <u>Conclusions</u>

In this study I set out to establish an efficient classification approach to accurately map all broad LC classes in a large, heterogeneous tropical area of Bolivia. I found that SVM classifiers outperform other parametric (ML), non-parametric (KNN) and hybrid (MMHC) classifiers. I also found that the inclusion of two textural indices (homogeneity and entropy) can significantly enhance LC classification results. Specifically, I observed that the inclusion of HI significantly improves the overall accuracy of the classifications regardless of the algorithm used, which is an important finding since the use of textural homogeneity has been neglected so far in LC mapping efforts. The most accurate results through the inclusion of homogeneity are achieved by SVM classifiers (particularly SVM RBF and sigmoid), which further outperform the rest of classifiers compared in the study, thus optimizing the use of HI. The use of both spectral and textural homogeneity information for LC classification with SVM algorithms enabled me to map the two forested classes (early-growth/degraded forest and old-growth forest) with producer's and user's accuracies >90% for both Landsat imagery dates (2001 and 2009) and types of accuracy assessment (hard and soft) used, which makes my approach very suitable to map and monitor tropical forest cover change as needed for ecological assessments and REDD+ schemes. Similarly, the rest of LC classes included in this study were mapped to producer's and user's accuracies of ~90%, thus rendering my approach very interesting too for land change analysis, ecological studies, and natural resource assessments in areas other than forests.

As LC mapping endeavors are key to conservation initiatives, climate change mitigation strategies such as REDD+, and the design of management plans and rural development policies, any advancement in this challenging task may have wide-ranging applications. My classification approach presents the advantage of being easy to implement, as both the calculation of the homogeneity index and the presence of SVM classifiers are readily available in common remote sensing software, and cost-effective, as SVM classifiers may use smaller training datasets without compromising classification accuracy. More importantly, the very high accuracies obtained with this classification approach suggest its great potential for accurate LC mapping in the Amazon basin, and quite possibly in other tropical and non-tropical areas too, which I will assess in the near future.

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Chapter 3

The effects of land tenure on spatio-temporal patterns of forest cover change in the Bolivian Amazon (1986-2009)

A los tojolabales les parece una locura que la sociedad dominante, con las leyes que ha hecho, considere propiedad a la tierra... La razón es que gracias a la tierra tenemos comida y crece el maíz que nos sostiene [...] Para los tojolabales, la tierra es fuente de vida y por ello, se llama Nuestra Madre Tierra, que queremos respetar. Para la sociedad dominante, la tierra es propiedad y, por tanto, mercancía, sometida a los mecanismos del mercado

(Sobre los Tojolabales, en *Los hombres verdaderos*, Carlos Lenkersdorf)

Abstract

As land use change continues to increase throughout the Amazon basin, there is a pressing need for accurately mapping, quantifying and assessing the effects of different factors on forest cover change (FCC). Land tenure is known to have potentially important effects on forest cover, yet such effects remain poorly understood in Amazonia. The main goal of this chapter is to assess whether significant differences in trends of FCC can be explained by different land tenure systems across my study area in the Bolivian Amazon. I examine spatio-temporal dynamics of FCC across four land tenure systems (indigenous titled territory, protected area, logging concession, and private land) by classifying forests using a time-series of Landsat satellite imagery consisting of four dates (1986, 1996, 2001, 2009). Specifically, I unravel 1) trends in early-growth and old-growth forest extent, including changes in total cover area, annual change rates, and spatial change dynamics, and 2) trends in old-growth forest fragmentation. Among the land tenure systems analyzed, I found that 1) private lands underwent, by far, the largest FCC, 2) indigenous territories and the protected area examined had relatively little FCC, and 3) logging concessions were responsible for the lowest FCC. The study sheds light into the effects of land tenure on FCC and has important implications for public policies aimed at socioeconomic development and environmental conservation in the

Amazon. I give some policy recommendations drawn from a biocultural conservation perspective that may contribute to implement more inclusive conservation policies in the region.

Keywords: Bolivian lowlands; tropical deforestation and forest degradation; tropical forest fragmentation; indigenous territory; logging concession; protected area; private land; biocultural conservation

1. Introduction

Amazonian tropical forests are home to an incredible wealth of biological, cultural and linguistic diversity (Maffi, 2005). They have long been inhabited and managed by indigenous groups (Heckenberger *et al.*, 2007; Mann, 2008; Lombardo *et al.*, 2011) and, in more recent times, have attracted a myriad of outsiders seeking fortune by extracting commodities such as rubber, gold, and wood (Hetch and Cockburn, 2011). From the second half of the 20th century, population growth, slash-and-burn agriculture, and the severe intensification of market-oriented economic activities (e.g., cattle ranching, industrial farming and forestry) have brought about the loss, fragmentation, and degradation of many old-growth forests in the region (Rudel and Roper, 1997; Geist and Lambin, 2001). Such FCC bears significant implications for local livelihoods, poverty alleviation (Sunderlin *et al.*, 2008), biocultural conservation (Gorenflo *et al.*, 2012), and global climate (Luyssaert *et al.*, 2008). As land use change continues to increase throughout the Amazon basin (Hecht, 2005; Davidson *et al.*, 2012), there is a pressing need for mapping and quantifying FCC to implement biodiversity conservation mechanisms and climate change mitigation schemes, while ensuring the well-being of people in the region. Likewise, identifying the main drivers of FCC in the Amazon and their effects on FCC is essential to model future changes under different scenarios (Soares-Filho *et al.*, 2006), a tool that may inform the design and implementation of conservation and rural development policies.

Many studies have sought to map, quantify and/or identify the main factors associated with Amazonian forest loss and fragmentation (e.g., Steininger *et al.*, 2001a; Laurance *et al.*, 2002a; Fearnside, 2005) and, less often, of forest degradation and/or regrowth (e.g., Perz and Skole, 2003; Walsh *et al.*, 2008). In that vein, several studies have recently aimed at documenting and explaining FCC in the Bolivian Amazon (e.g., Kaimowitz, 1997; Steininger *et al.*, 2001b; Pacheco, 2002, 2006; Killeen *et al.*, 2007; Killeen *et al.*, 2008; Marsik *et al.*, 2011; Müller *et al.*, 2011). Research on this topic has highlighted an increase in the rates of deforestation and forest degradation since the first Bolivian agrarian reform was deployed in 1952-1953 following the National Revolution of 1952 (Pacheco, 2006). However, much FCC has been ultimately explained through more recent underlying factors such as the 1974 forestry law, the colonization boom that took place since the mid-1980s, the agrarian and forestry reforms put forward in 1996, and the more recent agrarian reform of 2006, all of which have provoked significant forest clearance, fragmentation and degradation across the eastern lowlands of Bolivia (Pacheco, 1998). Such reforms have led to a specific configuration of land tenure systems, each one characterized by the allocation of specific land uses and property rights. For example, across the Bolivian Amazon, some state (public) lands were declared protected areas for biological conservation in the 1980s, others were granted to companies as logging concessions for timber extraction, and others began being titled indigenous territories in the early-1990s. In addition, particularly since the 1980s, different colonization projects have given away state lands to colonists, mainly Andean peasants and miners who became unemployed with the mining industry collapsed of the mid-1980s (Pacheco, 2006; Killeen *et al.*, 2008).

The effects of land tenure systems and tenure (in)security as factors associated with deforestation, fragmentation, and/or forest degradation have been found to be significant in some case studies in the Amazon (Fearnside, 1993; Messina *et al.*, 2006; Araujo *et al.*, 2009). Since land tenure and tenure insecurity affect the migration of populations and landholders' decisions on land use, labor, and capital investment, deforestation and logging are closely associated with them (Fearnside, 2001). Nevertheless, these types of effects have not been sufficiently explored in the Bolivian lowlands. Since different land tenure systems are legally restricted to specific land use types (Reyes-García *et al.*, 2012), I contend that land tenure (and therefore land use allocation and property-rights) may have had profound effects on the spatio-temporal patterns of FCC, and I test such potential effects in the Bolivian lowlands. Thus, my main goal in this chapter is to assess whether significant differences regarding trends in FCC can be explained by different land tenure systems across my study area. I examine spatio-temporal dynamics of FCC across two indigenous titled territories, a protected area, six logging concessions, and private lands. I hypothesize that indigenous territories and the protected area may have undergone less FCC than private lands and logging concessions. Specifically, for the four land tenure systems aforementioned, I aim to map and quantify 1) the trends in extent, change rates, and spatial dynamics of both old-growth and early-growth forests, and 2) the trends in old-growth forest fragmentation patterns. I conduct the assessment for the period 1986-2009 because the current configuration of land tenure systems and most FCC in the Bolivian lowlands has occurred since the mid-1980s following the structural adjustment program initiated by the Bolivian government in 1985, and the economic development policies that were implemented as a result (Pacheco, 2006; Killeen *et al.*, 2008).

2. <u>Case study</u>

2.1. Biophysical setting

The study area is located in the department of Beni, in northeastern Bolivia. It has a high diversity of habitats that may be broadly grouped into montane tropical forests, lowland tropical forests, and wet savanna areas. Here I focus on lowland tropical forests as they occupy ~80-90% of the different land tenure systems examined; most of them are old-growth *terra firme* forests though a range of *bajío* forests thrive in areas seasonally or permanently flooded (Guèze *et al.*, 2012). In addition, there are degraded forests in selectively logged areas (Gullison *et al.*, 1996), and early-growth forests surrounding both indigenous and non-indigenous settlements, where swidden-fallow agroforestry systems are commonplace (Huanca, 1999). Lowland forests across the study area contain semi-deciduous tree species owing to the existence of contrasting dry and wet seasons (four months having <100 mm of precipitation (Guèze *et al.*, 2012)). Mean annual temperature is of 25.8ºC (Navarro and Maldonado, 2002) and mean annual rainfall of 1743 mm (Godoy *et al.*, 2008). Most soils are quaternary alluvial sediments of fluvial origin, particularly acrisols and ferrasols (Navarro and Maldonado, 2002).

2.2. Land tenure systems, property-rights, land use types, and social groups

I find four land tenure regimes across the study area: titled indigenous territories (TCOs, the acronym for the Spanish *Tierra Comunitaria de Origen*), protected areas, logging concessions, and private lands. In this study I analyze FCC for such land tenure systems using five areas (Figure 3.1). TCOs are indigenous titled territories with communal property-rights where land cannot be sold. I consider two such territories in the analyses: Tsimane' and Multiethnic TCOs, both of which were recognized in 1990 and initially accounted for some 400,000ha each. However, since the 1996 agrarian reform, both TCOs have lost much land as a result of an ongoing land tenure regularization process (known as *saneamiento*) that gives land to third parties who can demonstrate land occupancy before the TCOs were established, and land's socioeconomic function as defined in the reform (Reyes-Garcia *et al.*, in review). The Tsimane' TCO is entirely inhabited by Tsimane' indigenous people, a native Amazonian society of hunter-gatherers and farmers, whilst the Multiethnic TCO is inhabited by four native indigenous groups: Moxeño, Yuracaré, Tsimane', and Movima. Additionally, mestizo cattle ranchers have long been settled in the Multiethnic TCO and, in fact, the land-use plan for the Beni department (approved in 2002 by Law DS No.26732) allocates grazing as the primary activity across ~15% of the Multiethnic TCO, thus acknowledging land use rights to cattle ranchers over those of indigenous peoples. Typical land uses of native indigenous peoples in both TCOs include subsistence slash-and-burn agriculture, limited cash cropping, fishing, hunting, and gathering of fruits and non-timber forest products. Selective logging is allowed in TCOs for self-consumption and, under approved management plans, for commercial purposes too (though the Tsimane' TCO still did not have a forestry management plan in 2012).

I analyze one protected area, the Beni Biological Station (EBB, the Spanish acronym for *Estación Biológica del Beni*), created in 1982 and declared as UNESCO's Biosphere Reserve in 1987. This protected area comprises about 135,000ha of state land, 35,000 (~30%) of which were declared in 1990 to belong to the Tsimane' TCO as well, hence sharing dual status as indigenous titled land and as protected area. The main land use of the EBB is biological conservation, though indigenous people living within it have similar rights to use land and resources as they do in TCOs, except that commercial logging and intensive land uses are prohibited. To avoid confusion, in this work I consider the overlapping area as part of the Tsimane' TCO, and the non-overlapping area as the protected area. I also examine six out of the seven logging concessions that were granted in this area to logging companies at the end of 1986 (Lehm, 1994; Gullison *et al.*, 1996). Such logging concessions are located on state lands between the Tsimane' and Multiethnic TCOs, thus overlapping the traditional territories of several indigenous groups (Reyes-Garcia *et al.*, in review). Some indigenous settlements are found within these logging concessions and, aside from commercial forestry, they have the same rights to use natural resources as have indigenous people in communities settled in TCOs and protected areas. The main land use in logging concessions is industrial timber extraction. Finally, I look at private lands corresponding to 105 settlements around the Yucumo-Rurrenabaque road that were mostly established from the mid-1980s following the Rurrenabaque-Sécure colonization project. These private lands are mostly inhabited by Andean colonist farmers (Bottazzi and Dao, 2013) and their main land uses are small-scale commercial agriculture and cattle ranching. Table 3.1 presents a summary of key information about each of the five areas for which FCC is analyzed.

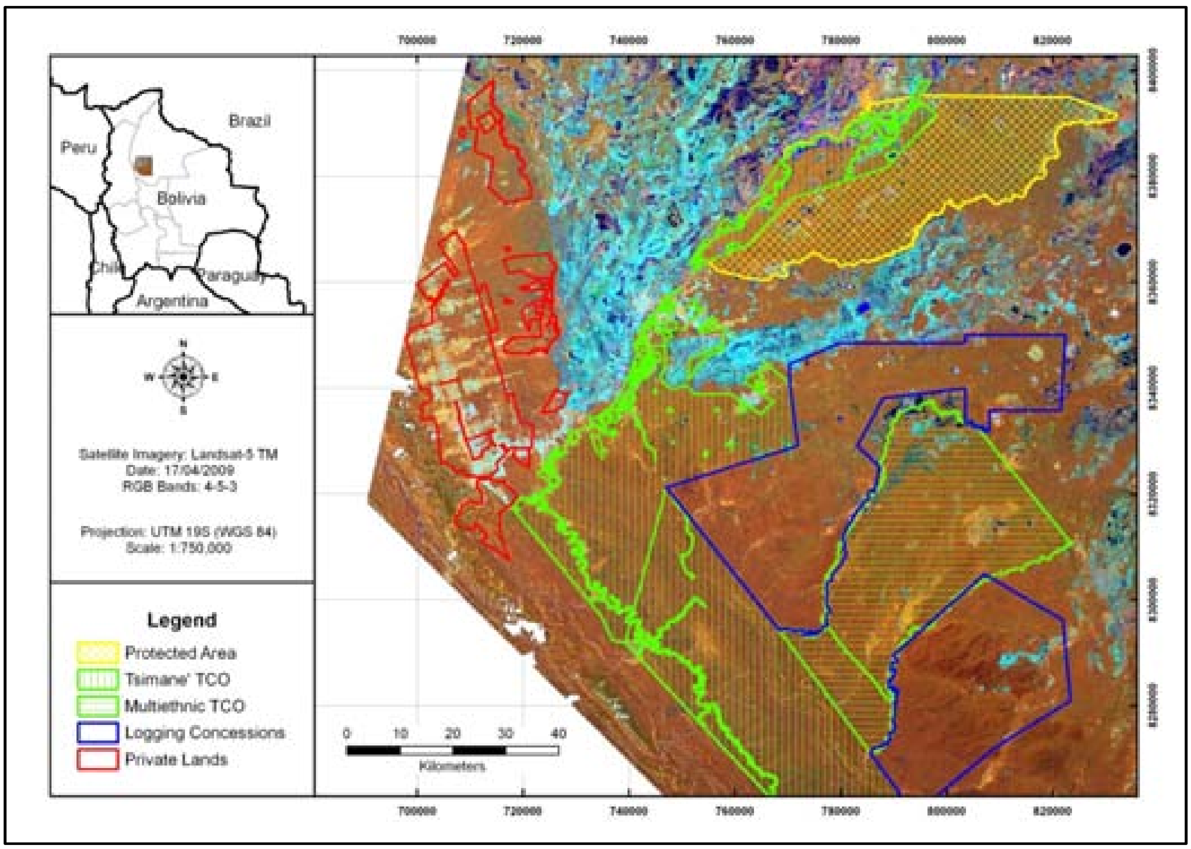


Figure 3.1. Entire study area showing the five areas used to analyze forest cover change according to land tenure systems.

Table 3.1. Information on the five areas studied to analyze trends in forest cover change.

Name	Land Property-Rights	Land Tenure	Main Land Use(s)	Main Social Group(s)	Creation (Date, Law)	Area Analyzed (ha)
Tsimane' Indigenous Territory	Communal	Indigenous Lands (TCO)	Slash & burn agriculture for self-subsistence, hunting, fishing, foraging	Tsimane'	1990, Law No.23611	~280,000
Multiethnic Indigenous Territory		Indigenous Lands (TCO)	Slash & burn agriculture for self-subsistence, hunting, fishing, foraging, selective logging, cattle ranching	Tsimane', Yuracarés, Moxeños, Movimas, Mestizo (Cambas), Cattle ranchers	1990, Law No.23611	~146,000
Beni Biological Station	State	Protected Area	Biological conservation	Tsimane'	1982, Law No.19191	~105,000
Logging Concessions	State, but leased to logging companies	Logging Concessions	Industrial timber extraction, Indigenous self-subsistence activities	Mestizo and colonist laborers, Tsimane'	1981, Forestry Law No.11686	~250,000
Private Lands	Private	Private lands	Slash & burn agriculture for cash crops, cattle ranching	Andean colonists, Mestizos, Cattle ranchers, Tsimane'	Mostly since the mid-1980s, Colonization Law No.107765	~86,000

3. Material and methods

3.1. Satellite imagery and GIS data

I analyzed FCC based on classifying a time-series of satellite imagery, which is a standard procedure (Lu *et al.*, 2004), and used Landsat-5 TM and Landsat-7 ETM+ satellite imagery to construct a time-series consisting of four dates. To cover the study area I acquired 6 images from 3 dates (27/10/1986, 18/07/1996 and 25/08/2001) from the United States Geological Service (USGS), and 2 images (17/04/2009) from the Brazilian National Institute for Space Research (INPE), corresponding to path 233, rows 70 and 71. I used the ASTER's Global Digital Elevation Model (GDEM) v.1 to perform geometric and radiometric corrections on Landsat imagery. To assist in the process of geometric corrections, during 2009-2010 I collected GPS points at road crossings and other human-made features on the ground, and GPS tracks along the main roads and rivers in the study area. During fieldwork I also collected GPS points to gather information on land use/cover. To map and quantify FCC I used a GIS database of 2007 from Bolivia's National Institute for Agrarian Reform (INRA), from which I derived the five study areas described in the previous section as independent GIS layers.

3.2. Multi-temporal forest cover classification

I pre-processed and then classified the time-series of Landsat satellite imagery. Pre-processing steps consisted of geometric and radiometric corrections, cloud and cloud-shadow masking, image mosaicking, and cropping to the study area extent. I then carried out, one by one, four land cover classifications corresponding to the four imagery dates. To classify the four images I used the approach devised in the second chapter, i.e., support vector machines (SVM) with the radial basis function kernel, and using textural homogeneity bands along with Landsat reflectance bands (1-5,7). Upon time-series land cover classification completion I performed Card's correction (Card, 1982) on each classification. I then constructed new confusion matrices to estimate the final overall accuracy of land use/cover classifications, and both producer's and user's accuracies for each land use/cover class. In addition, I retrieved the extent and percentage of the eight land use/cover classes considered. Finally, I aggregated all non-forest classes into a single class to facilitate the subsequent FCC analyses and the presentation and interpretation of results. Hence, I performed FCC analyses using four forest classifications that included three thematic classes: early-growth/degraded forest (hereafter just early-growth), old-growth forest, and non-forest. Prior to carrying out FCC analyses I constructed a mask that contained any pixel that had not been allocated to a specific forest/non-forest cover class in all four classifications. I then applied such a mask to each forest classification so that all four classifications contained exactly the same amount of pixels with forest/non-forest data.

3.3. Forest cover change analyses by land tenure system

To examine general trends across the study area I used the entire forest classifications. In addition, to assess potential differences in forest trends according to different land tenure systems, I cropped each forest classification to the extent of the five areas analyzed (see Figure 3.1)

3.3.1. ***Trends in forest extent***

To examine trends in forest extent I retrieved forest cover areas for both early-growth and old-growth forests and estimated their net area change throughout the three study periods (1986-1996, 1996-2001, 2001-2009). I considered forest extent in the oldest classification (1986) as the baseline level and thereby as the 100% of original forest cover area. Then, to facilitate comparisons across the three study periods, I calculated the net annual rates of change in both early-growth and old-growth forests with the method suggested by Puyravaud (2003). In addition, I used IDRISI Taiga's Land Change Modeler software to calculate the percentage of gains and losses for both forests and non-forest areas throughout the three study periods. I also calculated swap, a very important measure to fully understand the dynamics of land use/cover change (Pontius *et al.*, 2004), defined as the difference between the absolute total change (gains + |losses|) and the absolute net change (|gains - losses|),. Thus, for example, if over a given period and for a specific land tenure, 10% of old-growth forests were cleared in one location, but 10% were recovered through regrowth in another location, the net change would be 0%, yet swap would amount to 20%. Finally, to detect the spatial distribution of persistent vs. dynamic forest areas, I mapped the total number of forest changes along the three study periods, and quantified the extent of each type of area (i.e., areas with no FCC vs. areas with 1, 2 and 3 changes).

3.3.2. ***Trends in forest fragmentation***

To unravel trends in forest fragmentation, I restricted the analysis to old-growth forests given their greater ecological importance (Gibson *et al.*, 2011) and coverage across the study area. I conducted morphological spatial pattern analysis over the multi-temporal forest classifications using GUIDOS software (Vogt *et al.*, 2007). GUIDOS outputs a map consisting of seven morphological classes, from which percentage and frequency statistics are readily retrieved. Here I focus on two morphological classes, core and edge, as they are the most intuitive and best suited to evaluate forest fragmentation. I selected an edge width of 10 pixels (i.e., 300m in Landsat imagery) to perform the analysis because most ecological effects occur within this edge width (Harper *et al.*, 2005; Broadbent *et al.*, 2008) and because land uses in the study areas do not usually create wider edges in old-growth forests.

3.4. Limitations of the study

Although the focus of this chapter is on land tenure systems, accounting for the effects of factors operating within them would have been insightful. For instance, population density, accessibility, or institutional arrangements within each study area have not been evaluated owing to the lack of data. However, such factors are sometimes important (Perz *et al.*, 2005; Southworth *et al.*, 2011; Bottazzi and Dao, 2013) and may have ultimately been responsible for FCC. Nevertheless, I claim that such an in-depth analysis would require specific case studies for each study area, which is beyond the scope of this thesis. In addition, I acknowledge that some land tenure systems were not in place since the beginning of the study periods (1986) and their exact limits have slightly changed through time. I have not been able to account for such changes owing to the lack of historical GIS data but since the extent of the study areas assessed have not substantially changed throughout the three study periods, nor have the main actors operating within them, I believe that my findings are not significantly affected. It is likewise important to acknowledge that I cannot provide evidence of causality between a specific land tenure system and FCC within it before 1986, and that the direction of the relation between both phenomena before 1986 remains unknown (i.e., a specific land tenure system might have led to FCC, but also FCC might have driven the change of land tenure, from state land to private land).

4. <u>Results</u>

4.1. Multi-temporal forest cover classification

The classification approach selected rendered accuracies >90% for the four forest cover classifications (Table 3.2). I obtained extremely accurate classification results for old-growth forests but was less successful in mapping early-growth forests, probably given the high heterogeneity in composition and structure of these forests. I could nevertheless map early-growth forests with producer's accuracies ranging from 86% to 95% and user's accuracies from 77% to 88%. Figure 3.2 shows the four forest cover classifications along with the relative extent of forests and non-forests for the entire study area. Considering the period 1986-2009, the total relative cover of early-growth forests increased from 3.5% to nearly 7% (~48,500ha), while the relative cover of old-growth forests decreased from 72% to 66%, (~64,000ha). This finding evidenced a trend toward old-growth forest clearance and early-growth forest spread across the entire study area.

Table 3.2. Summary of multi-temporal classification accuracy assessments. OA: Overall Accuracy; PA: Producer's Accuracy; UA: User's Accuracy; EGF: Early-growth forest; OGF: Old-growth forest.

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

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

4.2.1. *Trends in forest extent*

The extent of early-growth forests increased 77% for the entire area over 1986-2009, with important differences among land tenure systems (Figure 3.3). Relative to the levels of 1986 and in terms of percentage, the largest increase was found in logging concessions, where in 2009 the area of early-growth forest had increased 350%. However, this area accounted for ~3,650ha and represented only ~1.5% of the total area of the six logging concessions analyzed here. Conversely, the lowest increase was found in the Tsimane' TCO (~5%) where, nonetheless, it translated into ~15,500ha given its large size, representing 5.5% of the total area of this TCO. In the Multiethnic TCO, though early-growth forest had increased 215% by 2009, it accounted for ~3,700ha (i.e., 2.5% of the total area of the TCO, half than in the Tsimane' TCO). Yet, I observed a very sharp increase in early-growth forest extent in the Multiethnic TCO over 1996-2001, as in 2001 early-growth forest had reached 4% of the total area of this TCO. Regarding the protected area, the extent of early-growth forest was 85% higher in 2009 than in 1986, reaching ~3500ha, which amounted to ~3.3% of its total area. Finally, private lands were responsible for a large increase of early-growth forest (280%

by 2009), which was the largest in terms of total area (~18,500ha) and, more importantly, as regards their relative extent (~21.5%).

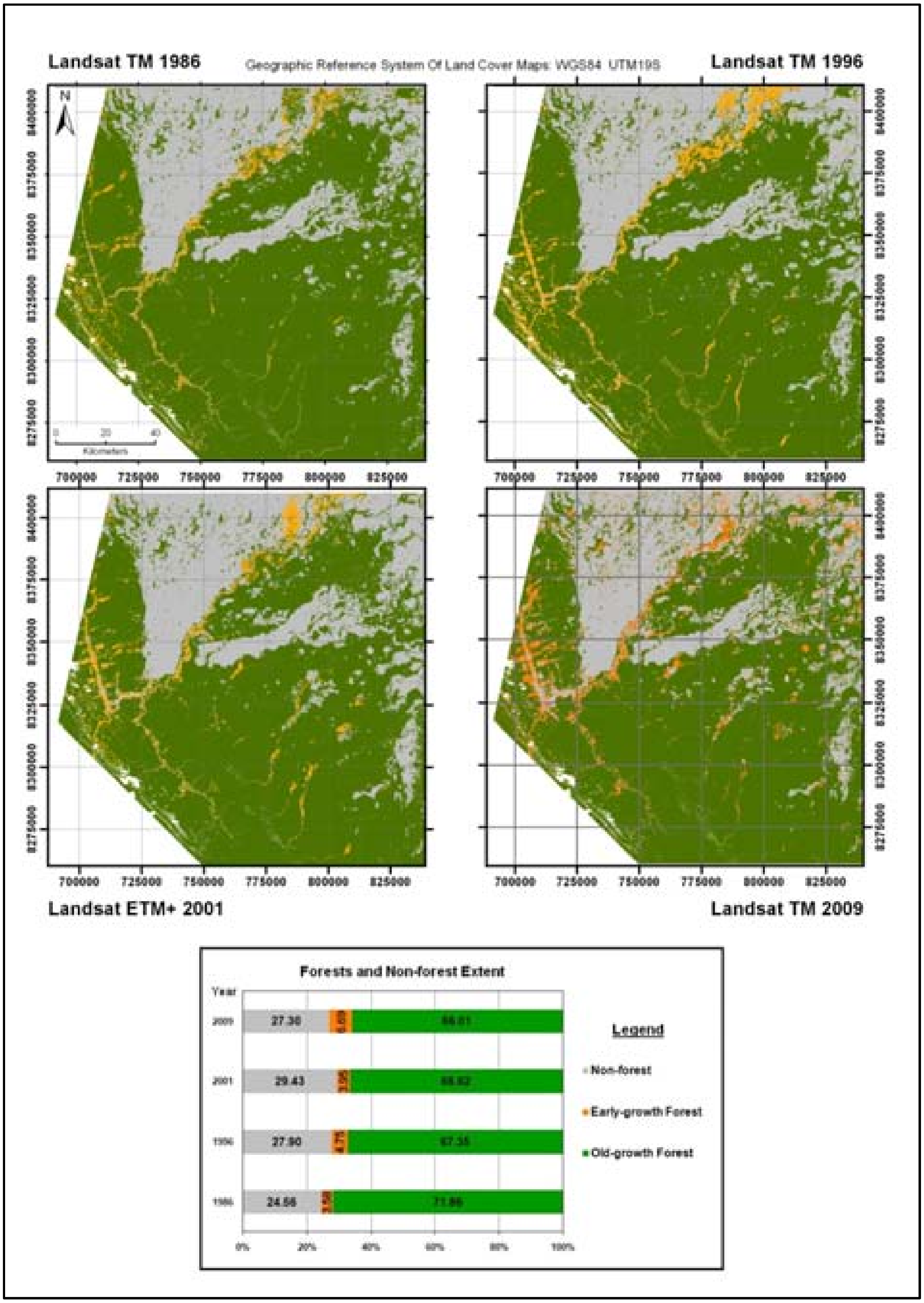


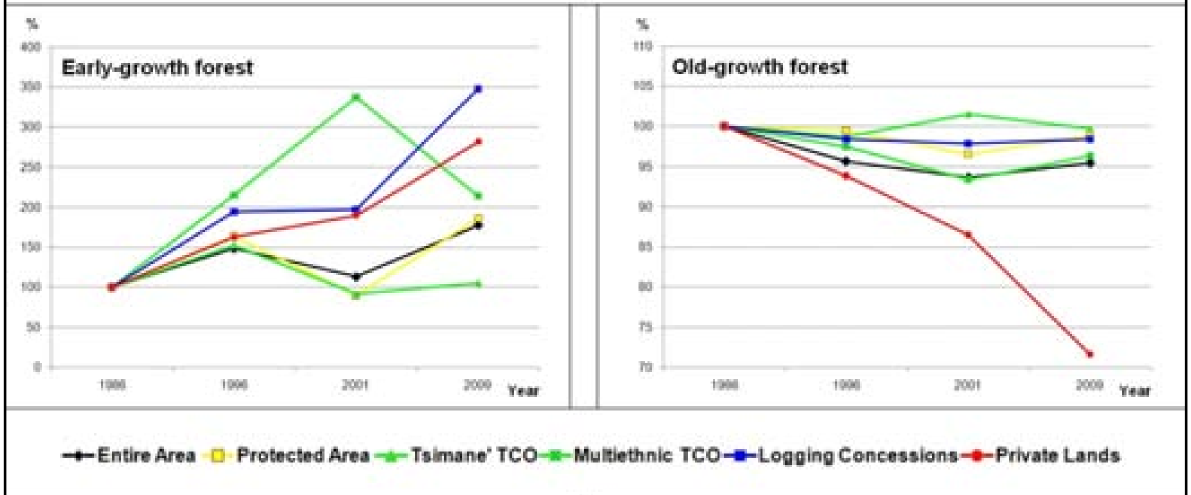
Figure 3.2. Multi-temporal forest cover classifications showing the relative extent of forests and non-forest cover for each date.

In parallel with the increase of early-growth forest extent across the entire area throughout 1986-2009, the area covered by old-growth forests decreased 4.5%. Likewise, I found important differences among land tenure systems, although in terms of old-growth forest percentage relative to the baseline levels of 1986, differences appeared to be subtle (aside from private lands) given the large extent of old-growth forests within each land tenure system (Figure 3.3). Therefore, here I just refer to total areas of old-growth forest change and the percentage they represent in relation to the total extent of each study area. By far, the biggest loss of old-growth forest by 2009 occurred in private lands (~22,000ha), which equals to ~25% of their total extent in this study. Logging concessions lost nearly 4,000ha, though it only meant ~1.5% of their total extent. The two TCOs followed very different trends; the Multiethnic TCO lost ~5100ha (3.5% of its total extent), while the Tsimane' TCO lost only ~700ha of old-growth forest (representing barely 0.25% of its extent). Finally, the protected area also showed little old-growth forest loss by 2009 (~1,050ha, ~1% of its extent).

4.2.2. *Forest change rates*

Throughout 1986-1996 I found <0.5% annual net old-growth forest losses in all the types of land tenure but in private areas (Figure 3.4). The lowest losses were found in the protected area (-0.05%). Conversely, annual early-growth forest change rates were >4% everywhere, and they were highest in logging concessions and the Multiethnic TCO (6.6% and 7.6%, respectively). Over 1996-2001, annual net old-growth forest losses increased particularly in private lands (-1.64%), and occurred everywhere aside from the Tsimane' TCO. In the Tsimane’ TCO I observed a small rate of net annual OGF regrowth (0.57%), representing a gain of ~7,000ha over the whole period (see Figure 3.3). Annual early-growth forest change rates differed from the previous period as increases were only significant in the Multiethnic TCO (9%) and private lands (~3%), and there were decreases >10% in the protected area and the Tsimane' TCO. In fact, early-growth forests for the entire area decreased by 5.5% annually over this second period while it had increased nearly 4% annually over the first study period. Finally, throughout 2001-2009 I found small positive annual net rates of change for the protected area, the Multiethnic TCO and logging concessions, which translates into positive annual net rates for the entire area indicating moderate net old-growth recovery. However, net old-growth forest clearance occurred across private lands at higher annual rates (~2.4%) than in the previous two periods. Rates of annual early-growth forest change followed similar patterns to the first period. The main differences were that early-growth forest decreased 5.7% annually in the Multiethnic TCO and that the protected area increased 9% annually.

Trends of early-growth and old-growth forest in relation to the 1986 baseline level (%)



Trends in total extent of early-growth forest (ha)

Early-growth forest	1986	1996	2001	2009
Entire Area	62,942	93,364	71,078	111,598
Protected Area	1,875	3,078	1,688	3,482
Tsimane' TCO	14,645	22,336	13,449	15,445
Multiethnic TCO	1,730	3,719	5,829	3,693
Logging Concessions	1,051	2,035	2,064	3,649
Private Lands	6,531	10,609	12,385	18,376

Trends in total extent of old-growth forest (ha)

Old-growth forest	1986	1996	2001	2009
Entire Area	1,401,194	1,340,832	1,312,655	1,337,408
Protected Area	93,008	92,543	89,782	91,951
Tsimane' TCO	253,110	249,809	257,048	252,426
Multiethnic TCO	139,822	136,298	130,592	134,704
Logging Concessions	242,846	238,922	237,671	238,947
Private Lands	76,447	71,740	66,103	54,742

Trends of early-growth forest relative to the extent of each study area (%)

Early-growth forest	1986	1996	2001	2009
Entire Area	3.22	4.78	3.64	5.72
Protected Area	1.79	2.93	1.61	3.32
Tsimane' TCO	5.23	7.98	4.80	5.52
Multiethnic TCO	1.19	2.55	3.99	2.53
Logging Concessions	0.42	0.81	0.83	1.46
Private Lands	7.59	12.34	14.40	21.37

Trends of old-growth forest relative to the extent of each study area (%)

Old-growth forest	1986	1996	2001	2009
Entire Area	71.79	68.70	67.26	68.52
Protected Area	88.58	88.14	85.51	87.57
Tsimane' TCO	90.40	89.22	91.80	90.15
Multiethnic TCO	95.77	93.35	89.45	92.26
Logging Concessions	97.14	95.57	95.07	95.58
Private Lands	88.89	83.42	76.86	63.65

Figure 3.3. Trends in forest cover derived from multi-temporal forest cover classifications.

4.2.3. *Spatial distribution of forest changes*

I also found important differences among land tenure systems regarding gains, losses and swap of both early-growth forest (Figure 3.5) and old-growth forest (Figure 3.6). Again, private lands underwent much more forest changes than the other land tenure types, having 1) more early-growth forest gains than losses and swap changes ~3% for the 3 study periods, and 2) 3-4 times more old-growth forest losses than gains, with swap changes always ~2%. The protected area and the indigenous TCOs showed low levels of gains, losses and swaps for both early-growth and old-growth forests, that ranged ~-1%-1% and ~-2%-2%, respectively. Finally, logging concessions revealed the lowest levels of gains, losses and swaps for both types of forests, particularly for early-growth forests. Yet, in the case of old-growth forest gains and losses were <0.75% and swap reached a maximum of ~1% over 2001-2009. Accordingly, I found that private lands were by far the less persistent areas (~75%) and the only ones undergoing 3 forest changes in >1% (Figure 3.7). Lands under all the other tenures were highly persistent, particularly logging concessions and the protected area. The Tsimane' TCO was 4% less persistent than the Multiethnic TCO (91% vs. 95%), though I observed that the majority of changes across the Tsimane' TCO occurred in areas adjacent to the protected area and close to the main market town (San Borja).

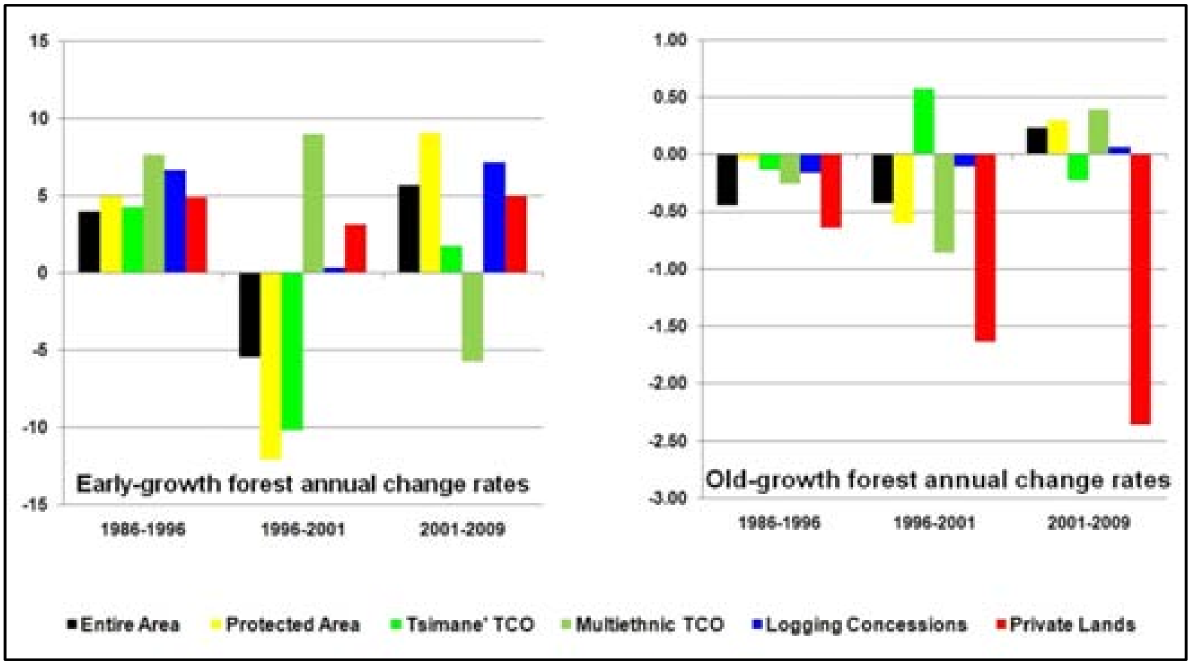


Figure 3.4. Annual net rates of change of old-growth and early-growth forests.

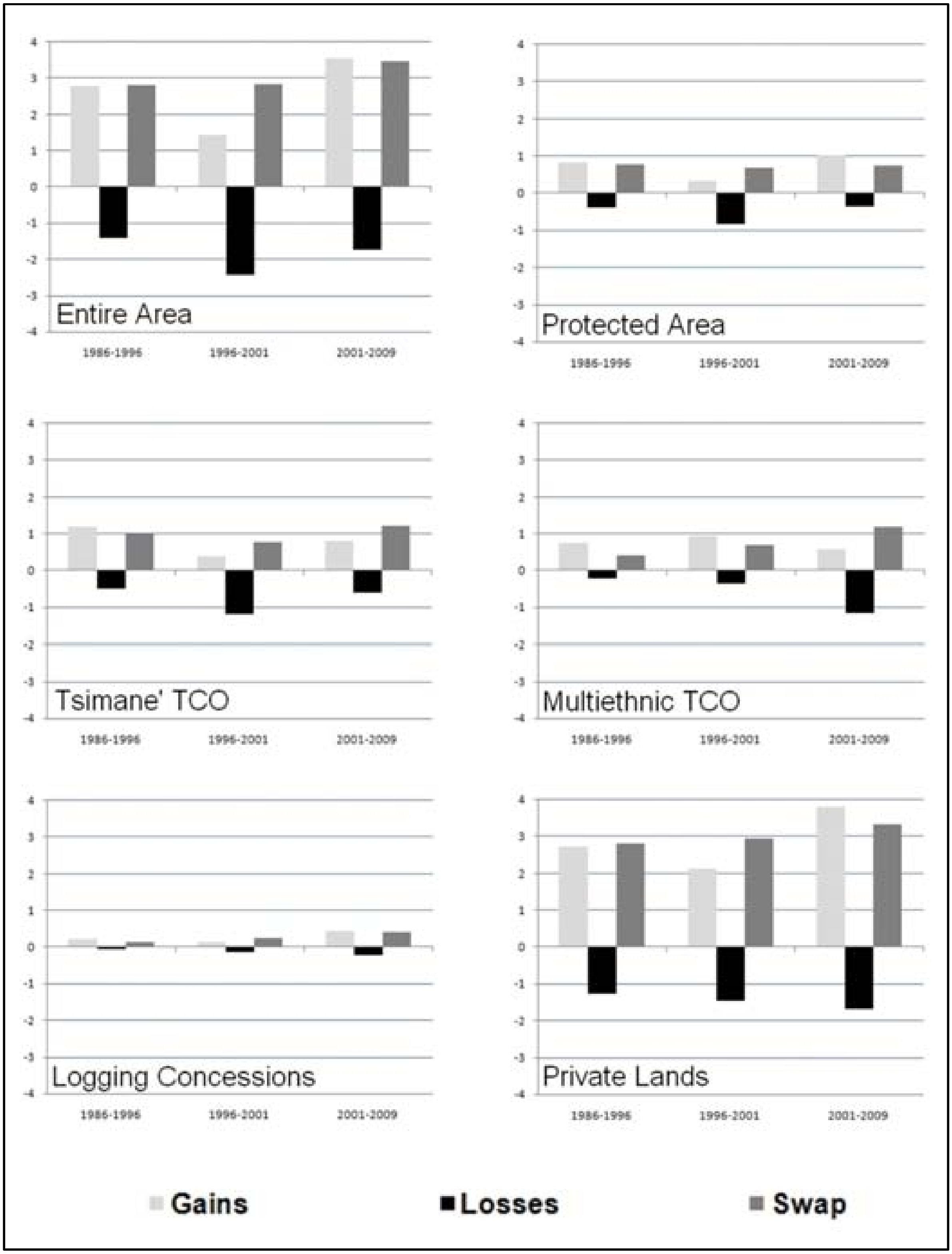


Figure 3.5. Gains, losses and swap in early-growth forest (in percentage relative to the total extent of each study area).

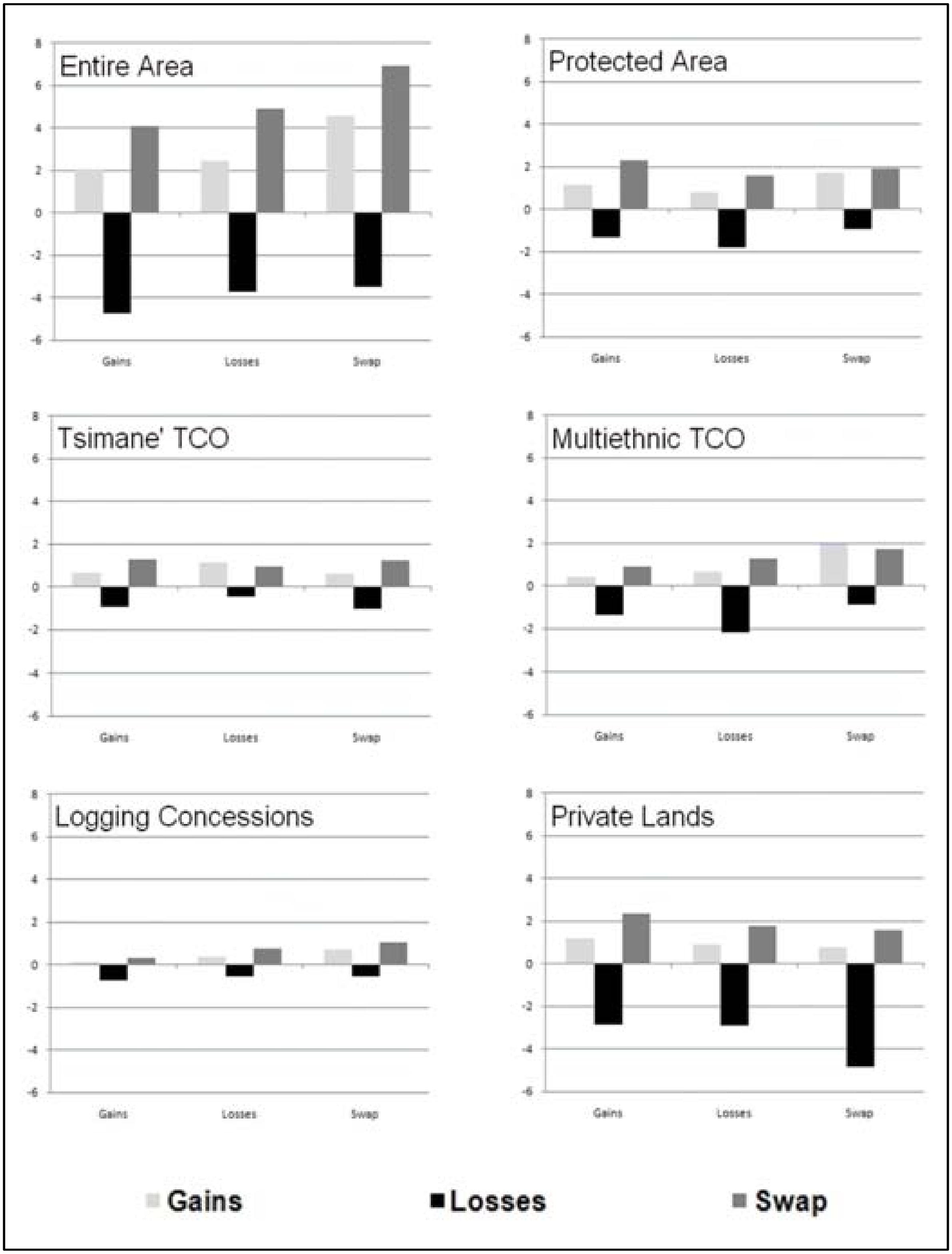
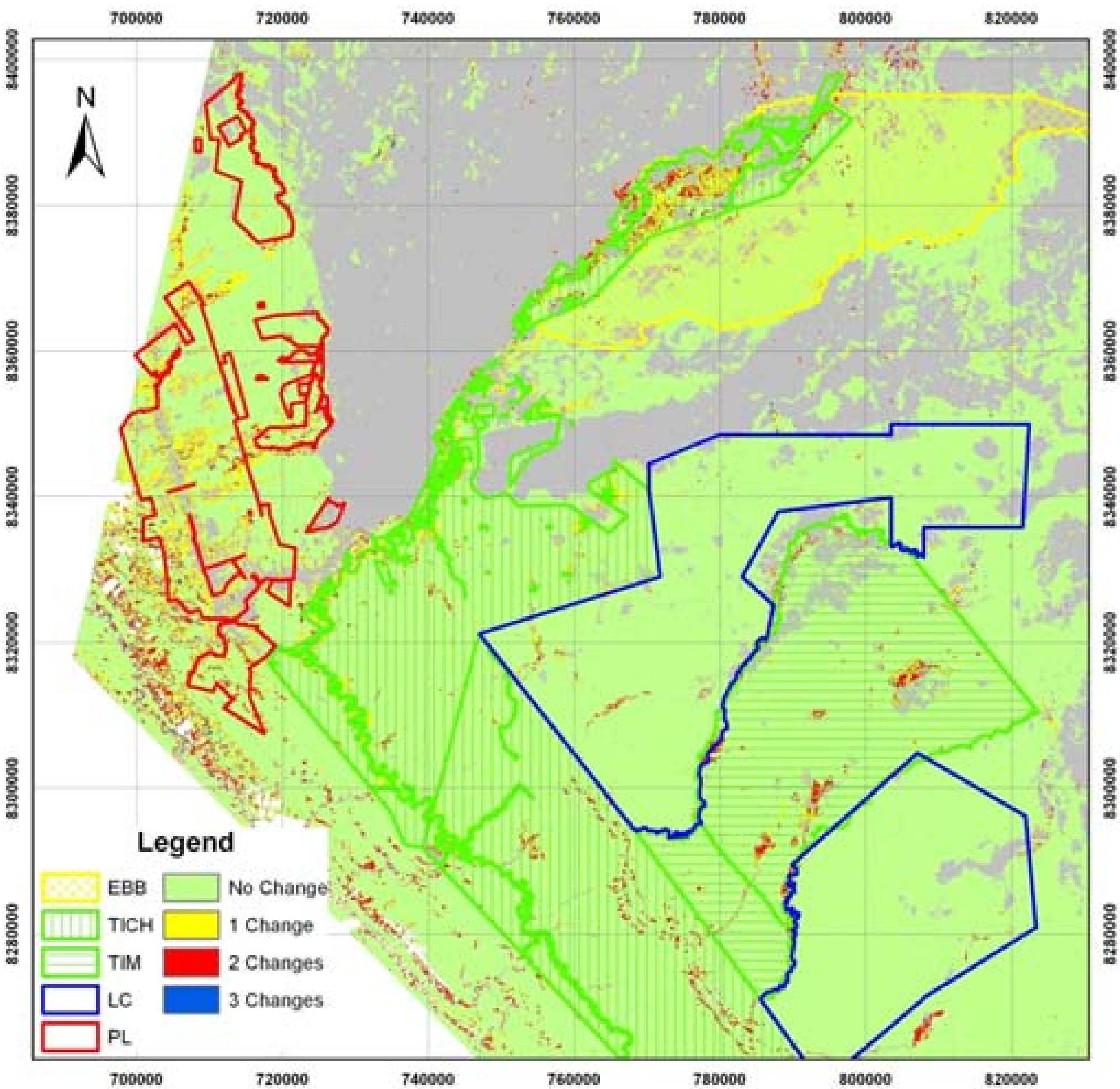


Figure 3.6. Gains, losses and swap in old-growth forest (in percentage relative to the total extent of each study area).



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

Figure 3.7. Percentage and extent (in hectares) of unchanged forested areas vs. forested areas that underwent 1, 2, and 3 changes, relative to the total coverage of forest (i.e., both early-growth and old-growth forests) within each study. Gray areas correspond to non-forest covers.

4.2.4. ***Fragmentation trends in old-growth forests***

Relative to the total extent of old-growth forest within each study area analyzed, the percentages of core old-growth forest areas were far higher in indigenous TCOs, logging concessions, and the protected area, than in private lands (Table 3.3). In the former study areas core old-growth forest ranged between ~76% and ~86% in 2009. The only land tenure system where there was an increase in core area of old-growth forest (~5%) throughout 1986-2009 was the protected area. Over the same period, the Tsimane' TCO lost ~15%, the Multiethnic TCO ~2.5%, and logging concessions ~4% of their core area of old-growth forest. In private lands core area of old-growth forest fell from ~67-70% in the first two dates, to ~54% in 2001 and finally to ~44% in 2009. Simultaneously, throughout 1986-2009 edge areas increased from ~8% to ~15% in private areas, while in the rest of land tenure types the proportion of edge areas did not increase over the three study periods and remained low (~2-3%). Remarkably, logging concessions showed the lowest levels of edge, ranging from 1.8% to 2.7% over 1986-2009.

Table 3.3. Trends in old-growth forest fragmentation. All figures refer to percentage of old-growth forest cover.

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

5. <u>Discussion</u>

My results indicate that different trends in FCC exist according to different land tenure systems, which suggests that, to a great extent, land tenure has an important effect on the fate of forests in the Bolivian Amazon. Specifically, I observe that 1) private lands underwent, by far, the largest FCC among all the land tenure systems analyzed, 2) indigenous TCOs and the protected area had relatively little FCC, yet their trends somewhat differed, and 3) logging concessions were responsible for the lowest FCC. Therefore, my initial hypothesis was not fully supported, as logging concessions underwent less FCC than both indigenous territories and the protected area. I discuss these findings and conclude the section highlighting their implications for conservation.

Results of FCC from private lands confirm the remarkable impact they exert upon forests in the Amazon (Rudel *et al.*, 2002; Fearnside, 2008; Killeen *et al.*, 2008; Lu *et al.*, 2010). Interestingly, the rates of FCC in private lands have rocketed in the last study period (2001-2009), signaling an intensification in the agricultural activities. I believe this must have been due, at the beginning of the 2001-2009 period, to the increasing need for demonstrating the socioeconomic function of land (given the increasing population growth across colonization areas), as a way to secure tenure after the 1996 agrarian reform, which triggered extensive old-growth clearance in colonization areas since its deployment (Bottazzi and Dao, 2013). And later on, the new agrarian reform launched in 2006 after the arrival of the indigenous leader Evo Morales to the presidency, must that played an important part in FCC. In effect, such agrarian reform has given public lands (mostly forestland) in private property to rural and indigenous communities, thus triggering FCC in new areas. In addition, there may be other factors associated with the trends of FCC observed (e.g., illegal logging and agricultural expansion owing to national and international market stimuli).

Regarding results for the protected area and the two indigenous TCOs, trends in FCC are not as clear as in private lands and logging concessions, yet a few conclusions can be withdrawn. Forests across the protected area are extremely persistent and clearance and fragmentation of old-growth forests occurred at very low rates in all three periods. Even though I found a moderate increase in early-growth forests, I believe is mostly due to the annual and inter-annual flooding regimes typical of this protected area, rather than to extractive or productive activities (e.g., timber extraction, cattle-ranching), which are illegal in the biological reserve. Therefore, I claim early-growth forests within the protected area would mostly be the result of natural dynamics. Forests in the Tsimane' TCO are likewise very persistent, but not as much as those in the protected area. Yet, I found that forest changes occurred mostly in areas adjacent to the protected are and, therefore, I believe they may also be explained by natural flooding dynamics. Moreover, forest changes occurred also in areas close to the market town of San Borja, where most Tsimane' market-oriented activities take place. Old-growth forests underwent only moderate fragmentation and very little deforestation over the three study periods, and increase in early-growth forest cover was only significant over the first period, probably because of logging companies, illegal loggers and other actors encroaching upon those lands (Godoy *et al.*, 1998) before they were declared TCO.

As for the Multiethnic TCO, I found different spatio-temporal patterns of FCC in both the protected area and the Tsimane' TCO. I saw that despite forests also being highly persistent in the Multiethnic TCO, old-growth forests underwent moderate fragmentation and deforestation over the first and second periods, when a severe increased in early-growth forest extent occurred at even higher rates than in private lands and logging concessions. However, I saw an opposite trend over the third period, when significant net forest regrowth occurred. I believe such trends may be explained by the long-term presence of cattle ranchers across this TCO, and the fact that cattle ranching has been a major land use activity in compliance with the land use plan for the area (probably its suitability given the natural occurrence of patches of savanna and semi-natural grasslands). Even though the Multiethnic TCO was legally recognized in 1990, any person who could demonstrate permanence in the area prior to the creation of the Multiethnic TCO could claim land ownership through the aforementioned *saneamiento* process. This fact is likely to explain why rates of old-growth forest loss and early-growth forest gains are so high over the second period, as cattle ranchers must have claimed legal rights over the land they occupied. The contrasting FCC trends observed over the third period may be the result of most cattle ranchers being already settled with land property rights and, perhaps, lack of significant encroachment upon new land as a consequence of increasing indigenous governance, which may have also reduced the likely leakage effect occurred in the Multiethnic TCO over the first two periods as this area is virtually surrounded by logging concessions.

I claim that the differences observed as regards FCC trends between the two TCOs examined here reveal the fragility of this land tenure type. The asymmetric power between indigenous organizations and organizations representing other social groups such as colonists and mestizo cattle ranchers have resulted in land development policies that favor intensive land uses and concede indigenous peoples the lowest priority with respect to land rights (Assies, 2006; Bottazzi and Dao, 2013). Thus, particularly since the 1996 agrarian reform, abutters have kept encroaching upon indigenous lands to clear forest and claim land property-rights, which has been facilitated by a relatively late political awakening of indigenous people (Reyes-Garcia *et al.*, 2010). As a consequence of initial weak indigenous governance in TCOs, other factors may have explained the differences observed in FCC trends (e.g., accessibility, distance to markets). In the case of the Multiethnic TCO, we argue that governance may have been far more difficult owing to the co-existence of four indigenous groups, and the adjacency of logging concessions.

Results for logging concessions revealed that this land tenure system is indeed very effective in protecting old-growth forests from clear-cutting, which coincides with what Oliveira *et al.* (2007) found across the Peruvian Amazon but contrasts with what Asner *et al.* (2006) have observed for logged forests in the Brazilian Amazon. In addition, I found that old-growth forest fragmentation in logging concessions has kept very low levels and that forests are extremely persistent across these areas. These facts may be explained because companies only extracted precious woods such as mahogany and cedar, given their abundance, hence having a very low incidence on total forest cover (Gullison *et al.*, 1996), and because companies have stopped outsiders from using *their* forests. Regarding early-growth forest change, I observed that its extent notably increased over the first and particularly the third period, which can possibly be explained in accordance with the two forestry reforms undertaken by the Bolivian government. The first one was issued in 1974 and, at the end of 1986, seven logging concessions were granted in the area until 2011. Therefore, a rapid increase in selective logging from the mid 1980s seems reasonable. However, a second forestry law issued in 1996 was not as beneficial to logging companies as the previous one because royalties were now based on area rather than on volume harvested (Pacheco, 2002), thus preventing companies from evading money by declaring lower harvests than real. Therefore, I claim that conflicts between companies and forestry authorities in relation to these issues may have triggered a relative decrease in logging activities, probably exacerbated because of a severe decline in the stocks of precious woods after at least two decades of intense timber extraction (Gullison *et al.*, 1996). The rapid increase observed in the amount and change rates of early-growth forest over the third period may be explained by the end of the logging grants in 2011 and because logging concessions across the study area were expected to become part of TCOs or be given to colonists (Reyes-Garcia *et al.*, in review). The expected end of logging concessions may have greatly boosted timber harvesting up to utterly unsustainable levels over 2001-2009, and may have triggered colonists to move in over the last years so as to claim land after the end of logging concessions.

Overall, my results are in agreement with other studies that have sought to evaluate how FCC across the Amazon basin may be affected by land tenure systems and land use allocation (e.g., Nepstad *et al.*, 2006; Oliveira *et al.*, 2007; Killeen *et al.*, 2008; Lu *et al.*, 2010; Soares-Filho *et al.*, 2010). From a biocultural conservation perspective, my results suggest that future conservation policies in Bolivia should emphasize the key role of native Amazonians in effectively protecting old-growth forests and expand the existing network of indigenous TCOs accordingly. Previous studies support the importance of taking into account indigenous peoples in conservation policy (Alcorn, 1993; Gadgil *et al.*, 1993; Colchester, 2004) and of establishing alliances or partnerships to promote conservation (Schwartzman and Zimmerman, 2005; Vermeulen and Sheil, 2007). Since the area previously granted to logging concessions could now be adhered to TCOs, I claim that community-based forest management based on traditional ecological knowledge should be encouraged by the authorities. This type of management has proven to have a beneficial effect on protecting forest cover while enhancing indigenous livelihoods (Berkes, 2007), and to have the potential to be more effective than forest protected areas (Porter-Bolland *et al.*, 2012). Nevertheless, indigenous governance need to be strengthened to avert the negative consequences of abutters encroaching upon TCOs' lands owing to the fragility of this land tenure type (Assies, 2006). In addition, my findings suggest that protected areas and also logging concessions (provided that timber extraction is carried out at low intensities), may be very effective in protecting forest cover. Therefore, I argue these land tenure systems should be favored in state lands with low rural populations, whether indigenous or not, insofar their rights are respected. Finally, given the commodity frontier expansion and the high levels of FCC associated with private lands documented in this study, I argue that some conservation incentives (e.g., subsidies to sustainable agroforestry systems) are needed in private lands to effectively address climate change mitigation strategies (Soares-Filho *et al.*, 2006), and to maintain at least some biodiversity refugia areas and corridors to diminish the pervasive effects of fragmentation in old-growth forests (Laurance *et al.*, 2002b). Moreover, as recent research has shown that levels of human development follows a boost-and-bust pattern as deforestation takes place in Amazonian frontier settings (Rodrigues *et al.*, 2009), financial incentives and policies that promote more sustainable development scenarios should be sought.

Further research is needed to assess land cover/use change drivers operating within the study areas, particularly regarding household land-use decision-making along the agricultural frontier, so as to implement effective conservation measures while ensuring local peoples' well-being.

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Chapter 4

The role of traditional ecological knowledge in old-growth forest conservation. A spatial analysis among Tsimane' Amerindians (Bolivian Amazon)

Dijimos que la sociedad humana representa sólo en parte la sociedad de iguales a la cual pertenecemos [los Tojolabales]. De hecho, la naturaleza entera está incluida. Animales de casa y del monte; milpa, flores y árboles; piedras, cerros y barrancos; el agua y las nubes; la multitud de cosas que llenan la naturaleza están incluidas en el nosotros del cual se afirma *lajan lajan `aytik* (estamos parejos)

(Sobre los Tojolabales, en *Los hombres verdaderos*, Carlos Lenkersdorf)

Abstract

Cultural and biological diversity are being rapidly eroded, often by the same socio-economic and political forces. Research in the emerging field of biocultural conservation claims that both forms of diversity are interconnected and mutually dependent, highlighting the striking spatial overlap between both diversities, particularly in forests inhabited by indigenous peoples across tropical regions. Indigenous traditional ecological knowledge (TEK) has been said to play a key role in forest conservation, and different mechanisms have been proposed to explain it. However, empirical studies assessing to what extent TEK is important in forest conservation are rare. Furthermore, to my knowledge, the spatial overlap of TEK and forest conservation has not been evaluated at local spatial scales. In this chapter I address both issues and aim to provide insights into the potential role of TEK in tropical old-growth forest conservation. The case study focuses on the Tsimane' Amerindians of the Bolivian Amazon, using a sample of 624 households to estimate ethnobotanical knowledge and skills (my proxy for TEK), and remote sensing data to estimate the extent and level of fragmentation of old-growth forests (my estimate of forest conservation) for 59 villages. I find that, besides other important factors such as distance to markets and accessibility, TEK plays an important role in forest conservation, though not as important as acculturation. I also find that there is a significant (p~0) overlap between levels of TEK and forest conservation, both of which show very similar spatial patterns. I discuss the potential reasons underpinning the apparent

functional connection between TEK and forest conservation, and provide insights that may be useful for developing integrative conservation policies that acknowledge the need to protect both culture and biodiversity, while putting indigenous peoples at the centre of such endeavors.

Key words: Bolivian lowlands, forest fragmentation, ethnobotanical knowledge; indigenous knowledge, acculturation; biocultural conservation

1. Introduction

Researchers have noted a significant spatial overlap between areas of high cultural and linguistic diversity and areas of high biological diversity, highlighting that such co-occurrence takes place mostly in areas inhabited by indigenous peoples across the tropics (Moore *et al.*, 2002; Maffi, 2005). The reasons underlying this spatial overlap are complex and vary at different scales, yet recent research suggests there may be some form of functional connection among such diversities, in addition to historical human settlement patterns in areas of high biological diversity (Gorenflo *et al.*, 2012) such as the Amazon. Although the alleged functional connection remains poorly understood, it seems clear that certain indigenous cultural systems and practices favor the conservation of species and the ecosystems that host them. In Amazonia, indigenous people have been actively managing forests since prehistoric times (Denevan, 1992; Heckenberger *et al.*, 2008). Although indigenous land use has not always led to satisfactory forest conservation outcomes, on many occasions native Amazonians have purposely safeguarded and even enhanced the continuous availability of forest resources through different management strategies adapted to local ecological conditions and shaped by culture throughout centuries (e.g., Posey, 1985). Such indigenous forest utilization and manipulation may create a forest-culture continuum within villages, resulting in a biodiversity-rich domesticated landscape characterized by managed forests and agroforestry systems (Wiersum, 1997). For instance, swidden cultivation-fallow management systems are agroforestry systems often found among native Amazonian groups, which have significant ecological and economic benefits for indigenous peoples (Coomes *et al.*, 2000). Intrinsically tied to such management practices, indigenous Amazonians have developed an in-depth local environmental knowledge and a comprehensive set of beliefs as part of their cosmology. This practice-knowledge-belief complex, typical of indigenous and traditional societies worldwide, is what has been coined as traditional ecological knowledge - TEK (Berkes, 1999).

Several authors have emphasized the key role that indigenous reserves play in forest conservation across Amazonia (Nepstad *et al.*, 2006; Soares-Filho *et al.*, 2010), and the indigenous role in conservation due to managing their forestlands in a more sustainable manner than non-indigenous peoples (Rudel *et al.*, 2002; Stocks *et al.*, 2007; Lu *et al.*, 2010). Nonetheless, the question of whether forest conservation across indigenous lands is typically the result of low population density, lack of technology, and absence of markets due to isolation, rather than of a *real* indigenous conservation ethic, remains controversial (Stearman, 1994; Smith and Wishnie, 2000; Raymond, 2007). In that regard, empirical studies assessing the potential role of TEK in purposely seeking forest conservation may be particularly clarifying. Focusing on that topic, some works have been recently published (e.g., Berkes and Davidson-Hunt, 2006; Posey and Balick, 2006; Herrmann and Torri, 2009; Rerkasem *et al.*, 2009; Reyes-Garcia *et al.*, 2011), suggesting that TEK plays an important part in forest conservation. However, this type of studies are often qualitative and have been carried out in few indigenous villages, which makes difficult to extract general conclusions even for the entire indigenous society studied. There are also quantitative studies yet among them there is a lack of empirical assessments using a large number of indigenous villages, making use of detailed information for both TEK and forest conservation, and I do not know of any that uses spatially-explicit information for TEK. As for studies focusing on the spatial overlap between cultural and biological diversity, to date they have been made at macro-geographical scales (i.e., global and continental/sub-continental), and thereby the extent and nature of the associations between the realms of biodiversity and culture at the local scale remain poorly understood (Zent, 2009). Nevertheless, Manne (2003) found that the spatial correlation between linguistic (used as a proxy for cultural diversity) and biological diversity in Central and South America weakened at finer scales. Assessing whether biological and cultural diversities are linked at the local scale is crucial from a biocultural conservation perspective because, provided that they are, policies aimed at biological conservation should go hand in hand with the protection of cultural diversity (Zent, 2009).

To address the issues of the potential association between cultural and biological diversities, in this study I spatialize TEK data (my proxy for cultural diversity) and use satellite imagery to retrieve different forest metrics and characterize old-growth forest conservation (my proxy for biological diversity). I test whether there exists an association between the level of old-growth forest conservation around a village and the level of TEK in the same village. In addition, I evaluate whether the spatial patterns of old-growth forest conservation can be related to the spatial patterns of TEK (i.e., if there is a significant spatial overlap between both). The case study focuses on the Tsimane' Amerindians (Bolivian Amazon), who constitute an ideal indigenous group for this analysis as Tsimane' villages exhibit a large gradient in both TEK and forest conservation around them. I focus on old-growth forests, which occupy much of the extent across the study area (Paneque-Gálvez *et al.*, 2011), because this type of forest is of greater importance for biodiversity conservation and carbon sequestration than early-growth or disturbed forests (Barlow *et al.*, 2007; Luyssaert *et al.*, 2008; Gibson *et al.*, 2011). Based on previous research, I advance two hypotheses. First, villages with higher levels of TEK will have higher proportions of old-growth forest around them than villages with lower levels of TEK. And second, villages with higher levels of TEK will have lower levels of old-growth forest fragmentation around them than villages with lower levels of TEK. The theoretical framework underpinning my hypotheses has been suggested by different authors (e.g., Gadgil *et al.*, 1993; Berkes *et al.*, 2000) who claim that TEK is a complex knowledge system that encodes knowledge, skills, practices and beliefs that favors forest conservation through extensive land use, sustainable natural resource management, and even ecological restoration. As cultural and biological diversity are increasingly threaten by the same forces (Nabhan *et al.*, 2002; Sutherland, 2003), this case study sheds light into the association between both diversities and matters for policy-making seeking to achieve biocultural conservation while promoting economic development among indigenous peoples in the Bolivian lowlands.

2. The Tsimane' and their current use of forests

The Tsimane' Amerindians are native to the Amazon and live in the lowland forests of the southwest of the Beni and the east of La Paz departments, Bolivia. They number ~15,000 people settled in ~125 villages, mostly along the Maniqui, Quiquibey and Apere Rivers, and along logging roads (Reyes-Garcia *et al.*, in review-b). The Tsimane' economy centers on hunting, fishing, plant foraging and slash-and-burn farming (Godoy *et al.*, 2009) for subsistence, though some Tsimane', particularly those living in villages closer to the main market towns (San Borja, Yucumo and Rurrenabaque), are increasingly engaging in market-oriented activities such as cash cropping and wage labor (Vadez *et al.*, 2004). The increasing integration into the market economy of the Tsimane' society leads to important socioeconomic and cultural changes, which in turn affect the way the Tsimane' manage and use their forest resources (Godoy *et al.*, 2005a). Thus, although outsiders such as cattle ranchers, colonist farmers and logging companies are mostly responsible for the deforestation and forest degradation caused in previous decades in the area inhabited by the Tsimane' (Godoy *et al.*, 1998; Bottazzi and Dao, 2013), the Tsimane' themselves are increasingly accountable for clearing and degrading forest. The main reasons for the increasing role of the Tsimane' in deforestation and forest degradation relate to the increase of the area cultivated with rice and other cash crops, the engagement in timber and non-timber forest products extraction for sale and barter, and (to a lesser extent) the adoption of cattle ranching (Vadez *et al.*, 2004; Vadez *et al.*, 2008; Godoy *et al.*, 2009; Reyes-García *et al.*, 2012a).

In addition, researchers have pointed out other socioeconomic and cultural factors that may be associated with the way Tsimane' households use their forests. For instance, Godoy *et al.* (1998) found a positive (but weak) association between tenure insecurity (leading to conflicts with abutters) and forest clearance, which they argued might be explained because Tsimane' households might feel the need to clear more forestland as a way to curtail abutters encroachment. Godoy *et al.* (1998) also found a negative association between household heads' time preference and clearance of old-growth forest (something later confirmed too by Pendleton and Howe (2002)), a finding they explained arguing that impatient households would seek wage labor rather than clearing old-growth forest for farming as financial returns were obtained immediately. Nevertheless, in a more detailed study Godoy *et al.* (2001) found that both tenure insecurity and private time preference had an insignificant effect on the clearing of forest among the Tsimane'; therefore, the influence of both factors remains unclear. Regarding tenure, Bottazzi and Dao (2013) concluded that, among villages around the buffer zone of the Pilón-Lajas Biosphere Reserve, property rights were a secondary driver of forest clearance, being historical political processes concerned with land-use allocation and the existing institutional arrangement (different stakeholders claiming land rights and land policies favorable to their socioeconomic interests) the main factors underlying forest cover changes. Another important factor that has been shown to bear a significant association with Tsimane' forest clearance is education (or more broadly, acculturation). Godoy and Contreras (2001) and Pendleton and Howe (2002) found sginificant negative associations between the level of household education attainment and forest clearance among the Tsimane', which they explained as a consequence of having more opportunities to eke out a living working for wages as laborers outside of their villages.

Traditional ecological knowledge (TEK) is another factor that may affect forest use and therefore be associated with forest conservation (Berkes and Turner, 2006), yet it has often been neglected in most deforestation and forest degradation analyses. TEK has been extensively studied among the Tsimane' (e.g., Reyes-Garcia *et al.*, 2003; Reyes-Garcia *et al.*, 2005; Reyes-Garcia *et al.*, 2007a); as regards Tsimane' forest use, Reyes-Garcia *et al.* (2007b) and Reyes-Garcia *et al.* (2011) explored the associations of TEK with forest clearance, finding a negative relation between the level of TEK of the male household head (proxied by his ethnobotanical knowledge and skills) and the amount of forest cleared by households, though results differ in relation to old-growth forests and fallow forests. Thus, Reyes-Garcia *et al.* (2007b) observed that when the ethnobotanical skills of the household head were doubled, the amount of forest cleared was reduced by 25% and that the association was stronger for old-growth forests than for fallow forests. However, Reyes-Garcia *et al.* (2011) found a direct effect of ethnobotanical skills in lowering the extent of fallow forests but not of old-growth forests once they controlled for the interaction of ethnobotanical skills with labor productivity (although they observed that households with above-average ecological knowledge cleared less old-growth forest per unit of labor than those with below-average knowledge). Nevertheless, both studies were carried out at the household level, without accounting for potential differences at the village level, and without controlling for the spatial distribution of TEK and forest cover. In addition, both studies focused on the relation between TEK and old-growth and fallow forest clearance for agriculture, but did not take into account other important ecological considerations such as the amount of forest surrounding each village, or how well those forests were preserved (e.g., their level of fragmentation), both of which are key features in forest biodiversity conservation.

3. Data

To assess old-growth forest conservation at the village level, I used the mosaic composed of the two Landsat-5 TM satellite images from April 2009 I had been previously classified in the first chapter. In addition, both for producing maps and for analytical purposes, I used GPS points collected at the center of the studied villages, and several GIS layers (e.g., roads, rivers, main towns) obtained from different sources. To analyze TEK and other socioeconomic, cultural and environmental aspects relevant to the study, I used data from a cross-sectional survey conducted at the household level throughout 2008 and 2009 in ~80 Tsimane' villages in coordination with TAPS (The Amazonian Panel Study: tsimane.org). Villages were selected based on a recent survey (Reyes-García *et al.*, 2012a) taking into account their spatial location so that they reflected differences in their social and environmental attributes (Figure 4.1). Survey data were collected at each village in 10 households randomly selected out of a census provided by the highest-rank authority of the village or in 25% of the households if there were more than 40 households in a village. In villages with less than 10 households data were collected in all the households willing to participate in the study. Prior informed consent was always obtained from each participant and refusal rate was typically <5%. We interviewed the male household head unless he was absent (then the female household head was interviewed) for two main reasons: 1) men tend to display larger variation in relation to TEK and other attributes potentially associated with TEK (e.g., formal education, acculturation, health, economic activities) (Reyes-García *et al.*, in review), and 2) data collection was designed in coordination with a larger project that focused on hunters (Reyes-García *et al.*, 2012b). To match the scale of analysis of forest data, household survey data were aggregated at the village level and the analyses was restricted to 59 villages (~50% of Tsimane' villages) for which I could derive forest data from the imagery.

4. Methods

4.1. Assessment of old-growth forest conservation and TEK

I used FRAGSTATS v.3.3 software to assess forest conservation at the village level and estimated 1) forest area and 2) forest fragmentation, both within a 5-km buffer around the village school (which Tsimane' regard as the village center). I used 5-km buffers as that is roughly the area the Tsimane' use for their subsistence activities (e.g., hunting, foraging) (Cruz-Burga *et al.*, in review). Table 4.1 shows the four standard forest class metrics used to retrieve 1) the extent of forest (*PLAND*) and 2) three different aspects of forest fragmentation (*ED, CPLAND, PAFRAC*), which were the outcome variables of the statistical models. I chose a distance of 300m to define the edge size of old-growth forest as most ecological effects take place within this distance (Harper *et al.*, 2005; Broadbent *et al.*, 2008) and, based on my fieldwork experience, Tsimane' typical land-use do not cause edges >300m. I proxied TEK, my explanatory variable, with informants' ethnobotanical knowledge and skills (Reyes-Garcia *et al.*, 2003; Reyes-Garcia *et al.*, 2011) and restricted my analysis to adults (>16yrs) (Zarger, 2002). Specifically, a questionnaire was used to ask respondents to list all the uses they knew from a list of 20 plants that had been randomly selected from a previous free-listing exercise and which uses had been verified by scan observations (Reyes-Garcia *et al.*, 2006). For each plant in our list we asked the interviewee if the plant could be used for medicine, food, firewood, canoe building, house building, and/or other uses. Thus, for each plant we recorded all the uses known by household heads (n=624), and averaged total uses known at each village so as to assess TEK at the village level (n=59).

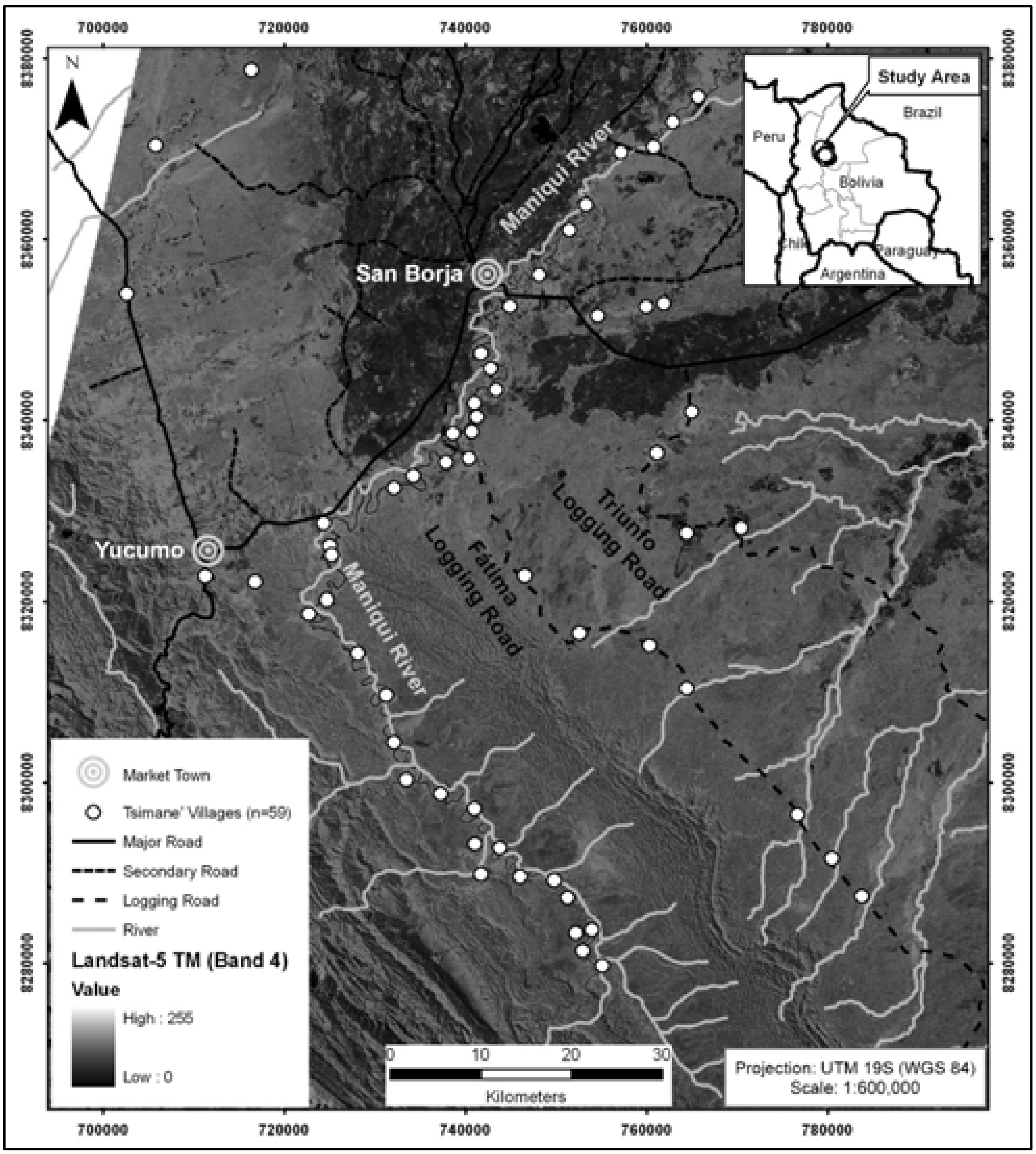

Figure 4.1. Landsat-5 TM mosaic (17/04/2009) used to classify old-growth forests across the study area, overlaid with the Tsimane' villages surveyed, roads, rivers and main market-towns.

Table 4.1. Class metrics used to assess the extent and fragmentation of old-growth forests at the village level (see McGarigal *et al.*, 2002 for further details). These metrics are used as outcome variables in OLS regressions. Landscape here refers to the 5-km buffer around the village school.

Class Metric	Metric Type	Range and Units	Description
Percentage of Landscape (PLAND)	Area (Extent)	$0 < PLAND \leq 100$ %	Quantifies the percentage of the landscape covered by OGF
Edge Density (ED)	Edge (Fragmentation)	$ED \geq 0$ m/ha	Quantifies the total length of OGF edges in relation to the landscape area
Cora Area Percent of Landscape (CPLAND)	Core Area (Fragmentation)	$0 < CPLAND \leq 100$ %	Quantifies the percentage of the landscape covered by core areas of OGF
Perimeter-Area Fractal Dimension (PAFRAC)	Shape (Fragmentation)	$1 \leq PAFRAC \leq 2$ None	Reflects shape complexity across a range of OGF patch sizes. PAFRAC approaches 1 for OGF simple patch shapes (e.g., squares) and diverges towards 2 as OGF patches are more complex

4.2. Data analysis

Data analyses proceeded as follows. I first built a spatially-explicit database containing all the variables used in this study and retrieved their descriptive statistics at the village level. I then sought correlations between the four outcome variables (forest extent and forest fragmentation) and the explanatory variable (TEK) to estimate the strength of their associations. Specifically, I ran Pearson correlations. Lastly, I performed ordinary least square (OLS) regressions to assess the existence and potential importance of associations between forest conservation and TEK, while controlling for the influence of other variables. Specifically, I used the following model:

$$Y_i = \alpha + \beta A_i + \gamma D_i + \varepsilon_i \quad [1]$$

where, for village *i*, *Y* is an outcome variable, *A* is an explanatory variable, *D* is variable used as control, and *ε* is a random error term. *α* is a constant (intercept), and *β* and *γ* are the coefficients associated with the explanatory and control variables. As my sample of villages was relatively low for regression analysis (n=59), besides the main explanatory variable (TEK) I controlled for just one additional variable in each regression. I began by running three regressions models: one without controls, a second one with an explanatory variable controlling for distance to market-towns, and a third controlling for population density. Subsequently, I performed a robustness analysis using equation [1] and controlled for other village-level attributes that may potentially affect forest conservation in tropical areas (e.g., variables related to acculturation and market integration) (Angelsen and Kaimowitz, 1999; Geist and Lambin, 2002). Table 4.2 shows the definition of all the variables I used in the OLS models. I hypothesized that the extent of forest and the proportion of core forest would have a positive and significant association with TEK and, conversely, that forest edge density and forest shape complexity would bear a significant but negative association with TEK. Finally, I mapped each of the four pairs of forest-TEK variables alongside to 1) unravel differences among villages according to their spatial location and 2) assess whether the spatial patterns of forest metrics and TEK overlapped. To evaluate this potential overlap in statistical terms I categorized the four forest variables and TEK as above/below average and applied chi-squared tests. That way, I could assess whether villages with high levels of forest conservation had also high levels of TEK (and vice versa), and the statistical significance of such overlapping spatial patterns (if any).

Table 4.2. Definition of explanatory and control variables used in the regression analysis. Variables refer to villages.

Variables	Definition
Traditional Ecological Knowledge	
TEK	Mean total number of plant uses known, i.e., ethnobotanical knowledge (TEK)
Acculturation	
Schooling	Mean higher level of schooling (grades 0-13) of respondents
Spanish	Proportion of informants that speak Spanish fluently
TV	Total number of TVs
Population	
HH	Total number of households
Spatial Location	
DistSBY	Linear distance to the closest main market town (San Borja or Yucumo)
Market Integration	
Cows	Total number of cows
TravelSB	Mean number of respondents trips to the main market town (San Borja) over a year
RiceEarnings	Meant total household earnings (Bolivianos)[1] from the sale of rice since last harvest
RiceSold	Meant total amount (arrobas)[2] of rice sold/bartered by households since last harvest
Forest Cleared for Agriculture	
Def	Mean total area (tareas)[3] of forest (old-growth and fallow) cut over the previous year

[1] 1$US~7 Bs (Bolivianos); [2] 1arroba=11.5kg; [3] 10Tareas=1ha.

5. <u>Results</u>

5.1. Descriptive statistics

Most selected variables showed a large variation among Tsimane' villages, including all the explanatory and the outcome variables. I could gather village-level statistics for the majority of variables in all sampled villages (n=59), yet FRAGSTATS computed one of the outcome variables (*PAFRAC*) for just 56 villages. Table 4.3 shows descriptive statistics for all the variables used in the study. I found that forest cover was high on average (~66%) though it greatly varied (SD~25%), ranging from 16.7% to 98.4%, thus signaling that some villages may have undergone important deforestation rates while others have their forest cover still relatively intact. As regards forest fragmentation, I found that 1) edge density peaked at ~30 m/ha in 7 villages and was <8m/ha in 5 villages, 2) mean core forest area was ~45% (SD=26.5%) but 14 villages had <20% core forest left whereas 7 had over 80% core forest left, and 3) forest shape-complexity showed a mean value of 1.25 (SD=0.04). These three findings indicate that, as forest coverage, forest fragmentation surrounding Tsimane' villages display large variations. The explanatory variable (TEK) ranged from 14 to 41 plant uses known for our list of 20 common plants, with an average value of 22 uses known per village (SD~5.5).

Table 4.3. Descriptive statistics of the variables used in the regression analysis.

Variables	N	Unit	Mean	SD	Min	Max
Outcome variables						
Forest Conservation						
PLAND	59	%	65.87	24.80	16.70	98.40
ED	59	m/ha	18.52	7.00	3.35	33.31
CPLAND	59	%	45.46	26.52	3.65	91.47
PAFRAC	56	-	1.25	0.04	1.11	1.32
Explanatory variable						
Traditional Ecological Knowledge						
TEK	59	n	22.17	5.34	13.93	40.86
Control variables						
Acculturation						
Schooling	59	n years	1.86	1.22	0	4.62
Spanish	58	%/100	0.20	0.22	0	0.91
TV	59	n	1.36	1.32	0	7
Population						
HH	59	n	27.03	28.44	3	190
Spatial Location						
DistSBY	59	km	30.42	18.93	2.81	80.16
Market Integration						
Cows	59	n	4.49	8.93	0	41
TravelSB	59	n	18.71	16.11	2.14	99.11
RiceEarnings	59	$Bs	871.57	2180.65	0	16651.25
RiceSold	58	arroba	22.18	25.60	0	166
Forest Cleared for Agriculture						
Def	59	tarea	10.19	5.60	3.08	43

5.2. Association between traditional ecological knowledge and forest conservation

I found moderate to strong significant correlations (p~0) between the explanatory and outcome variables (Figure 4.2). As expected, I observed a positive relation between the average TEK in a village and both the extent of forest (*PLAND*) and core forest area (*CPLAND*) in the same village (Pearson's R=0.53 and R~0.6, respectively). I also found a negative relation between TEK and both forest edge density (*ED*) and forest shape-complexity (*PAFRAC*) (Pearson's R=-0.6 and R=-0.7, respectively). The initial OLS regression models confirmed the results obtained in correlation analyses. The association between TEK and the four outcome variables was very significant (p~0) in all regressions with no control variables, and remained so after controlling for distance to the closest market-town and population density (Table 4.4). I also found that the regression coefficient (R^2) was significantly higher when using distance as a control variable than when using population density, thus indicating its important association with the outcome variables.

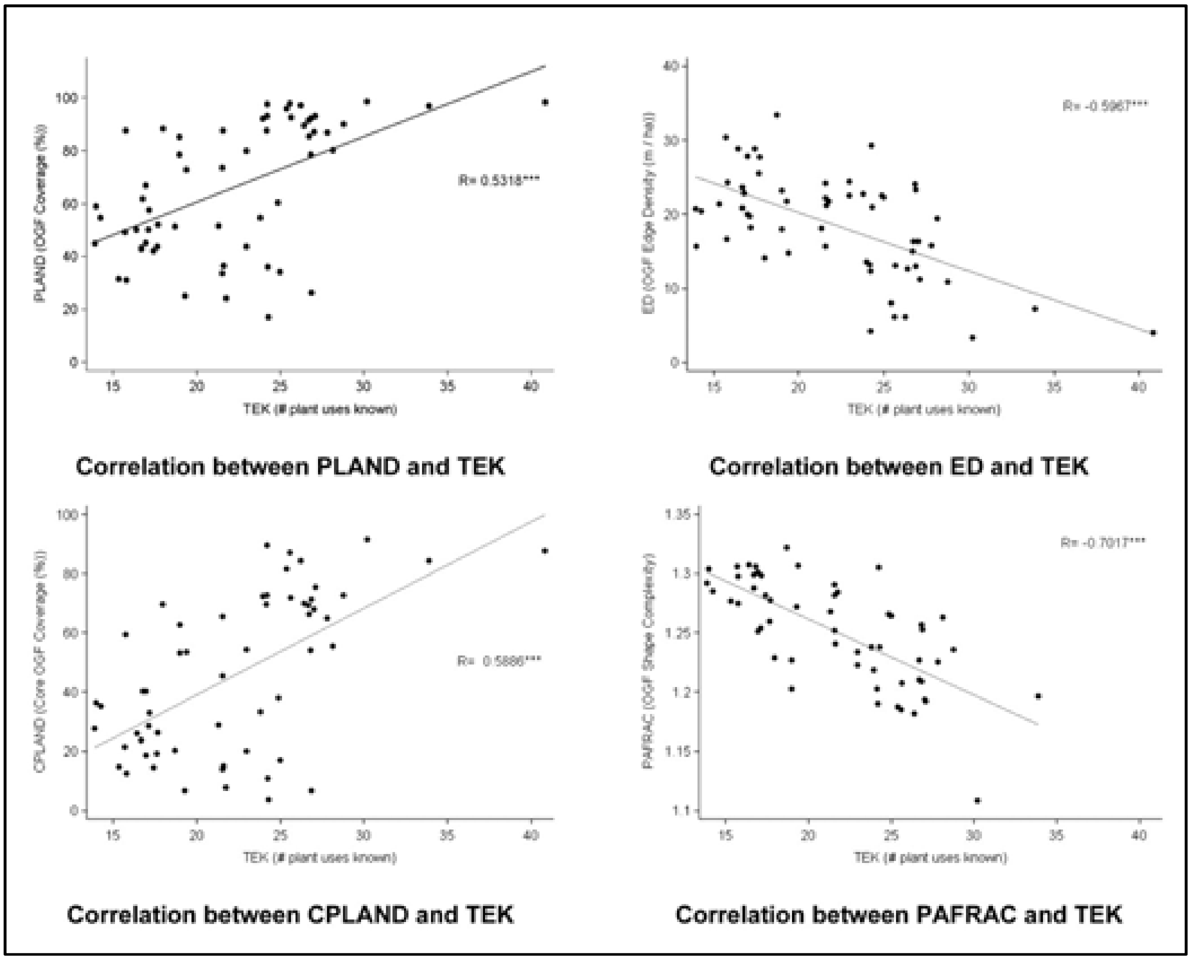

Figure 4.2. Correlations between the explanatory and the outcome variables (Pearson's R correlation coefficient shown; *** significant at 99.9% (p<0.001)).

The robustness analysis allowed me to further confirm the association between TEK and both forest extent and forest fragmentation, while identifying other factors that might affect such an association (Table 4.5). Thus, I found TEK remained significantly associated with all four outcome variables while controlling for variables related to acculturation, population density, spatial location, market integration, and forest cleared for agriculture over the previous year. Interestingly, some of such control variables, namely population density, rice earnings, rice sold/bartered, and forest clearance over the previous year, did not seemingly affect the association between TEK and forest variables. The robustness analysis allowed me to better estimate the regression coefficients for the explanatory variables as I could infer ranges rather than single values. Therefore, I estimated the coefficient for the association between TEK and forest extent to range between ~1.1 and 2.6, between TEK and forest edge density between ~-0.5 and -0.8, between TEK and core forest extent between ~1.5 and 3.0, and between TEK and forest shape-complexity between ~-0.0065 and -0.0045 (all with $p<0.01$). Of special interest are the range values related to TEK and both forest and core forest extent. Thus, according to my results, an increase of 1 plant use known in a village would be associated with an increase of 1.1-2.6% of forest area and of 1.5-3.0% of core forest area, within a 5-km buffer surrounding the village.

Table 4.4. Regression results showing the association between traditional ecological knowledge and old-growth forest extent and fragmentation. [x] models include *TEK* as unique explanatory variable, while [x'] models control for distance to the closest market-town and [x''] models control for population density.

	Forest extent			**Forest fragmentation**								
	Forest cover (*PLAND*)			Forest edge density (*ED*)			Core forest cover (*CPLAND*)			Forest shape-complexity (*PAFRAC*)		
Explanatory variable	[1]	[1']	[1'']	[2]	[2']	[2'']	[3]	[3']	[3'']	[4]	[4']	[4'']
TEK	2.47 (0.000)	1.09 (0.010)	2.47 (0.000)	-0.78 (0.000)	-0.49 (0.000)	-0.77 (0.000)	2.92 (0.000)	1.46 (0.001)	2.91 (0.000)	-0.006 (0.000)	-0.004 (0.000)	-0.006 (0.000)
Control variable												
DistSBY	^	0.88 (0.000)	^	^	-0.18 (0.000)	^	^	0.93 (0.000)	^	^	-0.001 (0.000)	^
HH	^	^	0.001 (0.989)	^	^	0.02 (0.556)	^	^	-0.04 (0.702)	^	^	0.000 (0.094)
N	59	59	59	59	59	59	59	59	59	56	56	56
Constant	11.09 (0.355)	14.80 (0.084)	11.04 (0.384)	35.87 (0.000)	35.09 (0.000)	35.27 (0.000)	-19.36 (0.116)	-15.42 (0.066)	-17.88 (0.168)	1.39 (0.000)	1.38 (0.000)	1.38 (0.000)
R-squared	0.283	0.648	0.28	0.345	0.558	0.360	0.346	0.705	0.348	0.492	0.646	0.519

Nevertheless, though the regression analysis suggests TEK is an important factor for forest conservation, the analysis also suggests that variables related to the overall village level of acculturation are more determinant than TEK regarding forest conservation. Thus, for example, I observed that 1 year more of schooling in the village average was associated with the loss of ~10% of forest cover and ~11% of core forest cover without controlling for other explanatory variables (results not shown). When controlling for TEK these associations slightly diminished (loss of ~8% for both forest and core forest cover; Table 4.5). The number of TVs in villages bore a significant and negative association with forest conservation (loss of ~6% of forest and core forest cover with and without controlling for TEK). Yet, Spanish fluency bore the most remarkable associations with forest conservation. Thus, I observed that a high proportion of Spanish fluency in villages was associated with a decrease of ~34% and ~32% of forest and core forest extent, respectively, and with an increase of edge density of ~4m/ha, even after controlling for average level of village TEK.

Table 4.5. Robustness analysis showing results from multivariate regression models using different control variables. Core models refer to OLS regressions without any control variable ([x] in Table 4.4).TEK=Coefficient of the main explanatory variable (*TEK)*; Control=Coefficient of control variable. *, **. ***: Regressions are significant at p<0.1, p<0.05, p<0.01, respectively.

	PLAND			**ED**			**CPLAND**			**PAFRAC**		
	TEK	**Control**	**R^2**	**TEK**	**Control**	**R^2**	**TEK**	**Control**	**R^2**	**TEK**	**Control**	**R^2**
Core												
(without control variable)	2.47***	-	0.283	-0.78***	-	0.356	2.92***	-	0.346	-0.0064***	-	0.492
Acculturation												
Schooling	1.94***	-7.83***	0.418	-0.67***	1.71***	0.437	2.37***	-8.18***	0.476	-0.0058***	0.01***	0.561
Spanish	1.70***	-34.45**	0.343	-0.70***	4.14	0.369	2.21***	-32.55**	0.393	-0.0051***	0.05**	0.536
TV	2.52***	-6.35***	0.397	-0.79***	1.46***	0.432	2.97***	-6.88***	0.464	-0.0065***	0.01**	0.534
Population												
HH	2.47***	0.01	0.283	-0.78***	0.02	0.361	2.91***	-0.03	0.347	-0.0064***	0.00	0.516
Spatial Location												
DistSBY	1.09**	0.88***	0.648	-0.49***	-0.18***	0.558	1.46***	0.93***	0.705	-0.0045***	-0.00***	0.646
Market Integration												
Cows	2.29***	-0.58*	0.324	-0.74***	0.13	0.385	2.73***	-0.61*	0.387	-0.0061***	0.00*	0.527
TravelSB	1.51***	-0.77***	0.494	-0.60***	0.15***	0.456	1.88***	-0.84***	0.565	-0.0055***	0.00**	0.547
RiceEarnings	2.38***	-0.00	0.291	-0.75***	0.00	0.367	2.82***	-0.00	0.357	-0.0062***	0.00	0.509
RiceSold	2.37***	-0.11	0.293	-0.74***	0.02	0.364	2.80***	-0.11	0.354	-0.0058***	0.00***	0.576
Forest Cleared for Agriculture												
Def	2.39***	-0.18	0.284	-0.74***	0.09	0.361	2.83***	-0.21	0.348	-0.0056***	0.00**	0.528

5.3. Spatial overlap between traditional ecological knowledge and forest conservation

I mapped alongside the values of forest metrics and TEK for my sample (Figure 4.3) and observed that Tsimane' villages along the Fátima logging road have the highest levels of TEK and forest conservation. I found a gradient in TEK and forest conservation along the Maniqui River, as upstream villages show high values on both variables and, barring few exceptions, downstream villages have low values. Remarkably, Tsimane' villages close to the market-town of San Borja have very little forests left, which moreover are highly fragmented. Regarding TEK in such villages, those with lowest levels of ethnobotanical knowledge and skills are between the two market-towns and along the lowest part of the river.

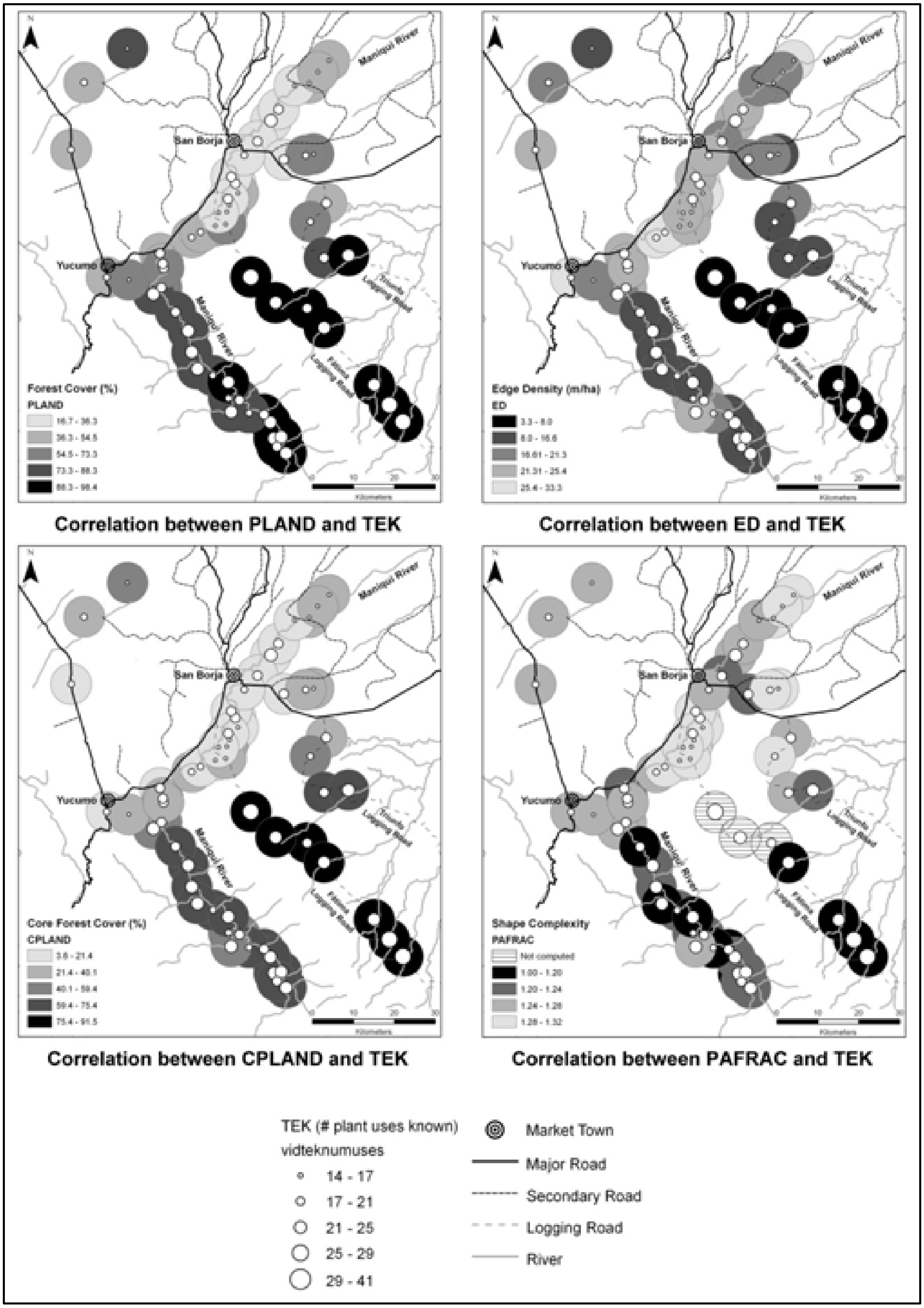

Figure 4.3. Spatial correlations between TEK and the four forest metrics (n=59 aside from PAFRAC which n=56). While buffers with darker colors indicate higher degrees of forest conservation, bigger dots signal higher levels of TEK; and vice versa.

Finally, I found two other clusters of villages; the three villages north of Yucumo display low levels of TEK and low to moderate values in forest extent and forest fragmentation, and the four villages along the Triunfo logging road show moderate to high levels of both TEK and forest fragmentation. Chi-squared tests demonstrated that villages that have conserved more of their forests also have higher levels of TEK than villages that have conserved less of their forests: I found Pearson's chi-squared values of 14.28, 12.51, 16.28 and 18.91 (all with p~0.000), for PLAND, ED, CPLAND and PAFRAC vs. TEK, respectively. In all the clusters of villages, forest conservation also seemed to be associated with accessibility as a function of distance to the main market-towns and cost of access by road or river.

6. <u>Discussion</u>

Three main findings stem from my research: 1) there exists a very significant (p~0) association between TEK and forest conservation, 2) there is a significant (p~0) spatial overlap between high levels of TEK and high levels of forest conservation, and 3) acculturation appears to have a greater influence than TEK on forest conservation. I discuss each finding next and conclude with some reflections on the main implications of the results.

The first finding supports the long-standing view in ethnoecology that sustains indigenous ecological knowledge plays a key role in tropical forest conservation (e.g., Dufour, 1990; Toledo *et al.*, 2003; Rerkasem *et al.*, 2009). Overall, the case study suggests that Tsimane' TEK is strongly associated with forest conservation in the study area. But, what may be the mechanisms underlying this finding? A previous study among the Tsimane' (Reyes-Garcia *et al.*, 2007b) found a strong and significant negative association between individual levels of TEK and forest clearance (and therefore between TEK and forest extent), which in their opinion was explained because people who had higher TEK levels used more the forest and were therefore less prone to cut it. In this study, carried out at the village level, this explanation seems appropriate too. That it, villages with higher average levels of TEK may reflect on a higher communal dependency on forest resources which, in turn, may result in higher forest coverage around them because villagers clear little to maintain their supply of forest resources.

Nevertheless, such a simple rationale does not seem valid to explain the association found between TEK and forest fragmentation. In that respect, I claim that the combination of the two other aspects of TEK (practice and beliefs) may be more relevant than the knowledge component itself. Thus, for example, forest edges are created through Tsimane' swidden-fallow systems, which in addition affect the extent of core forest and the shape-complexity of forests surrounding villages. As I have shown in regression results, population density bears no significant association with these forest aspects and, consequently, forest fragmentation is not related to the number of swidden-fallow plots within a village. Thereby, I think that in villages in which people have more TEK on average, swidden-fallow systems must be more efficient so that they create less forest fragmentation. This could be achieved by different mechanisms such as cropping more useful plants in swidden fields, rotating crops more efficiently, arranging crops in layers according to their ecological needs to optimize space usage, lengthening the fallow, clearing fallow forest rather than old-growth forest, or any combination of such mechanisms. All these techniques would improve crop yields without depleting soil nutrients, and would reduce the need for clearing and fragmenting more old-growth forest than strictly needed for household self-subsistence. This hypothesis is consistent with the findings of Reyes-Garcia *et al.* (2008), who found a positive association between the level of TEK of male household heads and crop diversity in their swidden fields. Similarly, it fits well with the results of Reyes-Garcia *et al.* (2011), who claimed that the more TEK Tsimane' individuals had 1) the more selective and efficient they were in clearing old-growth forest (because they practiced joint production while clearing), and 2) the less fallow forest they cleared (which suggests they lengthened the fallow because they used these forests more efficiently too).

Further, I argue that villages with higher levels of TEK may not only have more efficient cultivators and forest managers, but also more experienced foragers who can gather edible wild food in the forest, as well as more skilled hunters and fishers. All these traditional subsistence-oriented activities are carried out without affecting forest structure (i.e., without creating forest fragmentation), and may make people less dependent on agricultural production, thus reducing the time and the area of cleared forest invested in cropping. In addition, based on our ethnographic knowledge of the Tsimane', we can affirm that individuals with more ecological knowledge tend to hold more onto ancestral beliefs than those who have little TEK (Reyes-García *et al.*, in review). With regard to forests, Tsimane' traditional beliefs unravel the existence of a variety of spirits living in them, which translates into conservative rules of management of certain trees or other elements of the landscape (i.e., water sources, salt sources). Similarly, Tsimane' beliefs convey a series of taboos and prohibitions that effectively safeguard certain forest areas because no human activities are allowed, and underpin social norms and practices that limit the use of forest resources (Huanca, 2006). Therefore, such beliefs may have significant effects on both the extent and the configuration of village forest, as well as on the abundance and diversity of wildlife and flora, as these sacred forest areas may act as biodiversity havens.

The second finding indicates that, with few exceptions, villages with above-average TEK show above-average forest conservation (and vice versa), and that this association is extremely significant in Pearson's chi-squared tests between TEK and all four forest conservation variables. Furthermore, a clear spatial pattern can be observed in those associations. First of all, the visual interpretation of such spatial patterns and the regression analyses suggest that both TEK and the forest variables are also associated, to a great extent, with distance to the main market-towns, and with accessibility. Thus, the villages with the highest levels of forest conservation are those along the Fátima logging road. This road becomes unusable every year during several months due to the abundant rain that carries away the artisanal bridges built to cross some tributaries of the Maniqui River. This constitutes a real barrier to the movement of people and goods (e.g., timber), which has led these villages to remain very isolated. Conversely, access to villages along the other logging road is much easier; yet, though more subtle, there is also a gradient in TEK and forest conservation with distance and accessibility. Regarding the majority of villages, which are settled along the Maniqui River, the highest levels of TEK and forest conservation are found in the upper section of the river (the southern part), i.e., the farthest from the market-towns. However, although the most remote villages there take 2.5-3 days to be reached by canoe, access is always possible (even in the dry season), which may explain why both TEK and forest conservation are not as high as in villages along the Fátima logging road.

As expected, villages close to the market-towns show low levels of forest conservation and, in general, of TEK too. This is easily explained because these villages are relatively integrated into the market economy and have severely changed their lifestyles as a consequence of this process, thus transforming their productive system to sell cash crops such as rice (Vadez *et al.*, 2008), rear cattle, and extract forest goods such as timber (Godoy *et al.*, 2005b). These villages have also suffered from encroachment upon their land since colonists started to arrive in the area in the 1970s and settled close to the main roads (Reyes-García *et al.*, 2012a). Such encroachers have cleared much indigenous forestland as forest clearing was regarded as a requirement to claim land ownership under national colonization plans and the 1996 agrarian reform (Bottazzi and Dao, 2013). Finally, some villages (the two upper ones north to Yucumo, and the last four in the lower section of the Maniqui River) had very low levels of TEK and yet, their forests were relatively well preserved. I believe this reflects a limitation in the TEK variable, as most likely the average ethnobotanical knowledge in these villages is not that low, but rather people living in them do not know as many plant uses from our 20-species list owing to local floristic differences. For instance, the four villages downstream the Maniqui River are settled within the Beni Biological Station, a UNESCO biosphere reserve that includes different forest types (e.g., swampy forests); therefore their floristic composition must be significantly different from the rest of forests present in the territory sampled (Guèze, 2011). Thus, I argue that our TEK variable cannot accurately capture the ethnobotanical knowledge of people in these villages.

Finally, from the robustness analysis I found that the three acculturation measures used as controls in regressions (schooling, Spanish fluency, and number of TVs) bore larger associations with forest conservation than TEK. This finding contrasts with previous results obtained among the Tsimane' (Godoy *et al.*, 1997; Godoy and Contreras, 2001), which have shown that having more formal education and being fluent in Spanish allow Tsimane' individuals to work as laborers outside of their villages, something associated with a decrease in deforestation in such studies. It is also contrary to the long-lasting view of Kuznets curves as regards forest conservation, which states that when households drive themselves out of poverty through increasing their income (something usually associated with education attainment; e.g., Godoy *et al.* (2007)), they increasingly stop clearing forest, though this view remains equivocal (Chowdhury and Moran, 2012). However, other studies have suggested that acculturation is associated with forest destruction because of agricultural expansion and a more intense extraction of forest resources (Kingsbury, 2001). In my case study, I believe Tsimane' acculturation negatively affects forest conservation through both direct and indirect effects. On the one hand, the most acculturated villages largely coincide with those that are more integrated into the market and produce more cash crops, which causes extensive forest clearance (Vadez *et al.*, 2008). Moreover, I have observed that Tsimane' individuals who are engaged in logging activities are often very acculturated and live in villages near the market-towns. Thus, for instance, during fieldwork I found out that some school teachers engage in selective logging because they have the economic resources to purchase a chainsaw and the ability to negotiate in Spanish to sell their harvest to non-indigenous intermediaries. On the other hand, previous findings indicate the existence of an inverse significant relation between TEK and education among the Tsimane', largely explained because the more time children spend at school the less time they spend acquiring TEK (Reyes-García *et al.*, 2010). Hence, I hypothesize that aside from the direct effects education has on forest conservation, education may also pose indirect threats to the preservation of forests in the study area through the loss of TEK, as it may entail the loss of beliefs and of knowledge and skills that underpin Tsimane' sustainable forest practices.

7. <u>Conclusion</u>

In this chapter I have shown with quantitative and spatial analyses that TEK plays a significant role in old-growth forest conservation among the Tsimane' Amerindians of the Bolivian Amazon, and that there is a significant overlap between the spatial patterns of TEK and those of forest conservation. I have also provided evidence of the negative effect that Tsimane' acculturation have on forest conservation, which I partly attribute to its negative association with TEK (Reyes-García *et al.*, in review) and the ongoing process of loss of TEK we have recently estimated among this indigenous group (Reyes-Garcia *et al.*, in review-a). Although there are other factors that do also seem to play an important role in forest conservation across the study area (e.g., village distance to market-towns and accessibility), my results suggest that there may be some form of functional connection between TEK and forest conservation at the local scale of analyses. In that respect, I have provided some insights into the mechanisms that may underlie such a connection when discussing the results, and contributed to research that stresses the need to acknowledge the importance of indigenous peoples' TEK for biodiversity conservation. Future research to further our understanding of the role of TEK in biological conservation should include other dimensions of TEK not accounted for in this study (e.g., beliefs, resource use norms), the inclusion of the temporal dimension in relation to forest conservation (i.e., disturbance dynamics such as deforestation, selective logging, and/or fire), and other proxies for biological diversity (e.g., fauna, flora).

As the world's cultural and biological diversities are being rapidly eroded, often by the very same forces (Nabhan *et al.*, 2002; Sutherland, 2003), research in the field of biocultural conservation provides clues that may allow for the development of integrative conservation policies that do not exclude cultural protection and that see indigenous and traditional peoples as conservation allies (Schwartzman and Zimmerman, 2005). In addition, conservation practitioners and advocates of indigenous rights to land, resources and political autonomy, should seek to take advantage of potential synergies between TEK and conservation science (Huntington, 2000; Becker and Ghimire, 2003) as a way to protect indigenous livelihoods and strengthen their endogenous development besides protecting biodiversity. In that sense, policies that ensure indigenous community-based forest management (or co-management where different stakeholders co-exist) should be prioritized over classic conservation policies that focus on strict biological conservation (i.e., uninhabited protected areas) (Porter-Bolland *et al.*, 2012) and that have neglected indigenous peoples' rights and their knowledge, thus curtailing the loss of culture needed to nurture biodiversity in an increasingly populated world.

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Chapter 5

Summary of main results and conclusions

> We can also hope that the adoption of biocultural diversity as a domain for academic inquiry will foster a transdisciplinary turn in academe, leading to greater communication and exchanges among disciplines, as well as more work by interdisciplinary teams, and thus to the elaboration of a new synthesis about the connections between linguistic, cultural, and biological diversity
>
> A transdisciplinary approach should also make research more sensitive to real world needs and research findings more relevant for policy and other applications
>
> (Luisa Maffi)

Summary of main results and conclusions

This PhD thesis is the result of a multidisciplinary approach through which I have attempted to bring together theory and methods from geographical, ecological, environmental, and social sciences, as required to adequately address the study of land change in coupled human and natural systems (Liu *et al.*, 2007; Turner *et al.*, 2007; Rindfuss *et al.*, 2008) and biocultural diversity (UNESCO, 2008). Below I summarize the main results obtained in each research chapter and provide some concluding remarks in relation to potential methodological limitations, main contributions, and suggestions for further research. In addition, I give some policy recommendations based on my findings.

I set out the PhD thesis with the primary goal of devising an efficient classification approach to accurately map all broad LULC classes present across the study area. I compare different algorithms and find that support vector machines (SVM) classifiers outperform other parametric (maximum likelihood), non-parametric (*k*-nearest neighbors) and hybrid (MiraMon's unsupervised-supervised) classifiers. I also find that the inclusion of two textural indices (homogeneity and entropy) can significantly enhance LULC classification results. Specifically, I find that the inclusion of textural homogeneity significantly improves the overall accuracy of the classifications regardless of the algorithm used. Crucially to the aims of this thesis, the use of both spectral and textural homogeneity data with SVM algorithms has enabled me to map the two forested classes (early-growth forest and old-growth forest) with producer's and user's accuracies >90% for both Landsat imagery dates (2001 and 2009) and types of accuracy assessment (hard and soft) used. Similarly, the rest of LULC classes included in this study are mapped with producer's and user's accuracies of

~90%. Within the context of this PhD thesis, attaining such accurate results is paramount to provide a sound basis for deriving reliable trends in FCC (second chapter) and for assessing the level of old-growth forest conservation in a rigorous manner (third chapter).

The methodological improvements resulting from the second chapter are important because tropical LULC mapping endeavors are key to conservation initiatives, climate change mitigation strategies, the design of natural resource management plans, and rural development policies. And yet -over tropical regions- mapping LULC is very challenging as discussed in the introduction. Therefore, any advancement regarding this complex task might result in a wide range of applications. My classification approach is novel because the use of textural homogeneity has so far been neglected in LULC mapping efforts. Furthermore, it presents the advantage of being easy to implement because both the calculation of the homogeneity index and the presence of SVM classifiers are readily available in common remote sensing software. Moreover, it is cost-effective because SVM classifiers can use smaller training datasets without compromising classification accuracy (Foody and Mathur, 2006). Importantly, the very high accuracies I obtain with this classification approach suggest it may also lead to accurate LULC mapping in other tropical regions, and quite possibly in other non-tropical areas. Further research should therefore assess the validity and usefulness of this classification method elsewhere. In addition, similar approaches might be explored to seek further improvements, such as the use of textural homogeneity and entropy with other novel and powerful non-parametric classifiers (e.g., random forests) or with object-based classifiers. Also, although classifications based on Landsat satellite imagery remain the most useful for mapping LULC and assessing LULC change (Cohen and Goward, 2004), the increasing availability of low-cost high-spatial resolution imagery (e.g., CBERS-2, ALOS) may open new paths in the near future for exploring classification approaches based on data fusion between Landsat data and other remote sensing data sources, which could also lead to improvements in my classification approach.

In the third chapter my main goal is to assess whether significant differences regarding trends in forest cover change (FCC) across the study area can be explained by land tenure. I examine spatio-temporal dynamics of FCC in four land tenure systems (indigenous titled territory, protected area, logging concession, and private land) and find that different trends in FCC exist according to different land tenure systems, which suggests that, to a great extent, land tenure determines the fate of forests in the Bolivian Amazon. Specifically, I observe that over the three study periods analyzed (1986-1996, 1996-2001, 2001-2009), 1) private lands underwent, by far, the largest FCC among the four land tenure systems analyzed, 2) indigenous TCOs and the protected area had relatively little FCC, and 3) logging concessions were responsible for the lowest FCC. As I derive the trends in FCC from very accurate forest classifications (obtained through the classification approached devised in the second chapter), I believe my results are not biased. Moreover, even though there have been factors operating within each land tenure system that may be directly responsible for driving FCC (e.g., proximate causes following the term used by Geist and Lambin (2002)), such as agricultural expansion or infrastructure extension, those factors do not affect the analysis undertaken because they are, to a large extent, controlled by land tenure too (e.g., through land uses permitted or prohibited). I look at the effects of land tenure as an underlying driving force (regardless of what drives change inside, even though I attempt to explain it in the discussion). The fact that neither the boundaries of the different land tenure systems nor the social groups living in them have substantially changed throughout the three study periods suggest that the results are robust.

The study brings insights that have important implications for public policies aimed at economic development and environmental conservation in the Bolivian Amazon because understanding different trends in FCC may help in better planning and management for conservation outcomes. From a biocultural conservation perspective, my results suggest that future conservation policies in Bolivia should emphasize the key role of native Amazonians in effectively protecting old-growth forests and expand the existing network of indigenous TCOs accordingly. As previously suggested (Alcorn, 1993; Gadgil *et al.*, 1993; Colchester, 2004), I claim that it is necessary to take into account indigenous peoples in conservation policy and to establish alliances or partnerships with indigenous groups as a way to achieve biological conservation, which has already been proposed in the Brazilian Amazon (Schwartzman and Zimmerman, 2005; Vermeulen and Sheil, 2007). Such inclusive conservation approaches would also lead to preserve cultural diversity and guarantee the cultural and political rights of indigenous peoples. In addition, community-based forest management based on traditional ecological knowledge should be encouraged by the authorities as this type of management has proven to have a beneficial effect on protecting forest cover while enhancing indigenous livelihoods (Berkes, 2007), and to hold the potential to be more effective than forest protected areas (Porter-Bolland *et al.*, 2012). Nevertheless, indigenous governance need to be strengthened to avert the negative consequences of abutters encroaching upon TCOs' lands owing to the fragility of this land tenure type (Assies, 2006).

Besides the role of indigenous territories in forest conservation, my findings suggest the importance of biological reserves and, more interestingly, the benefits of logging concessions to prevent FCC provided that timber extraction activities remain at low, sustainable levels, a strategy already implemented in the Brazilian Amazon (Veríssimo *et al.*, 2002). Based on my findings, I suggest that new biological reserves and sustainable logging concessions be favored in areas with low rural populations, whether indigenous or not, insofar their rights are respected to avoid conflicts, sustainable management plans are implemented, and economic benefits are shared. Moreover, given the current expansion of the commodity frontiers in the Bolivian Amazon, and the high levels of FCC associated with private lands documented in this study, I argue that some conservation incentives (e.g., subsidies to sustainable agroforestry systems) are needed in private lands to conserve carbon (Soares-Filho *et al.*, 2006) and to maintain at least some biodiversity refugia areas and corridors and hence diminish the pervasive effects of fragmentation in old-growth forests (Laurance *et al.*, 2002). Furthermore, as recent research has shown that levels of human development follows a boost-and-bust pattern as deforestation takes place in Amazonian frontier settings (Rodrigues *et al.*, 2009), financial incentives and policies that promote more sustainable development scenarios should be sought to protect forest and people. Further research is needed to assess the proximate causes of LULC within each land tenure system so as to better understand the observed trends in FCC and the potential effects of land tenure on such causes. In that sense, it would be particularly useful to gather data on household land-use decision-making in the agricultural frontier, where most FCC is taking place, so as to implement economic policies that may be more compatible with conservation measures. Collecting such data would allow for the construction of agent-based models, which would be useful to predict future FCC under different scenarios in these areas; such models could also be complemented with process-based models, which are better suited for non-behavioral datasets and facilitate the extrapolation of results. I will endeavor to model FCC across the study area as a follow-up of this PhD thesis.

Finally, in the fourth chapter I conduct an empirical study to assess whether Tsimane' traditional ecological knowledge (TEK) is associated with the levels of old-growth forest conservation observed in their territory. Furthermore, I evaluate whether there is a spatial overlap between TEK and forest conservation. In spite of its relevance to shed light into the alleged importance of TEK for biological conservation, this may be the first time such an analysis is conducted. My results are based on robust quantitative and spatial data analyses and suggest that TEK plays an important role in old-growth forest conservation among the Tsimane'. Results also show a significant overlap between the spatial patterns of TEK and those of old-growth forest conservation. In addition, I provide evidence of the negative effects that Tsimane' acculturation have on forest conservation, which I partly attribute to the negative association between acculturation and TEK (Reyes-García *et al.*, in review) and the ongoing process of loss of TEK our research team have recently estimated among this indigenous group (Reyes-Garcia *et al.*, in review). Although there are other factors that seem to play an important role in forest conservation (e.g., village distance to market-towns and accessibility), my findings suggest there must be some form of functional connection between TEK and forest conservation at the local scale. In that respect, I have provided some insights into the mechanisms that may underlie such a connection and contributed to research that stresses the importance of acknowledging the role of indigenous peoples' TEK in biodiversity conservation.

My findings make a significant contribution to the field of biocultural conservation since, to the best of my knowledge, I provide the first attempt to assess the spatial overlap of cultural and biological diversity at a local scale. Given the very high spatial overlap I find, my findings suggest there may be some form of functional connection between both diversities, aside from the complex historical human settlement patterns that may led to in-migration into this biodiversity-rich region centuries or thousands of years ago. My findings on the spatial overlap of TEK and forest conservation levels are significant because previous research on this topic has been conducted at global and continental or sub-continental scales and it has been suggested that the high levels of co-occurrence found in such assessments may not hold when scaling down to local levels (Manne, 2003). Therefore, my results have very important policy implications because they suggest that biological and cultural conservation should proceed hand in hand in this area of the Amazon. This is particularly urgent nowadays as we know that biological and cultural (and linguistic) diversities are rapidly being eroded throughout the world, often by the same socioeconomic and political forces (Nabhan *et al.*, 2002; Sutherland, 2003) and because we have documented that the Tsimane' have lost TEK at a very high rate over the last decade (Reyes-Garcia *et al.*, in review).

Based on my results, I argue that the Bolivian government should focus on the development of integrative conservation policies that do not exclude cultural protection and that see indigenous peoples as conservation allies. In addition, conservation practitioners and advocates of indigenous rights to land, resources and political autonomy, should seek to take advantage of potential synergies between TEK and conservation science (Huntington, 2000; Becker and Ghimire, 2003) as a way to protect indigenous livelihoods and strengthen their endogenous development besides protecting biodiversity. In that respect, I claim that policies that ensure indigenous community-based forest management (or co-management where different stakeholders co-exist) should be prioritized over classic conservation policies that have neglected indigenous peoples' rights and their knowledge (Porter-Bolland *et al.*, 2012), thus curtailing the loss of culture needed to nurture biodiversity in increasingly human-dominated forests (Noble and Dirzo, 1997). This may be particularly relevant in the current context as the lease of land to logging concessions have expired in 2011 and part of such land may be given back to the indigenous TCOs, which is currently under negotiation. Future research to further our understanding of the role of Tsimane' TEK in biological conservation should include a better assessment of different agroforestry systems and their potential outcomes as regards biodiversity, other dimensions of TEK not accounted for in our study (e.g., beliefs, resource use norms), the inclusion of the temporal dimension in relation to forest conservation (e.g., disturbance dynamics such as deforestation, selective logging, and/or fire), and other proxies for biological diversity (e.g., fauna, flora).

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Appendix 1

Academic collaborations and team publications throughout the PhD thesis

This PhD thesis was funded through a FBBVA research grant (BIOCON_06_106-07) to the project *Conservación del Bosque Amazónico y Territorios Indígenas: del Conflicto a la Colaboración. Estudio de Caso en la Amazonía Boliviana*, led by Dra. Victoria Reyes García (ICREA Research Professor at ICTA-UAB) and one of my PhD advisors. Over the course of the PhD, besides designing, conducting, and writing up my own three research papers, I have participated in a number of publications led by V. Reyes García and my two fellow PhD candidates working within the project, Maximilien Guèze and Ana Catarina Luz. Thus, collaboration within our research team has led to three papers that have already been published, some more that are in review, and a few more that are underway and will be sent for review during fall 2012, all in international peer-review journals. In addition, in 2009-2010 I helped Zoila Cruz-Burga with her MSc thesis, and a publication out of it in now under review, and also I collaborated with an undergraduated thesis from which another publication is under review. Further, over 2011-2012 I have co-directed the MSc of Irene Pérez-Llorente, together with Dra. Reyes García, and this work will also be submitted for publication in fall 2012. A list of all these publications is provided at the end of this appendix.

Besides the work carried out in Barcelona at ICTA-UAB, and the field work I undertook in 2009 in Bolivia, over 2011-2012 I have carried out three visiting periods at the Centro de Investigaciones en Geografía Ambiental (CIGA), Universidad Nacional Autónoma de México (UNAM), in Morelia, Michoacan, Mexico. During those visits I have worked with Dr. Jean-François Mas, who has been my other PhD advisor, I have completed three postgraduate courses on advanced remote sensing, geostatistics using R software, and political ecology, respectively, and I have set future collaborations with some researchers at CIGA-UNAM. Furthermore, during the PhD I have also attended several international workshops, conferences, and training courses on various topics.

Throughout the PhD I have participated in two research projects that focused on common-pool resources management in the Island of Cyprus. The first one, that took place in 2009, was titled *The Cypriot Natural Resources as a Common Space* and was funded by the Peace Research Institute of Oslo. The main objective of this project was to seek opportunities for fostering future bi-communal (i.e., between the Greek and the Turkish Cypriot communities) cooperation by means of scarce natural resources (e.g., water, forests) co-management. Several social policy experiments on common-pool natural resources management amongst different stakeholders were carried out and two workshops to disseminate the results were organized. I organized and conducted the experiments and the workshops in Cyprus along with three other fellow researchers from ICTA-UAB, the Helmholtz Centre for Environmental Research UFZ (Germany) and the Humboldt University of Berlin (Germany). The second project, that was titled *Sharing Water and Environmental Values: Peace Construction Efforts in Cyprus*, took place in 2011-2012 and was funded by the Institut Català Internacional per la Pau. It built on the previous project and aimed to further investigate the role that some scientific approaches drawn from both natural and social sciences may have in promoting collective action rather than competition over natural resources and, more specifically, over water. The central research objective was to test whether the combination of certain innovative, interdisciplinary methods can result in synergies that may help reveal the potential of collaborative efforts regarding water management in Cyprus, which suffers from severe water scarcity. If so, we argued this approach could be employed to foster social learning, promote capacity building and result in joint strategies that prevent or resolve existing conflicts and enhance security and peace. My leading role in the project was to explore the synergies that the inclusion of remote sensing data coupled with GIS analysis may bring within the water availability and usage assessment conducted in both Greek and Turkish Cypriot communities. Research was undertaken with colleagues from the UAB and the Humboldt University of Berlin (Germany). Further information and a report with preliminary results can be obtained at: http://www.sharewatercyprus.net

Finally, I am currently participating in two ongoing research projects. The first one's titled *Social and Environmental Transitions: Simulating the Past to Understand Human Behaviour (SimulPast)* and it is a CONSOLIDER-INGENIO 2010 project (http://simulpast.imf.csic.es/sp/index.php) led and coordinated by Marco Madella (ICREA Professor at the Laboratory for Palaeoecology and Plant Palaeoeconomy, Department of Archaeology and Anthropology, Institució Milá i Fontanals (CSIC), Barcelona). I participate in the case study 1 –*Resources, seasonality and landscape in the transition from hunter-gathers to agricultural/pastoral societies in Northern Gujarat (India)*– led by Dra. V. Reyes García. The second project's name is *"Construction ahead": The effects of roads on indigenous people's well-being and use of natural resources. A natural experiment in lowland Bolivia*, it is funded by the National Science Foundation (NSF) of USA and is led by Dr. Ricardo Godoy (Brandeis University, Boston). My role in this project is to analyze a time-series of satellite imagery to 1) map land use/cover and 2) assess forest change dynamics, across the indigenous territories affected by the road.

<u>List of peer-reviewed publications (it does not include the three ones I have written as part of my PhD thesis)</u>

Accepted in September 2012

Guèze, M., **J. Paneque-Gálvez**, A.C. Luz, M.J. Macía, M. Orta-Martínez, J. Pino, and V. Reyes-García, 2012. Determinants of tree species turnover in a southern Amazonian rainforest. Journal of Applied Vegetation Science. DOI: 10.1111/j.1654-1103.2012.01461.x

Reyes-García, V., M. Orta-Martínez, M. Guèze, A.C. Luz, **J. Paneque-Gálvez**, M.J. Macía, J. Pino, J. Cristóbal, T. Huanca and TAPS Bolivian Study Team, 2012. Does participatory mapping increase conflict? A randomized experimental evaluation in the Bolivian Amazon. *Applied Geography*, 34, 650-658.

Reyes-García, V., J.C. Ledezma, **J. Paneque-Gálvez**, M. Orta, M. Guèze, A. Lobo, D. Guinart and A.C. Luz. 2012. Presence and purpose of non-indigenous peoples on indigenous lands. A descriptive account from the Bolivian lowlands. *Society & Natural Resources: An International Journal*, 25:3, 270-284.

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Reyes-García, V., **J. Paneque-Gálvez**, A.C. Luz, P. Bottazzi, M. Guèze, M.J. Macía, M. Orta-Martínez, P. Pacheco, The historical roots of indigenous lands in Bolivia. A political ecology account of traditional Tsimane' lands. In review: *Journal of Rural Studies* (2012).

Reyes-García, V., M. Guèze, A.C. Luz, **J. Paneque-Gálvez**, M.J. Macía, M. Orta-Martínez, J. Pino, and TAPS Bolivian Study Team. Evidence of traditional ecological knowledge loss from a contemporary indigenous society. In review: *Evolution and Human Behavior* (2012).

Cruz-Burga, Z., V. Reyes-García, J. Alarcón Novoa, **J. Paneque-Gálvez**, A.C. Luz. Aprovechamiento de los recursos naturales por los Tsimane' y su relación con la economía de mercado. Un caso de estudio en la Amazonía Boliviana. In review: *Natura@Economía* (2012).

Reyes-García, V., A.C. Luz, M. Guèze, **J. Paneque-Gálvez**, J. Cristóbal, M.J. Macía, M. Orta-Martínez, J. Pino, and TAPS Bolivian Study Team. Secular trends of traditional ecological knowledge: an analysis of different domains of knowledge among Tsimane' indigenous people. In review: *Learning and Individual Differences* (2011).

To be submitted in fall 2012

Pérez-Llorente I., **Paneque-Gálvez, J.**, M. Guèze, A.C. Luz, M. Orta-Martínez, J. Pino, M.J. Macía, and V. Reyes-García. Indigeneous people's acculturation and the physical landscape: what are the links? An empirical study from the Bolivian Amazon. To be submitted to: *Landscape and Urban Planning* (2012).

Reyes-García, V., **J. Paneque-Gálvez**, A.C. Luz, M. Guèze, M.J. Macía, M. Orta-Martínez, J. Pino, and TAPS Bolivian Study Team. Acculturation and traditional ecological knowledge. To be submitted to: *Human Ecology* (2012).

Guèze, M., **J. Paneque-Gálvez**, A.C. Luz, M.J. Macía, V. Reyes-García, M. Orta-Martínez, and J. Pino. Does ecological importance of tree species relate to their usefulness? A case study from the Tsimane' indigenous territory, Bolivian Amazon. To be submitted to: *Economic Botany* (2012)

Luz, A.C., J. Brashares, **J. Paneque-Gálvez**, M. Guèze, J. Pino, M. Orta-Martínez, M.J. Macía, and V. Reyes-García. Does hunting pressure vary with acculturation? A study among indigenous people in the Bolivian Amazon. To be submitted to: *Biological Conservation* or *Animal Conservation* (2012).

Luz, A.C., M. Guèze, **J. Paneque-Gálvez**, J. Pino, M. Orta-Martínez, M.J. Macía, and V. Reyes-García. Does acculturation affect indigenous peoples' hunting behavior? Estimates from the Tsimane' in the Bolivian Amazon. To be submitted to: *Conservation Biology* (2012).

Riu-Bosoms, C., T. Vidal-Amat, A. Duane, M. Guèze,, A.C. Luz, **J. Paneque-Gálvez**, TAPS Bolivian Study Team, and V. Reyes-García. Landscape perception, classification and use among the Tsimane' Amerindians, Bolivia. To be submitted to: *Ambio* (2012).