Assessment of forest cover dynamics in Paraguay

A case study of the Upper Parana Atlantic Forest

Kumulative Dissertation zur Erlangung des Doktorgrades der Mathematisch-Naturwissenschaftlichen Fakultät der Christian-Albrechts-Universität zu Kiel

vorgelegt von
Emmanuel Da Ponte Canova
München, 2018

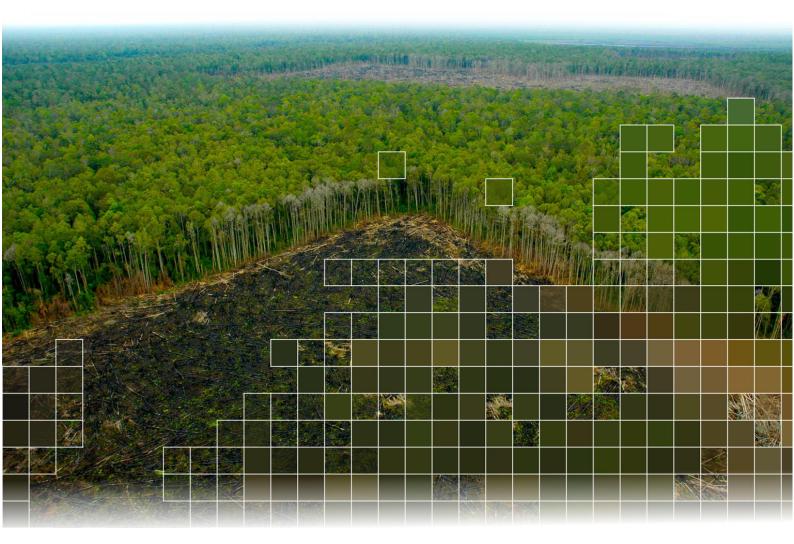
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Termin der mündlichen Prüfung: 17. Juli 2018 Zum Druck genehmight: 17. Juli 2018

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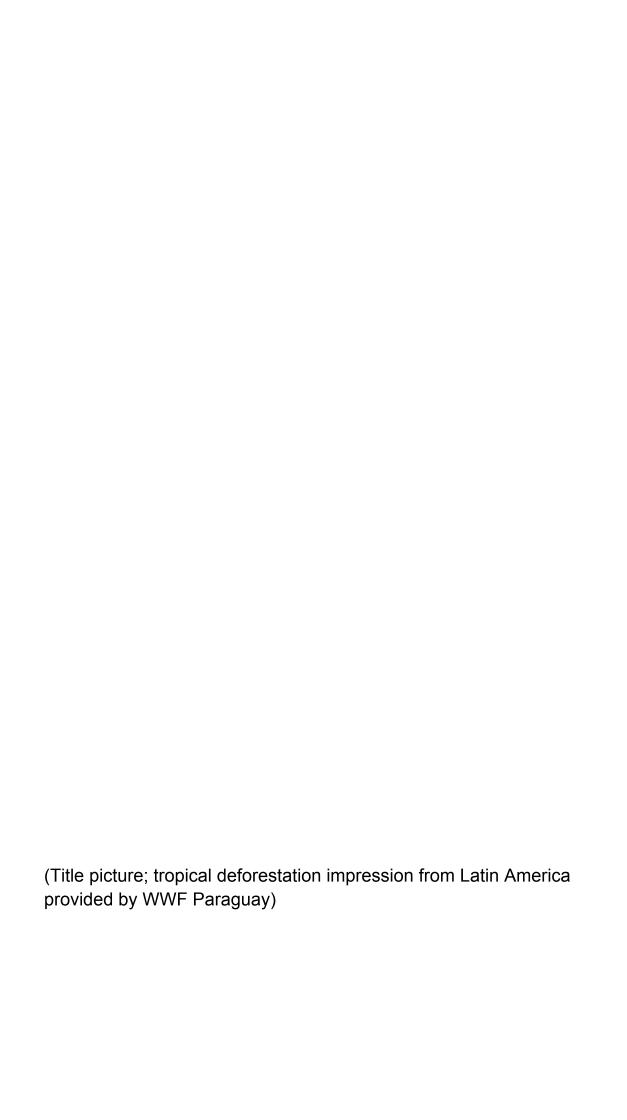


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Acknowledgements

Writing this dissertation would not have been possible without the help of many people and institutions. I would like to express my gratitude to them. I would especially like to thank the following persons:

- to my supervisor at Kiel University, Prof. Dr. Natascha Oppelt, for her support, generous advice and rapid response to all my concerns. These were of great help in completing the present dissertation.
- to my mentor and supervisor at the German Remote Sensing Data Center (DFD) of the German Aerospace Center (DLR), Dr. Claudia Kuenzer, for her constant support, commitment, and guidance throughout my PhD period. Her supervision not only helped me to finish this dissertation but also encouraged me to develop at a personal and professional level. Without her continuous feedback regarding all aspect of my research, this dissertation would not have been concluded. Additionally, I want to thank her for her confidence in me and commitment to nursing my professional development.
- to all the colleagues that have been working on the PARLU Project, particularly Amanda Parker, Martina Fleckenstein, Lucy Aquino Oscar Rodas, Francisco Pereira, Sonia Delphin and Andrea Garay. They gave me the opportunity and trusted me to conduct this investigation.
- to my colleagues from DFD-DLR, specifically to those from the Land Surface Dynamics team: Dr. Ursula Gessner, Kersten Claus, Kim Knauer, Aiym Orynbaikyzy, Igor Klein, Juliane Huth, and Dr. Benjamin Mack. They all provided fruitful discussions, criticism, and support during all phases of this dissertation. Furthermore, I would like to express my sincere thanks to Dr. Patrick Leinenkugel, Dr. Andreas Dietz, and Marco Ottinger for their discussions and support on remote sensing issues, particularly during the first stages on this research.
- to Christian Wohlfart, for endless discussions and frequent feedback regarding the content of this thesis. Furthermore, I want to remark on his continuous support beyond this dissertation, beginning from the first day that I arrived in Germany right up to the present.
- to Kai Sandbrink, for his continuous support throughout this research, especially for his careful proofreading of all my published articles.
- to my parents, Fernando and Hildegard Da Ponte, and my siblings--Elizabeth, Giovanna, and Horacio--for their encouragement, constant support, and advice. They have supported me not only during the dissertation work but throughout my entire professional carrier. They have taught me the value of education and sacrifice. This dissertation is dedicated to them.
- to Mayerlin Rua Patino, for her love, tolerance and emotional support throughout my studies, in particular, during the final stages of this dissertation. She has shown me that sometimes taking some time off from study reveals new perspectives and can improve the outcome of my work.

This dissertation has been carried out in the framework of the PARLU Project, funded by the Federal Ministry for the Environment, Nature Conservation Building and Nuclear Safety (BMUB).

English Summary

The subtropical Atlantic Forest in South America has been acknowledged as one of the most endangered rain forests in the world. Despite its highly diverse ecosystem, the rapid advance of the agricultural frontier has turned the last forest remnants into isolated patches, compromising the continuity of the forest and its biodiversity. The Atlantic Forest ecoregion stretches along three countries, starting from the Brazilian Atlantic Coast, passing though the eastern region of Paraguay, and ending in northern Argentina. While the portion of the ecoregion contained in Paraguay (also known as the Upper Parana Forest (BAAPA)) only represents a small share of the total geographical extent of the Atlantic Forest, it has long been recognized as a hotspot for biodiversity conservation. However, over the last 40 years, the BAAPA forest has been subjected to intense deforestation activities, which is a consequence of the continuous expansion of mechanized agriculture, especially soybean production. The activities was supported by the government between the years 1945 and 1985, where forest areas were seen as an impediment to the country's economic development, and even labelled as "non-productive lands". By the year 2004, Paraguay was identified as one the countries with the highest deforestation rates worldwide. Currently, there are more than 3 million ha of soybean plantations in the BAAPA, a figure that is expected to increase to 6 million over the next 10 years. To date, less than 10% of the original BAAPA forest cover remains. Over the last decades, the Paraguayan government has implemented several policies and conservation programs addressed to halt deforestation activities. For example, in 2004, the government implemented a "Zero Deforestation" law in the eastern region of the country. The law banned the conversion of forest lands for agricultural or other uses, and several reports stated that deforestation rates have declined substantially since then. Although the initiatives started by the Paraguayan government apparently diminished the pressure exerted on natural resources, proper scientific information related to their dynamics is lacking.

Remote sensing data has been continuously applied over the years as a key component to support and understand changes in forest lands. The large variety of sensors available permits the generation of novel research perspectives in forest dynamics over complex and inaccessible areas in the tropics. Despite the availability of such information, the BAAPA forest remains understudied. Several governmental and non-governmental institutions in Paraguay have addressed the problem of deforestation in the country. However, the number of scientific studies that properly institute a systematic analysis of the changes remains limited.

Based on the described research gaps, five major objectives were delineated in the present dissertation: 1) to provide a comprehensive overview of remote sensing-based studies conducted in Latin America to assess tropical forest cover dynamics; 2) to detect and characterize changes in the BAAPA forest based on a bi-temporal analysis of the years 2003 and 2013; 3) to offer insight on the farmer's perception of the forest based on an extensive household survey to understand the reasons behind the changes in the

BAAPA forest cover; 4) to assess deforestation processes and changes by increasing the temporal scale, with a special focus on the impact of forest policies and the effectiveness of protected areas under different management regimes; and 5) to combine remote sensing data and household information to understand how the farmers' view on forest service's affects the dynamics of the forest at the farm level.

As a first step in this thesis, a comprehensive review of remote sensing-based research was conducted to provide an extensive delineation of which sensors, methods, and scales were applied to assess tropical forest dynamics in Latin America. Generally, global forest mapping started in the earliest 1990s with a spatial resolution fluctuating from 1 km down to 300 m based on coarse imagery from sensors such as MERIS, AVHRR, and MODIS (9% of the studies reviewed). More recent products implemented Landsat and ALOS PALSAR sensors to increase the spatial resolution of the global forest products up to 25 m. When considering the forest processes assessed, over 90% of the studies reviewed focused on analyzing deforestation and degradation, and outlining patterns of change and deforestation hotspots and associated drivers. Around 65% of the studies were conducted at the local level and were frequently based on Landsat imagery, applying multi-temporal and bi-temporal analyses (around 95% of the studies reviewed). Overall, the approaches implemented to assess the deforestation process were based on manual interpretation, thematic maps, and continuous variables (e.g. vegetation indexes, subpixel vegetation fractions, continuous fields of tree cover, PCA components, or TC metrics). However, forest degradation did not present a standardized method. Difficulties in finding a proper definition of the process itself and the short time required to map the disturbance before the secondary vegetation covers the logged areas represent significant challenges to its detection. Nevertheless, continuous variables such as fraction images have presented improvements in detecting logged areas up to 3 years after the disturbance. Finally, distribution of the areas examined in the reviewed studies was quantified and found to be mainly centered in the Brazilian Amazon (over 72% of the studies), leaving other areas in Latin America equally threatened and without proper scientific data.

In a second step, to fill the research gaps stated above, forest cover loss in the BAAPA region was characterized based on Landsat Imagery obtained for the years 2003 and 2013, yielding a detailed analysis of spatial patterns of deforestation, effectiveness of protected areas, fragmentation levels, and connectivity of critical areas for biodiversity. Forest cover masks were obtained from Landsat ETM+ and OLI imagery applying a threshold classification approach with overall accuracies of 83% and 95%, respectively. General results revealed that over 6000 km² of natural forest were cleared between the study years 2003 and 2013. A deeper analysis on the landscape metrics of the BAAPA presented an increment on the levels of fragmentation of the forest. In summary, large patches decreased in size, and the total core area declined even as the number of patches increased. However, the designation of protected areas proved highly effective in forest conservation. Moving further away from the reserves, deforestation rates increased abruptly, leaving large forest areas isolated from each other. Additionally, connectivity between main forest patches is often interrupted by minor gaps, compromising the existence of natural corridors that are essential for biodiversity conservation in highly fragmented areas

To understand the reasons behind the changes in forest cover, this thesis presents a comprehensive analysis of how farmers located within the boundaries of the BAAPA perceive the forest and how this perception influences its conservation. The analysis is based on an extensive socioeconomic household survey conducted in January 2016 among different farmers' groups (small, medium and large-scale farmers) concealed in the ecoregion. A total of 277 farmers were interviewed. The field survey was based on a set of questions related to general aspects of the rural population, their perception and use of forest resources, and their general outlook on environmental laws and conservation programs. Overall results demonstrated a high level of environmental awareness among the farmers' groups. Around 84% of the farmers acknowledge that the forest is important to their livelihoods and over 91% state that, if the forest disappeared, this would have a remarkable impact on the environment. Additionally, the present study highlights a notable difference in the level of dependency on the forest eco-services among different farm groups. Whereas small-scale farmers stated that the forest was essential for their daily subsistence (e.g. firewood, construction, and food), medium and large-scale farmers considered the forest's main value to be cultural and recreational. With respect to the environmental laws and conservation programs, a large percentage of the farmers interviewed expressed their preference for the "Valuation and Retribution of Ecosystem Service Law 3001/2006" (PES 3001/2006" (73% of the interviewees) over the "Reforestation Incentives" program (27% of the interviewees). The program encourages the preservation of forest lands by providing economic incentives to landowners with natural reserves above the percentage established by the law (more than 25% of the total area of their farms). However, 90% of farmers concluded that, as a consequence of the high levels of corruption in the country, implementation of any environmental program or regulation remains ineffective.

To improve the results obtained in the second step, a multi-temporal analysis of forest cover changes in the BAAPA region was conducted, extending the temporal resolution up to 17 years including the time frame between 1999 and 2016. The study identified the changes that occurred between the reference years and analyzed the impact of different management regimes on forest conservation in protected areas. Dense Landsat scenes, which are publically available, were used to derive spatially continuous spectral-temporal, multi-spectral metrics for the study years. The described features were inputted into a RF classifier to estimate the forest cover for each reference year. Results indicate that the BAAPA forest lost around 7,500 km² (almost 28% or its original cover) over the 17-year period. Additionally, an increase in deforestation rates was observed from 2002-2004 (almost four times higher than previous rates). This tendency can be attributed to the announced implementation of the "Zero Deforestation" law in 2004. According to landowners interviewed, local farmers were aware of the upcoming deforestation law, and therefore increased their deforestation activities in the period before the law was actually implemented. With respect to the impact of different management regimes over protected areas, this thesis reveals that every reserve owned by the ITAPU hydroelectric company showed an increase in their forest cover, whereas every reserve managed by the government lost forest cover to some extent.

Based on the results obtained from the multi-temporal analysis and household surveys, both data types were combined to understand how farmers' perceptions of the forest influence its dynamics at a farm level. Forest masks produced for the years 1999 and 2016 were correlated with the responses from the field survey using cadastral information from each of the farmers interviewed. Overall results from this study demonstrate that forest dynamics at the farm level are influenced by farm type (small, medium, or large-scale farmers), educational background, and environmental awareness. For example, a higher percentage of small farmers' properties showed a decrease in forest cover than those of other groups. As the farm size increases, the percentage of farmers showing forest loss decreases. However, considering the educational background, a larger percentage of farms with forest gains was observed in the group of farmers with a higher education. However, this tendency decreased with farm size. The groups of land owners with no education had the lowest percentage of farms with increases in forest cover and the highest percentage of farms with forest loss. Farmers who participated in conservation programs or had contact with environmental agencies were less likely to have forest loss on their properties than farmers with no environmental education. Overall, the social value given to the forest is a remarkable contribution to the conservation of natural resources.

This dissertation presented the first study conducted for the BAAPA region in which remote sensing data and house level information are combined to provide an inclusive understanding on the changes that occurred in forest cover over the last 17 years. The product delineated above shows great potential to generate and support environmental policies that will preserve the last remnants of the forest in the eco-region. This valuable information could serve as an effective component for conservation programs, where the outlook for the rural population could ensure the sustainability of such initiatives over time

Zusammenfasssung

Der subtropische Atlantische Regenwald in Südamerika gehört zu den weltweit am bedrohtesten Primärwaldsystemen. Aufgrund des rapiden sozio-ökonomischen Wandels und der dadurch steigenden Nachfrage nach Fleisch- und Sojaprodukten, ist dieser vielfältige und fragile Naturraum über Jahrzehnte zum Großteil verschwunden oder stark degradiert. Diese Entwicklung gefährdet nicht nur den Fortbestand zahlreicher endemischer Tier- und Pflanzenarten, sondern bedroht die Lebensgrundlage der lokalen Bevölkerung. Insgesamt umfasst das Gebiet des Atlantischen Regenwaldes drei verschiedene Länder – Brasilien, Argentinien und Paraguay. Im internationalem Vergleich wurde Paraguay als ein Land mit den global höchsten Abholzugsraten identifiziert. Seit 1940 wurden insgesamt 90% der wertvollen Waldökosystemen zerstört. Paraguay ist geographisch in zwei große Region unterteilt: die westlich gelegene Chaco Region und die östliche BAAPA Region (Atlantic Forest of Alto Parana). Obwohl der Flächenanteil des Atlantischen Regenwaldes in Paraguay vergleichsweise gering ist, markiert dieses Gebiet einen Biodiversitäts-Hotspot. Ein striktes Entwaldungsverbot verlangsamte die Abholzung in der BAAPA Region seit 2004 deutlich. Trotz dieser drastischen Maßnahmen sind zuverlässige wissenschaftliche Arbeiten über die gegenwärtigen Veränderungsprozesse rar.

Satellitenbasierte Daten liefern heute flächendeckende und konsistente Informationen über die Landoberflächen- und Waldbedeckung und dynamische Prozesse. Infolge der technologischen Entwicklung steht eine Vielzahl unterschiedlicher Sensoren mit immer besseren zeitlichen und räumlichen Auflösungen zur Verfügung. Diese Daten erlauben neue und vielversprechende Forschungsperspektiven, die räumlich heterogenen und schwerzugänglichen BAAPA Region zu erfassen und somit zum Verständnis zum Zustand und den Veränderungen in diesem Ökosystem beizutragen. Trotz dieser neunen Informationsquellen sind aktuelle und regionalspezifische Informationen rar.

Vor diesem Hintergrund beschäftigt sich diese Dissertation mit der fernerkundlichen Erfassung und Interpretation von Waldstrukturen und –dynamiken in der BAAPA Region in Paraguay, wobei folgende Schwerpunkte gesetzt werden: 1) Ein Überblick aller fernerkundlichen Studien zum Thema Wald und -dynamiken in Lateinamerika gegeben; 2) Eine bi-temporale Analyse der BAAPA Waldbedeckung und –veränderung für die Jahre 2003 und 2013; 3) Eine Analyse über die Wahrnehmung ihres Waldes der lokalen Waldbesitzer basierend auf Haushaltsbefragungen, um die Treiber des Waldverlustes besser zu verstehen; (4) Analyse der Abholzungsmuster auf einer höheren zeitlichen Skala mit Fokus auf waldpolitischen Entscheidungen sowie die Effizienz von Schutzgebieten; (5) Kombination von fernerkundlichen Daten mit Haushaltsbefragungen, um den Blickwinkel der Waldbesitzer auf Farmlevel zu verstehen.

Zu Beginn dieser Dissertation wird eine umfassende Literaturstudie zu fernerkundlichen Forschungsaktivitäten sowie Methoden zur Ableitung von Wald und –dynamiken in Lateinamerika gegeben. Die ersten globalen Waldprodukte existieren seit den frühen

1990er mit räumlichen Auflösungen zwischen 300-1000m. Aktuellere Produkte mit besserer räumlichen Auflösung nutzen Landsat oder ALOS PALSAR Aufnahmen. Über 90% der Studien in Lateinamerika analysieren Muster und Treiber von Waldrodung oder degrationsprozesse. Davon wurden 65% auf lokaler Ebene durchgeführt und oft basierend auf Landsat Aufnahmen. Die meisten wissenschaftlichen Arbeiten waren bi- oder multitemporal. Die angewendeten methodischen Ansätze zur Ableitung von dynamischen Prozessen erfolgten durch manuelle Interpretation, thematische kontinuierlichen Variablen (u.a. Vegetationsindex, Subpixel-Analyse, PCA Komponenten). Diese aufgelisteten Ansätze wurden insbesondere für die Charakterisierung von Entwaldung verwendet, weniger um Degradierungsprozesse abzuleiten. Weiterhin zeigt sich eine Einseitigkeit bei der räumlichen Verteilung der Studien, da mehr als 72% der publizierten Arbeiten das brasilianische Amazonasgebiet untersucht wurden.

Die erste fernerkundliche Untersuchung dieser Arbeit leitet den Waldverlust zwischen 2003 und 2013 in der BAAPA Region basierend auf Landsat Aufnahmen ab und beschreibt räumliche Entwaldungsmuster, Effizienz von Schutzgebieten, Fragmentation sowie Konnektivität. Beide Landsatprodukte mit hohen Genauigkeiten (83% und 95%) zeigen einen Waldverlust von 6000 km2 zwischen 2003 und 2013. Es werden außerdem verschiedene Landschaftsmetriken berechnen, welche eine zunehmende Fragmentierung der Waldgebiete außerhalb von Schutzgebieten aufweisen sowie einen Verlust an Konnektivität zwischen intakten Waldflächen. Geringe bis keine Entwaldungsraten zeigen Waldflächen innerhalb von ausgewiesenen Schutzgebieten.

Im Rahmen dieser Dissertation wurde außerdem eine detaillierte Haushaltsbefragung mit Waldbesitzern in der BAAPA Region durchgeführt. Insgesamt 277 Waldbesitzer, unterteilt in kleine, mittel, und große Besitzer, wurden über Einkünfte, persönliche Wahrnehmung und Wichtigkeit ihres Waldes, Umweltbewusstsein sowie ihre Meinung zu den politischen Entwaldungsverboten. Insgesamt zeigt die Befragung ein großes Umweltbewusstsein aller Beteiligten unabhängig ihrer Waldgröße. Eine Mehrheit von 84% bestätigen die Wichtigkeit des Waldes als Lebensgrundlage und sogar 91% sind der Meinung, dass ein Verschwinden des Waldes massive Auswirkungen auf die Umwelt haben würde. Bezüglich der persönlichen Wichtigkeit zeigt sich eine deutlich höhere Abhängigkeit von kleinen Waldbesitzern, da diese die Waldressourcen für Feuerholz, als Baumaterial, oder Nahrung intensiver nutzen als mittlere und Großgrundbesitzer. Diese sehen den Wert im Ökosystem Wald eher als Erholungsfläche. Bezüglich der Gesetzgebung sprechen sich 73% für das "Valuation and Retribution of Ecosystem Service Law 3001/2006" (PES 3001/2006)" aus. Mehr als 90% der Befragten zeigen sich skeptisch bei der Implementierung und Durchführung beschlossener Gesetzte und Regelungen aufgrund der hohen Korruption.

In Ergänzung zu der bi-temporalen Analyse des zweiten Kapitels, werden aus einer langjährigen Landsat Zeitserie multi-temporale Walddynamiken für die BAAPA Region abgeleitet für den Zeitraum 1999 bis 2016. Basierend auf dichten kontinuierlichen Landsat Zeitserien werden verschiedene spektrale-zeitliche und multi-spektrale Metriken berechnet, um mit einem Random Forest Klassifikationsverfahren jährliche Waldbedeckungsprodukte zu abzuleiten. Zwischen 1999 und 2016 wurden insgesamt 7500 km2 des Atlantischen Regenwaldes in Paraguay abgeholt, was einem Verlust von 28

% der Waldfläche gegenüber dem Jahr 1999 entspricht. Genauere Analysen zeigen einen drastischen Anstieg der Abholzung im Zeitraum 2002 bis 2004, kurz bevor das "Zero Deforestation Law" ratifiziert wurde. Die Interviews mit den Waldbesitzern bestätigen, dass bewusst stärker gerodet wurde, bevor das strenge Gesetz in Kraft tritt. Bezüglich Schutzgebiete zeigt sich deutlich, dass öffentlich verwaltete Gebiete Verluste von Waldgebieten zeigen, wohingegen private Schutzflächen stabil blieben.

Das letzte Kapitel dieser Dissertation vereint die fernerkundlich abgeleiteten Waldprodukte mit den Informationen aus den Haushaltsbefragungen der Waldbesitzer. Die generierten Waldinformationen wurden mit lokalen Katasterdaten verglichen. Die Ergebnisse dieser Analyse zeigen deutlich einen Zusammenhang zwischen Walddynamiken und Bildungsgrad, Flächengröße und Umweltbewusstsein der befragten Waldbesitzer. Da das Ökosystem Wald insbesondere den kleinen Waldbesitzern als Lebensgrundlage dient, nutzen diese den Wald intensiver als andere Gruppen. Neben der Waldgröße spielt der Bildungsgrad der Besitzer eine wichtige Rolle. In Waldgebiete von Besitzern mit einem hohen Bildungsabschluss, zeigen sich sogar substantielle Waldzuwächse. Die höchsten Abholzungsraten findet man auf Flächen von Besitzern mit niedrigem Bildungsgrad. Waldzuwächse findet man auch bei Besitzern, die in Bildungsprogrammen der Naturschutzbehörde teilnahmen. Generell kann man sagen, dass alle Befragten ein hohes Umweltbewusstsein innehaben und der Wald einen immensen persönlichen Stellenwert trägt.

Diese Dissertation vereint als erste Studie fernerkundliche Informationsprodukte mit Haushaltsbefragungen von Waldbesitzern für die BAAPA Region in Paraguay, um die sozio-ökonomischen Treiber der Walddynamiken besser zu verstehen. Die multitemporalen Informationsprodukte der letzten 17 Jahre zeigen die drastische Veränderungen, welche nicht nur die dort vorkommenden Tier- und Pflanzenarten bedrohen, sondern auch die Lebensgrundlage der lokalen Bevölkerung gefährden. Diese wichtigen Informationsprodukte können als wichtige Entscheidungsgrundlage mit dem Ziel eines angemessen und nachhaltigem Landmanagement für die BAAPA Region dienen.

Portuguese Summary

A Floresta Atlântica subtropical na América do Sul tem sido reconhecida como uma das florestas chuvosas em maior perigo no mundo. Contudo o fato de ter um eco-sistema muito diverso, o rápido avanço da fronteira agrícola tornou os últimos remanescentes das florestas em ilhotes isolados, pondo sob risco a continuidade da floresta e da sua biodiversidade. A ecorregião da Floresta Atlântica estende-se entre três países, começando na Costa Atlântica Brasileira, passando através da Região Oriental do Paraguai e finalizando no Norte Argentino. Contudo a ecorregião localizada no Paraguai (também conhecida como a "Floresta Atlântica do Alto Paraná" (em português FAAP)) representar só uma pequena porção da área geográfica total da Floresta Atlântica, ela tem sido reconhecida há muito tempo atrás como um sítio chave para a conservação da biodiversidade. Outrossim, durante os últimos 40 anos, a Floresta Atlântica do Alto Paraná tem sido submetida a uma intensa atividade de desmatamento, uma conseqüência da continua expansão da agricultura mecanizada, notadamente a produção de soja. Essa atividade foi encorajada pelo Governo entre os anos 1945 e 1985, período no qual as áreas com florestas eram consideradas como um obstáculo ao desenvolvimento econômico do país e inclusive rotuladas como "terras improdutivas". No ano 2004, o Paraquai foi identificado como um dos países com os mais elevados índices de desmatamento no mundo. Hoje, tem mais de 3 milhões de hectares de plantações de soja na Floresta Atlântica do Alto Paraná, uma quantidade que poderá atingir 6 milhões nos próximos 10 anos. Até hoje, menos do 10% da cobertura florestal da Floresta Atlântica do Alto Paraná remanesce. Durante as últimas décadas, o Governo Paraquaio tem implementado diversas políticas e programas de conservação visando deter as atividades de desmatamento. Por exemplo, no ano 2004, o Governo implementou uma "lei de desmatamento zero" na Região Oriental do país. A referida lei vedava a conversão de terras florestais em agrícolas ou para outros usos. Diversos reportes indicavam que os índices de desmatamento caíram de maneira significativa desde então. Contudo as iniciativas iniciadas pelo Governo Paraguaio diminuírem em aparência a pressão exercida sobre os recursos naturais, ainda falta uma informação científica própria com relação às suas dinâmicas.

Os dados obtidos através de sensores remotos têm sido continuadamente aplicados no decurso dos anos como um elemento chave para suportar e compreender as alterações ocorridas nas terras florestais. A grande variedade de sensores disponíveis permite a geração de novas perspectivas de pesquisas nas dinâmicas florestais em áreas complexas e inaccessíveis dos trópicos. Outrossim, contudo a disponibilidade dessa informação, a Floresta Atlântica do Alto Paraná remanesce sem ser estudada de maneira bastante. Diversas instituições governamentais e não governamentais no país tinham encarado o problema do desmatamento no país. Outrossim, o número de estudos científicos abrangendo uma análise sistemática das alterações remanesce limitado.

Por força das lacunas nas pesquisas acima referidas, foram desenhados 5 objetivos principais na presente exposição. No primeiro lugar, fornecer um panorama integral dos

estudos baseados em dados obtidos através de sensores remotos conduzidos na América Latina para o fim de apurar as dinâmicas da cobertura florestal tropical. No segundo lugar, são detectadas as alterações na Floresta Atlântica do Alto Paraná, sendo elas caracterizadas na base de uma análise bi-temporal dos anos 2003 e 2013. No terceiro lugar, a presente tese visa conhecer em profundeza a visão dos agricultores com relação à floresta através de uma extensa sondagem domiciliária visando compreender as razões subjacentes às alterações que ocorrem na Floresta Atlântica do Alto Paraná. No quarto lugar, foram apurados os processos de desmatamento e as alterações acrescentando a escala temporal, com ênfase especial no impacto das políticas florestais e a efetividade das áreas protegidas sob diferentes regimes de gestão. No quinto lugar, os dados obtidos através de sensores remotos e a informação da sondagem foram juntados para o fim de compreender a maneira na qual a visão dos agricultores com relação aos serviços florestais tem um efeito sobre suas dinâmicas no âmbito da propriedade agrícola.

No primeiro estágio da presente tese foi realizada uma análise exaustiva da pesquisa feita na base dos dados obtidos através de sensores remotos, visando obter uma extensa delineação sobre quais são os sensores, métodos e escalas que foram aplicados na apuração das dinâmicas florestais tropicais na América Latina. Em geral, o mapeamento florestal mundial foi iniciado no começo dos 90, com uma resolução espacial flutuando desde 1 km para abaixo até 300 metros na base de imagens obtidas em bruto através de sensores como MERIS, AVHRR e MODIS (9% dos estudos analisados). Produtos mais recentes têm implementado sensores LANDSAT e ALOS PALSAR para acrescentar a resolução espacial dos produtos florestais mundiais até 25 m. Em consideração dos processos florestais avaliados, mais do 90% dos estudos analisados centraram a atenção em analisar o desmatamento e a degradação, em indicar os padrões de alteração, dos fatores chave do desmatamento e elementos associados. Aproximadamente o 85% dos estudos foi realizado localmente e com frequência na base de imagens obtidas através de Landsat, aplicando uma análise multi-temporal e bi-temporal (aproximadamente o 95% dos estudos analisados). Em geral, a abordagem implementada para avaliar o processo de desmatamento baseou-se na interpretação manual, mapas temáticos e variáveis continuas (por exemplo, índices de vegetação, frações de vegetação em sub-pixeles, campos contínuos de cobertura florestal, componentes PCA ou medições TC). Em contrário, a degradação das florestas não apresentou um método padrão. As dificuldades para achar uma definição própria do processo e o curto tempo requerido para o mapeamento dos distúrbios antes que a vegetação secundária possa cobrir as áreas desmatadas, representam desafios relevantes para sua detecção. Contudo, as continuas variáveis, que são as imagens fracionárias, apresentaram melhoramentos na detecção das áreas desmatadas até 3 anos após do distúrbio. Por fim, a distribuição das áreas examinadas dos estudos analisados foi quantificada e foi constatada a sua centralização na Amazônia Brasileira (mais do 72% dos estudos), deixando às outras áreas na América Latina igualmente ameaçadas, sem dados científicos próprios.

No segundo estágio, para o fim de dar solução às lacunas nas pesquisas acima referidas, tínhamos caracterizado a perda de cobertura florestal na região da Floresta Atlântica do Alto Paraná na base de imagens de Landsat obtidas com relação aos anos 2003 e 2013, atingindo uma análise em detalhe dos padrões espaciais de desmatamento, efetividade

das áreas protegidas, níveis de fragmentação e conectividade de áreas críticas para a biodiversidade. Foram obtidas máscaras de cobertura florestal através das imagens de Landsat ETM+ e OLI, aplicando uma ênfase de classificação de umbral, com precisões gerais de 83 e 95%, respectivamente. Os resultados gerais revelaram que mais de 6.000 km² de florestas naturais foram desmatados no período entre os anos 2003 e 2013 do estudo. Uma análise mais profunda das medições das terras da Floresta Atlântica do Alto Paraná exibiu um acrescentamento nos níveis de fragmentação da floresta. Em resumo, os grandes ilhotes diminuíram em tamanho e a superfície núcleo total desceu, contudo o acrescentamento do número de ilhotes. Por outra parte, a designação de áreas protegidas demonstrou ser altamente efetiva na preservação da floresta. Contudo, em áreas afastadas das reservas, os índices de desmatamento se acrescentam muito, deixando grandes áreas florestais isoladas umas das outras. Ainda, a conectividade entre os principais ilhotes florestais fica com freqüência interrompida por brechas menores, pondo sob risco a existência de corredores, que são essenciais para a conservação da biodiversidade em áreas de elevada fragmentação.

Visando compreender as razões subjacentes às alterações produzidas em uma cobertura florestal, esta tese apresenta uma análise exaustiva da maneira na qual os agricultores localizados dentro do perímetro da Floresta Atlântica do Alto Paraná percebem a floresta e a maneira na qual essa percepção tem influência na sua conservação. A análise baseiase em uma extensa sondagem domiciliária conduzida em janeiro de 2016 entre os diferentes grupos de agricultores (pequenos, médios e grandes agricultores) desenvolvendo atividades dentro da ecorregião. Um número total de 277 agricultores foi entrevistado. A sondagem no terreno se baseou em um jogo de perguntas relativas aos aspectos gerais da população rural, a sua percepção e o uso dos recursos florestais e uma visão geral das leis ambientais e dos programas de conservação. Os resultados gerais demonstraram um elevado nível de consciência ambiental entre os grupos de agricultores. Aproximadamente o 84% dos agricultores reconhece que a floresta é importante para a sua manutenção e mais do 91% expressa que se a floresta sumir, isso teria um impacto significativo no meio ambiente. Ainda, o presente estudo salienta o fato de uma notável diferença no nível de dependência dos eco-serviços florestais entre os diferentes grupos de propriedades agrícolas. Considerando que os pequenos agricultores manifestaram que a floresta era essencial para sua manutenção diária (por exemplo lenha para fogueira, construção e alimentação), os agricultores de médio e grande porte, em contrário, consideraram que o principal valor da floresta era cultural e recreativa. Com relação às leis ambientais e programas de conservação, uma grande percentagem destes agricultores entrevistados expressou a sua preferência pelo programa de "Valoração e Retribuição dos Serviços Ambientais", sob a Lei 3001/2006" (PES 3001/2006) (73% dos entrevistados) com relação aos "Incentivos ao Reflorestamento" (27% dos entrevistados). O programa encoraja a conservação das terras florestais através do fornecimento de incentivos econômicos aos proprietários de terras com reservas naturais ultrapassando a percentagem estabelecida pela lei (mais do 25 por cento da área das suas propriedades agrícolas). Outrossim, 90% dos agricultores concluiu que, como conseqüência dos elevados níveis de corrupção no país, a implementação de qualquer programa o regulamentação ambiental remanesce sem eficácia.

Visando melhorar os resultados obtidos no segundo estágio, foi feita uma análise multitemporal das alterações na cobertura florestal na região da Floresta Atlântica do Alto Paraná, estendendo a resolução temporal até 17 anos, abrangendo o período de tempo entre 1999 e 2016. O estudo não identificou somente as alterações ocorridas entre os anos referidos, mas também analisou os impactos que os diferentes regimes de gestão tinham sobre a conservação florestal em áreas protegidas. Densos cenários de Landsat, disponíveis para todos, foram utilizados para a derivação espacial das medições continuas espectrais-temporais e multi-espectrais com relação aos anos do estudo. Os resultados descritos foram ingressados a um classificador RF para estimar a cobertura florestal com relação a cada ano de referência. Os resultados indicam que a Floresta Atlântica do Alto Paraná perdeu aproximadamente 7.500 km² (quase o 28% da sua cobertura original) em um período de 17 anos. Ainda, um acrescentamento nos índices de desmatamento foi observado entre os anos 2002-2004 (quase quatro vezes mais altos que os índices anteriores). Essa tendência pode ser atribuída à implementação anunciada da lei de "desmatamento zero" no ano 2004. Segundo os proprietários entrevistados, os agricultores locais tiveram consciência da chegada da lei de desmatamento zero e em consequência incrementaram as suas atividades de desmatamento no período anterior à implementação efetiva da lei. Com relação ao impacto de diferentes regimes de gestão sobre as áreas protegidas, esta tese revela que cada reserva de propriedade da usina hidrelétrica ITAIPÚ acrescenta a sua cobertura florestal; no entanto, cada reserva administrada pelo Governo perde cobertura florestal em alguma percentagem.

Por fim, na base dos resultados obtidos da análise multi-temporal e da sondagem domiciliária, ambos os tipos de dados foram juntados para compreender a maneira na qual as percepções dos agricultores com relação à floresta influenciam suas dinâmicas no âmbito de uma propriedade agrícola. Assim, as máscaras florestais produzidas para os anos 1999 e 2016 tiveram correlação com as respostas adquiridas na sondagem no terreno utilizando informação cadastral de cada um dos agricultores entrevistados. Os resultados gerais deste estudo demonstram que as dinâmicas florestais no âmbito de uma propriedade agrícola são influenciadas pelo tipo de propriedade agrícola (agricultores pequenos, médios e de grande porte), os antecedentes educacionais e a consciência ambiental. Por exemplo, uma maior percentagem de propriedades de pequenos agricultores apresentou uma diminuição da cobertura florestal com relação às dos outros grupos. Quando o tamanho da propriedade agrícola for maior, diminui a percentagem de propriedades agrícolas apresentando perdas na cobertura florestal. Por outra parte, considerando os antecedentes educacionais, foi observada uma maior percentagem de propriedades agrícolas com ganhos florestais no grupo de agricultores com uma melhor educação. Outrossim, essa tendência diminuiu segundo o tamanho da propriedade agrícola. Os grupos de proprietários de terras sem qualquer educação não apresentaram só a menor percentagem de propriedades agrícolas com acrescentamentos na cobertura florestal, mas também a maior percentagem de propriedades agrícolas com perdas na cobertura florestal. Os agricultores que participaram nos programas de conservação ou que tiveram contato com entidades ambientais tiveram menos tendência a evidenciarem perdas florestais em suas propriedades que os agricultores sem qualquer educação ambiental. Em forma geral, cabe salientar que o valor social outorque à floresta é uma contribuição relevante à conservação dos recursos naturais.

O presente trabalho apresenta o primeiro estudo com relação à região da Floresta Atlântica do Alto Paraná no qual foram juntados os dados obtidos através de sensores remotos e informações no âmbito domiciliário visando uma melhor compreensão abrangente com relação às alterações ocorridas na cobertura florestal durante os últimos 17 anos. O produto acima desenhado envolve um grande potencial para gerar e suportar políticas ambientais que visam a conservação dos últimos remanescentes da floresta na ecorregião. Esta valiosa informação poderia servir como um elemento efetivo para os programas de conservação, onde a atitude da população rural poderia garantir a sustentabilidade das referidas iniciativas no decurso do tempo.

Spanish Summary

El Bosque Atlántico subtropical en América del Sur ha sido reconocido como uno de los bosques lluviosos en mayor situación de peligro en el mundo. A pesar de su ecosistema altamente diverso, el rápido avance de la frontera agrícola ha convertido a los últimos restos de bosques en islas distantes entre si, poniendo en riesgo la continuidad del bosque y de su biodiversidad. La eco-región del Bosque Atlántico se extiende a lo largo de tres países, comenzando desde la Costa Atlántica Brasileña, pasando a través de la Región Oriental del Paraguay y terminando en el Norte Argentino. Mientras que la ecoregión localizada en el Paraguay (también conocida como el "Bosque Atlántico del Alto Paraná" (BAAPA)) representa solamente una pequeña porción del área geográfica total del Bosque Atlántico, la misma ha sido reconocida desde hace mucho tiempo como un punto clave para la conservación de la biodiversidad. Sin embargo, durante los últimos 40 años, el Bosque Atlántico del Alto Paraná ha sido sometido a una intensa actividad de deforestación, una consecuencia de la continua expansión de la agricultura mecanizada, especialmente la producción de soja. Esta actividad fue promocionada por el Gobierno entre los años 1945 y 1985, período en el cual las áreas boscosas eran vistas como un impedimento para el desarrollo económico del país e incluso etiquetadas como "tierras improductivas". En el año 2004, el Paraquay fue identificado como uno de los países con los más altos índices de deforestación a nivel mundial. Actualmente hay más de 3 millones de hectáreas de plantaciones de soja en el Bosque Atlántico del Alto Paraná, una cifra que se espera aumente a 6 millones en los próximos 10 años. Hasta la fecha, menos del 10% de la cobertura forestal del Bosque Atlántico del Alto Paraná permanece. Durante las últimas décadas, el Gobierno Paraguayo ha implementado diversas políticas y programas de conservación tendientes a detener las actividades de deforestación. Por ejemplo, en el año 2004, el Gobierno implementó una "ley de deforestación cero" en la Región Oriental del país. Dicha ley prohibía la conversión de tierras forestales en agrícolas o para otros usos. Diversos informes manifestaban que los índices de deforestación cayeron substancialmente desde entonces. A pesar de que las iniciativas iniciadas por el Gobierno Paraquayo aparentemente disminuyeron la presión ejercida sobre los recursos naturales, falta una información científica adecuada con relación a sus dinámicas.

Los datos obtenidos a través de sensores remotos han sido continuamente aplicados a través de los años como un componente clave para apoyar y comprender los cambios que tienen lugar en las tierras forestales. La gran variedad de sensores disponibles permite la generación de nuevas perspectivas de investigación en las dinámicas forestales en áreas complejas e inaccesibles en los trópicos. Sin embargo, a pesar de la disponibilidad de dicha información, el Bosque Atlántico del Alto Paraná sigue sin ser estudiado de manera suficiente. Diversas instituciones gubernamentales y no gubernamentales en el país han encarado el problema de la deforestación en el país. Sin embargo, el número de estudios científicos que abarcan un análisis sistemático de los cambios permanece limitado.

En vista de las brechas investigativas descriptas, fueron delineados 5 objetivos principales en la presente exposición. En primer término, brindar un panorama integral de los estudios basados en datos obtenidos con sensores remotos conducidos en América Latina a los efectos de determinar las dinámicas de la cobertura forestal tropical. En segunda instancia se detectan los cambios en el Bosque Atlántico del Alto Paraná y éstos son caracterizados sobre una base de análisis bi-temporal de los años 2003 y 2013. En tercer término, esta tesis busca adentrarse en la perspectiva de los agricultores con respecto al bosque sobre la base de una extensa encuesta socioeconómica a fin de comprender las razones subyacentes a los cambios que tienen lugar en el Bosque Atlántico del Alto Paraná. En cuarto lugar, fueron determinados los procesos de deforestación y los cambios aumentando la escala temporal, con un enfoque especial en el impacto de las políticas forestales y la efectividad de las áreas protegidas bajo diferentes regímenes de gestión. En quinto lugar, los datos obtenidos a través de sensores remotos y la información obtenida en la encuesta socioeconómica fueron combinados a fin de comprender la manera en que la visión de los agricultores con respecto a los servicios forestales tiene un efecto sobre sus dinámicas a nivel de finca agrícola.

A modo de primera etapa en esta tesis, fue realizado un análisis exhaustivo de las investigaciones hecha en base a datos obtenidos a través de sensores remotos a los efectos de obtener una extensa delineación sobre qué sensores, métodos y escalas fueron aplicados para determinar las dinámicas forestales tropicales en América Latina. En general, el mapeo forestal mundial fue iniciado a comienzos de los 90, con una resolución espacial fluctuando desde 1 km abajo hasta los 300 metros en base a imágenes en bruto obtenidas de sensores tales como MERIS, AVHRR y MODIS (9% de los estudios analizados). Productos más recientes han implementado sensores LANDSAT y ALOS PALSAR para aumentar la resolución espacial de los productos forestales globales hasta 25 m. Al considerar los procesos forestales evaluados, más del 90% de los estudios analizados se ha enfocado en estudiar la deforestación y la degradación, en indicar los patrones de cambio, de puntos clave de deforestación y factores conexos. Aproximadamente el 85% de los estudios fue realizado a nivel local y frecuentemente en base a imágenes obtenidas a través de sensores Landsat, aplicando un análisis multitemporal y bi-temporal (aproximadamente el 95% de los estudios analizados). En términos generales, los enfoques implementados para evaluar el proceso de deforestación se basaron en la interpretación manual, mapas temáticos y variables continuas (por ejemplo, índices de vegetación, fracciones de vegetación en sub-pixeles, campos continuos de cobertura forestal, componentes PCA o mediciones TC). Por el contrario, la degradación de los bosques no presentó un método estandarizado. Las dificultades para hallar una definición adecuada del proceso en sí y el corto tiempo requerido para mapear los disturbios antes que la vegetación secundaria cubra las áreas taladas, representan desafíos significativos para su detección. No obstante, las continuas variables, tales como imágenes fraccionales, han presentado mejoras en la detección de áreas taladas hasta los 3 años posteriores al disturbio. Finalmente, la distribución de las áreas examinadas de los estudios analizados fue cuantificada y se constató su centralización en la Amazonia Brasileña (más del 72% de los estudios), dejando a otras áreas en América Latina igualmente amenazadas, sin datos científicos adecuados.

En una segunda etapa, a fin de subsanar las brechas investigativas indicadas precedentemente, hemos caracterizado la pérdida de cobertura forestal en la región del Bosque Atlántico del Alto Paraná en base a imágenes de Landsat obtenidas con respecto a los años 2003 y 2013, logrando un análisis detallado de los patrones espaciales de deforestación, efectividad de las áreas protegidas, niveles de fragmentación y conectividad de áreas críticas para la biodiversidad. Fueron obtenidas máscaras de cobertura forestal a través de las imágenes de Landsat ETM+ y OLI, aplicando un enfoque de clasificación de umbral, con precisiones generales de 83 y 95%, respectivamente. Los resultados generales revelaron que más de 6.000 km2 de bosques naturales fueron deforestados entre los años 2003 y 2013. Un análisis más profundo exhibió un aumento en los niveles de fragmentación del bosque. En resumen, los grandes remanentes disminuyeron en tamaño y la superficie núcleo total declinó. Por otra parte, la designación de áreas protegidas demostró ser altamente efectiva en la conservación del bosque. No obstante, los índices de deforestación aumentan abruptamente en áreas lindantes a las reservas, dejando grandes áreas forestales aisladas unas de otras. Además, la conectividad entre los principales remanentes forestales es a menudo interrumpida por brechas menores, poniendo en riesgo la existencia de corredores, que son fundamentales para la conservación de la biodiversidad en áreas altamente fragmentadas.

A fin de comprender las razones subvacentes a los cambios producidos en una cobertura forestal, esta tesis presenta un análisis exhaustivo de la manera en que los agricultores localizados dentro del perímetro del Bosque Atlántico del Alto Paraná perciben el bosque y la manera en que esta percepción influencia su conservación. El análisis se basa en una extensa encuesta domiciliaria realizada en Enero de 2016 entre los diferentes grupos de agricultores (pequeños, medianos y grandes agricultores) desarrollando actividades dentro de la eco-región. Un total de 277 agricultores fueron entrevistados. La encuesta en el terreno se basó en un grupo de preguntas relacionadas a aspectos generales de la población rural, su percepción y el uso de los recursos forestales, un panorama general sobre las leyes ambientales y los programas de conservación. Los resultados generales demostraron un alto nivel de conciencia ambiental entre los grupos de agricultores. Aproximadamente el 84% de los agricultores reconoce que el bosque es importante para su sustento y más del 91% manifiesta que si el bosque desapareciera, ello tendría un impacto significativo en el medio ambiente. Además, el presente estudio destaca una notable diferencia en el nivel de dependencia de los eco-servicios forestales entre los diferentes grupos de fincas agrícolas. Considerando que los agricultores a pequeña escala manifestaron que el bosque era fundamental para su subsistencia diaria (por ejemplo leña, construcción y alimentación), los agricultores de mediano y gran porte, por el contrario, consideraron que el principal valor del bosque era cultural y recreativo. Con respecto a las leyes ambientales y programas de conservación, un gran porcentaje de estos agricultores entrevistados expresó su preferencia por el programa de "Valoración y Retribución de los Servicios Ambientales", bajo la Ley 3001/2006" (PES 3001/2006) (73% de los entrevistados) sobre los "Incentivos a la Reforestación" (27% de los entrevistados). El programa alienta la conservación de las tierras forestales mediante el suministro de incentivos económicos a los propietarios de tierras con reservas naturales por encima del porcentaje establecido por la ley (más del 25 por ciento de la superficie de sus fincas agrícolas). Sin embargo, 90% de los agricultores concluyó que, como consecuencia de los altos niveles de corrupción en el país, la implementación de cualquier programa o reglamentación ambiental permanece ineficaz.

A fin de mejorar los resultados obtenidos en la segunda etapa, fue realizado un análisis multi-temporal de los cambios en la cobertura forestal en la región del Bosque Atlántico del Alto Paraná, extendiendo la resolución temporal hasta 17 años, abarcando el período de tiempo entre 1999 y 2016. El estudio no solamente identificó los cambios que han tenido lugar entre los años de referencia, sino que también analizó los impactos que los diferentes regímenes de gestión han tenido sobre la conservación forestal en áreas protegidas. Un gran número de imágenes Landsat, disponibles para todos años de observación, fueron utilizadas para derivar espacialmente las mediciones continuas espectrales-temporales y multi-espectrales. Los resultados descriptos fueron ingresados a un clasificador RF para estimar la cobertura forestal con respecto a cada año de referencia. Los resultados indican que el Bosque Atlántico del Alto Paraná perdió alrededor de 7.500 km2 (casi el 28% de su cobertura original) en un período de 17 años. Además, un aumento en los índices de deforestación fue observado entre los años 2002-2004 (casi cuatro veces más altos que los índices anteriores). Esta tendencia puede ser atribuida a la implementación anunciada de la ley de "deforestación cero" en el año 2004. Conforme a los propietarios entrevistados, los agricultores locales estuvieron conscientes del advenimiento de la ley de deforestación cero y por consiguiente aumentaron sus actividades de deforestación en el período anterior a la implementación efectiva de la ley. Con respecto al impacto de diferentes regímenes de gestión sobre las áreas protegidas, esta tesis revela que cada reserva manejada por la compañía hidroeléctrica ITAIPÚ aumenta su cobertura forestal, mientras que cada reserva administrada por el Gobierno pierde cobertura forestal en alguna medida.

Finalmente, en base a los resultados obtenidos del análisis multi-temporal y a las encuestas de campo, ambos tipos de datos fueron combinados para comprender la manera en que las percepciones de los agricultores con respecto al bosque influencian sus dinámicas a nivel de una finca agrícola. En este sentido, las máscaras forestales producidas para los años 1999 y 2016 tuvieron correlación con las respuestas adquiridas en la encuesta en el terreno utilizando información catastral de cada uno de los agricultores entrevistados. Los resultados generales de este estudio demuestran que las dinámicas forestales a nivel de una finca agrícola son influenciadas por el tipo de finca agrícola (agricultores pequeños, medianos y de gran porte), los antecedentes educativos y la consciencia ambiental. Por ejemplo, un mayor porcentaje de propiedades de pequeños agricultores ha presentado una disminución de la cobertura forestal con relación a las de los demás grupos. A medida que aumenta el tamaño de la finca agrícola, disminuye el porcentaje de fincas que presentan pérdidas en la cobertura forestal. Por otro lado, considerando los antecedentes educativos, se ha observado un mayor porcentaje de fincas con ganancia forestal se encuentran en el grupo de agricultores con mejor educación. Sin embargo, esta tendencia disminuye conforme al tamaño de la propiedad. Los grupos de propietarios de tierras sin ninguna educación no solamente presentaron el menor porcentaje de fincas con aumentos en la cobertura forestal, sino también el mayor porcentaje de propiedad con pérdida en la cobertura forestal. Los agricultores que participaron en los programas de conservación o que han tenido contacto

con entidades ambientales fueron menos propensos a evidenciar pérdida forestal en sus propiedades que los agricultores sin ninguna educación ambiental. En forma general, es importante resaltar que el valor social asignado al bosque es una contribución significativa a la conservación de los recursos naturales.

El presente trabajo ha presentado el primer estudio con respecto a la región del Bosque Atlántico del Alto Paraná en el cual se han combinado datos obtenidos a través de sensores remotos e informaciones a nivel rural a fin de permitir una comprensión incluyente con relación a los cambios ocurridos en la cobertura forestal durante los últimos 17 años. El producto delineado precedentemente conlleva un gran potencial para generar y apoyar políticas ambientales dirigidas a conservar los últimos remanentes del bosque en la eco-región. Esta valiosa información podría servir como un componente efectivo para los programas de conservación, donde la visión de la población rural podría garantizar la sustentabilidad de dichas iniciativas a través del tiempo.

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Abbreviations and Acronyms

ALOS Advanced Land Observing Satellite

ANN Artificial Neural Networks

ASTER ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)

AVHRR Advanced Very High Resolution Radiometer

AVNIR Advanced Visible and Near Infrared Radiometer

BAAPA Paraguayan Upper Parana Forest

CAI Core area index

CATIE Agronomic centre for research and training

CBD Convention on Biological Diversity

COICA Coordinator of Indigenous Communities from the Amazonian Basin

DEM Digital Elevation Model

DETER Real Time Deforestation Detection
DFD German Remote Sensing Data Center
DGEEC National Direction of Census and Statistics

DLR German Aerospace Center ENVISAT Environmental Satellite

EO Earth Observing

ERS European Remote Sensing

ES Ecosystem services
ESA European Space Agency

ETM+ Enhanced Thematic Mapper of Landsat-7

EVI Enhanced Vegetation Index

FAO United Nations Food and Agriculture Organization FFPRI Forest Products Research Institute from Japan

FLEGT law enforcement strategies

FMASK Function mask

FRA Global Forest Resources Assessments of the FAO

FROM- Finer Resolution Observation and Monitoring - Global Land Cover

GLC

GDP Gross Domestic Product
GEF Global Environment Facility
GIS Geographic information systems

GLC Global Land Cover

GLCM Grey Level Co-ocurrence Matrix

Gov Governmental entity

GV Green vegetation

НН Horizontal transmitting, horizontal receiving HV Horizontal transmitting, vertical receiving

На Hectare

IGBP International Geosphere-Biosphere Programme

INFONA Forest National Institute

INPE National institute for space research

ΙT ITAIPU Hydroelectric

IUCN International Union for Conservation of Nature

JERS Japan Earth Resources Satellite

JRC Joint Research Centre of the European Comission

Km Kilometre

LIDAR Light Detection And Ranging (remote sensing technology)

Land Use and Land Cover Change LULCC

Μ Meter

MAG Ministry of Agriculture of Paraguay

Mha Millions of hectares

Mm Millimetre

MERIS Medium Resolution Imaging Spectrometer

MESH Real mesh size

MFRACT Mean fractal dimension

MDGs The Millennium Development Goals

MODIS Moderate Resolution Imaging Spectroradiometer

MPAR Mean Perimeter - Area Ratio

MPE Mean patch edge **MPS** Mean patch size

MSAVI Modified Soil Adjusted Vegetation Index

MSI Mean shape index

MSS Multi Spectral Scanner sensor

NASA National Aeronautics and Space Administration

NDVI Normalised Difference Vegetation Index

NGO Non-Governmental Organisation NGV Nonphotosynthetic vegetation

NOAA National Oceanic and Atmospheric Administration

NΡ Number of patches

OLI (OLI) and Thermal Infrared Sensor

PAL Pathfinder Land (dataset originating from the AVHRR sensor)

PALSAR Phased Array Type L-band Synthetic Aperture Radar

Paraguay land use PARLU

Proximity buffer distance PB

PES Payment for Ecosystem Services

PC Principal component

PCA Principal component analysis

PGY Paraguayan guaranies
PRODES Basin Restoration Program

PROX Proximity index
Prv Privately own

PSSD Patch Size Standard Deviation

REDD+ Reducing Emissions from Deforestation and forest Degradation + enhancing

forest carbon stocks

Redf Agroforestry network from Chaco Argentina

RF Random Forests

TA Total area
TE Total edge
TCA Total core area

SAR Synthetic Aperture Radar
SAVI Soil Adjusted Vegetation Index
SEAM National Ministry of Environment

SIAC Environmental servicie center of Colombia

SIR Shuttle Imaging Radar
SNC National cadastral service

SPOT Satellite Pour l'Observation de la Terre SPSS Statistical *Package* for the Social Sciences

SRTM Shuttle Radar Topography Mission

SVM Support Vector Machine

TC Tasselled cap

TM Thematic Mapper of Landsat-5 satellite

TREES Tropical Resources and Environment monitoring by Satellites

UBA University of Buenos Aires
UMD University of Maryland

UN United Nations

UNA National University of Asuncion

UNFCCC United Nations Framework Convention on Climate Change

UNFF UN Forum on Forests UNGC UN Global Compact

USAID The United States Agency for International Development

USD United States Dollar

USGS United States Geological Survey VCF Vegetation Continuous Fields

WWF World Wildlife Found

CHAPTER 1

1 Introduction

Tropical and subtropical forest ecosystems around the world are immensely important for regulating climate, preserving biological diversity, and balancing biochemical cycles, leading to rising concerns regarding their future and conservation (Mittimer et al., 1999; FAO, 2010; Houghton, 2012; WWF, 2013). Twenty-five percent of the carbon in the terrestrial biosphere is contained in tropical forest ecosystems, accounting for more than 33 percent of net carbon biomass production (Mittimer et al., 1999; FAO, 2007; Joseph, Murthy and Thomas, 2010; WWF, 2013). The described ecosystems are further acknowledged as key components in the water cycle (Fleytas, 2007), and they also serve as a biodiversity reservoir (Fleytas, 2007; Macedo and Cartes, 2003). Although they represent less than 7 percent of the earth's total land surface, these rich biodiverse areas contain more than half of the globe's animal and plant species (Joseph, Murthy and Thomas 2010; WWF, 2013). As a result of these vital ecosystem functions, 18 of the world's 25 biodiversity hotspots are tropical forest (Carlson and Mitchell, 2011; WWF, 2008). However, continuous threats from deforestation and degradation processes have destroyed their integrity (FAO, 2007; WWF, 2013; Hansen et al. 2013). Recent studies conducted at a global scale have estimated deforestation rates as being up to 13 million ha per year, representing almost 17 percent of human greenhouse gas emissions (FAO, 2010). Therefore, attempts have been made to address deforestation as a global threat to society. Within the United Nations Framework Convention on Climate Change (UNFCC), deforestation and degradation issues were set as a central topic for the developing post-Kyoto Protocol policy process. For example, evolving mechanisms for Reducing Emissions from Deforestation and Degradation (REDD+) are considered to be crucial instruments within the ongoing climate change initiatives (FAO, 2010). Although several strategies have been put in place to halt tropical deforestation, it still remains a crucial concern. For example, between the years 1999 and 2005, almost 7% of the forest cover in Latin America was lost (over 69 million ha). Reports from the WWF (World Wildlife Fund) have acknowledged Paraguay (by the year 2004) as the country with the second highest deforestation rate worldwide (WWF, 2013). The continuous advance of the agricultural frontier has led to the disappearance of almost 90% of the forest cover in the eastern region of the country, where the Atlantic Forest is situated.

The Atlantic Forest eco-region in South America has been acknowledged as one of the 25 most important biodiversity hotspots areas in the world (Myers et al. 2000; Fleytas, 2007; Hutchison and Aquino, 2011; Conservation International, 2013). The ecoregion holds a vast variety of species, including around 20,000 plant species and almost 13,000 fish vertebrate species (Fleytas, 2007). Additionally, its importance not only rest on the richness of its biodiversity but also in the fact that one of the largest acquirers in the world (Guarani Aquifer with a total area of 1.200.000 km²) is located below the eco-region (Fragano and Clay, 2003). However, less than 30 percent of its original vegetative cover

remains (Hutchison and Aquino, 2011). Over 1.1 billion habitants are situated within its boundaries, including rural and urban areas, and over one-quarter of the population are considered to be living in extreme poverty. Whenever regions of high biodiversity converge with a high population density of people living in extreme poverty, this indicates that social and economic factors might be creating the perfect scenario for rapid loss of natural areas. In this context, there is a crucial need to conduct comprehensive studies in the Atlantic Forest region to understand the forest dynamics and biodiversity over the last decades, to recognize the patterns of change and to identify the reasons behind these changes. Over the last years, earth observation and remote sensing approaches have become essential tools for monitoring programs (FAO, 2010; Strand et al., 2007). The application of precise multi-temporal information to detect land use/cover dynamics from global to local scales has supported the design and creation of conservation strategies addressed to protect the natural resources. A better understanding of drivers and patterns of change would be a relevant tool to anticipate future threats and develop novel policies addressed specifically to mitigate the degradation of natural resources.

1.1 The need for regional studies in the Atlantic Forest of Paraguay

Between the years 1945 and 1975, the Eastern Region of Paraguay was the subject of intense wood harvesting activities that transformed dense forest into isolated patches, endangering the forest continuity and its biodiversity. Most deforestation activities were focused in the areas of Concepcion, Upper Parana, Caaguazú, Amambay, and Itapúa (departments of the Atlantic Forest ecoregion in Paraguay). In the early 1950s, deforestation activities increased drastically as a direct consequence of agricultural expansion, urbanization, and especially colonization programs (Fleytas, 2007). From 1954 until 1989, during the government regime of General Alfredo Stroessner, forests were identified as unproductive lands that did not further the government's agricultural goals (such as the development of monoculture plantations). Moreover, forest areas without proper management/utilization were promoted by the state to decentralize the population in the western region of country and incentivize the colonization of rural areas. Governmental programs were established with no consensus from the local population or indigenous communities in the relevant regions (Fleytas, 2007). By the year 1963, the National Agrarian Statute established the right to exploit forest lands (tagged as wastelands) for agricultural purposes. Following the implementation of colonization and agricultural expansion programs, deforestation rates increased up to 2000 km²/year, turning Paraguay into one of the countries with the largest losses of forest surfaces on an international level (Macedo and Cartes, 2003). Deforestation activities where mainly attributed to large compact clearings for use in soybean production. However, by the year 2004, the Paraguayan government implemented the "Forest Conversion Moratorium" as a means to safeguard the last remnants of the forest, and to restore as much forest as possible. The Forest Conversion Moratorium prohibited the conversion of forest lands into other types of land use and it was enforced by the "Zero Deforestation Law (2524/04)". Recent studies conducted by the Forest Engineering faculty of the National University of Asuncion-Paraguay and the Forest Products Research Institute from Japan (FFPRI),

spanning the years 1999 to 2011, identified a 10% decrease in deforestation rate compared with the 2002 level (Caldas et al., 2013).

As described previously, the Atlantic Forest in Paraguay (also known as BAAPA) has changed drastically over the last decades. The continuous pressures exerted by both external and internal factors have influenced its dynamics until the point that only few small forest patches remain. Studies examining remote sensing data of the Paraguayan ecoregion were able to provide a systematic analysis of the changes in forest cover and size based on Landsat imagery obtained for the years 1970 and 2001 (Huang et al., 2007, 2009). However, these studies focused mainly on the scale of deforestation and not on detailed examinations of the forest landscape, fragmentation level, and its influence upon biodiversity conservation. To our knowledge, no attempt has been made to understand the principal causes and drivers of the change or the actual impact of the current conservation initiatives and policies. Additionally, no ground information has been included to capture how local circumstances (such as the use of the forest, farm types, local perception on natural resources) affects the dynamics of the forest itself. The time frame considered in local studies published in international scientific journals only extends to the year 2001, leaving subsequent years without any proper environmental scientific data.

Over the last years, several national and international institutions such as the Food and Agriculture Organization (FAO), the Forest National Institute (INFONA), and the United States Agency for International Development (USAID) (Catterson and Fragano, 2004) have applied optical data on a yearly basis to assess deforestation activities in the BAAPA region. Regardless of the existence of numerous environmental reports, most results of spatial analyses are kept in clusters and are frequently not accessible. Therefore, because of the continuous changes affecting the BAAPA forest, there is currently a need for reliable, precise, and more up-to-date information. It is important for further scientific studies to build an understanding of BAAPA forest dynamics, tackle relevant issues such as the influence of socio-economic factors on the forest, broaden multi-temporal analyses, and strengthen our overview of the current status of the region's land cover.

1.2 Remote sensing data and forest cover mapping: from global to local studies

Numerous studies have applied remote sensing data to obtain global land cover products at medium and low spatial resolutions, ranging from 30 m to 4 km (Hansen et al., 2002, 2008; Mayaux et al., 2005; Fagan and Defries, 2009). One of the first land cover maps created at a continental level was generated by Tucker et al. (1985) and Townshend (1987), and it incorporated satellite imagery from the Advanced Very High Resolution Radiometer (AVHRR) sensor with a spatial resolution of 4 km. Following this effort and with funding from the International Geosphere – Biosphere Program (IGBP), Loveland et al. (2000) delivered the first pan-continental cartography differentiating forest covers based their leaf type (1 km resolution) for the reference years 1992–93 and 1981–94. Subsequently, when MODIDS data became accessible in the year 2000, a first land cover product was generated in 2002 with a spatial resolution of 1 km (Fried et al., 2002). This was closely followed by the "Global Land Cover 2000" (GLC2000), where multiple forest

classes and densities were identified based on SPOT-4 VEGETATION data (1 km resolution) for the year 2000 (Bartholome and Belward, 2005). The product was downscaled to 300 m resolution under the GLOBECOVER initiative that applied a Medium Resolution Imaging Spectrometer (MERIS) sensor for the years 2005-2006 (Arino et al., 2007). Consequently, further efforts were used to generate a global product specifically orientated to forest cover detection. For example, Hansen et al. (2004) applied MODIS data to produce a global subpixel tree cover map and Vegetation Continuous Fields (VCF) at a resolution of 500 m. On the other hand, international programs such as the "The Global Forest Resource Assessment" (FRA) 2000 and TREES focused on the dynamics of a humid tropical forest at a global level using NOAA-AVHRR data with a spatial resolution of 1 km × 1 km (Mayaux et al., 2005). Whereas the outcomes obtained by FRA 2000 aimed to characterize forest cover and forest cover dynamics at a global scale, the TREES program focused on identifying hotspots of deforestation in humid sub-tropical forest (Mayaux et al., 2005). By the year 2010, the outcomes produced by FRA 2000 were enhanced by the FRA 2010 program, which considered deforestation rates based on a systematic sampling approach developed previously by the program TREE II (FAO 2012). Recent investigations yielded more precise characterization of the forest compared to previous global products by applying higher resolution imagery from sensors such as Landsat (30 m) and ALOS-PALSAR (25 m). Such sensors increased the general accuracy of the products and helped build a better understanding of the changes in forest cover over time. For example, Hansen et al. (2013) generated a global forest cover map with a resolution of 30 m by incorporating Landsat images from 2000 and 2012. Apart from identifying the spatial distribution of forest worldwide, the product quantized global tree cover loss and gains. It identified Cambodia, Paraguay, and Malaysia as the countries with the highest rates of deforestation.

Although such datasets have undoubtedly bettered our understanding of forest distribution and dynamics at the global level, several studies noted large discrepancies in quality between products (Herold, 2008). Grainer (2008), for example, remarked on the relative lack of consistency of deforestation assessments in global data sets. This low reliability can be explained by the following factors: the lack of a standardized definition of a forest and a common statistical design; the variability of data used in the different products; and inconsistency in identifying and dealing with local peculiarities and trends when studies are conducted at a local or regional level. Thus, relevant information that could serve as the focal point for developing environmental laws and policies was neglected. In conclusion, whereas global data sets are highly valuable for policy makers, NGOs, and scientists as a systematic documentation of forest cover change process, their findings do not provide sufficient information to understand patterns of change on other spatial scales.

Because of the limitations described above, a strong need for studies conducted at the regional and national scales existed. Thus, sensors with medium spatial resolution (particularly Landsat with 30 m) and a high temporal scale have largely been implemented over the last decades. In terms of deforestation/degradation activities in the tropics, the following regions have been the most studied around the globe: the Amazon Forest in Brazil (Souza, 2013; Wang, Qi and Cochrane, 2005), the Democratic Republic of Congo (Duveiller, Defourny, Desclée and Mayaux, 2008; Laporte and Lin, 2001; Potapov et al.,

2012), and Indonesia (Schoen, 2004). Generally, the applied approaches were chosen according to the type of both the forest and the disturbance. For example, unsupervised isodata clustering, supervised classification (Achard et al. 2012), object-based analysis (Nascimiento Jr. et al 2012; Huth et al. 2012; Vo et al. 2013), decision-tree algorithms (Potapov et al., 2012), wall-to-wall change mapping (Aide et al. 2012; Hansen et al. 2013), or the combination of these methods have all been implemented to assess large, medium, and small-scale forests. With a special focus on the Atlantic Forest in Paraguay, one of the few scientific studies conducted on a regional scale applied a supervised classification approach based on Landsat images to assess changes in forest cover using two points in time between 1970 and 2001 (Huang et al., 2007, 2009). The study estimated changes in the BAAPA forest by applying a bi-temporal analysis focusing on deforestation patterns, quantification of forest loss, and efficiency of protected areas.

More recently, additional parameters such as species types and structural properties of plants were integrated into the studies based on very high resolution data and hyper spectral measurements (Kalacska and Sanchez-Azofeifa, 2008). In addition to implementation of very high resolution images, a further trend has emerged over the last few years. The use of radar data has become the most prominent asset in monitoring frequently-overcast regions in the tropics, especially in countries such as Brazil, Colombia, and Peru. The capacity of radar sensors to penetrate clouds and provide very high resolution data allowed other studies to combine optical data and radar measurements to monitor forest changes in tropical regions where the presence of clouds inhibits the acquisition of clear observations throughout the year (Achard and Hansen, 2012; Belward, Achard, Hansen and Arino, 2012).

Overall, while remote sensing data has been intensively used over the years for mapping forest dynamics, the studies conducted remain clustered in regions such as the Amazon, Congo, or Asia. Regions equally threatened continue to be understudied despite their ecological importance, such as the Atlantic Forest. Further research should be addressed in such eco-regions to understand the complexity concealed behind its dynamics.

1.3 Research focus and objectives

The BAAPA forest has experienced uninterrupted pressure from anthropological activities over the last decades. The expansion of agricultural lands along with fragile environmental regulations have compromised its continuity and vast biodiversity. The level of degradation in the eco-region was so severe that by the year 2004, international agencies and well-known research institutions (USAID, FAO and WWF) characterized the BAAPA as one of the world's most deforested areas. However, most research focuses on the Amazon forest, leaving similar and equally important regions without any proper scientific environmental data. The BAAPA provides an exceptional research opportunity to understand how forest cover has evolved over the last decade, but this has been neglected entirely in previous studies. Several environmental regulations and programs have been put into place in the region in an attempt to reverse the damage caused in the past, but so far, no research has been conducted to analyze the impact of such regulations. The use of remote sensing data is a key tool to monitor changes in the forest

and the vast number of sensors available provides the potential for detailed analysis. However, regional forest change patterns and the perception of land owners towards their natural resources remain understudied. Within this context, five main research objectives were defined in this research:

Objective 1: "Provide a comprehensive review of all studies that have applied earth observation data to assess forest disturbance in Latin America"

Over the past 40 years, numerous studies have integrated satellite data to analyze and monitor losses in the forest cover, study patterns, and comprehend drivers associated with forest land conversion. However, review studies that analyze such information for Latin America have not been conducted. Therefore, this thesis conducts an exhaustive review of remote sensing-based studies in Latin America, with a focus on tropical forest dynamics. This research aims to delineate which methods have been implemented and which sensors have been employed at which spatial and temporal resolution, as well as distribution of the studies, variables employed to assess the accuracy and validation of results, current challenges and research gaps, and an outline of future trends. A case study for the whole Paraguayan region is also included, highlighting the main results, constraints, and methods used.

Objective 2: "Detect and characterize changes in the Paraguayan Atlantic Forest ecoregion between 2003 and 2013"

This objective focuses on filling the current research gap on the status of the BAAPA forest. A detailed analysis is conducted to understand how the forest has behaved over a period of 10 years (considering the date of the last scientific study conducted for the region), evaluate the effectiveness of current protection for endangered areas, assess the level of fragmentation, and analyze the connectivity of forest patches for biodiversity conservation. Forest characterization is performed using Landsat imagery implementing a supervised statistical thresholding approach for each reference year. Additionally, the behavior of conservation zones was analyzed, to estimate the pressure exerted by anthropogenic activities in protected areas. Finally, a series of well-known statistical metrics considered for landscape analysis are applied to estimate the level of forest fragmentation. This information is relevant for identifying potential biodiversity corridors between forest priority areas necessary for preserving the forest's biodiversity.

Objective 3: "Assess how farmers in the BAAPA perceive and benefit from the services provided by the forest and understand their influence on forest conservation"

To understand the reasons behind the changes in forest cover, a household survey focusing on land owners whose properties contain forest is conducted in the BAAPA region. To meet this objective, an extensive questionnaire focusing on socioeconomic factors containing relevant information regarding socio-economic aspects of each farmer was developed. The survey was conducted for a period of one month in households

spread over a total area of 12,500 km². The thesis provides a comprehensive understanding of the type of farmer, his or her educational background, usage of services derived from the forest, perception towards conservation programs and current threats facing the BAAPA. The focus of this objective is to identify how farmers perceive the forest and what is their level of dependency on forest services of different farm types (small, medium, and large).

Objective 4: "Generate the first multi-temporal analysis of changes in the BAAPA forest between the years 1999 and 2016"

The few studies previously conducted over the BAAPA region were based solely on bitemporal analysis, comparing two forest masks to quantify forest loss and identify deforestation patterns. In the context of this PhD thesis, the first multi-temporal analysis of the BAAPA region is performed comprehending a time frame of 17 years, between 1999 and 2016. Additionally, this research examines how environmental policies aimed at halting deforestation activities impact the dynamics of the forest. Finally, an assessment of long-term differences in forest dynamics in protected areas of varying ownership is conducted. To approach this objective, a multi-temporal analysis was developed based on a dense stack of Landsat imagery applying continuous spectral-temporal metrics and vegetation indices. A forest and non-forest map is produced for every reference year, applying a semi-automatic classification approach.

Objective 5: "Analyse how land owners' perception of the forest influences its dynamics at the farm level"

This research aims to comprehend how farmers' educational background has an effect on forest cover change, how deforestation frequency varies with farm type, how the level of dependency on forest service's influences the dynamics of the forest, and what is the impact of farmers' participation on environmentally-orientated programs on forest conservation. Based on a novel, approach results obtained from the multi-temporal analysis are combined with the main outcomes of the household survey. Forest cover masks obtained for the years 1999 and 2016 are correlated with cadastral data from each of the farms where the interviews are conducted. Changes in the forest cover of each farm are assessed based on bi-temporal change detection analysis.

1.4 Thesis structure

This dissertation consists of seven chapters. In chapter one, a short introduction of the Atlantic Forest is presented, showing a review of the history behind deforestation activities in the region. Additionally, this section provides an overview of previous land cover studies, outlines the motivation and objectives of this research, and finally describes the general structure of the thesis. In chapter two, a broad characterization of the study area is presented that encompasses the most relevant of both environmental and socio-economic aspects. The principal body of the thesis is presented in chapters three to seven. Of these,

chapters three to six are introduced in the form of induvial articles already published in peer-reviewed scientific journals

Chapter three focuses on the revision of remote sensing studies that have used remote sensing data to assess forest cover dynamics in Latin America. The study examines methods and sensors applied, which temporal and spatial scale was implemented, distribution of the studies, validation approaches, research gaps, and future trends. This research is essential to understanding the current research status and main findings at a continental and regional scale. Findings from this study were used as the basis for data and method selection in subsequent applications. The outcomes of this chapter were published in the following journal article:

Da Ponte, Emmanuel and Fleckenstein, Martina and Leinenkugel, Patrick and Parker, Amanda and Oppelt, Natascha and Kuenzer, Claudia (2015) Tropical forest cover dynamics for Latin America using Earth observation data: a review covering the continental, regional, and local scale. International Journal of Remote Sensing, 36 (12), pp. 3196-3242. DOI: 10.1080/01431161.2015.1058539ISSN0143-1161

Chapter four fills the research gaps identified in chapter three by providing a characterization of deforestation and fragmentation in the Paraguay Atlantic Forest based on Landsat images acquired in 2003 and 2013. The study examines the spatial impact of forest loss, focusing on quantification of the total area deforested, patterns of deforestation, effectiveness of the protection for endangered areas, and measurement of the landscape fragmentation level and its impact upon biodiversity conservation. The research described in this chapter was published in the following journal article:

Da Ponte, Emmanuel and Roch, Marthe and Dech, Stefan and Kuenzer, Claudia (2016) Paraguay's Atlantic Forest cover loss e Satellite-based change detection and fragmentation analysis between 2003 and 2013. Applied Geography, 79, pp. 37-49. Elsevier. DOI: http://dx.doi.org/10.1016/j.apgeog.2016.12.005 ISBN 0143-6228 ISSN 0143-6228

Chapter five delineates the perception of forest owners towards ecosystem services provided by the BAAPA. Based on a comprehensive field survey conducted in January 2016, the research identifies main farmer types, their educational background, and their perception of environmental laws and conservation programs. The investigation also emphasizes the level of dependency of forest products/services by different farm groups and discusses the threats and future challenges in the region. This information is relevant to understand the level at which forest land owners have an influence on forest conservation in the BAAPA. The results of this research was published as follows:

Da Ponte, Emmanuel and Kuenzer, Claudia and Parker, Amanda and Rodas, Oscar and Oppelt, Natascha and Fleckenstein, Martina (2017) Forest cover loss in Paraguay and perception of ecosystem services: A case study of the Upper Parana Forest. Ecosystem Services, 24, pp. 200-212. Elsevier. DOI: http://dx.doi.org/10.1016/j.ecoser.2017.03.009 ISBN 2212-0416 ISSN 2212-0416

Chapter six, spatial patterns of detected forest loss, are further investigated by performing the first multi-temporal analysis in the region spanning the study period between 1999 and 2016. Farmers' influence over the dynamics of the forest was assessed by combining earth observation data, and the main outcomes obtained from the household survey were already presented in chapter five. The results of this investigation were published as follows:

Da Ponte, Emmanuel and Mack, Benjamin and Wohlfart, Christian and Rodas, Oscar and Fleckenstein, Martina and Oppelt, Natascha and Dech, Stefan and Kuenzer, Claudia (2017) Assessing Forest Cover Dynamics and Forest Perception in the Atlantic Forest of Paraguay, Combining Remote Sensing and Household Level Data. Forests, 8 (10), pp. 1-21. MDPI. DOI: 10.3390/f8100389 ISSN 1999-4907 (http://www.mdpi.com/1999-4907/8/10/389)

Finally, chapter seven presents a summary of the results and conclusions from chapters 3 to 6. This chapter additionally includes future research challenges and opportunities.

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CHAPTER 2

2 Key characteristics of the Atlantic Forest in Paraguay

The Atlantic Forest ecoregion in South America has been acknowledged as one of the 25 most important hotspots for biodiversity conversation in the world. However, less than 30 percent of its original vegetative cover remains. In this area, more than 60 percent of all terrestrial species of the planet are located. In the following chapter, the principal characteristics of the Atlantic Forest ecoregion in Paraguay such as climate, biodiversity, socio-economic characteristics, and conservation initiatives are delineated. The main characteristics of deforestation drivers have been deliberately omitted in this review, since these features will be discussed in chapter's four to seven.

2.1 The Atlantic Forest ecoregion: a general overview

The Atlantic Forest in South America is a tri-national ecoregion whose boundaries stretch along the Atlantic coast in Brazil, passing through the Eastern region of Paraguay and encompassing the northeastern share of Misiones in Argentina (Fleytas, 2007) (see Figure 2-1). Within Brazilian coast two of the main Atlantic Forest sub-ecoregions known as "Coastal Atlantic Forest" are located. These make up about 20 percent of the region, screeching over a narrow strip for about 50 - 100 km long (Fleytas, 2007). The second largest sub-ecoregion in the Atlantic Forest has been identified as "Upper Parana Atlantic Forest" which extends across the southern region of Brazil, eastern Paraguay and northern Argentina. The sub-ecoregion has diameter of 500 to 600 km and lies up to 2,000 meters above sea level. Due to the large variation in altitude, three vegetation types can be identified in the Atlantic Forest: lowland forest, high-altitude grasslands, and mountainous forest (Conservation International, 2013). Even though only a small share of its original cover remains, it's still considered as one of the most diverse tropical ecosystems on earth, second only to the Amazon region. The high levels of biodiversity and endemism in the ecoregion are a consequence of long floristic isolation from the main rainforest blocks in South America such as woodlands and savannas. Due to its critical status, the Atlantic Forest has been identified as a hotspot for biodiversity conservation by the WWF Global 200 Project and the International Union for Conservation of Nature (IUCN, 2013). Studies such as Conservation International (2013) have identified over 20,000 plants in the ecoregion, of which 40 % are endemic and cannot be found anywhere else in the world. Many of these carry high economic or social value. For instance, when considering levels of endemism among tree species, the Brazilian-wood (Caesalpinia echinata) and Brazilian rosewood (Dalbergia nigra) are known to be highly valuable for the wood industry. Nevertheless, due to continuous exploitation, the frequency of the species has decreased considerably and not many specicemen can still be found today.

Similar to the tree species above, the paratecoma peroba is considered to be close to extinction in the region. Furthermore, over 900 different bird species were identified in the area, of which 15% are found solely in the ecoregion. Similar to the three species above, several bird species are considered endangered and close to disappearance (e.g. redbillow curassow (Crax blumenbachii), the Brazilian merganser (Mergus octosetaceus), the red-tailed Amazon (Amazona brasiliensis) and the red-browed Amazon (Amazona rhodocorytha)). Within the Atlantic Forest ecoregion, the direct causes of biodiversity loss have been extremely complex, fueled by a long-term history of systems of land tenancy and local, national and international trade agreements. Additionally, over 1.1 billion of habitants are situated in the boundaries of the ecoregion, concerning rural and urban areas, and around one quarter of the population are considered to live in extreme poverty. In addition, a vast number of families still depend on the resources and products provided by the forest for their daily subsistence. When considering the world's hotspots for biodiversity conservation, a convergence of areas and people living in extreme poverty can be noticed, where several social and economic factors create the perfect scenario for the rapid loss of natural areas.

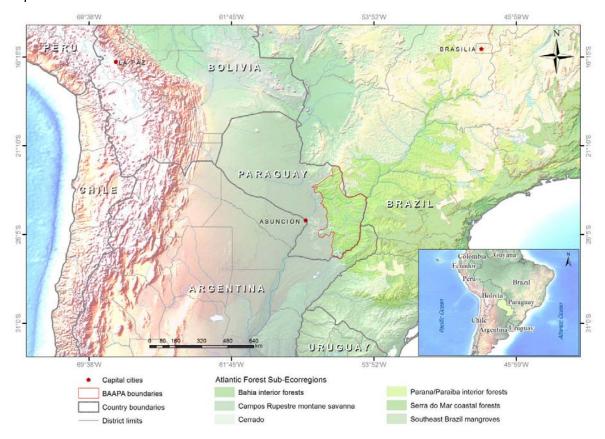


Figure 2-1. Physical unit of the Atlantic Forest ecoregion in Paraguay (BAAPA) (Base layer provided by Natural Earth community and Conservation International (Earth, 2013; International, 2011))

Overall, the Atlantic Forest can be considered one of the most endangered and devastated ecosystems in the world. Even though the Atlantic Forest was originally considered to have had 1 to 1.5 million km2 of sub-humid tropical forest, several newer studies and reports and estimated that less than 8 percent of the original forest cover remains.

2.2 Main characteristics of the Atlantic Forest eco-region in Paraguay

Paraguay is a landlocked country situated in the center of South America and bordering Brazil, Argentina, and Bolivia. The country encompasses a total surface area of 406,700 km², of which over 397,000 km² are land and 9,400 km² water. Paraguay is divided into two main regions by the Paraguavan river. Eastern and Western Paraguav. The Atlantic Forest in Paraguay (also known as the Upper Parana Forest or in Spanish: El Bosque Atlántico del Alto Paraná (BAAPA)) is located in the eastern region of the country and encompasses a total area of 86,000 km2. The ecoregion covers portions of 10 departments (Alto Paraná, Caaguazú, Caazapá, Canindeyú, Concepción, Guairá, Itapúa, Paraguarí and San Pedro) and 114 districts of the country. The Atlantic Forest in Paraguay is naturally divided by two main rivers: The Paraguay River shapes the southwestern border to Argentina, and the Paraná River whittles along the eastern border of Brazil. The high levels of biodiversity of the BAAPA forest are due to three main ecoregions: the Amambay/Montane Forests in the north, the Upper Paraná Forests in the east and the Central Jungle/Central Forests in the south (Fragano and Clay, 2003). The relevance of the BAAPA lies not only in its biological richness, but also in the fact that the area is located above one of the greatest freshwater basins in the world (Guaraní Aquifer). (Bitetti Di, M.S., Placci, G and Alves, 2003). Overall, the eastern region of the country is characterized by the high richness of its physical and geographical features, encompassing a vast number of rivers and grasslands (Bitetti Di, M.S., Placci, G and Alves, 2003)

2.2.1 Topography, climate and biodiversity

The topography of the Eastern region of the country, excluding four varieties of hills (Cordilleras of Amambay, Maracayú, Ybutyruzú and Caaguazú), is mostly flat. The highest peaks in the ecoregion can be found in the department of Guairá at an elevation of 842 m above the sea level. In addition, 65% of the soil in the BAAPA region is both fertile and highly drained, making it very suitable as agricultural and pastoral lands. In regard to meteorological conditions, as can be seen in Figure 2-2 the climate is considered subtropical and humid with a high degree of rainfall, varying from 1300 to 1800 mm per year. However, in the southeastern region of the BAAPA, the climate becomes drier, with a lower frequency of rainfalls, and a magnitude reaching only 400 mm per year. In general, over the eastern region of the country, the mean temperature fluctuates from 21 °C in the northeast to 25 °C in the southeast. The ecology of the BAAPA is mainly dominated by three different forest types: Closed to open broadleaved evergreen or semi-deciduous

forest, closed broadleaved deciduous forest, and open boradleaved deciduous forest (ESA, 2011). Furthermore, a more detailed stratification of the forest can be achieved by classifying the type of forest according to the trees' height: high forest, tree species with high timber value (*Handroanthus heptaphyllus, Cordia trichotoma*) of a length up to 35 m tall; low forest, tree species mainly used for charcoal and fire wood (*Peltophorum dubium, Luehea divaricata*) distributed often in open savannas and flooded areas; riparian forest, located along riverside and flood plain and mainly important due to their ecological function (*Ruprechtia laxifolia, Cupania vernalis*); and savanna forest (*Gochnatia polymorpha, Helietta apiculata*), principally located in small areas and highly valuable for research purposes (Stern, M. and Kernan, 2011).

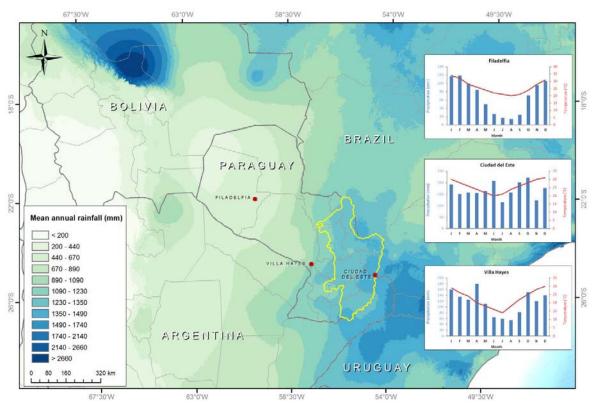


Figure 2-2. Mean annual rainfall based on data and climate diagrams for Filadelfia, Villa Hayes and Ciudad del Este (data source provided by Worldclim)

In regard to the biodiversity of the ecoregion, no significant studies have been conducted to providing a clear understanding of the ecology in the BAAPA. However, research carried out in 2003 by Fragano and Clay managed to provide a general overview of the dominating species. Overall, the research distinguished about 100,000 species of invertebrates, 13,000 vascular plants, 167 mammals, 100 reptiles and 46 amphibians (see Figure 2-3). In addition, the national NGO Guyra paraguay identified over 700 avian species in the BAAPA (Guyra Paraguay, 2004; Fragano and Clay, 2003). A vast number of these species are considered endemic in the Atlantic region or are from Paraguay itself. In particular, the northeastern Amambay Mountains is home to endemic plants such as the

mastic tree (*Schinus wein manniifolia var. hassleri*), six species of custard apple (*Annona*), and the *Callistene hassleri*, *Peltastes stemmadeniiflorus*, and *Rhodacalyx rotundifolius*. Furthermore, the BAAPA is the habitat of large mammals recognized to be threatened or endangered such as the jaguar (*Panthera onca*), the puma (*Felis concolor*) and the ocelot (*Felis pardalis*) (IUCN, 2013). In addition, Fragano and Clay (2003) comment on the high economical value of wild crops such as custard apple, guaya, cassava, papaya, guayava; tree and herb species such as Yvaro (*prunus*), kino (*Rauvolfia sellowi*) and yerba mate (*Ilex paraguariensis*)). In summary, the BAAPA ecoregion contains high levels of biodiversity which need to be studied. As remarked in previous chapters, the lack of information in the area makes the proper implementation of management plans difficult. More research and the easy flow of information is needed to ensure the protection and conservation of the last remnants of the original biodiversity of the region.

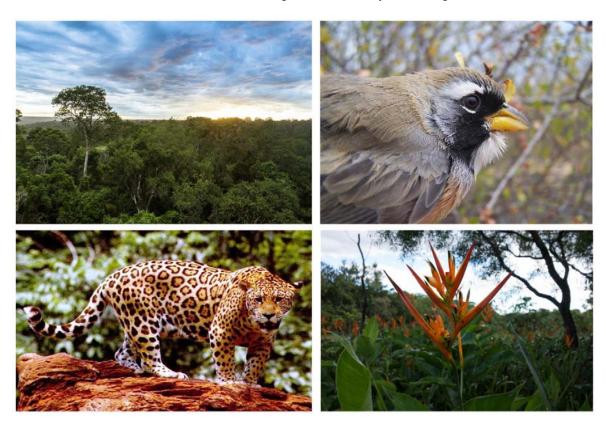


Figure 2-3. BAAPA general impressions in respect to local flora, fauna and landscape.

2.2.2 Demography and socio economic settings

Paraguay has an estimated population of 7 million habitants, and a growth rate of 1.23 percent. As a consequence of its particular geographic conditions, more than 90 percent of the country's population is located in the eastern region. Over 2 million habitants live in the capital (Asunción) and surrounding cities. 50% (around 3,000 inhabitants) of the country population lives within the boundaries of the BAAPA, divided into 65% (over 2,000 million inhabitants) in urban settlements and 35% (almost 1,100 million inhabitants) in rural areas.

The largest cities in the Ecoregion are Ciudad del Este located in the East and Encarnación in the South. Based on estimates from the Landscan Project in 2010 (Oak Ridge National Laboratory, 2013), the population density outside urban areas averages between 5 and 100 residents per km2 (Oak Ridge National Laboratory, 2013). In addition, a census carried out by the Direction of Census and Statistics from Paraguay (DGEEC) identified around 20 indigenous groups in the region, accounting for a total population of 87,000 people (Kernan et al., 2010).

Paraguay, with an average salary of \$3,290 USD per capita per year, is categorized as a low middle income country. In comparison to other Latin American and Caribbean countries, the GINI coefficient indicates an income twice as high, reaching almost \$7,733 USD per capita. The GINI coefficient measures the income distribution of economies. By the year 2010, Paraguay was listed in the last quarter of the Global Ranking, Additionally, as a consequence of the historical system of latifundios, or great landed estates, the country faces extreme difference between wealth and property. The system benefits large farms and estates belonging to a single owner and mainly destined to large scale agrobusiness activities based on monoculture plantations (soy in particular) and cattle ranching. Today, more than 90% of Paraguayan exports are dependent on agricultural and meat products. Furthermore, over the last years, soybean prices have risen drastically in the worlds' market. As a consequence, soy production in the country has become more and more prominent, and today over 4 million ha of the soy crop plantations are located in the BAAPA region. Soy production is nowadays considered one of the main pillars of the economy of the country. However, most of the poor rural communities do not benefit from these high revenues and depend on small scale farming for subsistence. The economy of Paraguay is dominated by the service sector (which represents over 67 percent of GDP and 55 percent of the labor force). In the meantime, the agricultural sector is weakening overall (currently representing around 16% of GDP and 26,5 % of labour force) and the industry sector remains relatively scarce (17% of GDP and 18% labour force).

2.2.3 Environmental governance and conservation initiatives

In general, environmental regulations in Paraguay have not been a priority for politicians in previous years. The implementation of protected areas started rather late in comparison to other countries in Latin America (Cartes, 2003). In the year 1945, the law 9.535 was passed, which put in place "reserve areas" to portions of natural vegetation placed along the national highways. Subsequently, in the year 1963, the Ministry of Defense was designated the first agency responsible for the implementation and administration of public areas. One decade later, in 1973, the responsibility shifted to the Ministry of Agriculture and its National Forest Service. During this period, the Paraguayan Government classified several large remnants of forest as protected areas. However, the legislation and implementation of environmental regulations aimed at forest conservation was not efficient. For instance, the Forest Law 422/73 approved in the same year allowed the conversion of 75 % of forested areas into crop or pastures, whereas only 25 % had to remain as forest. Nevertheless, as a consequence of unclear boundaries in the regulation's text, some land owners divided their lands into several independent farms, clearing up to 75% of their forest area. Consequently, large remnants of forest were shifted

to agricultural crops in the late 80's. A study conducted by Cartes (2003) identified two main factors which contributed to the loss of forest cover and biodiversity in the region: "inequalities in the land tenure" and the long-time perception of forest as "unproductive lands". Between the years 1954 and 1989, during the military dictatorship, forests were seen as an impediment for agricultural production. As a consequence, large areas of forest were cleared to incentive the production of agricultural crops. During this period, there was no clear understanding of the impact that forest clearings would have on ecosystem functions or the ecology in the region. Furthermore, as a consequence of the disproportionally large areas belonging to land tenure systems and the scarce number of public lands available for settlement, the illegal invasions of private lands became frequent, further accelerating the pace of deforestation activities in the BAAPA region.

Over the past years, the environmental consciousness of the country has grown considerably. Today, more than 100 large private landowners have indicated their interest in preserving natural areas and having their areas of the forest classified by the National Ministry of Environment (SEAM) as private reserves, resulting in the setting aside of a total area of 117.000 ha (Kernan et al., 2010). In order to enhance conservation activities in the BAAPA region, the government implemented an initiative based on instituting financial incentives for conservation, sustainable forest management and reforestation. For instance, in the year 2009, the Paraguayan government approved the law 3703 addressed at reducing taxes on reforestation and forest management projects.

On the other hand, in the year 2006, the government passed the law 3.001/06, Payment for Environmental Sciences, to encourage the preservation of natural resources based on direct financial incentives. The law establishes that land owners who preserve more than 25% of their natural forest can receive an environmental certificate for the additional area they protected. These certificates can further be sold to other land owners which are not in complacence with the environmental laws (Kernan et al., 2010). Finally, a further initiative proposed by several environmental actors in the country creates biological corridors between the main forest areas in the ecoregion. Due to the high levels of fragmentation of the BAAPA forest, numerous NGOs together with governmental environmental agencies started an initiative planning to reconnect main protected areas in the country to ensure the conservation of biodiversity. However, until today, the initiative remains in the planning face, due to the complexity of balancing the interests of land owners, politicians, and rural settlements in the ecoregion. (Kernan et al., 2010).

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CHAPTER 3

3 Tropical Forest Cover Dynamics for Latin America using Earth Observation Data: A Review covering the continental, regional, and local scale.

Abstract

Tropical forest cover has varied greatly over the last few decades. The rapid advance of agricultural crops and illegal clearings in natural areas has resulted in the conversion of the majority of the world's forest into desolated patches. Although rates of deforestation have decreased compared to previous years, forest loss still remains a crucial concern. Latest studies conducted on a global scale identified the Latin American continent as one of the regions exhibiting the highest rates of deforestation in world. The dynamics of forest over the past 40 years has attracted numerous remote-sensing-based studies to monitor forest loss, analyze patterns, and understand the drivers of land conversion. This review article provides a comprehensive overview of the remote-sensing-based studies of tropical forest dynamics in Latin America. Following an introduction in respect to global forest mapping products, a general outline of tropical forest ecoregions and drivers of deforestation in Latin America are provided. Subsequently a review and categorization of existing studies is presented, where focus is laid on selected sensors and data analysis methodologies applies. Furthermore a case study for the whole of Paraguay is presented; a region which contains highly diverse ecosystems that have been ravaged as a result of deforestation over the past 40 years. The main results, challenges, and future needs are discussed.

3.1 Introduction

Tropical forest ecosystems around the world are immensely important. Their unquestionable role as a key component of climate regulation, biochemical cycles and biological diversity (Joseph et al., 2011) has led to concerns about their future and protection. The rapid advance of deforestation over recent decades has resulted in the conversion of the majority of the world's tropical forest into isolated patches; endangering not only their continuity but the biodiversity within them. Deforestation has been defined by FAO (2007) as the decrease of the tree canopy below 10 % boundary, due to the conversion of forests to another land use such as farms, ranches, mines or urban sites. Degradation, on the other hand, is described as "the decrease of the canopy cover within the forest, provided that the canopy stays above 10%" (FAO, 2001). Between the years 1990 and 2005, Latin America lost 69 Mha of forest, which is equivalent to 7% of the forest cover of the region. Moreover, this region contains one of the highest numbers of endangered tree species worldwide (FAO, 2007). The latest studies conducted on a global

scale identified Argentina, Paraguay and Brazil as the regions exhibiting the highest rates of deforestation in Latin America (Hansen et al., 2008). Although rates of deforestation have decreased in comparison with previous years, the process still remains an ongoing threat. In order to halt the predation of forest, several strategies, decisions, conventions, and monitoring programs were carried out in an international context. The Millennium Development Goals (MDGs), the UN Convention on Biological Diversity (CBD), the UN Convention To Combat Desertification (UNCCD), UN Forum on Forests (UNFF), UN Global Compact (UNGC), the Global Environment Facility (GEF), the United Nations Framework Convention on Climate Change (UNFCCC) and the mechanism for Reducing Emissions from Deforestation and Degradation (REDD+) are just some of the programs and strategies implemented (GCP, 2013). For instance, the international REDD + negotiations sponsored by the UNFCC have provided methodological guidance on the REDD + program since 2005 through conservation of forest carbon stocks, sustainable forest management, and improvement of the carbon stocks in developing countries (Potapov et al., 2014). Following this, efforts of governmental and non-governmental institutions from Latin America such as the Instituto Nacional de Pesquisas Espaciais (INPE), Universidad Federal de Paraná, Universidad de Buenos Aires (UBA) Sistema de Información Ambiental de Colombia (SIAC), Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), World Wildlife Fund (WWF), Guyra Paraguay, Red Agroforestal Chaco Argentina (Redf), and the Proyungas, have all contributed over the years to monitoring and, where necessary, informing the relevant bodies of illegal deforestation activities (Sesnie et al., 2008; Hutchison and Aquino, 2011). Numerous approaches were developed over the last few decades to understand the current dynamics of forests. The use of Earth Observation (EO) data to monitor forest has supported other methodologies such as ground forest inventories, primarily due to their lower cost and easier accessibility (Fagan and Defries 2009). Satellite-based measurements offer monthly or daily data, unbiased measurements, and the capability to synthesize large amounts of data. For example, the inclusion of remote sensing technologies has more recently become crucial in the support and assessment of environmental programmes such as REDD +; an initiative which endeavors to protect the integrity of remaining forests (Fagan and Defries, 2009; Gebhardt et al., 2014; Hosonuma et al., 2012; Kuenzer et al., 2014; Potapov et al., 2014)

This article provides a comprehensive review of the approaches that have been implemented to study the changes in tropical forests in Latin America using remote sensing technology. The context of the articles reviewed varies in scale from continental to local scale, covering almost all the countries in Latin America. Particular focus was given to the Atlantic Forest in Paraguay, which is considered one of the most threatened rain forests in the world; a highly diverse ecosystem that unfortunately has been ravaged over the past 40 years (Huang et al., 2007, 2009). Considerations are given to variations solely induced by anthropological activities, with particular emphasis on the deforestation and degradation process. The goal of this review article is to assess, analyze, categorize, and discuss all the studies which have integrated EO data to study the dynamics of tropical forests in Latin America, and to present how the studies are distributed, which sensors have been applied at which spatial and temporal resolution, which are the most prominent forest cover change detection techniques and which variables are employed to reach high-

accuracy results. Furthermore, current needs, challenges, research gaps and future trends are discussed.

3.2 Global forest cover mapping approaches.

Remote sensing data has been crucial in numerous studies to obtain especially accurate information about the distribution, state and composition of forests at a global scale (Hansen et al., 2002, 2008; Mayaux et al., 2005; Fagan and Defries, 2009). Tucker et al. (1985) and Townshend (1987) created the first continental map of land cover applying 4 km satellite imagery from the Advanced Very High Resolution Radiometer (AVHRR). Loveland et al. (2000) under the funding of the International Geosphere - Biosphere Program (IGBP) delivered the first pan-continental map at 1.1 km for the period between 1992 and 1993; different from Tucker et al (1985) forest covers were stratified according to their leaf type. A following study was conducted by Hansen et al. (2000) applied the same data to produce a new legend. Additionally, the European Commission's Joint Research Center (JRC) in cooperation with several other institutions, generated the "GLOBAL Land Cover 2000" (GLC2000) product by using Spot - 4 Vegetation data from the year 2000 (Bartholomé and Belward 2005). This product identified multiple forest classes and densities. Moreover, under the initiative of the GLOBCOVER program, a higher resolution land cover map of 300 m was obtained by means of Europe's Medium Resolution Imaging Spectrometer (MERIS) data for 2005-2006, which contains several global classes at global scale (Arino et al., 2007).

Subsequently, additional efforts were put into the global mapping of forest cover, specifically. Hansen et al. (2004) produced a global subpixel tree cover map and Vegetation Continues Field (VCF) using MODIS data, with a spatial resolution of 500m x 500m. Consequently, international programs such as The Global Forest Resources Assessments (FRA) 2000 and TREES were carried out to assess tropical forest cover extent and dynamics with a special focus on the humid tropical forest. Both programs used NOAA-AVHRR data with a spatial resolution of 1 km x 1 km and Landsat Images as sample frames for forest cover characterization. While the FRA programme aimed to identify forest cover and forest cover change globally, the TREES programme targeted deforestation hotspots within humid tropical forest (Mayaux et al., 2005). The results obtained by the FRA 2000 initiative were improved in a following programme named FRA 2010 which considered deforestation hot spots in a preliminary step in order to determine deforestation rates (Pacheco et al. 2014), applying the same systematic sampling methodology developed by TREES II (FAO, 2012).

Later investigations have yielded more accurate data than previous global maps, owing primarily to the increased spatial resolution of imagery such as Landsat and ALOS-PALSAR, which offer a better understanding of forest cover change over time. For instance, a team of researchers from the University of Maryland generated a global forest cover map using Landsat Images with a resolution of 30m (Hansen et al., 2013). The study processed over 65,0000 images using the computing power of the Google Earth Engine in order to quantify forest gain and loss over the entire globe between the years 2000 and 2012 (see Figure 3-1) (Hansen et al. 2013). Similar to Hansen et al. (2013), Gong et al.

(2013) under the Finer Resolution Observation and Monitoring of Global Land Cover (FROM-GLC) project produced the first Global land cover map with a resolution of 30 m based on Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data derived from Landsat satellites. The global data produced in the most recent years (FAO, 2012 and Hansen et al., 2010) has been used extensively by policy makers, NGOs, and scientists as a baseline tool for forest cover estimation around the world (Puyravaud, 2003; Mather, 2005; Mayaux et al., 2005; Achard et al., 2007, 2010).

Table 3-1. Main global land-cover maps derived from remote sensing data 1 km to 25 m spatial resolution. (Adapted from Achard and Hansen 2012)

Title	Author	Domain	Sensor	Resolution	Forest classes assessed
International Geosphere – Biosphere Program (IGBP) Discover	Loveland et al. (1999)	Global	AVHRR	1 km	Evergreen needle leaf forests, evergreen broadleaf forests, deciduous needle leaf forests, deciduous broadleaf forests and mixed forests (IGBP classes).
Global land cover classification 1km spatial resolution. University of Maryland (UMD)	Hansen et al. (2000)	Global	AVHRR	1km	IGBP classes.
TREES	Mayaux et al. (1999) and Eva et al. (1999)	Humid Tropics	AVHRR	1 km	Lowland moist forests, sub- montane forest, montane forest, secondary forests and deciduous forests.
FRA-2000	FAO (2001)	Global	AVHRR	1 km	Tropical rain, moist, deciduous, and dry forests. Subtropical humid and dry forests. Temperate oceanic and continental forests. Boral coniferous forests.
MODIS-land-cover	Friedl et al. (2002)	Global	MODIS-Terra	1 km	IGBP classes.
Global Land Cover (GLC)	Eva et. Al (2004) Mayaux et al. (2004)	Global	SPOT- VEGETATION	1 km	IGBP classes.
Vegetation continuous field (VCF)	Hansen et al. (2003)	Global	MODIS-Terra	500 m	No differentiation among forest classes. Percentage of Forest in every pixel.
GlobCover	Arino et al. (2007)	Global	Envisat MERIS	300 m	IGBP classes.
Forest cover loss (2000- 2012)	Hansen et al. (2013)	Global	Landsat	30 m	Tropical, subtropical, temperate and boreal forests.
Finer resolution observation and monitoring a global land cover: first mapping results with Landsat TM and ETM+ data	Gong et al. (2013)	Global	Landsat	30 m	Broadleaf forests, needle leaf forests, mixed forests and orchards grouped as a single forest class.
New global forest /non forest map	Shimada et al. (2014)	Global (Tropical Forest)	ALOS PALSAR	25 m	No differentiation among forest classes (forest or non-forest).

This information allowed the authors to discuss policies, environmental programmes such as the Payment for Ecosystem Services (PES) under REDD +, and conservation initiatives which aim to promote the protection of the remaining forests. Even though the accuracy of the global products was widely discussed by several authors (Steininger et al., 2001; Sánchez-Cuervo et al., 2012; Kuenzer et al., 2014; Brovelli et al., 2015; Leinenkugel et al., 2015), a general overview of the distribution of forests around the globe can be obtained from these products. An overview of the products is presented in table 2-1.

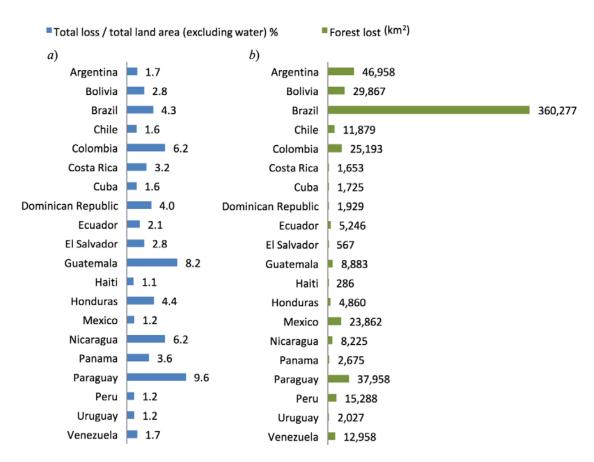


Figure 3-1. (a) Deforestation rates in Latin America based on the total surface of the country (2000–2012). (b) Total area deforested in Latin America between 2000 and 2012 (Hansen et al. 2013).

3.3 Tropical forest cover change in Latin America

According to FAO (2010), taking into account reforestations, the world's entire forest cover area, has an extent of 4.000 Mha – corresponding to almost 31 % of the global land surface. Latin America and the Caribbean possess 22 % of the world's forest, with an approximate area of 860 Mha. A further breakdown of these figures shows that 831.5 ha are located in South America (97%), 22,4 Mha in Central America, and 5,9 Mha in the Caribbean region (Pnuma and Cathalac, 2010). This region is considered one of the most

bio-diverse on the planet: containing 33 % of the world's total mammals, 35% of the reptile species, 41 % of avian species, and 50% of amphibians. The vast majority of forest cover is distributed throughout South America. This includes the Amazonian Basin—the world's largest rain forest, with over 20 types of rainforest ecosystems (Pnuma and Cathalac, 2010). Furthermore, the COICA (Coordinator of Indigenous Communities from the Amazonian Basin) estimates that almost 390 indigenous communities with 2.78 million inhabitants are residing in the area (Cordero, 2011).

Despite high levels of biodiversity and its importance in terms of ecological resources, the humid tropical forest in Latin America still remains under threat. Internal and external drivers which include the constant increase in global population and consumption per capita have direct effects on the forest (Morton et al., 2006). Large multi-national companies, land grabbing, and lack of polices and law enforcement are some of the most prominent drivers in tropical deforestation (Rautner et al., 2013).

3.3.1 Forest ecoregions and drivers of deforestation

The following characterization of tropical forest in Latin America is based on FAO (2001) terrestrial ecoregions; generated predominantly through a collection of data provided by each country. The FAO 2000 product not only provides a general overview of the distribution of the various forest types throughout Latin America (see Figure 3-2) but also a general description of each eco region as well. Moreover, the current work only considers tropical forest ecoregions: tropical rain forests, tropical moist deciduous forest, tropical dry forest, and tropical mountain domains (see Figure 3-2).

The largest ecoregion in Latin America is represented by tropical rain forest, which extends for approximately 37 % of the South American territory and which covers 2 % of Central America (FAO, 2001). The Latin American climate varies considerably from South to North. Whilst annual temperatures range from 20° C to 30° C in the South, further North it only reaches a maximum of 26° C. Rainfall, on the other hand, is more frequent in South America, especially in the Amazonian region, varying from 1500–3000 mm per year. Vegetation is dominated by evergreen and semi-evergreen trees; uneven age forest stands with canopies reaching almost 40–50 m and a dense sub layer containing trees varying from 5 to 25 m tall. Tree species such as: Cedrella spp, Cordia spp. Ceiba spp., Cordia spp. and Swietenia macrophyla are distributed from North to South. In spite of recent efforts from governmental and non-governmental agencies the tropical rain forests remain threatened. Illegal logging, agricultural expansion, mining activities, and clearing for pasture are some of the main deforestation drivers identified (Ichii et al., 2003; Ferraz et al., 2006; Matricardi et al., 2007; Hutchison and Aquino, 2011; Aide et al., 2012).

For instance, Nicaragua, Honduras, and Peten Guatemala have been historically exploited, especially their semi-green and ever-green forests characterized by valuable hard wood species, such as Swietenia macrophyla, Manikara, Haematoxilum and Red Cedar (FAO, 2001). Further to the south, Morton et al. (2006), documented the conversion of 540 000 ha of forest into crop lands during 2001–2004 in the state of Mato Grosso Brazil.

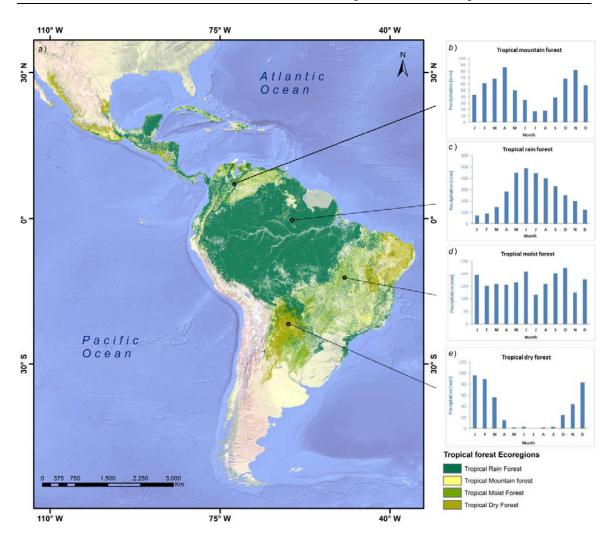


Figure 3-2. (a) Tropical forest cover distribution of Latin America (source: base layers adapted from MERIS GlobCover Project (v.2.2), 2008, FAO FRA 2000 Program (Fao 2001) and Natural Earth (2014)). (b)–(e) Precipitation diagrams for selected locations (Hijmans et al. 2005).

Following the stratification of FAO (2001), tropical moist deciduous forest is the second largest ecoregion in Latin America. The climate here has similar rates of precipitation; however, it differs from that of the rain forest because of longer periods of dryness (FAO, 2001; Olson and Dinerstein, 2002). Evergreen seasonal or semi deciduous forest can be found in drier parts within the outskirts of the Amazonian Basin, Argentina, and Paraguay which even includes tree species up to 30 m tall. Nevertheless, no continuous forest stands along the continent, but indeed in patches along with tree savannas and shrub lands (FAO, 2001). Aspidosperma polyneuron, Balfourodendron riedcianum, Cedrela spp and Eschweilera calyculata are prevalent among tree vegetation. Similar to the ecoregions described above deciduous forests are highly threatened. In South America, several authors identified that in Bolivia's Tierras Bajas region, 20 000 km² of deciduous forest was converted into crop lands from the 1980s to the late 1990s (Steininger et al., 2001; Killeen et al., 2007, 2008). Lack of policies and pressure on food production were identified as the main causes of forest loss during this period.

The FAO ecoregions of mountain forest systems cover over 11% of the Latin American continent (FAO, 2001). Variations in altitude and wind direction within mountainous regions results in diversity in both climate and vegetation. For instance, in the highlands of Mexico broad leaf forest are more frequent, while in the mountains of Guatemala, where precipitation is well below 1000 mm annually, tree species formations including *Pinus pseudostrobus* and *Quercus* dominate. Furthermore, dense tall forests characterized by Oak or *Lauracae* species can be found in Costa Rica and Panama at altitudes ranging from 1600–3500 m. Further south in the central and northern Andean regions, evergreen seasonal forests are spread within altitudes of 3200–3800 m (FAO, 2001). Tree species such as *Alchornea bogotensis*, *Burnellia comocladifolia*, *and Cinchona cuatrecasasii* are common in the Colombian Andes, where the upper montane forest starts at 1800 m and extends up to 3400 m (FAO, 2001).

The vast tree species diversity and the richness of the soil of mountainous systems results in different drivers of deforestation. Besides agro-industrial expansion and the illegal logging of valuable tree species, the forest is under intense pressure by human colonization that goes along with illegal cropping activities (Viña et al., 2004; Armenteras et al., 2006; Etter et al., 2006; Sanchez-Cuervo and Aide, 2013). For example, high deforestation rates were experienced between 2002–2007 in the northern Andes Chaco and Amazon Forest of Colombia; resulting in a loss of 27 952 km² and 1160 km², respectively. This was primarily due to coca plantations (Dávalos et al., 2011). Figure 3-3 depicts examples of different patterns of deforestation resulting from different drivers of forest loss.

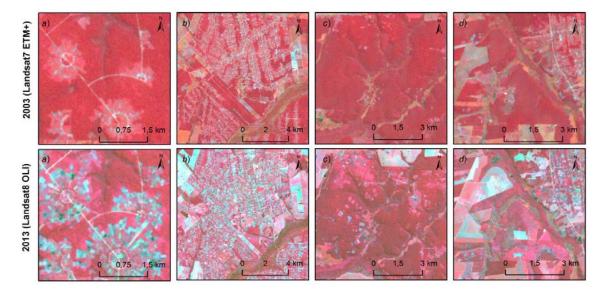


Figure 3-3. Deforestation pattern examples from the Atlantic Forest in Paraguay based on Landsat images from 2003 to 2007. (a) Circle clearing, (b) fishbone clearing, (c) small-scale clearings, and (d) compact clearings. Patterns were based on Roberts et al. (2002), Huang et al. (2009), and Souza and Verburg (2010).

Extended dry and rainy seasons characterize climate conditions of the last ecoregion: tropical dry forests. Short and semi-deciduous forest dominates the main stratus of vegetation formed by leguminous tree species, such as *Mimosa, Caesalpinia,* and *Acacia* (FAO, 2001). Alternatively, the Chaco area of South America is characterized by *Schinopsis, Aspidosperma, Chorisia speciosa, Tabebuia impetiginos, and Ruprechtia triflora* originating from a *xerophilous* forest (FAO, 2001). According to Hansen et al. (2013), in the time from 2000 to 2012, tropical dry forests in Paraguay, Argentina, and the Bolivian Chaco were affected by the highest deforestation rates among tropical forest remnants around the world. This is caused by poor soil conditions and a lack of precipitation coupled with agricultural practices, that have turned many tropical dry forest areas into focus regions for cattle and ranching activities (Killeen et al., 2007; Gasparri and Grau, 2009; Caldas et al., 2013; Mereles and Rodas, 2014).

3.4 Categorization of tropical forest studies employing EO data

For Latin America a total of 137 articles were found that employed remote sensing data to derive tropical forest dynamics. The articles focus on major themes such as global and continental characterization (19), deforestation (88), degradation (17), and fragmentation (13). Figure 3-6c presents the percentage of articles which included either degradation or deforestation processes; studies related to fragmentation were counted as deforestation studies since fragmentation itself is a negative effect of the deforestation process. The publication period of articles investigated covered time frames from 1989 to 2015. Whereas the number of articles related to deforestation and fragmentation commenced to appear in the late 1980s, articles which studied forest degradation did not appear before the late 1990s. For instance, Skole and Tucker (1993), Alves (2002), Lu et al. (2004), Southworth et al. (2004), and Ferraz et al. (2006) assessed deforestation and change patterns over the Brazilian Amazon, focusing on the Rondonia state based on Landsat imagery spanning the years 1978 to 2002. Whilst Souza et al. (2003, 2005), Matricardi et al. (2005), and Wang et al. (2005) analyzed the degraded forest consequence of selected loggings operations in Mato Grosso Brazil using Landsat, SPOT, and IKONOS images covering the years from 1988 to 2006. It is important to remark that degradation studies increased considerably over the years, apparently following the initial stages of development of the REDD program. The constant difficulties experienced in the definition and detection of degraded forests are often discussed in these articles (Asner et al., 2002; Souza et al., 2003, 2005).

3.4.1 Spatial patterns

The focus regions of the articles reviewed are presented in figure 3-4, in which the numbers of investigations are represented for each country. 19 articles were found regarding the global and continental scale. However, most of the studies were carried out at a regional and local level. Almost 84% of the articles were concerned with studies carried out within the South American region.

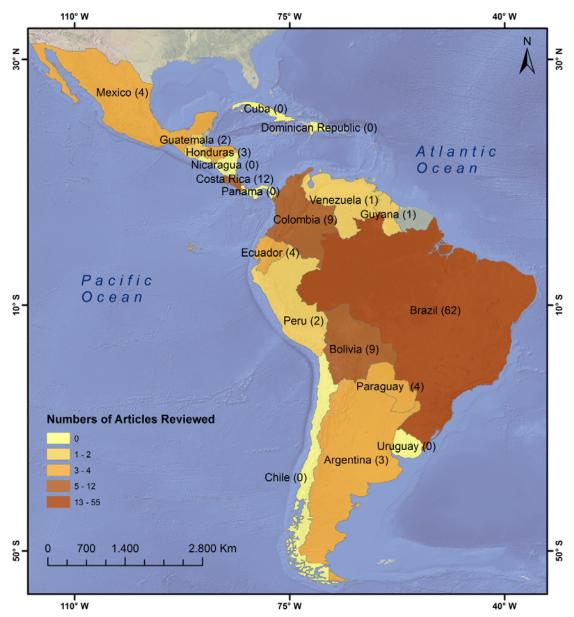


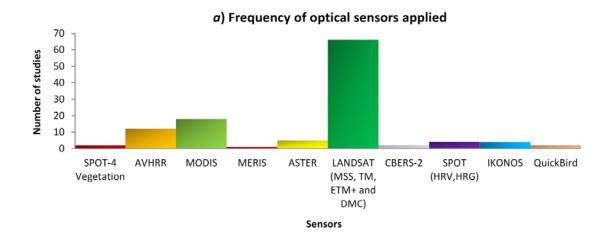
Figure 3-4. Country focus of studies reviewed. The number of studies per country is represented in parentheses (base layer source: Natural Earth 2014).

The majority of studies centered on Brazil with 62 studies focusing on the topics of deforestation, degradation, and fragmentation. Most of these focused on the Brazilian Amazon particularly in Rondonia and Mato Grosso states, where the majority of the disturbances occur. Other regions of South America, on the other hand, were the subject of far fewer studies, even though countries such as Paraguay (4 articles), Argentina (3 Articles), and Bolivia (9 Articles) still demonstrated remarkable rates of deforestation (Hansen et al., 2013). Further north in Central America, Costa Rica is the subject of the majority of studies (12 studies), many of which focus especially on dry forest ecosystems.

Fewer articles were conducted for other countries from the same region such as Mexico (4), Guatemala (2) and Honduras (3). The present review article includes all the countries of Latin America. However, no articles were found for the regions of El Salvador, Panama, Nicaragua, or Cuba. The general trend identified is that the distribution of studies could be related either to the availability of information or the importance given by the scientific community to a specific region. While Costa Rica and the Amazon Basin have been specified as main sources of biodiversity, carbon stocks, and natural resources, other similar regions have not been given the same importance.

3.4.2 Applied sensors used to assess forest dynamics

Overall, 17 different satellite sensors were employed by the 137 studies reviewed. The Landsat sensor appears to be the most frequently used satellite in these studies with 66 articles, followed by MODIS (18 studies), and the Advanced Very high Resolution Radiometer (AVHRR) with 12 studies.



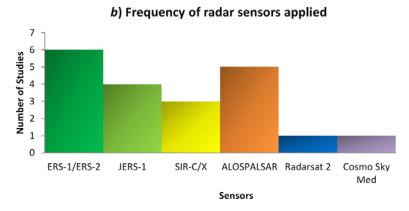


Figure 3-5. (a) Frequency of optical sensors applied in the reviewed studies. (b) Frequency of radar sensors applied in the reviewed studies.

In addition, 20 articles were gathered which implemented other sensors such as SPOT-4 Vegetation, MERIS, ASTER, CBERS, SPOT (HRV, HRG), IKONOS, and QuickBird, which were used less frequently either as a single data set or in conjunction with Landsat imagery. Furthermore 20 studies applied radar sensors such as ERS-1/ERS-2, JERS-1, SIR-C/X, ALOS PALSAR, RADARSAT 2, and COSMO Sky Med to assess deforested areas principally in the Brazilian Amazon (see Figure 3-5b). Since the Amazonian region is characterized by high cloud cover, radar sensors that can penetrate clouds have been favored in many cases. Most of the studies which evaluated the dynamics of forests at a continental or global scale were based on coarse resolution data (MODIS and AVHRR) (DeFries et al. 2000; FAO 2001; Hansen et al. 2003; Clark et al. 2010), whereas only a few recent studies (Hansen et al. 2013 and Shimada et al. 2014) integrated medium resolution data (Landsat, ALOS PALSAR) to assess changes in the forest at a global scale. For example, Clark et al. (2012) produced an annual land cover map to analyze the changes exhibited in the Dry Chaco ecoregion of South America (Paraguay, Argentina, and Bolivia) based on MODIS imagery from 2001 to 2007.

As demonstrated in figure 3-5a, the dominant sensor applied in the majority of the studies is the Landsat sensor including the Multi Spectral Scanner sensor (MSS), the Thematic Mapper sensor (TM), the Enhanced Thematic Mapper (ETM+), and the Operational Land Manager (OLI). The Landsat programme started as a joint initiative of the United States Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA). The sheer volume of data available (since 1972), free acquisition, and the favorable spatial (79m-30m), temporal (16 days), and spectral resolution (0.45 µm-0.90 µm) have turned the Landsat sensors into the main source of information for numerous monitoring program studies (Fagan and Defries, 2009). According to the articles reviewed, Landsat images were mostly applied in studies focusing on the monitoring of deforestation (Van Laake and Sánchez-Azofeifa, 2004; Hayes and Cohen, 2007; Alves et al., 2009), followed by studies focusing on degradation (Almeida-Filho and Shimabukuro, 2002; Souza et al., 2005; Matricardi et al., 2005), and fragmentation (Steininger et al., 2001; Hansen et al., 2000; Cayuela et al., 2006). Additionally some studies integrated Landsat imagery with different sensors such as IKONOS, CBERS, ALOS PALSAR, and SPOT in the case of validation, shortage of free-cloud data, or to increment the temporal resolution.

For instance Vollmar et al. (2013) and Ichii (2003) integrated ALOS AVNIR 2 (10 m resolution) and AVHRR (1km) images to perform multi-temporal cover change analysis, at both regional and continental levels. Both studies intended to fill the missing data from Landsat ETM+. Wang (2005) used IKONOS 1-m pansharpened imagery to validate canopy fractional cover maps resulting from ETM+ Landsat data. Redo (2012) applied Landsat series data in conjunction with Chinese-Brazil Earth Resources Satellite (CBERS-2 and CBERS-2B) in order to correct the residual banding distortion from Landsat 7 data and to map LULCC from 1975–2008 in Tierras Bajas, Bolivia. Other approaches combined active and passive sensors as an alternative in obtaining information *not affected* by atmospheric conditions (Salas et al., 2002; Zaloti et al., 2006; Lu et al., 2011; Gutiérrez-Vélez and DeFries, 2013; Nascimento et al., 2013).

As presented in the figure 2-5b the dominant sensor among the radar studies was ERS-1/ERS-2 with 6 studies, followed by ALOS PALSAR (5 studies), JERS-1 (4 studies), and SIR-C/X with 3 studies. A small number of articles were found for the sensors RADARSAT 2 and COSMO Sky Med, with only one study for each sensor. For instance, Reiche et al. (2013) integrated ALOS PALSAR with Landsat images to monitor tropical and forest degradation in the central part of the South American Republic of Guyana. SAR and optical medium resolution sub-pixel fraction information were analyzed independently and fused with a decision tree classifier to detect tropical deforestation and degradation from 2007 to 2010 (Reiche et al., 2013).

3.4.3 Spatial scale

Throughout the studies reviewed, different spatial scales have been used to assess changes in forests at local, regional, and global level (Figure 3-6a). Whereas local (65%) and regional (26%) scale studies were found to be more frequent, only a few articles assessed forest variations at a global scale (9%). The majority of articles which fall into this category focused on detecting changes only, as is regularly done for tropical forests around the world (Achard et al., 2002, 2001; Hansen et al., 2004, 2008, 2010, 2013; Huang and Friedl, 2014; Shimada et al., 2014). Commonly, this has been done using either wall to wall coverage or statistical sampling strategies from medium (30 m) to coarse resolution (1 km) data designed to evaluate global land cover changes. For instance, a stratified sampling design was implemented by the Forest Resources Assessment (1990) and the Global Resource Assessment 2000 (FAO, 2001), to estimate forest cover and deforestation.

Remote sensing surveys in the context of the Forest Resources Assessments for 1990 and 2000 were based on a stratified design which applied predicted deforestation rates to assign further samples into locations where higher deforestations activities were expected. Hansen et al. (2008) employed a stratified sampling design to estimate deforestations from 2000 to 2005 in the pan-humid tropical forest biome applying MODIS (500 m) imagery based on deforestation data extracted from Landsat images to quantify the deforestation per sample block. Recently Hansen et al. (2013) developed global wall to wall forest coverage with a resolution of 30 m by combining the computing power of the Google Earth Engine and the extensive Landsat data archive to process over 650 000 images in order to estimate forest variations in the tropics from 2000 to 2012. Following this effort, a global forest or non-forest map was generated by Shimada et al. (2014) at a resolution of 25 m using annual data sets from 2007–2010 based on ALOS PALSAR HH and HV polarized L-band data; just like Hansen et al. (2013) the global product aimed at estimating gain and loss of the forest in the tropics.

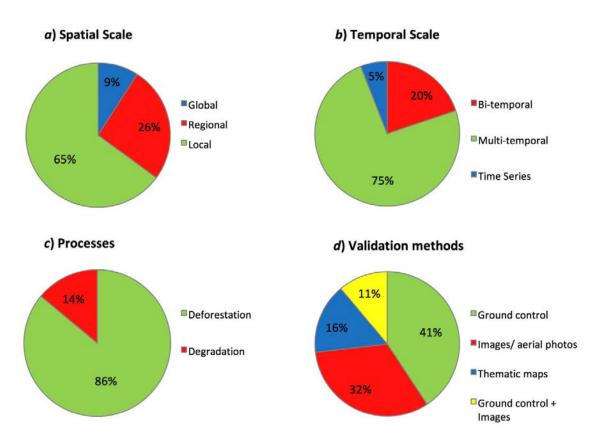


Figure 3-6. (a)-(d) Categorization of the studies with regard to spatial and temporal scales, process, and validation methods.

Assessments performed at regional scale generally monitored coarser changes in forests, variations patterns, and few studies on degradation. Regional studies vary in scale, considering not only broader areas such as the entire Amazon in Brazil (Alves, 2002; Matricardi et al., 2007; Broich et al., 2009) but also the entire country or continent of Latin America (Huang et al., 2007; Killeen et al., 2007; Clark et al., 2012; Sanchez-Cuervo and Aide, 2013; Vollmar et al., 2013; Gebhardt et al., 2014). A good example of forest change detection at a continental level is provided by Aide et al. (2012) which implemented a wall to wall approach to assess deforestation and reforestation rates over the Latin American continent from 2001 to 2010, using coarse resolution MODIS data onboard Aqua and Terra (250 m). Huang et al. (2007); Killeen et al. (2007); Pacheco et al. (2014), and Sanchez-Cuervo and Aide (2013) studied the natural forest cover lost country-wide for Paraguay, Bolivia, Venezuela and Colombia by implementing coarse (MODIS) and medium resolution (Landsat) data spanning the years from 1975 to 2010. More centralized regional assessments were often settled over the Brazlian Amazonian region; especially in the states of Rondonia and Mato Grosso (Alves, 2002; Carreiras and Pereira, 2005; Matricardi et al., 2007; Egler et al., 2013). Principally medium spatial resolution (30m) data was applied to identify the patterns which led to the deprivation of forest.

65 % of the articles reviewed (Figure 3-6a) were carried out at a local level. Similar to regional studies the majority of the articles were carried out within the Brazilian region (75 % of the studies); mainly covering the states of Mato Grosso, Rondonia, Para and Parana (Mantovani and Setzer, 1997; Alves et al., 1999; Ichii et al., 2003; Ferraz et al., 2005; Morton et al., 2006; Zaloti et al., 2006; Brown et al., 2007; Wynne et al., 2007; Souza and Verburg, 2010; Yoshikawa and Sanga-Ngoie, 2011). Local studies were often aiming at understanding the influences of anthropological activities impacting the forest; giving particular attention to agricultural expansion and urbanization (Sierra, 2000; Nagendra et al., 2003; Armenteras et al., 2006; Morton et al., 2006; Alves et al., 2009; Pinto-Ledezma and Centurión, 2010; Dávalos et al., 2011; Rodríguez et al., 2012). Unlike the global and regional scale, local studies more often address forest degradation (Almeida-Filho and Shimabukuro, 2002; Souza et al., 2003, 2005; Souza and Roberts, 2005; Matricardi et al., 2005; Wang et al., 2005; Maurício et al., 2015) (15% of the studies); smaller study areas permit a finer distinction of the disturbances occurring in the forest. In terms of EO data applied, not only the trend of using medium spatial resolution data (Landsat) prevails, but also the majority of the studies which incorporated radar data (Sanden and Hoekman, 1999; Salas et al., 2002; Zaloti et al., 2006; Servello et al., 2010; Liesenberg and Gloaguen, 2012; Rahman and Sumantyo, 2012; Reiche et al., 2013; Nascimento et al., 2013; Azevedo et al., 2014) were carried out at a local level. For instance, Ferraz et al. (2005) used Landsat imagery from 1984 and 2002 to monitor deforested areas in Rondonia state Brazil. Furthermore, deforestation drivers and patterns were assessed by Cayuela (2006) and Armenteras et al. (2011) over the Mexico and Colombian highlands based on Landsat images, covering the years 1975 to 2000 and 1985 to 2005. Schmidt et al. (1997) on the other hand applied ERS-1 data to monitor forest dynamics in the Brazilian Amazon spanning the years 1992 and 1994. More recently, Rahman and Sumantyo (2012) used Shuttle Imaging Radar (SIR - C) and ALOS PALSAR L-band data to quantify deforestation from 1994 to 2004 within the state of Mato Grosso in Brazil.

3.4.4 Temporal scales

As presented in the figure 3-6b, variations in forest cover were studied through bitemporal, multi-temporal, or time series analysis. Studies which encompassed bi-temporal assessments (Saatchi et al., 1997; Alves et al., 1999; Strozzi et al., 1999; Van Laake and Sánchez-Azofeifa, 2004; Shimabukuro et al., 2007; Sesnie et al., 2008; Redo et al., 2009; Mello et al., 2011;) basically estimated changes in the forest by comparing thematic maps previously generated from two satellite images obtained at different points in time. The time span of the majority of the studies varied from 1 to 10 years locally focusing on the Amazonian region and applying medium resolution data (Landsat). Representative examples are the deforestation maps provided by Skole and Tucker, (1993), Alves et al. (1999), and Souza Soler and Verburg (2010) using Landsat images from 1978 to 1988, 1985 to 1995, and 2000 to 2008 to assess deforestation in the state Rondonia, Brazil. Unlike the studies conducted with medium resolution imagery, some studies which included radar data assessed changes in the forest considering monthly spans among the images.

For instance Eva et al. (1995) and Strozzi et al. (1999) applied ERS-1/ERS-2 sensors to discriminate deforested areas in the Amazon region from May to June (1992) and March to April (1996), with a spatial resolution of 26 m. Recently Servello et al. (2010) compared thematic maps obtained from classified RADARSAT-2 polarimetric images acquired in 2008 and 2009 to detect forest conversion in the Para region of Brazil.

Studies which incorporated multi-temporal analysis made up almost 75 % of the studies (see Figure 2-6b). Different from bi-temporal assessments, multi-temporal evaluations cover longer time periods permitting not only the quantification of the changes in the forest cover (Alves and Skole, 1996; Guild et al., 2001; Sanchez-Azofeifa et al., 2001; Salas et al., 2002; Viña et al., 2004; Arroyo-Mora et al., 2005; Cayuela et al., 2006; Etter et al., 2006; Reyes Hernández et al., 2006; Renó et al., 2011; Lima et al., 2012;) but also providing information related to the status of the forest (Almeida-Filho and Shimabukuro, 2002; Souza et al., 2003; Matricardi et al., 2007; Reiche et al., 2013; Maurício et al., 2015). Overall the focus of the studies varied with the three main applications, identification and analyses of deforestation patterns (Cayuela et al., 2006; Lira et al., 2012; Rodríguez et al., 2012; Bianchi and Haig, 2013; Egler et al., 2013; Bonilla-Bedoya et al., 2014), quantification of forest cover increase and decrease (Tucker and Townshend, 2000; Viña et al., 2004; Cayuela et al., 2006; Michalski et al., 2008; Daniel Redo, 2012) and assessment of forest degradation (Souza and Roberts, 2005; Broadbent et al., 2008; Joseph et al., 2011). Similar to the bi-temporal analysis, Landsat imagery was identified as the dominant sensor applied in almost 88 % of the studies, whereas MODIS and radar sensors were used less frequently.

In regards to the time steps used to distinguish changes between images different temporal patterns were observed. For instance, some studies evaluated changes in the forest considering regular time intervals between the images (Hayes and Sader, 2001; Alves et al., 2003; Ferraz et al., 2005; Shimabukuro et al., 2006; Killeen et al., 2007; Michalski et al., 2008; Marsik, 2011a; Beuchle et al., 2012; Lira et al., 2012; Interbacia et al., 2013; Schmitt-Harsh, 2013). For example annual data from MODIS were used by Hansen et al. (2010) to produce global forest change maps covering the years 2000–2005; a quantification of the global gross forest loss was derived from the results. Matricardi et al. (2005) assessed selective logging operations in Mato Grosso Brazil by applying annual time series analysis based on 11-year series of Landsat imagery (30m) from 1992 to 2002. The authors concluded that multi-temporal analysis made it possible not only to estimate the dynamics of deforested and logged areas but also the interaction among them. Michalski et al. (2008) analyzed changes in the landscape of Alta Floresta (Mato Grosso) Brazil based on a biennial sequence of 11 Landsat images from (1984-1998) and (2000-2004) with 30 m resolution in order to compare deforestation rates over the years and to estimate the influence of human intervention. Souza et al. (2013) assessed degradation and deforestation rates in the Brazilian amazon over a period of 10 years using annual Landsat imagery from 2000 to 2010. Results obtained from the study demonstrated a significant decline of annual deforestation rates by 46 % at the end of 2005 and a 20 % increment of annual forest degradation. Based on radar sensors, Filho et al. (2005) evaluated the use of multi-temporal JERS-1 SAR images from 1994, 1995, and 1996 in order to assess deforestation by comparing forest covers obtained for every year.

Shimada et al. (2014) applied PALSAR images to asses annual rates of deforestation at a global level covering 2007 to 2010. Different from regular temporal intervals, other studies applied irregular time intervals between images acquired. Imagery was selected according to the aim of the study including up to 7 time steps over the analysis (Sanchez-azofeifa et al., 2002; Maruyama, and Yamaguchi, 2003; Armenteras et al., 2006; Rodríguez et al., 2012; Bianchi and Haig, 2013; Lu et al., 2013). For example Viña et al. (2004) analyzed deforestation drivers and rates over the Colombian and Ecuadorian Amazon using Landsat images from 1973, 1985, and 1996 thereby comparing the deforestation rates obtained for each of these years. Also Hernández et al. (2006) studied the changes over the forest cover in San Luis Mexico using Landsat data from 1973, 1985, 1990, and 2000 comparing cover maps generated for each year. Sanchez et al. (2012) evaluated the use of multi-temporal ALOS PALSAR data for monitoring the Brazilian Amazon rainforest in Mato Grosso state based on non-continuous monthly imagery acquired from 2009 to 2011.

Real time series analyses are less frequent over the literature reviewed (5%), covering local and regional assessments. In the studies reviewed, change detection assessments were conducted in daily, monthly, and yearly intervals (Aide et al., 2012; Clark et al., 2012; Sanchez-Cuervo and Aide, 2013; Huang and Friedl, 2014). Different from bitemporal analysis, time series can provide a quasi-continuous history of forest disturbances and regeneration processes. In terms of the sensor applied time-series analysis were mostly based on MODIS data with near-daily global coverage. A good example is provided by Clark et al. (2012) who assessed land cover changes (focusing on deforested areas) within all the municipalities in Latin America spanning the years 2001 to 2010. The authors applied 39 MODIS tiles which cover all the study area calculating annual statistics (min, max, mean, standard deviation and range) for three four-month periods, two six-month periods, and monthly intervals throughout the nine-year observation period. Similar to Clark et al. (2012), Sanchez-Cuervo et al. (2012, 2013) conducted a time series analysis to estimate deforestation hot spots and forest recovery in Colombia based on the same MODIS data set and time intervals applied by the previous study thereby incorporating annual statistics for the red, NIR and MIR reflectance bands as well as for the EVI from 2001 to 2010.

3.4.5 Methods employed to map and characterize forest cover

Most approaches for the detection of forest cover dynamics require the initial mapping or characterization of forests based on satellite data acquired at the beginning and the end of the respective period of investigation. Particularly the early studies thereby delineated forest areas based on visual photointerpretation of satellite imagery and geographic information systems (GIS). Such as seen in Skole and Tucker (1993), who characterized the forests in the Brazilian Amazon based on photo interpretation of 210 panchromatic photographic images from the Landsat Thematic Mapper from 1978 and 1988 to assess the quality of forests including deforestation and fragmentation processes. The majority of studies, however, use automated, statistical classification approaches of satellite data to identify and differentiate between individual land cover classes, thereby taking into account their respective spectral properties, textural features, and object characteristics (e.g. size, texture, shape, and context).

Particularly useful for the classification and characterization of forests, and vegetation in general, are the contrasting spectral characteristics of photosynthetic active vegetation in the red (from 0.4 to 0.7 µm) and near-infrared (from 0.7 to 1.1 µm) portion of the spectrum, which forms the basis of nearly every vegetation index. This is why vegetation indices, such as the Normal Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), Modified Soil Adjusted Vegetation Index (MSAVI), Enhanced Vegetation Index (EVI) are, beside the sensor's reflectance bands, the most used input features for classifying forest ecosystems based on optical sensors. But also the outputs of image transforms such as the higher order components of principal component (PC) analyses (Hayes and Sader, 2001; Hartter et al., 2008; Guild et al., 2001, Yoshikawa and Sanga-Ngoie, 2011), or the indices of brightness, greenness, and wetness resulting from a tasselled cap (TC) linear transformation (Crist and Cicone, 1984, Schowengerdt, 1997, Guild et al., 2001, Hayes and Cohen, 2007, Beuchle et al., 2012) are used for improving forest differentiation in advance of change detection studies. Guild et al. (2001), for instance applied a TC prior to the classification of forest and forest change in Rondonia Brazil, based on Landsat 5 and Landsat 4 TM data. The TC thereby not only reduced the spectral redundancy of the visible and infrared bands but also enhanced the contrast between intact forests, cleared areas, and regrowth.

Forest classification approaches based on radar sensors differ by bands and polarization. The most frequent bands encountered over the articles reviewed were the L- band (from 15 to 30 cm), C- band (from 4 to 8 cm), and the X- band (from 2.5 to 4 cm) along with HH (horizontal transmitting, horizontal receiving) and HV (horizontal transmitting, vertical receiving) polarizations. The application of different wavelength bands not only results in different spatial resolutions but also shows effects on the capacity to penetrate the land surface and cloud cover. Higher penetration occurs when the wavelength increases meaning that L-band is less sensitive to cloud cover and can penetrate deeper into the forests than C- or X-band. Generally forest characterization can be performed by any band available in radar. Overall shorter wavelengths (2 to 6 cm) are applied best for detecting tree leaves (canopy). At these lengths the surface scattering from the soil is minimal and volume scattering prevails. Furthermore, shorter wavelengths are more sensitive to small changes in the surface (e.g. regrowth) and offers more information related to vegetation classes (e.g. forest types). Longer wavelengths (10 to 30 cm) on the other hand, are more suitable to differentiate forest from non-forest cover due to their deeper penetration into surfaces and less impact by vegetation covers (Achard and Hansen, 2012). Particularly in radar-based studies, textural characteristics of the land surface, i.e. the spatial variation of image tone as a function of scale, are important features for the identification and characterization of forests (Servello, Kuplich, and Shimabukuro, 2010; Filho et al., 2005; Salas et al., 2002; Shimada et al., 2014; Cutler et al., 2012). Particularly, the well-known occurrence and co-occurrence measures, such as range, mean, variance, homogeneity, dissimilarity, contrast entropy, skewness, second moment, and correlation are among the most often used texture metrics for classifying radar images (Haralick, Shanmugan, and Dinstein, 1973). For instance, Cutler et al. (2012) applied a Grey Level Co-ocurrence Matrix (GLCM) on JERS-1 (L-band) and Landsat images obtained in 1992 and 1995, respectively, to estimate tropical forest biomass in Manaus Brazil.

In this study the texture measures calculated from the GLCM were entropy, energy, correlation, contrast, dissimilarity, homogeneity, second moment and variance which were shown to be very useful to differentiate tropical forest types. Additional popular features used for classifying forests in Latin America were information on topography, such as elevation, azimuth, slope, or solar duration as derived from digital elevation models (DEM), first and foremost originating from the Space Shuttle Radar and Topography Mission (SRTM) (Mantovani and Setzer, 1997; Guild, 2001; Sesnie et al., 2008; Yoshikawa and Sanga-Ngoie, 2011; Egler et al., 2013; Sanchez-Cuervo and Aide, 2013; Souza et al., 2013; Leinenkugel et al., 2014).

Among the reviewed studies 20 % of all studies used unsupervised classification approaches (Tucker and Townshend, 2000; Hayes and Sader, 2001; Ichii et al., 2003; Souza et al., 2003; Wang et al., 2005; Anand, 2006; Huang et al., 2007; Killeen et al., 2007; Michalski et al., 2008; Bianchi and Haig, 2013; Caldas et al., 2013) whereby the Isodata clustering algorithm was more popular than the basic k-means optimisation algorithm. Among the supervised classification approaches (Sánchez-Azofeifa et al., 1999, 2001; Sierra, 2000; Nagendra et al., 2003; Armenteras et al., 2006; Cayuela et al., 2006; Rodríguez et al., 2012; Lu et al., 2013; Panegue-Gálvez et al., 2013) most studies applied the traditional maximum likelihood classification (Alves and Skole, 1996; Sanchez-Azofeifa et al., 2001; Ferraz et al., 2006; Redo, 2012;) followed by conventional non-parametric decision tree algorithms (Roberts et al., 2002; Morton et al., 2006; Marsik et al., 2011a; Reiche et al., 2013; Pacheco et al., 2014; Sun et al., 2014). Later, with increasing popularity of more-sophisticated machine learning algorithms also random forest classifiers (Clark et al., 2010; Aide et al., 2012; Sánchez-Cuervo et al., 2012; Gutiérrez-Vélez and DeFries, 2013) were applied, however, no study on forest cover dynamics for Latin America used modern non-parametric classifiers, such as Support Vector Machines (SVM) or Artificial Neural Networks (ANN).

Beside the traditional pixel-based approaches, object-based classification approaches for forest mapping have been used in Latin-America, however only since the beginning of 2010 (Renó et al., 2011; Beuchle et al., 2012; Nascimento et al., 2013; Vo et al., 2013; Gebhardt et al., 2014). Object-based approaches first aggregate image pixels into spectrally homogenous image objects using an image segmentation algorithm and then classify the individual objects. The generation of meaningful objects makes it possible not only to integrate additional spectral information compared to single pixels, but also to include complementary spatial, textural, and contextual object properties to potentially improve the classification accuracy (Guo et al., 2007, Liu, Xia, 2010). Nascimento et al. (2013), for instance, used criteria, such as the minimum area of objects, as well as contextual information, such as the distance to the coast or to other classes, to improve the mapping of mangrove forests along the Brazilian coastline. Also Gebhardt et al. (2014) used a set of object metrics (minimum, maximum, average, and standard deviation) calculated for multi-temporal NDVI metrics, elevation, slope, and aspect resulting in a total set of more than 200 features per object that were used for classifying forest cover and other land cover classes for the whole of Mexico. Both pixel- and object-based classification assume that forest classes are mutually exclusive with discrete boundaries separating each other.

Forest ecosystems, though, may vary in space in a continuous manner, such can be observed for example in the gradual transition from forests over woodlands to woody grassland, with the consequence that traditional maps with discrete boundary provide an unrealistic representation of such ecosystems (Foody, 1999). Furthermore, particularly when using coarse-resolution sensors, such as MODIS, MERIS, or SPOT-Vegetation for the mapping of heterogeneous and complex forest mosaics, mixed pixels may emerge, where multiple land cover types occur within the extent of the sensor's projected instantaneous field of view. It has been shown that assigning mixed pixels to a specific single type of land cover, results of inferior mapping performance are being obtained (Fernandes et al., 2004; Foody, 1997; Friedl et al., 2000; Leinenkugel et al., 2013) and in particular gives rise to an overall underestimation of non-dominant land-cover types (Nelson and Holben, 1986; Braswell et al., 2003). Moreover, the classification of continuous quantitative information into discrete labels is implicitly accompanied by information degradation. For most algorithms this leads to an increase in uncertainty that often remains hidden in the output maps and thus cannot be accounted for during further analysis (Rocchini et al., 2014). In this respect, the use of continuous variables, such as fractional forest cover estimates or biophysical properties such as tree cover at subpixellevel, has proved to be more effective in the quantification and characterization of forest ecosystems, particularly in the case of gradients and mosaics in the landscape (Adams et al., 1995; Carpenter et al., 1999; DeFries et al., 1997, Defries, Hansen, and Townshend, 2000; Fernandes et al., 2004; Hansen et al., 2002; Hansen et al., 2005; Tottrup et al., 2007, Gessner et al., 2013). Methods to derive these continuous variables include linear mixture models (Adams et al., 1995; DeFries, Hansen, and Townshend, 2000; Scanlon et al., 2002; Lu, Moran, and Batistella, 2003; Kuenzer et al., 2008; Kumar et al., 2008), fuzzy membership functions (Foody and Cox, 1994), neural networks (Foody et al., 1997; Carpenter et al., 1999; Braswell et al., 2003; Liu et al., 2004; Liu and Wu, 2005), support vector machines (Esch et al., 2009; Leinenkugel, Esch, and Kuenzer, 2011), and regression trees (DeFries et al., 1997; DeFries, Townshend, and Hansen, 1999; Hansen et al., 2002; Gessner et al., 2013).

The use of continuous variables for the analysis of forest cover and their dynamics in Latin America however is almost limited to the physically-based linear mixture models, such as applied by Wang et al. (2005), Souza et al. (2003; 2005); Filho et al. (2005) or Roberts et al. (2001). Souza (2003, 2005, 2012), Filho et al. (2005) and Roberts et al. (2002) for instance, applied linear spectral unmixing to separate subpixel fractions of green vegetation (GV), nonphotosynthetic vegetation (NGV), soils and shade for studying forest degradation and deforestation in the Brazilian Amazon. Wang et al. (2005) by contrast applied a two-component linear model based on the assumption that logged areas consist of only two components, i.e. tree canopies and open areas. The resulting forest canopy fractional cover was then used for identifying forest degradation caused by selective logging in the Amazonian state of Mato Grosso, Brazil. Kazuhito et al. (2003) in contrast used a multi-scale regression approach to derive continuous forest cover fraction from monthly Pathfinder AVHRR Land (PAL) NDVI layers at 8km resolution. Therefor higher resolution Landsat MSS, TM, and ETM+ data were classified and aggregated to AVHRR resolution to derive Landsat-based forest cover fractions for calibration.

A logarithmic relationship between the AVHRR-derived NDVI and Landsat-based forest cover fractions could then be examined which was finally utilized to estimate the forest cover fraction from the AVHRR-based NDVI data. Also Hayes and Cohen (2007) used an approach for estimating proportional forest change as a continuous variable for a study site in Central America based on a regression model that relates multispectral, multitemporal MODIS data to reference change data sets derived from a Landsat analysis.

3.4.6 Methods employed to assess forest cover dynamics

Forest dynamics are defined as the change in the shape and structure of a forest, related to its underlying physical and biological forces. For forest cover dynamics, two main elements are recognized: forest disturbance and forest succession. Forest disturbances are caused by changes induced primarily by fire, flood, human influence (logging) and diseases, whereas forest succession is characterized by the recovery of the vegetation after a disturbance event (GOFC, 2010). Several methods have been applied to monitor the dynamics of tropical forests; a summary of the main change detection approaches is presented in Table 3-2 and Table 3-3. Early studies (Skole and Tucker, 1993; Alves et al., 1996,1999, 2002) assessed forest changes by delineating logged areas through on-screen digitalization of disturbed areas based on medium (Landsat, SPOT) to high (IKONOS) spatial resolution imagery and GIS. For instance, Alves (2002) assessed the spatial patterns of deforestation in the Brazilian Amazon by manual interpretation of forest clearings based on Landsat MSS and TM images from 1991-1997. Manual interpretation has not only been used to quantify clearings in natural forest but also to identify degraded areas resulting from selected logging operations (Matricardi et al., 2005; Souza et al., 2003). While manual interpretation works particularly well for spatial assessments including geometric, textural, and contextual characteristics of deforestation patterns and for the general interpretation of direct deforestation drivers, this approach is rather timeconsuming and less effective in quantitative, wall-to-wall assessments of forest cover dynamics.

Table 3-2. Summary of main forest change detection methodologies applied for Latin America.

San Luis Potosi	Purpose	Forest Change	Methodology	Study Area (ha)	Platform	Resolution	Author
	Land cover change from 1973 -1983, 1985 -1990, and 1990 -2000	Almost 88.055 ha were deforested from 1973 to 2000.	Maximum like hood supervised classification. Post- classification comparison	305.600	Landsat MSS , ETM +	60 and 30 m.	Reyes- Hernandez (2005)
Northern Guatemala (Part of the Maya Biosphere Reserve)	Distinction of spectral change patterns from year to year in response to possible forest disturbance.	From 2000 to 2003 187.399 ha cleared.	Visual interpretation and clustering of multi-date NDVI composite imagery. Linear Regression analysis.	n/a	MODIS	500 and 250 m	Hayes (2007)
Colombian Andes	Estimate deforestation in lowlands and Highlands.	From 1985 to 2005 1.477.932 of forest cover lost.	Mixed digital supervised classification with onscreen visual Interpretation. GIS overlay	28.772.000	Landsat MSS, ETM.	60 and 30 m	Armenteras et al. (2011).
Machadinho d Oeste. Northeastern Rondonia state. Brazilian Amazon basin.	Explores the application of linear spectral mixture analysis to detect land cover changes.	Changes from 1994 to 1998 are mainly from the mature forest deforestation 56, 93 %. (14, 63 % from mature forest to successional vegetation and 42, 3 % from Mature forest to crop land.	Fractional Images base on spectral mixture models tree decision free classifier. From- to change detection using pixel by pixel comparison.	100.000	Landsat TM	30 m	Lu D et al. (2004)
Paraguay	Forest loss assessment for the entire Paraguayan Region.	From 1970 to 2000 the Atlantic Forest ecoregion lost almost 75 % of the cover. Chaco area lost 16,23 % from 1990 to 2000.	Hybrid method applying Iterative clustering-supervised labeling method (including unsupervised Isodata clustering and supervised). Systematic sampling approach to assess changes from 1970 to 1990. Final Wall to Wall change map.	40.675.200	Landsat TM MSS	30 m	Huang et al. (2009)

Table 3-2. (Continuation)

3 Tropical Forest Cover Dynamics for Latin America using Earth Observation Data: A Review covering the continental, regional and local scale

Location	Purpose	Forest Change	Methodology	Study Area (ha)	Platform	Resolution	Author
San Julian District. Santa Cruz, Bolivia	Deforestation and fragmentation patters assessed by Satellite images.	From 1976 to 2006 the forest lost around 382.276 ha	Unsupervised Isodata clustering for classifying the images. Relationship of Puyravaud (2003) to estimate deforestation rates.	n/a	Landsat TM, ETM	30 m	Pinto – Ledezma et al. (2010)
South-east to Amazon River Sao JoseBay - Brazil	Inclusion of SAR data and object-based approach to asses changes within the Brazilian Coastline	From 1996 to 2008 the mangroves decreased 121.300 ha.	Object based segmentation and classification. Comparison of the resultant maps.	759100	JERS – 1 SAR and ALOS PALSAR	18 and 20 m	Nascimiento Jr. et al (2012)
Ji – Parana Rondonia State. Brazil	Combination of Landsat and NOAAVHRR data to asses deforestation	Around 30 % of the study area was deforested from 1973 to 1999.	Unsupervised classification, forest fraction cover analysis. Change detection assessed base on Image comparison	3.422.500	Landsat MSS, TM ETM + and NOAA/AVHRR.	30 m and 8 km.	Ichii et al. (2003)
Mato Grosso. Brazil	Integration of GIS and NOAA/AHRR to asses deforestation dynamics	The study demonstrates that 76,1% of the changes in the forest occurs 30 km from the paved roads.	Extraction of the dominant characteristics of the vegetation distribution by principal component analysis. Unsupervised classification and GIS Overlay to assess the changes	903.38600	NOAA/AVHRR	8 km	Yoshikawa and Sanga- Ngoie (2011)

Table 3-3. Summary of main methodologies to asses' forest degradation for Latin America.

Mapping Approach	Studies	Sensor	Location	Objective	Advantages	Disadvantages
Visual interpretation	Stone and Lefebre (1998	Landsat TM	Pará state. Brazil	Mapping the total area logged	No complex image processing methodologies required.	The intensive work required when dealing with larger areas might bias the results.
Combination sensing with GIS (Detection of logging areas and buffer zones)	Souza and Barreto (2000) Matricardi (2001)	Landsat TM and ETM +	Pará state Brazil. Brazilian Amazon	Mapping the total area logged (clearings, canopy damage, and untouched forest).	Easy to apply. Provides a satisfactory estimation of the total are logged	The intensive work required when dealing with larger areas might bias the results.
Textural analysis	Asner et al. (2002), Matricardi et al (2007)	Landsat TM and ETM +	Pará state Brazil. Brazilian Amazon	Selective logging assessment.	Fully automated process and easy to implement	The actual shape of the logged it's been accurately represented by the buffer zones.
Decision tree	Souza et al. (2003)	Spot 4	Pará state Brazil.	Asses canopy damage caused by logging and burning.	No complex classification rules	Canopy damage caused by tree falling is difficult to detect.
Change detection	Souza Jr. and Roberts (2002)	Landsat TM and ETM +	Brazilian Amazon	Asses canopy damage caused by logging and burning.	Improves the detection of canopy-damaged areas.	Anthropogenic and natural forest changes are considered together. Two pair of images are required
Image Segmentation	Garca et al. (2005)	Landsat TM	Mato Grosso region. Brazil	Mapping the total area logged (clearings, canopy damage, and untouched forest).	Easy to apply. Provides a satisfactory estimation of the total are logged	Classification rules may differ along the landscape. It has not been tested in larger areas.
CLAS	Asner et al. (2005, 2006)	Landsat TM and ETM +	Brazilian Amazon	Mapping the total area logged (clearings, canopy damage, and untouched forest).	Standardized for large areas and highly automated	Intensive computation processing and pair images required.
NDFI	Souza Jr. and Roberts (2005)	Landsat TM and ETM +	Brazilian Amazon	Mapping the total area logged (clearings, canopy damage, and untouched forest).	Improves the detection of canopy-damaged areas.	Anthropogenic and natural forest changes are considered together. Has not been tested in larger areas.

Matricardi et al. (2007) tested the performance of an automatic textural algorithm against manual interpretation to identify selective logging operations in the Brazilian Amazon based on multi-temporal analysis of Landsat images obtained in 1992, 1996, and 1999. The author concluded that visual interpretation (92.8 %) and automated techniques (90.2 %) were equally effective to detect selectively logged areas. However, visual interpretation approaches were considered to involve a far greater workload and the precision of the final product was associated to the skills of the interpreter.

A rather simple but very effective approach to identify and evaluate forest cover dynamics is the post-classification comparison. The post-classification approach is performed by generating independent classification results from two images obtained in different time periods and subsequently compared pixel-by-pixel or object-by-object (Sesnie et al., 2008, Hayes and Sader, 2001; Van Laake and Sánchez-Azofeifa, 2004; Arroyo-Mora et al., 2005; Huang et al., 2007; Pinto-Ledezma and Centurión, 2010; Servello et al., 2010; Souza and Verburg, 2010; Lira et al., 2012; Bianchi and Haig, 2013; Caldas et al., 2013; Interbacia et al., 2013). By effectively tagging the classification results, a comprehensive matrix of change is generated and change classes can be labelled by the expert. The strength of this approach lies in its capacity of not only identifying change but also of gaining specific information on what has changed, e.g. forest to grassland (from-to change). However, this approach can only be applied in a bi-temporal manner and therefore requires multiple bi-temporal comparisons when more than two time points are compared. As an example Reyes-Hernández et al. (2006) studied the changes in forest cover and land use in San Luis Potosi Mexico from 1973 to 2000. The study applied a multiple bi-temporal comparison of paired Landsat images from 1973 to 1985, 1985 to 1990 and 1990 to 2000 to obtain changing rates from forest cover and land use over time. However, this approach requires highly accurate base maps, since errors caused from misclassifications of the individual maps, will multiply in the final change map (Husain et al., 2013).

Particularly in land cover maps derived from low resolution sensors, uncertainty levels often are higher than levels of area changes. As a consequence, post-classification comparisons based on low-resolution sensors frequently result in large proportions of spurious change (Achard and Hansen, 2012; Herold et al., 2008; Kuenzer et al., 2014), hampering the identification or real changes on the ground. Furthermore, traditional classification, where each pixel belongs to the class it most closely resembles, prohibits the identification of gradual processes over time, such as are evident in the case of forest degradation or selective logging or when forest cover within a coarse resolution pixel is successively converted or removed over periods of several years. By contrast, change detection approaches based on continuous variables permits the differentiation of gradual changes at a pixel level and incorporates information associated to the quality of the stand. Recent change detection approaches on continuous variables identify change by the wellestablished image algebra approach (Borak, Lambin, and Strahler, 2010; Haertel, Shimabukuro, and Almeida-Filho, 2004; Hansen and DeFries, 2004; Leinenkugel, Esch, and Kuenzer, 2011) whereby a difference image is calculated from the datasets of two respective dates and a threshold is set to differentiate between significant and insignificant change.

Typically, the threshold is based on a multiple of the difference image standard deviation, based on the assumption that change pixels generally represent outliers within the difference image (Hansen and DeFries, 2004). Greenberg et al. (2005) applied image differencing over the neo tropical rain forest in the National Park Yasumi located in the eastern region of Ecuador based on multi-temporal analysis of seven Landsat scenes between 1993 and 2002. As continuous variables, the authors derived shadow fractions from the Landsat data being more sensitive for vegetation- to-vegetation and vegetation-to-non vegetation changes in comparison to ordinary vegetation indices. Lighter regions (less shadow) were indicative of anthropogenically disturbed areas while darker regions (more shadow) were indicative of late successional forest. Finally, the individual shadow fraction images were pairwise compared and a deforestation occurrence was identified on a pixel basis when more than three standard deviations of the shadow fraction difference image was observed.

Besides the simple image-differencing technique also more complex relative change detection methods were developed for the identification of forest dynamics that are applied directly on the surface reflectance bands. Spectral-temporal transform approaches, such as principal component (PC) analysis (Hayes and Sader, 2001; Guild et al., 2001), for instance were applied to multi-temporal image stacks in order to extract patterns indicative of change over time. Guild et al. (2001) for instance tested three methods of change detection to map deforestation and land cover change between 1984, 1986, and 1992 in Rondonia, Brazil, based on three Landsat 4 and Landsat 5 TM scenes. The three indices of brightness, greenness, and wetness resulting from a TC transfrom formed the basis for a nine-layered multi-date TC data stack. Furthermore a PC transform was applied on this data stack to further highlight land cover changes evident in the resulting component layers. Finally the multi-temporal TC data stack, a manual selection of three PC layers, as well as two difference images of the TC image date pairs were each classified based on a maximum likelihood classification for the identification of land cover changes. The authors conclude that the multi-date TC composite classification had the best accuracy in identifying forest dynamics.

Most of the studies reviewed analyse forest dynamcis on a bi-temporal basis or for only a few points in time. However continuous time-series of low to medium resolution sensors, such as MODIS or Landsat theoretically allow for a quasi-continuous reconstruction of forest disturbance and regeneration histories over observation periods of several decades. However, only very few studies actually exploit the large potential of continuous spectral-temporal trajectories for the detection and analyses of forest dynamics, such as seen in Huang et al. 2010; Kennedy et al. 2010, Griffiths et al. 2013 and Leinenkugel et al. 2015. Among the studies reviewed, only four authors applied real trajectory-based or time series-based analyses (Aide et al., 2012; Clark et al., 2012; Sanchez-Cuervo and Aide, 2013; Huang and Friedl, 2014). Clark et al. (2012) applied 250 m MODIS time series data at 16-day intervals to produce annual land cover maps for Latin America and the Caribbean between 2001 and 2010. Finally land cover proportions were calculated for individual municipality- and biome-zones and a linear regression model was applied to these statistics to identify trends in land cover over the 10 year observation period.

Sanchez-Cuervo et al. (2012, 2013) applied the same data basis and methodological approach to statistically identify land cover trends and hot spots of land cover change at varying scales (country, biome, ecoregion, and municipality) over the same 10-year period for Colombia. Huang and Friedl (2014) tested a distance metric-based change detection method for identifying changed pixels at annual time steps using 500 m MODIS time series data. The approach utilises distance metrics to measure the similarity between a pixel's annual time series to annual time series for pixels of the same land cover class as well the similarity between annual time series from different years at the same pixel. The developed method successfully identified pixels affected by logging and fire disturbance in temperate and boreal forest sites in Mato Grosso, Brazil. Hayes and Cohen (2007) by contrast performed an analysis to highlight the distinct spectral change patterns from yearto-year in response to the possible land cover trajectories of forest clearing, regeneration and changes in climatic and land cover conditions through an analysis of 6 dates (2000 to 2005) of Landsat data for a study area located in northern Guatemala. Ferraz et al. (2009) prepared an 18-year Landsat TM and ETM+ time series in biennial intervals to examine the aspects of tropical deforestation through rates and patterns of change. Furthermore the authors developed four trajectory-based metrics, i.e. annual deforestation rate, secondary forest mean proportion, mean time since deforestation and deforestation profile curvature to measure historical changes. The authors concluded that the tested indicators were able to represent the main temporal land-use changes considered related to deforestation, cumulative effect, and forest regeneration. Others studies in Latin America also use continuous time series for analyzing forest dynamics over long time periods such as Roberts et al. (2002), Alves et al. (2009), Morton et al. (2006), Hartter et al. (2008) or Marsik et al. 2011. However these studies actually do not apply trajectory-based methods for detecting forest dynamics at a pixel level. Instead forest cover proportions for the study area are aggregated for each year and the long term trajectory of forest cover proportions for the entire study aras was interpreted by the authors.

3.5 Forest cover dynamics within the Atlantic Forest and Chaco areas of Paraguay

The following section provides a comprehensive overview in regards to the depravation of the forest occurred in the Paraguayan region over the last 40 years. A closer look into the rates of deforested areas, importance of the ecosystems affected, and the scarce number studies which applied EO to analyze the changes is provided. The aim of this section is to emphasize the significance of spreading the study areas over the Latin American continent in regions equally important and threatened as the Amazonian rain forest Paraguay has lost the majority of its natural forest cover in just 40 years; presenting one of the highest rates of deforestation in the world. Annually, forest losses were estimated to be approximately 1.64 % from 1984 to 1997 and 0.9 % until 2011 (Hansen and De Fries, 2004; FAO, 2011). Recent estimations demonstrate the remaining forest cover in Paraguay at 17.58 Mha - spanning almost 44 % of the total land area of the country. Further analysis revealed that 80 % of the remaining forests were located within the Western region of the country; an area characterized by poor soil conditions and extended

dry seasons not suitable for agriculture, as it covers 60 % of the country's surface but contains less than 5 % of the population (Macedo and Cartes, 2003) Unlike Paraguay's western region, the eastern area of the country possesses less than a quarter of the forest coverage, with the vast majority of the population and also includes the Atlantic Forest ecoregion. The following section provides a brief characterization of the Paraguayan regions, deforestation drivers and a review of the approaches implemented in order to assess variation in the forest cover using optical data

3.5.1 Site characterization

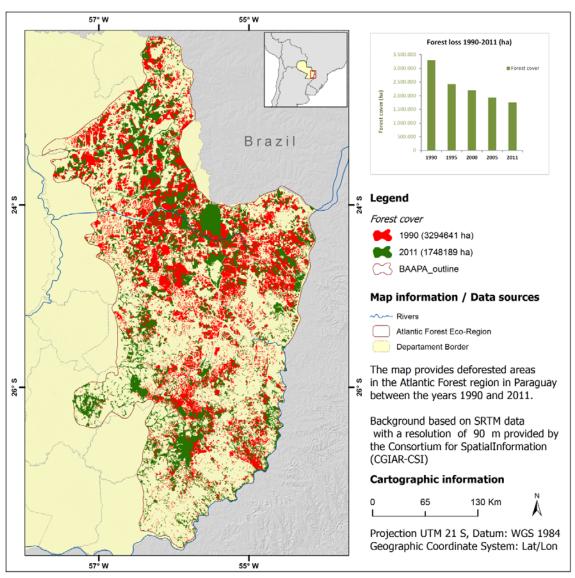


Figure 3-7. Atlantic Forest loss between the years 1990 and 2011 (Source for the forest cover layer for 1990 and 2011: FFPRI project and the Department of Statistics, Surveys and Census).

Paraguay is located in the heart of South America; located between 19° 18' and 27° 36' South and 54° 19' and 62° 38' West. The country has a total area of 406 752 km², neighboring Brazil, Argentina, and Bolivia. Geographically it is divided into two natural regions; the Oriental (eastern) region, which has a surface of 159 827 km² and the Occidental region (western), containing a total area of 246 925 km². The eastern part of the country is characterized by a high variety of physical and geographical aspects, containing forest, grasslands, and the vast majority of the country's croplands. Furthermore, it encompasses remnants of the Atlantic Forest ecoregion; one of the largest areas for biology conservation (Di Bitetti et al., 2003). According to an analysis carried out by WWF based on data relating to biodiversity, it is acknowledged that the Atlantic Forest is one of the most complete ecoregions in the world (Di Bitetti et al., 2003); with around 20 000 plant species and almost 13 000 fish vertebrate species (Mittimer et al., 1999). The Atlantic Forest is a combination of 15 ecoregions, starting from the Atlantic-coast of Brazil, passing through the eastern region of Paraguay and finally reaching the northwestern region of Argentina. Nevertheless, the Atlantic Forest is one of the most threatened tropical rain forests at the moment; only 7% of the original cover remains (Di Bitetti et al., 2003).

The biggest area of forest within the 15 ecoregions is located in the Atlantic Forest of Upper Parana; spanning an area of 471 204 km². One of the major aquifers in the world is located under the Atlantic Forest of Upper Parana; almost 1.2 million km², of which contains approximately 40 000 km² of fresh water (Di Bitetti et al., 2003). By 1945, the Atlantic Forest of Upper Parana in Paraguay covered almost 55% of the Eastern Region of the country (that is approximately 8.806 Mha), however, nowadays only 13% of the forest cover remains (Fleytas, 2007).

3.5.2 Deforestation drivers and actual state of the forest

Between 1945 and 1975, intensive wood harvesting activities took place in the eastern region of Paraguay primarily due to the vast amount of forest concentrated there. Most of the harvesting activities were concentrated in the areas of Concepcion, Upper Parana, Caaguazú, Amambay, San Pedro and Itapúa (regions of the Atlantic Forest of Alto Parana). The process of deforestation increased in the early 1950s, due to a process of agricultural expansion, human settlements and especially colonization programmes (Fleytas, 2007). During the government regime of General Alfredo Stroessner (1954-1989), intensive programmes for the agricultural development of the land were introduced and thus reduced pressure on the central areas of the Oriental region The areas that were considered empty or without appropriate utilization were promoted by the state, in order to commence the colonization; without consideration of the indigenous inhabitants of these areas. This programme was imposed without any consensus or participation of local communities (Fleytas, 2007). Law 854 of the Agrarian Statute established in 1963 recognized the right to the exploitation of the lands for agricultural purposes - including lands with forest cover tagged under the name of "wastelands". The lack of appropriate definition of land that is indeed suitable for production or conservation was one of the main factors in deforestation over the years (Fleytas, 2007). After the implementation of the colonization programmes and the agricultural expansion, the rates of deforestation in Paraguay were over 2000 km²/year and thus becoming one of the countries with the

highest rates of the deforestation at an international level (Macedo and Cartes, 2003). The process of deforestation occurred in the Oriental region during the early 1940s until the late 1980s; resulting in the loss of 4 900 000 ha of forest (around 123 000 ha/year). During the 40 year span, the peak in deforestation (1968 to 1976) saw 212 000 ha of forest logged per year. Further studies demonstrated that the remaining forests were constituted by residual patches (32.2%) and low commercial value stands (68. 8%). Although not as severe as in the Oriental region during this period, deforestation rates within Western areas reached almost 45 000 ha / year (Mereles and Rodas, 2014). Following the early 1990s, forest continued disappearing at an alarming rate. By the end of 1991, 32% of the Eastern region was covered by forest (45 000 km2 approximately), however, by the end of 2001 this was reduced to 22 %. Most of the forest loss was attributed to the conversion of forest to agricultural lands, timber harvesting and small scale invasion into forest by rural settlers (Guyra study under the supervision of Maryland).

More recent studies carried out by the Forest Engineering Faculty of the National University of Asuncion-Paraguay, in consortium with the Forestry and Forest Products Research Institute from Japan (FFPRI), applied supervised classification over Landsat 5 images to estimate the forest cover of the Atlantic Forest region for the years 1990, 1995, 2000, 2005 and 2011 (Figure 3-7). The resultant analysis exhibited that approximately 1 550 000 ha of the forest was logged during the study period, whereas the Occidental region presented an annual rate of approximately 174 000 by 2008 (Caldas et al., 2013).

According to several authors, it is important to not only establish the direct drivers affecting the forest, but also the external factors that are equally as crucial, such as: failures within the Environmental Policies, extensive corruption associated with lack of monitoring programmes and conservation laws (Jica 2002, Yanosky and Cabrera, 2003; FAO, 2004; Quintana and Morse, 2005; Wright et al., 2007). Only a few articles which encompassed the Paraguayan territory were found during the review. A total of 4 studies (Huang 2007, 2009; Caldas et al., 2013; Rodas and Mereles, 2014) were carried out in the country itself and 3 additional studies (Gasparri and Grau, 2009; Clark et al., 2010; Hoyos et al., 2013) were conducted in the border between Argentina and Paraguay. Although variations in the forest cover have been assessed continuously by NGOs (WWF and Guyra Paraguay) and governmental institutions (National Forestry Institute and Ministry of Environment) no publications of the results were found within indexed journals. Most of the outcomes from the investigations are only available in internal reports of the institutions.

3.6 Discussions

In the previous sections, an overview of the remote sensing approaches on tropical forest dynamics in Latin America was provided. In the following section discussions and the main findings were summarize for this review article along with the resultant needs of further studies on the Dynamics of Tropical forest in Latin America. The emerging needs of studies are not only addressed to the scientific community dealing with innovative remote sensing approaches, but also to environmental programmes, policy makers, and conservation institutions which rely on this valuable information to develop further strategies and policies.

3.6.1 Summary of main findings and results.

Within the articles reviewed several products were obtained from the different approaches discussed previously. For instance global forest products became available in the earliest 1990s from coarse resolution imagery (MODIS, AVHRR, or MERIS) varying from 1 km to 300 m resolution. More recent improvements on change detection procedures allowed the generation of global forest change products with higher resolutions, varying from 30 to 25 m based on Landsat and ALOS PALSAR L-band HH and HV polarization data (Hansen et al., 2013; Shimada et al., 2014). The vast majority of the articles focused their work on the understanding of deforestation and degradation processes, identifying change patterns, hot spots, and drivers. As mentioned repetitively within several sections in this article (3.3.1, 3.4.3, 3.4.5, 3.4.6, and 3.5.2) the constant advance of agricultural crops over natural areas still remains as the main threat affecting the forest in Latin America. In terms of EO data applied, Landsat satellite was by far the most used sensor (see Figure 3.2-6a). Other EO data less used such as ASTER, CBERS, IKONOS, QuickBird, and SPOT were incorporated primarily to fill in the gaps not covered by the Landsat satellites, or as means of validation. Similar to the sensors cited above, studies which applied radar data (ERS-1/ERS-2, JERS-1, SIR-C/X, ALOS PALSAR, RADARSAT 2, and COSMO Sky Med) were scarce and mainly conducted in the Brazilian region. As observed in the figure 2-5b most of the radar studies were carried out with ERS-1/ERS- 2 data at a local level based on bitemporal approaches to identify forest cover changes.

Over the articles reviewed deforestation and degradation maps were obtained by applying a variety of change detection methods (as described earlier in the section 3.4.6); the methodologies differed from each other according to the data available and the main objective of the research. Change detection technique is an inclusive procedure that requires the cautious consideration of each step; objective of the change detection analysis, selection of remotely sensed data, image processing, extraction of variables from satellite imagery, selection of suitable change detection technique, and final evaluation of the results. Overall, deforestation maps were obtained through manual interpretation, thematic maps, or continuous variables conducting bi-temporal, multi-temporal, or real time series analysis. The inclusion of continuous variables such as vegetation indexes, subpixel vegetation fractions, continuous fields of tree cover, PCA components, or TC metrics has clearly improved classification accuracies and change detection precision.

Contrary to deforestation, degradation analysis was more difficult to accomplish. Firstly forest degradation must be mapped within a short period of time, since the spectral signatures of the disturbed forest becomes less distinct already after the first year. Secondly, forest degradation can be confused with natural disturbances such as seasonal changes or wind throws. Thirdly, lack of economic resources designated for capacity building on the management and operation of algorithms and software's capable to detect degraded forest. Even though over the articles a standardized protocol to assess forest degradation was not found several methodologies which included fraction images (GV, NPV, soils and shade) and other continues variables (NDVI, SAVI, MSAVI, PC and TC) as well as textural metrics successfully detected logged areas expanding the detection time up to three years after the disturbance occurrence.

Generally the validation of classifications and the forest change maps was achieved through ground control data as presented in the figure 3.2-6d. When true ground data was not available alternative methods such as the use of high resolution imagery (ASTER, IKONOS, Quickbird, SPOT), aerial photography or previous knowledge from experts of the area were often applied.

Even though these substitute methods were shown to improve the accuracy of the results, some authors agreed that ground control data remains as the most effective method (Wang et al., 2005; Achard et al., 2010).

3.6.2 Current needs and challenges.

Presently there is an ongoing necessity for more accessible, fast and precise information on the world's forest dynamics among the scientific community, environmental institutions, monitoring programmes and governmental entities. The vast majority of the articles reviewed responded to at least one of the following questions: Which type of vegetation cover is changing and at what rate? What are the causes, and factors of deforestation? Are these causes natural or anthropological (Yoshikawa and Sanga-Ngoie, 2011)? Despite constant advances in remote sensing technologies the data generated so far appears not to be sufficient to satisfy the growing demand for information in terms of spatial extent, temporal resolution, and availability. For instance, deforestation and degradation processes occur on a daily basis and on different scales all over Latin America; yet many countries do not have the economical means or governmental support to introduce monitoring programmes addressed to assess disturbances of the forest. An exception is the Brazilian governmental project "Programa Despoluição de Bacias Hidrográficas or Basin Restoration Program" (PRODES) carried out through INPE, which monitors the forests over the Legal Amazon region (GOFC, 2010). The programme produces annual wall-to-wall forest cover maps based on Landsat imagery (GOFC, 2010) covering an area of approximately 5 M km² using a minimum unit area of 6.25 ha. Complementary to PRODES, since May 2005 the Brazilian government implemented a near-real time monitoring system called DETER (Detecção de Desmatamento em Tempo Real) capable of detecting forest disturbances larger than 25 ha (GOFC, 2010) in a 15-day interval on the basis of MODIS and CBERS satellite data. In addition in 2008 a new programme was introduced named DEGRAD to assess degradation particularly from selectively logged operations by using Landsat images and CBERS. Even though these programmes have been successfully monitoring the forests for over 15 years (PRODES), the large amount of data, human resources, and financial resources required to operate such as system is far beyond affordability for other Latin American countries.

With regard to the spatial resolution of current satellite sensors, coarse resolution data has been successfully applied to estimate large scale forest losses not smaller than 25-100 ha in size. However, since human induced change processes frequently result in much smaller spatial patterns, a major part of these changes remain undetected at coarse resolution even when change detection approaches based on continuous variables are implemented. This particularly applies for the detection of forest degradation processes that do not result in forest clearance but only modify the structure of the canopy. Nevertheless, only coarse resolution sensors possess the ability to continuously monitor

forest changes in a wall-to-wall manner at regional and global scale. Such detected deforestation hot spots can subsequently be analyzed in detail on the basis of high resolution imagery. Additionally coarse resolution sensors offer the only opportunity for almost real-time monitoring of the forest, a service growing on demand by a diverse range of forest stakeholders. Beside the Brazilian near-real time system DETER also Global Forest Watch, an open online platform for forest monitoring, provides almost near-real time information on forest loss based on 500m MODIS data at 16-day intervals. On the other hand, the use of high- to medium resolution data such as originating from RapidEye, SPOT, Landsat, or the upcoming Sentinel-2 satellite offer greater opportunities for the detailed analyses of deforestation patterns including those of forest degradation processes. In this respect these sensors are the most important means in terms of satellite-based monitoring as part of the REDD+ programme.

With respect to change detection methods, most forest change studies so far have been based on comparisons of bi-temporal remotely sensed information products. Bi-temporal approaches, however, only provide a static depiction of land cover change occurring between two particular time points, giving no scope for an evaluation of land cover between these dates, meaning that temporary disturbances occurring between these dates remain undetected. Furthermore by only analyzing changes at a bi-temporal basis, the temporal patterns of specific change processes, such as those of cyclical forest harvesting, e.g. shifting-cultivation practices cannot be accounted for. With respect to the estimation of carbon emissions, however, the detection of cyclical forest losses and their differentiation from permanent losses is highly relevant (Leinenkugel et al., 2015). Houghton (2012) for example, estimated that globally, the harvest of timber and shifting cultivation adds 32%-35% more to the net emissions calculated on the basis of deforestation alone. Also gradual, long-term degradation or regeneration processes of forests that may result in subtle trends within a satellite data time series remain undetectable when data are compared only at a bi-temporal basis. Trajectory-based change detection approaches based on long-term time series, in contrast provide excellent means to reconstruct and to analyze a quasi-continuous history on forest cover and their disturbances over periods of several decades. While there have already been some studies performed based on continuous time series thereby also taking into account temporal disturbance profiles, considerable potential still exists in the field of trajectorybased change detection approaches.

The scope for further development in this field has to be seen in view of the extensive archives holding historic satellite data from low resolution sensors, such as MODIS, SPOT Vegetation, or AVHRR that meanwhile span time periods up to 40 years and are continuing to grow. In addition, access policies for high- to medium resolution data have changed recently, particularly since the US Geological Survey (USGS) released for free to the public its Landsat archive in 2008. Landsat 8 meanwhile collects more than 700 images per day — 14 times as much as in the 1980s (Wulder and Coops, 2014). Future global coverage as well as free and open data access is continuing to improve with the European Union's free Copernicus data policy for the use of the European Space Agency (ESA) Sentinel satellites.

The ESA Sentinel 1 radar satellite currently provides an all-weather day-and-night supply of imagery at a 12-days repeat cycle and will be joined by the Sentinel-2 satellite in 2015, which will map the Earth's land area every 10 days at a maximum of 10m resolution.

3.6.3 Uneven distribution of the studies

Regarding to the distribution of the studies (see Figure 3-4) the vast majority of the investigations were carried out within the Brazilian region, particularly in the Brazilian Amazon (Rondonia and Matto Grosso state). The rapid advances of agricultural crops, illegal operations, and land grabbing have been common drivers of deforestation in these areas. However other countries in Latin America are affected by these land use and land cover transformations to the same degree often showing deforestation trends much more severe than observed in the Amazonian region (see Figure 3-1). The study case over the Paraguayan region included in this review article demonstrates a clear example of how the forests have been devastated over the years and only a scarce number of studies have been undertaken to observe the dynamics in this area. The same applies to Peru, Argentina, or Bolivia that have been already identified among the regions with the highest rates of deforestation in the world (Hansen et al., 2013; Shimada et al., 2014). It can be inferred that the shortage of the studies in these areas is related to a lack of expertise in the area, a lack of governmental concern, a lack of international interest from the scientific community, and a lack of financial support for local studies. However, it is important to mention that several institutions (NGOs) within the Latin American continent are currently involved in private monitoring programmes and forest assessments at regional scale; nevertheless the data generated is frequently classified as sensitive data and not available for public use.

3.7 Conclusions

In this review article, a complete overview of the studies of tropical forest dynamics in Latin America based on EO data was given. A comprehensive categorization of the reviewed studies with respect to the spatial distribution and areal coverage, the sensors applied and their spatial and temporal resolutions were provided. Furthermore, forest classification and change detection methodologies and their applications in detecting different forest processes were presented. Finally a summary of the main results was discussed along with gaps and current research needs. Based on the findings and discussion in this review paper, the major conclusions are:

(1) Studies relating to tropical forest dynamics are mainly centered on the Brazilian region; especially on the states of Mato Grosso and Rondonia. In view of this, there is a necessity to expand the study areas to other regions in Latin America which are equally important; particularly in the context of the REDD + programme. The Paraguayan study case presented in this article served as an example to show how forests have been massively devastated over the years and yet only a scarce number of studies were conducted for this region.

- (2) Concerning the scale and sensors used, the majority of the studies were carried out at a local level applying medium resolution imagery from the Landsat sensor. The studies carried out at regional and global level were mostly based on coarse resolution MODIS and AVHRR data. Moreover, only few studies included SAR imagery, all of which were performed exclusively for Brazil.
- (3) Multi-temporal and bi-temporal studies were often conducted to detect degradation and deforestation processes, covering almost 95 % of the studies reviewed. Change detection methods were mostly based on comparisons of thematic maps derived from Landsat imagery or based on image differencing approaches. Also the use of continuous variables such as vegetation indexes, or the outputs from principal component or tasseled cap analyses were regularly applied to increase the accuracy of detected changes.
- (4) Studies based on continuous time series of satellite data were less frequent in the reviewed studies (5% of the studies). Most of these studies applied MODIS time series spanning observation periods of up to 10 years thereby also utilizing intra-annual statistics. Trajectory-based change detection methodologies that analyze the entire disturbance history of a forest on a pixel basis were very rare. In view of this, more sophisticated change detection approaches are needed that are capable of utilizing the open data archive of the Landsat sensor or the high spatial and temporal resolution of the upcoming Sentinel satellites.
- (5) While most studies demonstrate high capabilities for the detection of deforestation processes, forest degradation was more difficult to identify and remains a challenge to be mapped even from high to medium resolution sensors such as SPOT or Landsat. Particularly the rapid advance of secondary vegetation formations over logged and small cleared areas presents a major constraint on the detection procedures. Nevertheless continuous variables for forest characterization, such as fraction images, showed to be highly useful for the mapping of degraded areas even up to 3 years after the actual disturbance event.
- (6) All scientific studies focus on the detection of historic forest dynamics. In view of this the development of real-time change detection approaches capable to be implemented in monitoring programmes at national levels have to be further promoted. The extent of Latin America's forests decline on a daily basis but no monitoring programmes are being implemented with the exception of INPE in Brazil and some operated by NGOs without any governmental support.

With the continuous expansion of agricultural land, the illegal extraction of timber and the increasing demand for natural goods, tropical forest stands remain threatened. In view of these developments, there is a necessity to continue the development of methods and information products in the field of Earth observation which facilitate the implementation and enforcement of laws, environmental programmes and policies in order to prevent the depredation of the remaining natural forest stands on the continent.

3.8. References

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3 Tropical Forest Cover Dynamics for Latin America using Earth Observation Data: A Review covering the continental, regional and local scale

CHAPTER 4

4 Paraguay's Atlantic Forest Cover Loss – satellitebased change detection and fragmentation analysis between 2003 and 2013.

Abstract

The subtropical Atlantic Forest is a highly diverse ecosystem in South America and one of the most endangered rain forests in the world. The present study focuses specifically on the Paraguayan part of the tri-national Atlantic Forest. Over the last decades, the Paraguayan Atlantic Forest presented one of the highest deforestation rates in the world, and today, only a small share remains. Hence, forest loss in Paraguay's Atlantic Forest was detected and analyzed through remote sensing and GIS methodologies based on Landsat images obtained in 2003 and 2013. The objective of this study was to examine the spatial impact of forest loss in Paraguay's Atlantic Forest over the past decade with a special focus on biodiversity conservation. Classifications results obtained overall accuracies above 83% and revealed that over 6000 km² of forest was cleared during the study period. The forest landscape and its fragmentation level were characterized through a set of landscape metrics, in particular the proximity analysis which support the identification of forest priority areas for nature conservation and potential biological corridors. In summary, the study revealed that deforestation and fragmentation of the Atlantic Forest area continued, but at a slower pace than that in the previous decade. Protected areas were conserved very effectively; however, forest core areas without any protection status require further attention. Intact forest patches and their connectivity are a crucial prerequisite to biodiversity conservation in a highly fragmented forest area. The combination of different remote sensing and GIS methods provides valuable information for sustainable forest management in the region.

4.1 Introduction

Tropical forest ecosystems have been acknowledged as one of the most diverse regions in the world (FAO, 2010). Their role as a major component of natural processes, climate regulation, and biological diversity has raised increasing concerns about their future and protection (Joseph, Murthy, and Thomas, 2011). The constant advance of agricultural crops, cattle ranching and illegal logging have converted the majority of the world's tropical forests into isolated patches, jeopardizing not only their continuity but also the biodiversity contained within them (FAO, 2007).

Between 1990 and 2005, Latin America lost over 69 million ha of forest, representing almost 7% of the total forest cover in the region (FAO, 2007). Over the past few decades, several studies and institutions have addressed this problem by monitoring the advance of

deforestation based on remote sensing data (Eva et al., 2012; Fernández et al., 2015; Gebhardt et al., 2014; Giri and Long, 2014; Hightower, Butterfield, and Weishampel, 2014; Kuenzer, Ottinger, Wegmann, and Guo, 2014; Leinenkugel, Wolters, Oppelt, and Kuenzer, 2015; Shimada et al., 2014; Song, Huang, Sexton, Channan, and Townshend, 2014; Souza et al., 2013; Sun and Southworth, 2013).

Even though changes in the forest cover have been documented repeatedly in Latin America, the vast majority of studies were conducted for the Amazonia region, leaving out numerous bordering areas that are equally threatened. Within this context, the study provides a comprehensive analysis of forest loss within the Upper Parana Atlantic Forest (BAAPA) region in Paraguay with a special focus on biodiversity conservation. The complete area of the Atlantic Forest represents a complex of 15 terrestrial ecoregions, comprising a total area of 471,204 km² that spans from the Atlantic coast of Brazil to the west and east side of Paraguay and reaching northern Argentina (Bitetti Di, M.S., Placci, G., and Alves, 2003). The eco-region holds high levels of biodiversity, hosting around 20,000 plant species and 1300 nonfish vertebrate species, many of them considered to be endemic and not found anywhere else in the world (Mayers, 1988; Mittermeier, R.A. Myers, N., and Mittermeier, 1999; Myers, Mittermeier, Mittermeier, Da Fonseca, and Kent, 2000; Olson and Dinerstein, 2002). Despite the fact that the portion concealed by the BAAPA only represents a small share of the full geographic extent of the Atlantic Forest, it has been acknowledged as a highly diverse ecosystem (Catterson and Fragano, 2004). Prior to the 1940's, much of the original BAAPA forest in Paraguay remained intact, covering almost 55% of the eastern region of the country (almost 9,000,000 ha). Nevertheless, the rapid advance of deforestation has resulted in the loss of 91% of the forest, thus becoming one of the most endangered rain forests in the world (Fleytas, 2007).

Despite the existence of several deforestation reports from international organizations such as Food and Agriculture Organization (FAO) of the United Nations, the World Wildlife Fund (WWF) and the United States Agency for International Development (USAID) (Catterson & Fragano, 2004), the number of scientific studies that involve a systematic analysis of the changes remains scarce. According to a review article conducted for the entire Latin American continent, only two studies considered the BAAPA region as their main area of research (Da Ponte et al., 2015). Both studies provided a methodical analysis of the variations in the forest based on Landsat images acquired in 1970 and 2001 (Huang et al., 2007, 2009). However, these articles focused primarily on the understanding of deforestation processes and drivers through remote sensing procedures, whilst the present study not only endeavors to comprehend deforestation process but also to provide a detailed insight into the forest landscape, its fragmentation level and impact upon biodiversity conservation. Therefore, the objectives of this research are:

- Analyze the forest cover change and spatial patterns of deforestation within the BAAPA region in Paraguay
- Assess the effectiveness of protected areas
- Evaluate the connectivity of forest patches for biodiversity conservation.

4.2 Materials and Methods

4.2.1 Study Area

The present study was conducted within the boundaries of the Atlantic Forest located in the eastern region of Paraguay. It covers the portions of 10 departments in the region with a total area of 86,000 km² (see Figure 4-1). The biological richness of the BAAPA region is distributed among three main ecoregions: the Amambay/Montane Forests in the north, the Upper Paraná Forests in the east and the Central Jungle/Central Forests in the south (Fragano and Clay, 2003). Furthermore, the importance of the BAAPA forest not only relies on the richness of its biodiversity, but also on the fact that it is located above one of the world's largest aquifers (Guarani Aquifer) (Bitetti Di, M.S., Placci, G., and Alves, 2003). The eastern region of Paraguay presents a high diversity of physical and geographical features, comprising numerous rivers, grasslands, forest and the vast majority of cropland areas of the country (Bitetti Di, M.S., Placci, G., and Alves, 2003). The climate is characterised as being humid with high rainfall, varying from 1300 to 1800 mm per year, along with a mean temperature that fluctuates from 21 to 25°C. Even though the forest cover occupied a significant portion of natural vegetation, the region has been transformed and degraded by human activities for decades. In the years following 1950, the rapid advance of agricultural areas and urban settlements increased deforestation practices in the BAAPA region considerably.

Although the use of timber was not deemed as a profitable source of income, clearing for agricultural purposes became more relevant. In the 1960s, the so-called Green Agricultural Revolution introduced high-yield crop varieties and mechanised farming equipment, leading to the appearance of large agribusiness, which aimed solely at single crop production (cotton or soy). Furthermore, in the early 1970s, extensive deforestation programs expanded exponentially, devastating almost two-thirds of its Atlantic Forest by 2000 (Gao, Skutsch, Masera, and Pacheco, 2011; Pacheko, 2012). The severe increase in forest loss from agricultural practices, livestock, urban areas and unclear political regulations have left the forest with less than 13% of its original cover (Fleytas, 2007).

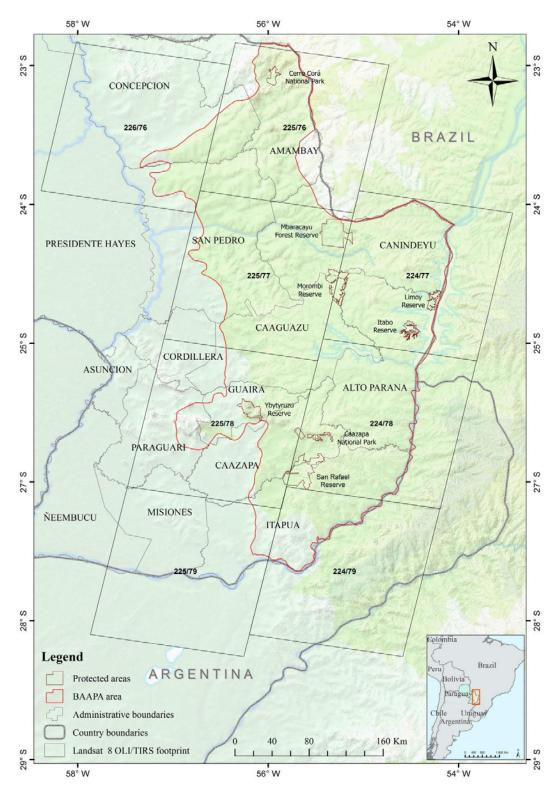


Figure 4-1. Overview of the study area and Landsat footprints (Base layer provided by Natural Earth community and Conservation International (Earth, 2013; International, 2011))

4.2.2. Data and procedures

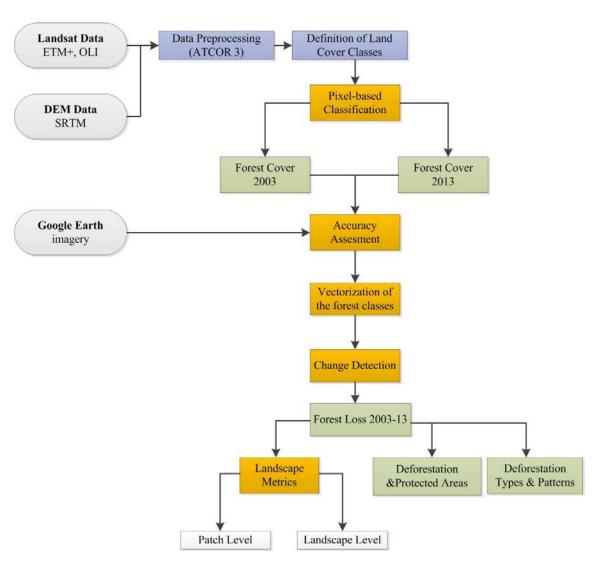


Figure 4-2. Workflow of remote sensing and GIS-based forest monitoring

4.2.2.1 Image acquisition and pre-processing

In this study, data from the Landsat Enhanced Thematic Mapper (ETM+) and the Landsat Operational Land Imager (OLI/TIRS) were obtained for the reference years of 2003 and 2013, respectively. A total of 16 L1T images (USGS, 2013) were acquired from the United States Geological Survey in such a way that each scene was characterised by relatively low cloud cover and that the scenes for each of the two reference years were acquired within the shortest possible time interval, to minimize phenologically related differences between the acquisitions (see Table 4-1). The L1T level of processing offers high methodical radiometric and geometric accuracy by integrating ground control points while

applying Digital Elevation Models for topographic accuracy (USGS, 2013). Each Landsat scene was atmospherically corrected using ATCOR-3 (Richter, 2007), transforming the original digital number values into physically comparable surface reflectance, while also incorporating the correction of topography-related biases through the inclusion of information on elevation and slope from the Shuttle Radar Topography Mission (see Figure 4-2). The ATCOR-3 package reduces the effect of the dominant atmospheric distortions originated from scattering and absorption (Song, Woodcock, Seto, Lenney, and Macomber, 2001) by estimating sensor-specific atmospheric look-up tables based on MODTRAN5 codes (Berk et al., 1998; Berk, Anderson, Acharya, and Shettle, 2008). Because the respective scenes were processed to Level 1T, the spatial coincidence between the scenes was highly accurate and thus no additional geometric correction was required. Further available geo-data included general physical and cultural vector data of Paraguay and South America (e.g. country and department borders, roads and rivers).

Table 4-1. Landsat data used in this study

Scene	Path/row	Acquisition date	Cloud cover (%)
LE72240772003148EDC00	224/77	28 May 2003	0
LE72240782003148EDC00	224/78	28 May 2003	2
LE72240792003148EDC00	224/79	28 May 2003	15
LE72250762003123COA00	225/76	3 May 2003	0
LE72250772003123COA00	225/77	3 May 2003	0
LE72250782003123EDC00	225/78	3 May 2003	0
LE72250792003123EDC00	225/79	3 May 2003	0
LE72260762003130COA00	226/76	10 May 2003	9
LC82240772013151LGN00	224/77	31 May 2013	1,18
LC82240782013183LGN00	224/78	2 July 2013	0,16
LC82240792013183LGN00	224/79	2 July 2013	0,06
LC82250762013126LGN01	225/76	6 May 2013	0
LC82250782013126LGN01	225/78	6 May 2013	0
LC82250792013126LGN01	225/79	6 May 203	0
LC82250772013158LGN00	225/77	6 June 2013	0
LC82260762013197LGN00	226/76	16 July 2013	0,12

4.2.2.2 Estimation of forest cover loss between 2003 and 2013

For each reference year, a forest/nonforest map was generated using a supervised statistical thresholding approach. In the first step, for each reference year, a training data set consisting of 40 training polygons for each of the five land cover and land use classes—forest, croplands, grasslands, water and bare soil—was created by manual interpretation. Subsequently, reflectance histograms and statistics (minimum, maximum, mean, median and standard deviation) were calculated from the sample points to define the respective class boundaries in all spectral Landsat bands.

Finally, a binary forest/nonforest mask was generated by classifying the satellite data on the basis of the defined class boundaries and by grouping all classes except the forest class to a uniform nonforest class. For validation purposes, an independent test set was generated by randomly distributing 100 sample points within each class (forest and nonforest) within each Landsat image. Subsequently, for each validation point, the respective land-cover type was evaluated by very-high-resolution imagery acquired from the historical imagery function of Google Earth for 2003 and 2013. Subsequently, a confusion matrix was calculated, and the standard measures of classification accuracy, i.e. overall accuracy, producers and user's accuracies and Kappa coefficient, were derived from the error matrix (Lillesand, T. M., Kiefer, R. W., and Chipman, 2008). The Kappa Coefficient shows the relative decrease in error caused by a classification process associated with the error of a different random classification (Congalton, 1991; Congalton and Green, 2008). The resultant forest mask was vectorised, and forest patches with area sizes below 0.5 ha were excluded to meet the minimum patch size required by the FAO forest definition (FAO, 2010). The total deforested area was estimated by calculating the differences between the forest cover masks from 2003 and 2013. Furthermore, only large continuous forest blocks (>100 km²) are resilient to environmental changes and able to maintain so-called umbrella species and ecological processes of the natural selection such as predation or pollination (Bitetti, Di, Placci, and Dietz, 2003). Therefore, deforestation inside protected areas was exclusively estimated for forest patches having area sizes greater than 100 km² in 2003, which corresponds to the minimum area required for survival by large mammals such as the puma (Puma concolor) and the jaguar (Panthera onca) (de Oliveira, T., Eizirik, E., Schipper, J., Valderrama, C., Leite-Pitman, R. and Payan, 2008; Fragano, F., and Clay, 2003; Lions, Mckinney, and Langley, 2015). In previous studies (Huang et al., 2007; Kintz, Young, and Crews-Meyer, 2006; Skole and Tucker, 1993), it was shown that anthropogenic changes become more pronounced when approaching the boundaries of protected areas, consequently leaving large intermittent patches compromising the biodiversity within them. To investigate this phenomenon, deforestation activities were additionally estimated within three buffer zones of increasing distance (5, 10 and 15 km) from the conservation area borders.

4.2.2.3 Fragmentation analysis

Forest fragmentation was assessed considering a set of well-known statistical metrics for landscape analyses. Table 4-1 includes all calculated metrics, the ecological topics they address associated, and how they are defined. The calculation was performed using V-Late Beta 2.0, an ArcGIS extension developed by Lang and Tiede, (2003), which in turn is based on the FRAGSTATS software program (McGarical and Marks, 1994). FRAGSTATS has been frequently implemented for spatial pattern analysis and quantifies the landscape structure at the three main levels, i.e. the landscape, patch and class level. Because, in this study, the forest was separated solely from nonforest types, forest fragmentation was analysed only at the landscape and patch levels. First, changes in the forest structure of the study area between 2003 and 2013 were analysed on the landscape level to elucidate the main effects of deforestation on forest fragmentation. The landscape-level metrics consider all patches within the data to characterize inherent patterns with respect to their composition, configuration and distribution of the patches over the entire landscape as a

whole (McGarical and Marks, 1994). At the landscape level, core area metrics were analysed to identify the most valuable forest patches. It is based on the ecological knowledge that many animal species avoid bordering areas and prefer to remain inside of the forest (Broadbent et al., 2008). Fragmentation metrics, on the other hand, were calculated to recognise highly fragmented patches or highly compact patches, whereas subdivision metrics provided information on the level of aggregation of the patches. Edge metrics were estimated to assess the changes in the structure of the forest occurred in the boundaries of the patches; as the edge effects increases, the greater is the biodiversity (Didham and Ewers, 2012). The reader can refer to McGarical and Marks (1994) for more detailed information regarding the metrics. In the second step, forest fragmentation was analysed on the patch level. Patch-level metrics are defined for single patches and describe the spatial characteristics and context of patches such as size, perimeter and shape (McGarical and Marks, 1994). In addition, a neighbourhood analysis (at a patch and landscape level) was performed, permitting a differentiation of forest patches regarding its embeddedness within the entire fragmented forest area (McGarical and Marks, 1994). This information is relevant when potential biodiversity corridors have to be identified between forest priority areas for nature conservation to allow the movement and distribution among species. In this case, a proximity index was calculated for all forest patches with an exemplary search radius of 500 m. The concept of proximity considers not only the distance to the nearest neighbour, but also the size and amount of nearby patches located within the search distance (Benchimol and Peres, 2015).

4.3 Results

4.3.1 Forest classification accuracy

Overall, classification accuracies derived from Landsat images obtained in 2003 and 2013 exhibited accuracy values ranging from 81% to 95% and Kappa coefficients fluctuating between 0.62 and 0.90 (see Table 4-2). and 224/77 (2013) showed the lowest accuracy values over the entire Landsat data set, reaching only 81% and 83%, respectively.

Table 4-2. Summary of accuracy assessment for Landsat images from 2003 and 2013

Landsat image data sets	Value	Overall Accuracy (%)		accuracy (%)	Producer's accuracy (%)		Kappa Statistics (%	
		Forest	Nonforest	Forest	Nonforest			
	Min	81.0	92.6	68.0	74.6	91.8	0.62	
2003	Max	95.0	99.0	92.0	92.1	98.9	0.90	
	Mean	90.21	94.78	85.87	86,94	94,38	0,80	
2013	Min	83.0	73.0	80.0	86.4	77.5	0.77	
	Max	94.0	98.0	94.0	97.7	97.8	0.88	
	Mean	90.64	91.50	89.38	91.93	92.05	0.84	

The highest accuracy value was seen in the 2003 Landsat data set. In the scene 225/76, almost 100% of the pixels were classified correctly. In contrast, the scenes 224/79 (2003) These lower values were principally the consequence of high spectral similarities between very densely vegetated crop fields (e.g. maize or soy) and forest areas.

4.3.2 Deforestation rates

In 2003, 37% (33,000 km²) of the BAAPA region was covered by forest located particularly along the north-western part of the country (see Table 4-3 and Figure 4-3). The departments of Canindeyú and San Pedro have the highest percentage of forest coverage (with 19%), each reaching forest areas estimated at more than 6000 km² (for departments see Figure 4-1). The lowest forest proportions could be found in the departments of Paraguarí (1.1%) and Guairá (3.2%), together totalling only 1493 km² forest cover.

Table 4.2	Forest cover estimation res	culte for 2003 and 2013
1 able 4-3	Foresi cover esilmation res	SHIIS TOT ZUU3 AND ZU 1.5

	BAAPA Area		Forest Cover		Forest Cover		Forest loss		Annual rate of	
			200)3	201	13			Deforestat	ion
Department	km²	%	km²	%	km²	%	km²	%	Km² /year	%
Alto Paraná	14.060	16.3	3.635	11	3.392	12.5	243	6.7	24.3	0.7
Amambay	7.356	8.5	3.219	9.7	2.461	9.1	758	23.5	75.8	2.4
Caaguazú	11.345	13.2	3.615	10.9	3.097	11.4	518	14.3	51.8	1.4
Caazapá	5.458	6.3	2.773	8.4	2.45	9.1	323	11.6	32.3	1.2
Canindeyú	14.404	16.7	6.444	19.5	5.69	21	755	11.7	75.5	1.2
Concepción	3.797	4.4	1.888	5.7	1.459	5.4	430	22.8	43	2.3
Guairá	3.423	4	1.064	3.2	985	3.6	79	7.4	7.9	0.7
Itapúa	12.122	14.1	3.755	11.4	2.968	11	787	21.0	78.7	2.1
Paraguarí	1.378	1.6	365	1.1	380	1.4	-15	-4.1	-1.5	-0.4
San Pedro	12.731	14.8	6.281	19	4.115	15.2	2.166	34.5	216.6	3.4
Total	86.073	100	33.039	37.09	26.996	30.30	6.044	18.29	604.3	1.8

By 2013, more than 6000 km² of forest cover was lost since 2003, resulting in an annual deforestation rate of 1.8% or an annual loss of approximately 604 km² over the entire BAAPA region. The department of San Pedro exhibited the highest forest loss by far, with more than 2000 km², depleting at an annual rate of 3.4%, nearly twice as fast as the other departments. The lowest deforestation rates were found in the departments of Alto Parana and Guairá, each with an annual deforestation rate of 0.7% representing an annual loss of 24.3 and 7.9 km², respectively. The only forest gain was shown in the department of Paraguarí with an annual increment of 1.5 km² (0.4%), totalling 15 km² over 10 years.

With regard to the status of protected areas, the results revealed two main findings. First, deforestation occurring inside protected areas was 3.3% (60 km²) almost six times lower than the average loss rates in the BAAPA region (18%). Second, deforestation occurring outside the boundaries of protected areas increased drastically, with rates ranging

between 13 and 35%. In addition, Figure 4-3 shows a slight gradient of cleared forest between buffer zones with larger distances from the protected areas. For instance, the protected areas of Itabó, Limoy and Mbaracayú barely presented deforestation in their boundaries.

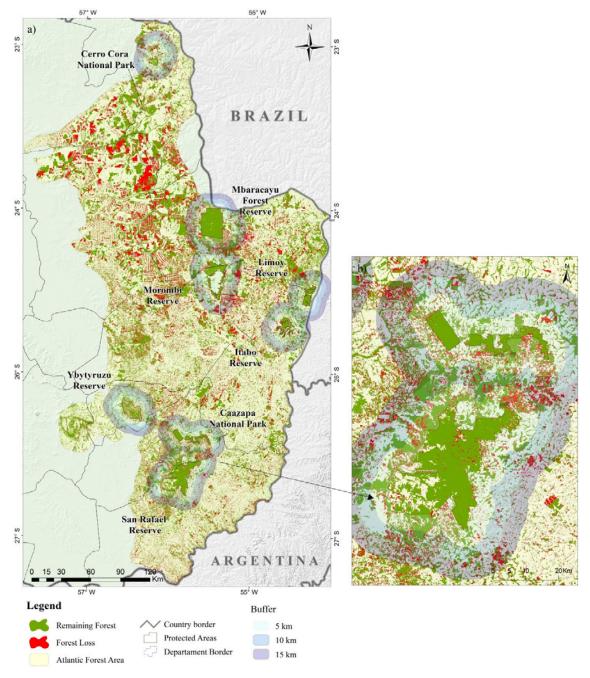


Figure 4-3. (a) Forest loss inside and outside the protected areas from 2003 to 2013, (b) Forest cover loss inside San Rafael and Caazapá National Park. (Source: Base layer provided by Natural Earth community and Conservation International (Earth, 2013; International, 2011).

However, forest loss abruptly increased in the 5-km buffer zones were approximately 41% (33 km²), 19% (15 km²), and 29% (92 km²) of forest was cleared, respectively. Similar patterns were observed in the areas of San Rafel, Morombi and Caazapá, where forest clearings inside the reserves varies between 2.8% and 4% and significantly increases along the buffer zones with rates ranging from 24% to 35%.

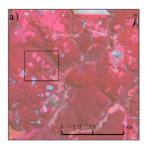
The highest percentage of deforestations that occurred inside protected areas was observed in the Cerro Corá and Ybyturzú reserves, with almost 13% (7,4 km²) and 10% (14 km²) of their forest cleared during the study period, respectively. However, clearings occurred inside their boundaries remained lower than those outside their frontiers.

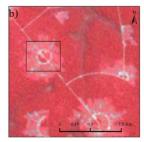
4.3.3 Deforestation patterns

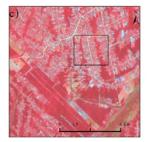
Over the study region, different patterns of deforestation were observed. In general, forest cover losses can be distinguished between small- and large-scale clearings. Defries et al. (2005) defined large-scale clearings as deforested areas greater than 100 ha, mainly the consequence of mechanised agricultural practices.

In contrast, small-scale clearing referred to cleared areas smaller than 10 ha is most often a result of subsistence agriculture, shifting cultivation and selective logging. Depending on the shape and form of the deforested areas, four main deforestation patterns were identified in the BAAPA region (Figure 4-4):

- Compact clearings: Forest loss objects that are larger than 100 ha with high values of compactness and rectangular borders.
- Fishbone clearings: Long and drawn-out objects of forest cover that are surrounded by likewise long drawn-out objects of forest loss.
- Circle clearings: Forest loss objects with shapes similar to circles.
- Speckle/spotted clearings: Forest loss objects that are smaller than 10 ha with high values of compactness and which are located within a larger forest cover area (and therefore have similar objects within its neighbourhood).







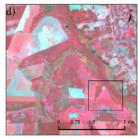


Figure 4-4. Examples of main deforestation patterns found in the BAAPA region in Paraguay based on Landsat Images from 2013. (a) Spotted or speckle clearing (< 10 ha); (b) Circle clearings (10 ha to 100 ha); (c) Fishbone clearing and (d) Compact clearing (> 100 ha).

Along the BAAPA area, large-scale clearings in the form of compact shapes (Figure 4-4d) or fishbone patterns (Figure 4-4c) were found to be more frequent comprising almost 50% of forest lost (see Figure 4-4d). Small-scale clearings in the shape of small spots or speckles below 10 ha presented the second largest deforestation pattern in the region, accounting for over 30% of the total areas deforested (see Figure 4-4a). Clearings between 10 and 100 ha were less common in the BAAPA region accounting for only 18% of the forest loss. The usual patterns found within this deforestation range corresponded to circle and fishbone clearings.

4.3.4 Forest fragmentation

Fragmentation status and priority patches were characterised by applying a range of landscape metrics to identify forest priority areas and potential biodiversity corridors (see Table 4-4). As mentioned previously in Section 4.2.2.3, fragmentation of the BAAPA was analysed on two main levels, the landscape and the patch level. The results shown in Table 4-4 provide a first insight on changing trends over the forest landscape that occurred within the last decade. At the landscape level, results derived from several metrics convey an increasing fragmentation of the forest in the BAAPA region. For instance, the total forest area (TA) was reduced from 23,000 km² in 2003 to 19,000 km² in 2013. Consequently, the number of single patches (NP) increased and the medium patch size (MPS) declined. These standard parameters already show that forest area has decreased from larger patches into smaller patches.

Furthermore, the comparison of the core forest areas in 2003 and 2013 describes the general status of forest areas with high ecological values. For example, forest area that provides a suitable habitat for species (TCA) was reduced from 11,300 km² in 2003 to 7500 km². The core area index (CAI) reveal that about 50% of the forest area in the BAAPA region was counted as core forest area in 2003, whereas in 2013, only 40% remained. In addition, the cority figures consider the number of forest patches without core areas; cority was also reduced from 0.324 in 2003 to 0.316 in 2013. In addition to forest size and its core areas, the edge length of forest patches also plays a crucial role in landscape structure analysis. For instance, a high edge density implies structural diversity. Edge density of the forest class was reduced from 94 to 77 within the last decade. The Mean Patch Edge (MPE) is the mean length of edges and was reduced from 11 to 10 km between 2003 and 2013 due to shrinking forest patch sizes. The declining edge density in combination with a decrease in the MPE also exposes an increasing fragmentation. Landscape metrics regarding the neighbourhood and subdivision also emphasise the increasing fragmentation process. For instance, the proximity index (PROX) measures the embeddedness of the forest patches in the forest mosaic; the higher the embeddedness, the lower is the fragmentation. In 2013, the PROX index had decreased from 11,000 to 8000, resulting in a higher fragmentation of the forest cover. At the first glance, the subdivision seems to stagnate at the very high level of 99% in the last decade. However, the additional subdivision indices demonstrate subdivision into increasingly unequally sized forest areas.

Table 4-4. Landscape metrics (adapted from McGarical and Marks, 1994) applied to forest patches in 2003 and 2013

Topic	Metrics [unit]	Explanation	2003	2013
Area	Total Area (TA) [km²]	Total area of the entire metrics	33,039	26,996
	Number of Patches (NP)	Number of patches in the landscape	16,343	17,786
	Medium Patch Size (MPS) [km²]	Landscape index based on the number of patches	1.4	1.1
	Patch Size Standard Deviation (PSSD) [km²]	Function of the mean patch size and the difference in patch size among patches.	18.8	12.4
Core Area	Total Core Area (TCA) [km²]	The sum of n core areas.	11,228	7596
	Core Area Index (CAI)	Relationship between the resulting core area size and the size of the total area.	48	39
	Cority	The difference in the amount of original patches and resulting patches without a core area is divided by the amount of resulted core areas.	0.324	0.316
Edge	Total Edge (TE) [km]	Total length of all edges within one class or within the whole landscape	180,401	179,127
	Edge Density (ED) [m/ha]	Amount of edge relative to the landscape area.	94	77
	Mean Patch Edge (MPE) [km]	Mean length of edges	11	10
Fragmentation	Mean Shape Index (MSI)	Indicates the level of fragmentation of forest patches by calculating the patch deviation from an ideal form of a circle	2.7	2.8
	Mean Perimeter-Area Ratio (MPAR)	Describes relationship between edge length and area of the patches	0.1	0.1
	Mean Fractal Dimension (MFRACT)	Mean curvilinearity of patch edges	1.3	1.4

Table 4-4. Continuation

Topic	Metrics [unit]	Explanation	2003	2013
Neighbourhood	Mean Proximity Index (PROX)	The shortest distance	11,377	8268
		between patches of the same		
		type within the landscape.		
	Proximity Buffer Distance (PB) [m]	Embedding of patches within	100	100
		the mosaic of the same class.		
Subdivision	Subdivision [%]	Probability that two random	99.2	98.9
		pixels are located within the		
		same patch		
	Split	Weighted average size of	132	93
		patches after subdivision		
	Mesh [km²]	Amount of equal size patches	250	145
		that result by subdivision		

The number of patches (SPLIT) decayed from 132 to 93 reflecting a decline of the real mesh size (MESH) of these areas from 250 to 145 km². Figure 4-5 presents the three patch metrics on fragmentation, MPAR, MSI and MFRACT. Very high-fragmented forest patches are highlighted in red, and the compact patches are highlighted in green and yellow. The subset shows the region of the Mbaracayú forest, which encompasses one of the largest forest patches remaining in Paraguay's Atlantic Forest. The high fragmentation level of this area is caused by many little branches that are interlinked with the large compact ones. In addition, the entire area has many little gaps, increasing the total edge length. The results demonstrate that the fragmentation level generally increases with larger patch sizes.

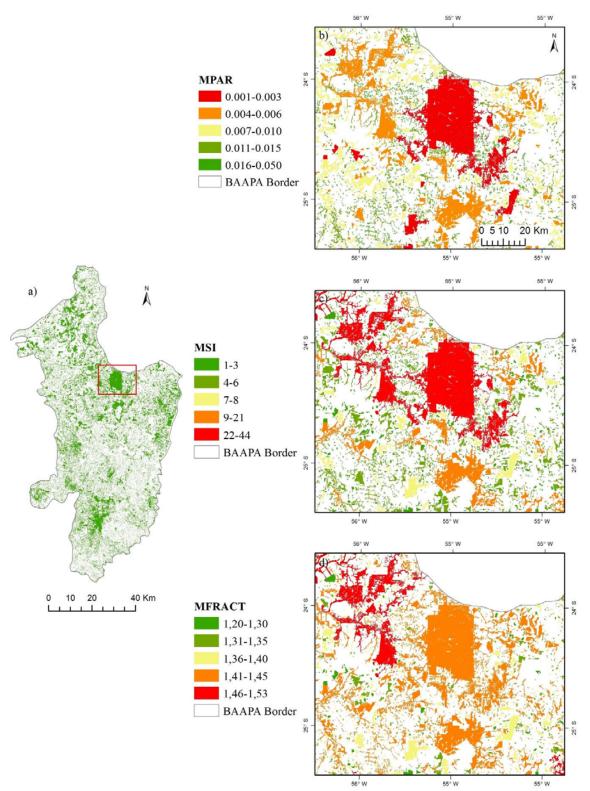


Figure 4-5. Form and shape-related landscape metrics of forest patches in 2013 in the Mabaracayú region.

4.3.5 Proximity outcomes and biological corridors.

As stated in Section 4.2.2.3, the neighbourhood analysis on a patch level permitted a distinction of forest patches with regard to their embeddedness in the entire forest area. The proximity index calculates the average distance-area relationship of forest patches within a specified neighbourhood. Figure 4-6 shows the effect of applying the patch proximity index with an exemplary search radius of 500 m over the forest landscape in the BAAPA. The forest proximity map indicates a coloured gradient of patches. The darker the colour of patches (dark brown), the greater is the proximity; lighter colours (yellow and orange) represent higher isolation between patches. Forest patches better embedded are more suitable to create biological corridors than patches with less or smaller fractions of forest within their neighbourhood (Chazdon, 2014). High proximity among patches was presented in the Caazapá, San Rafael and Mbaracayú reserves accounting for 15% of the total forest cover area in the BAAPA region. Similar conditions were observed in the eastern limits of the Mbaracayú reserve and the northern region of the BAAPA; however, no protection status was established in these areas thus far. Located mostly in the north, 19% of the forest patches fall into the medium proximity class, including fractions of Cerro Cora National park and the Ybyturzu reserve further in the south. However, the majority of the prevailing forest patches reveal low and very low proximity, accounting for 64% of the total forest coverage.

The potential biological corridors, as depicted in Figure 4-6, are an example of how the priority areas for nature conservation could be interlinked based on the proximity index as described above. Simultaneously, this also permits the identification of forest gaps within existing connections between important forest areas. In this study, exemplary forest gaps are identified if the distance between the forest pacthes are larger than 2 km. Well-connected forest remnants without any gaps exists, but only between the Mbaracayú Forest and the Morombi Reserve in the central northern part of the study area, as well as between the Caazapá and San Rafael Reserve located in the south. Potential corridors between protected areas in the north and south as well as between the north and east exist, but both are interrupted by several minor gaps. In the southern part, no connections were observed between the largest forest remnants and smaller forest areas, either in the southeastern border with Argentina or in the western corner of the BAAPA region. Protected areas such as the Itabó reserve, Arroyo Blanco and Cerro Cora National Park were identified as isolated forest islands.

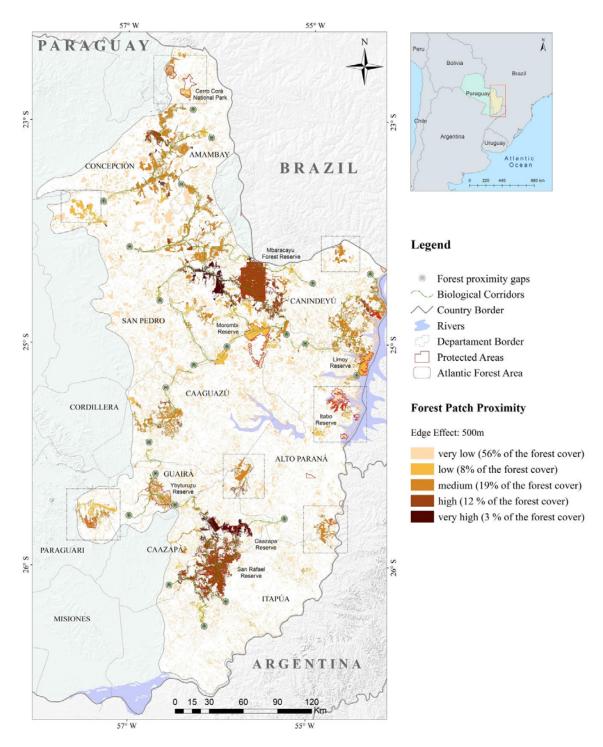


Figure 4-6. Potential biological corridors, forest core area and patch proximity within the BAAPA region (Source: Base layer provided by Natural Earth community and Conservation International (Earth, 2013; International, 2011)).

4.4 Discussion

This study focuses on the detection and characterisation of forest cover loss in the Paraguay Atlantic Forest region between 2003 and 2013. For this purpose, forest cover was mapped from Landsat ETM+ and OLI/TIRS data, applying a threshold-based classification approach with an overall classification accuracy ranging between 83 and 95%. In general, the change detection analysis revealed a forest loss of 6000 km² from 2003 and 2013 at an annual rate of 1.8 % (600 km²), mainly caused by the clearings of large areas for mechanised agricultural production. Studies from Huang et al. (2006, 2009), for instance, reported much higher deforestation rates observed for the 1990s, with about 40% of the forest lost between 1989 and 2000. With respect to the extent of the forest cover and forest loss, the resultant values from this study have shown inconsistencies with other studies. For instance, Altstatt et al. (2006) analysed forest cover losses in Eastern Paraguay between 1989 and 2001 based on Landsat images. Their study area covered entire Eastern Paraguay and therefore not only included the Atlantic Forest ecoregion but also parts of Humid Chaco and Cerrado ecoregions. Reported forest cover within their study region accounted for 31,463 km² (22%), whereas in this study, 24% (33,039 km²) of a smaller area were classified as forest in 2003. Conservation International (2013), on the other hand, exclusively considered primary forest and therefore stated that only 13% (11,618 km²) of the original forest cover remains. Discrepancies in the findings could have been related to the definition of forest, to the scale of the study or to the differentiation of forest types (e.g. primary, secondary, or riparian forest).

The analysis of forest loss inside and outside of protected areas illustrates the effectiveness of forest conservation. However, forest loss increased drastically outside of the borders of the protected areas. Deforestation rates 5-15 km from the buffer zones range from 13 up to 35%. Huang et al. (2006, 2009) described a similar trend of forest loss in the same protected areas in the 1990s. However, deforestation rates in the surrounding buffer zones of protected areas have been recorded as being much higher than in the current decade with rates ranging between 35 up to 55%. The little forest gains that were revealed in this study can be attributed to reforestation activities in the region. The textural characteristics as observed from high-resolution Google Earth images assume that these areas are forest plantations, most probably eucalyptus plantations. According to the literature and official statements of the government, Paraguay had a eucalyptus boom during recent years (INFONA, 2011). In 2011, approximately 530 km² were covered with tree plantations. Approximately, 80% of all forestry plantations in Paraguay were estimated as fast wood forestry of exotic eucalyptus species. The majority of plantations are located in the east of the country, mostly in the BAAPA area. The highest rates of eucalyptus plantations were reported in Caazapá, San Pedro and Alto Paraná with more than 100 km² of agroforestry plantations for each department (INFONA, 2011). Although forest plantations are meanwhile included in the FAO forest definition (Grainger, 2010), one has to consider their relatively low value in terms of biodiversity or compared to natural forests.

The spatial and spectral resolution of the Landsat sensor, however, did not allow for a reliable differentiation of different forest types or canopy structures. In this respect, the use of active sensors, such as LIDAR or SAR systems, as well as hyperspectral data may provide valuable inputs for the quantification and characterisation of forest quality or forest usage. Furthermore, very small disturbances or forest degradation in the BAAPA region could not be detected at 30-m resolution. Against this backdrop, great potential is seen in forest applications based on the higher resolution Sentinel-2 satellite, which maps the Earth's land area at a frequency of 5 days at 10 m resolution.

The analysis of forest fragmentation in the BAAPA area was conducted by applying different sets of landscape metrics on two levels (landscape and patch). The analysis of the landscape level allowed the comparison of landscape characteristics of the study area between the different reference years. Overall, results demonstrated an increment on the fragmentation process over the past decade. Forest loss was accompanied with a decline of the total core area, the increment in the number of patches and a decrease in the mean patch size. Similar results were already presented by several studies conducted in the tropics, where natural areas were replaced by agricultural crops, thereby causing the discontinuity of the forest and increasing the isolation level of the patches (Broadbent et al., 2008; Cayuela, Benayas, and Echeverría, 2006; Ferraz, Capão, and Vettorazzi, 2006; Marsik, Stevens, and Southworth, 2011). The patch-level analysis, on the other hand, permitted the spatial differences in the fragmentation process considering the forest landscape of 2013 to be revealed in detail. For instance, the analysis considering fragmentation metrics demonstrated the differences in shape and fragmentation between patches. Even though the values of shape-related metrics did not vary much between forest covers from 2003 and 2013, the outcome of the analysis conveys a higher tendency of fragmentation in larger patches; more little branches and higher edge lengths. Further analysis considering proximity indexes allowed for the identification of forest patches that were appropriate as a foundation for biological corridors. The connectivity between forest fragments has repeatedly been considered one of the most significant factors of population dynamics (Tischendorf and Fahrig, 2000). The capability of species to colonise a forest fragment depends on the distance of the fragments from other areas of native vegetation to some extent (Saunders, Hobbs, and Margules, 1991). Unfortunately, in the present work, it was shown that connectivity was often interrupted by larger gaps between neighbouring forest patches, and only few areas can serve as corridors. The pressure exerted by agricultural activities—especially soy bean plantations surrounding large forest patches has compromised their integrity and thus created numerous forest islands throughout the BAAPA landscape (Fleytas, 2007). An increase in the number of large isolated patches suggests a vast loss of forest cover, a recurrent trend that has already been exposed by Cayuela et al. (2006) and Imbernon and Branthomme (2001).

Finally, the methodology used in this study was appropriate to gather initial basic information on forest development and deforestation within the Atlantic Forest of Paraguay. Nevertheless, some limitations and recommendations are to be noted as follows:

- Not considering the bordering areas with other countries: Conservation strategies
 have to be evaluated beyond the national borders. For instance, the distance
 analysis used to examine forest losses inside and outside protected areas was
 limited only to forest losses within the BAAPA area. The buffer zones surrounding
 some protected areas also encompass forest losses located outside the study
 area, especially in the regions of the north and east.
- Beside the proximity or embeddedness of forest patches, there are other crucial parameters that were not accounted for in this study. For example, subdivision factors of forest landscapes, such as roads and settlements, may have other ecological impacts than fragmentation due to river networks, which would be worth examining if appropriate data were available.
- A more detailed analysis of different land cover and forest cover classes would improve and extend the results on forest fragmentation. Landscape metrics at class level, for instance, would allow determining characteristics and relationships between different land use types or forest density classes. For example, a differentiation of forest patches located in natural grassland areas in neighbouring settlements or in highly productive agricultural fields would indeed reveal additional information relevant to biological conservation.
- While in this study, the fragmentation analysis was based on different exemplary
 assumptions, for species-specific studies, the metrics related to proximity and
 connectivity have to be defined according to concrete ecological assumptions. For
 instance, birds can move more easily along the patches than other very small
 invertebrates; therefore, the distance among patches may not have the same
 significant influence on the bird population as that for other species.

4.5 Conclusions

This article provided a comprehensive analysis of forest loss within the BAAPA region in Paraguay, with a specific focus on biodiversity conservation. A detailed evaluation of spatial patterns of deforestation and fragmentation was provided, along with a characterisation of forest remnants, connectivity of the main patches and the identification of the areas considered critical for biodiversity conservation. Ultimately, a summary of the crucial findings was presented and consequently discussed, along with gaps and further recommendations. From the findings and discussion in this study, the major conclusions are as follows:

 The forest classification of the Landsat data and subsequent change detection analyses revealed a forest loss of approximately 6000 km² from 2003 to 2013, which resulted in an annual deforestation rate of 1.8% within the specified study area.

- The outcomes in this study demonstrate the effectiveness of protected areas. However, forest loss drastically increases further away from the border reserves. Consequently, protected areas are turned into isolated islands endangering the biodiversity in them as the possibility to move between reserves gradually declines. Furthermore, these tendencies indicate that there is substantial pressure on protected forest sites from outside land use, thus requiring adequate law enforcement strategies (FLEGT) to keep them effectively protected.
- Continued deforestation activities increase forest fragmentation and challenge biodiversity conservation in the BAAPA region. Fragmentation levels increase within larger patch sizes; large patches have smaller branches with higher edge lengths, whereas smaller patches are generally more compact.
- Within the highly fragmented Atlantic Forest, only very few intact forest areas for nature conservation remain and connectivity between these areas is limited or, in some cases, even blocked. Potential corridors between the protected areas in the north and south, as well as between the north and east, exist, but they are interspersed with several minor gaps.

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CHAPTER 5

Forest Cover Loss in Paraguay and perception of Ecosystem Services: a Case Study of the Upper Parana Forest.

Abstract

The Upper Parana Atlantic Forest (BAAPA) in Paraguay is one of the most threatened tropical forests in the world. Relentless agricultural encroachment has left less than 10% of its original cover intact. Many strategies and programs have been initiated, such as Payment for Ecosystem Services (PES) schemes, to halt forest cover loss. While the approach of ecosystem services (ES) has been continuously applied by policy makers, it has not been perceived strongly by the direct users of the forest. This study provides a comprehensive understanding on how landowners in the BAAPA perceive and benefits from ES derived from the forest and examines the influence of farmers on forest conservation. The results were obtained from an extensive household survey performed in the BAAPA region. An understanding of the high ecological value of the forest is common to all farmers. A strong dependency on forest-related products was observed for small and medium landowners whereas large-scale farmers considered the forest's main value to be mostly recreational and cultural. PES appears to be well accepted by forest owners, but it must receive stronger promotion. Understanding the importance of ecosystem services is a valuable contribution towards to conserving natural resources.

5.1 Introduction

Tropical forest cover has fluctuated greatly over recent decades. The continued encroachment of agricultural crops, cattle ranching, and illegal logging has endangered their connectivity, by converting the last remnants of tropical forest into isolated patches. (FAO, 2007). Between the 2000 and 2005 South America has lost over 22 million ha of forest, accounting for almost 60% (22, 3 million ha per year) of total forest cover loss in the world (FAO, 2007, 2010, 2015a). Even though deforestation rates have decreased compared with previous years (WWF, 2013), they remain a crucial concern. Recent studies conducted on a global scale identified Paraguay as one of the countries in Latin America with the highest deforestation rates worldwide (Hansen et al., 2010; Hansen et al., 2013). The rapid deforestation rate has resulted in the loss of 90% of the forest cover in the eastern region of the country, where the Upper Parana Forest is situated (Fleytas, 2007). The Upper Parana Forest includes 15 ecoregions that encompass a total area of 471,204 km². It extends from the Atlantic coast of Brazil, passing through the eastern region of Paraguay and reaching the northwestern side of Argentina (Bitetti et al., 2003).

The eco-region has a high level of biodiversity and includes numerous endemic species that are not found anywhere else in the world (Mayers, 1988; Mittermeier, Myers and Mittermeier, 1999; Myers et al., 2000; Olson and Dinerstein, 2002). Before the 1940s, much of the original Upper Parana Atlantic Forest in Paraguay (BAAPA) remained intact covering approximately 55% of the eastern region of the country (nearly 9,000,000 ha), but currently less than 10% of its original cover remains (Fleytas, 2007; Hutchison and Aguino, 2011, Da Ponte et al., 2015). One of the major reasons attributed to deforestation activities in the BAAPA, besides the continuous expansion of mechanized agriculture (particularly soybean production), is the lack of profitable opportunities for forest owners. There are few economical alternatives besides timber and charcoal production. Consequently, the high levels of income obtained from agricultural exports have encouraged the expansion of large-scale crop production, tempting small-scale farmers to lease their land to large companies that are interested solely in single crops such as soy bean and maize. There are several strategies, conventions, and monitoring programs that were implemented to halt forest loss. One of the most promising alternatives is the Payments for Ecosystem Services (PES) program, also known as payments for environmental services (WWF, 2015b). The PES compensates farmers with incentives for managing their land to provide any type of environmental service (WWF, 2015b). The described concept has been implemented by the Paraguayan Government under the name of "Valuation and Retribution of Ecosystem Service Law 3001/2006" (PES 3001/2006). The regulation establishes a mechanism in which forests owners receive compensation for preserving their forest reserves and other natural environments, rather than converting their land into other land uses. The Paraguay forest regulation (422/73) requires that properties larger than 20 ha must preserve the natural forest on 25% of its land area. The PES 3001/06 law permits landowners with environmental liabilities to purchase environmental certificates from those who exceed the 25% minimum forest cover required for a renewal period of 5 years (Kernan et al., 2010). The Ministry of Environment in Paraguay (SEAM) has established a fixed cost for environmental certificates based on the eco-region from which the certificate has been issued, and this cost varies between \$154 USD (Chaco Meadows) and \$885 USD (Central Littoral) per ha.

According to SEAM, of the 20 registered properties, seven are located in the BAAPA, and only one of these forest owners had made a successful transaction for the sale of one certificate for 15 ha (\$570 USD per ha) (SEAM, 2016). Ecosystem services (ES) was defined by the Millennium Ecosystem Assessment (2005) as "the benefits that people obtain from ecosystems" (Carpenter, 2005). The ES definition includes provisioning services such as timber and firewood; regulating services such as erosion and climate regulation; supporting services such as nutrient cycling and soil formation; and cultural services such as recreational and spiritual (Figure 5-1). ES can be differentiated based on their use value: direct use values (for forest, e.g., the provision of wood and medicine); indirect use values (for forest, e.g., purification of water strands and tourism); option values (for forest, e.g., genetic resources); and existential values (for forest, e.g., educational and spiritual) (Hein et. al, 2006).

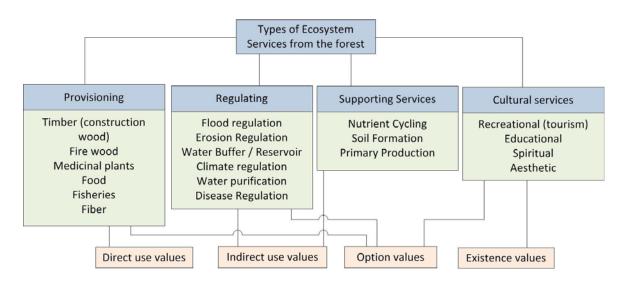


Figure 5-1. Ecosystem service and ecosystem service value derived from the forest. (Adapted from MEA, 2005)

While the ES approach has increasingly been included within environmental regulations as a way to support biodiversity conservation and sustainable management of ecosystems (e.g., National law 7575/1996 PES in Costa Rica, PES 3001/2006 law in Paraguay, and the 30215 law in Peru) (Bennet and Henninger, 2009; Kernan et al., 2010; Alegría, 2012; Casado-Arzuaga et al., 2013; WWF, 2015a), the comprehension of its concept remains limited (Lamarque et al., 2011). The small number of studies that considered the local peoples' perception of ES prevents effective implementation of proper ES-based conservation initiatives (Sodhi et al., 2009). Awareness about ES differs among sites, based on cultural characteristics, geographic location, life experiences, and use of natural resources (Daily, 1997; Costanza, 2000; Kuenzer, 2013; Grima; 2016). Thus, case studies are considered to be especially important for capturing these local differences (Lamarque et al., 2011). The goal of this study is to provide a comprehensive understanding of the perception of forest ecosystems services in the BAAPA; the type of landowners who inhabit in the area and their educational background; how the usage of the services derived from the forest differs among different farm types (small, medium, and large); the degree of interest towards to susceptibility to conservation/restoration programs; and the current challenges and threats facing the BAAPA. The outcomes obtained in this study provide useful information when contemplating the importance of social involvement in land-use planning.

5.2 Study area

The Upper Parana Atlantic Forest is located in the eastern region of Paraguay (Figure 5-2 (b)). It encompasses portions of ten departments and 141 districts in the region, accounting for a total area of 86,000 km² (DGEEC, 2002).

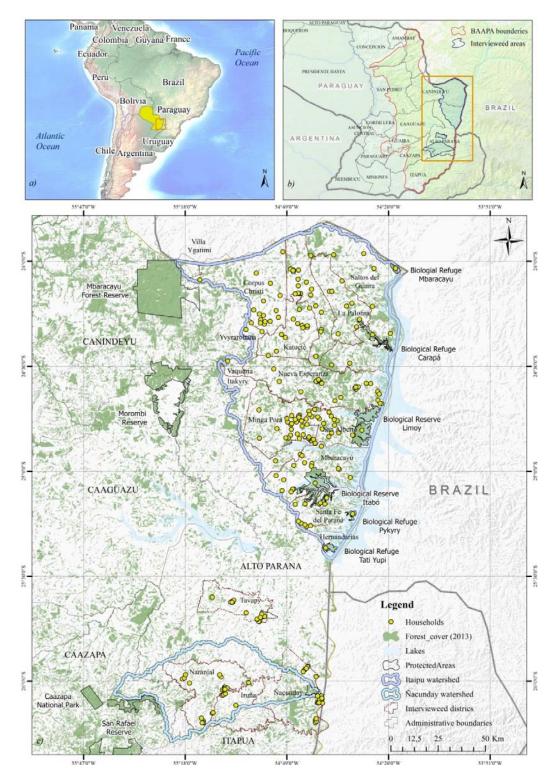


Figure 5-2. (a) - (b) Paraguay and BAAPA location (source: base layer adapted from Natural Natural Earth (2014). (c) Household's distribution within the selected study areas (source: base forest layer adapted from Da Ponte et. al (2016).

The BAAPA contains almost 50% (over 3,167 million inhabitants) of the country's population, who are distributed between 65% (around 2,065 million inhabitants) in urban settlements and 35% (over 1,102 million inhabitants) in rural areas (DGEEC, 2002). Cities with a larger population in the ecoregion are situated in the East (Ciudad Del Este) and South (Encarnación), whereas the North is less occupied. According to the Landscan Project (Oak Ridge National Laboratory, 2013), in 2010, the average population density outside urban areas varied between 5 and 100 residents per km² (Oak Ridge National Laboratory, 2013). The climate of the Atlantic Forest is typical for sub-humid tropical zones with frequent rainfall that varies from 1300-1800 mm per year. The annual average temperature is 22°C with a relative humidity of 80%. However, the temperature fluctuates considerably between seasons. During winter months (May-August), temperatures can drastically decrease to 0°C, whereas in summer, (December-March) they can rise to 42°C. The main economic activities in the region are cattle ranching, cotton and corn, sugar cane, mate tea (Ilex paraguariensis), and soy bean production. Paraguay produces approximately nine millions tons of soy beans per year, accounting for three percent of worldwide production (Markey, 2014). Currently, over 3 million ha (90% of the country's production) of soy bean plantations are located within the boundaries of the BAAPA region (MAG, 2008). However, projections from the United States Department of Agriculture (USDA) estimate that soy production could grow over the next 5-10 years, to cover up to 4 million ha (Markey, 2014).

The ecology of the region includes semi-deciduous forest, which predominates in the landscape of the BAAPA (Stern, M. and Kernan, 2011). Forest types in the area can broadly be classified as follows: high forest, with large trees up to 35 m tall that are of high timber value (*Handroanthus heptaphyllus, Cordia trichotoma*); low forest, with open savannas and flooded areas that are mainly used for charcoal and firewood (*Peltophorum dubium, Luehea divaricata*); riverside forest, along the riverside and flood plains with only a small commercial value (*Ruprechtia laxifolia, Cupania vernalis*); and savanna forest, which are small areas that are highly important for research purposes (*Gochnatia polymorpha, Helietta apiculata*) (Stern, M. and Kernan, 2011).

In the 1950s, much of the original BAAPA forest cover remained intact. At that time, forest cover still accounted for 8,931,000 ha (55% of the eastern region of the country). Since the late 1960s, deforestation rates have increased steadily. According to Huang et al. (2007, 2009), direct causes of deforestation were associated with the long-held perception of the forest as nonproductive land, the frequent *unsustainable use of forest resources by settlers*, and the expansion of the agricultural frontier. Between 1973 and 2000, Paraguay lost almost two thirds of its Atlantic Forest, reaching deforestation rates of 2,000 km² per year (Huang et al., 2007). Although, the government intended to encourage reforestation programs in the late 1990's as a mean to limit ecological damage (incentives to forestation and reforestation law 536/96), it did not achieve good results (UN-REDD, 2010). The lack of economic resources along with unclear regulations decreased the trust of local landowners towards the government, stating that in most of the cases "no financial support was given" (UN-REDD, 2010).

In 2004, the Paraguayan government passed the "Zero Deforestation Law" (2524/04), which forbids any conversion of forest lands in the eastern region of the country (Hutchison and Aquino, 2011; Kernan et al., 2010). According to the World Wildlife Fund (WWF) (2013), deforestation rates in the Atlantic Forest decreased by 90% from 2002 to 2009, from 110,000 ha per year to 8,000 ha per year. Following this initative, in 2003, the government created the PES law 3001/06 (Kernan et al., 2010).

The BAAPA forest provides various goods and services for the local people and industries who settle in the region. According to the Ministry of Agriculture of Paraguay (MAG), charcoal and firewood constitute the main source of energy for more than 51% of rural livelihoods and for 87% of the industrial sector in the area (MAG, 2008). Over 50,000 ha of fuel wood is harvested every year for the purposes of energy production (MAG, 2008). The BAAPA comprises suitable environmental conditions for forest farming such as *Ilex paraguayensis* (mate tea crops) or *Ananas comosus*. Additionally, the BAAPA has been frequently used as a source of food and medicinal goods. The forest supports soil erosion control, and is also used as a resting area. However, inhabitants with less economic resources tend to generate income via direct use of natural resources (frequently resulting in extensive wood harvesting) rather than sustainably generating a long-term income. The unsustainable extraction of forest resources has led to ever-increasing forest defragmentation and forest degradation.

5.3 Materials and methods

A socioeconomic household survey was conducted in the BAAPA region in January 2016. Two hundred seventy-seven interviews were conducted with the designated head of each household (Figure 5-3). Two field technicians from WWF Paraguay, two forestry students from the National University of Asuncion (U.N.A), and other field assistants (e.g. school teachers and local leaders) helped with performing the interviews. To ensure that the interviews were undertaken in an identical manner, interviewers were first trained and agreed on the questioner standards before the field survey started. Because of the BAAPA region's large size, three sample areas were selected to conduct the survey: the ITAIPU watershed (1,000,000 ha) in the North, and the \tilde{N} acunday watershed (250,000 ha) and Tayapy district (43,600 ha) in the South (see Figure 5-2(c)). The selected regions have been working closely with the United Nations (UN) program on Reducing Emissions from Deforestation and Forest Degradation (REDD+), PES, and restoration initiatives because of their status as priority areas for conservation (WWF, 2015a). They were considered to be pilot project areas for carbon stock and environmental credit programs (WWF, 2015a). For example, in 2012, WWF Paraguay started a project (Paraguay Land Use (PARLU)) under the framework of REDD+ program. PARLU aimed to integrate human activities and forest conservation by developing alternative livelihoods that could lower the pressure of deforestation and forest degradation. The total sampling area comprised two departments (Alto Parana and Canindeyú), and 19 districts inhabited by over 279,300 people who live in 42,490 individual households. To include all types of forest owners in the region, six protected areas within the ITAIPU watershed (see Figure 5-2(c)) were included in the survey, and the leader responsible for each forest reserve was interviewed.

The sampling approach was based on a "convenience sampling methodology" by taking into account factors such as the willingness of potential respondents, extreme weather events (such as severe flooding, intense rain storms, and blocked roads) restricting the access to farmers, and time limitations resulting from the size of the selected areas. The survey was carried out over a 6-week period. Each interview was conducted in Portuguese, Spanish, and Guarani (indigenous language) with each taking about two hours to complete. The survey consisted of a 13-page questionnaire that was designed in English and translated into Spanish and partially into Guaraní.



Figure 5-3. Different type of households in the BAAPA region. A) Precarious indigenous settlement (small-scale farmers group). B) Typical small farmer household. C) Medium farmer household. D) Large farmer household (soy bean producer

The sample size was calculated by applying the formula of Yamane (1967) after Israel (1992) and Kuenzer (2013), as shown in equation (1):

$$n = N / [1 + N(e)^{2}]$$
 (1)

where n is the samples needed; N is the sample population; and e is the sampling error (7%).

According to Equation 1, a total of 204 samples are necessary to achieve representative results. The present household survey yielded responses of a total of 277 households, and can thus be considered as representative of the region.

The survey comprises 117 questions overall, of which 41 were multiple choice questions allowing for a single answer only; 66 were multiple choice questions allowing for multiple answers; and 10 were open-ended questions. When analyzing the collected data, landowners were differentiated *according to the size* of their farm, as follows: small-scale farmers were landowners with <20 ha; medium-scale farmers were landowners with 20–50 ha; and large-scale farmers were landowners >50 ha (Figure 5-3). This stratification was based on the same standards applied by the Ministry of Agricultural of Paraguay in its rural censuses (PNUD, 2010). In regards to protected areas, there were not enough reserves to consider them as a separate category, so protected areas were placed into the large-scale farm group considering the size of the reserve (all of them larger than 50 ha). The collected data was analyzed using the Statistical *Package* for the Social Sciences (*SPSS*) software. Correlation exploration applying frequency and contingency tables was used to visualize relevant patterns and to present the findings as plots and charts, which are shown in the following sections.

Thus, a questionnaire was developed regarding the state of the BAAPA and local expertise from experienced working professionals (non-governmental organizations (NGOs)) in the region based on the above information. The survey also focuses on some broad properties of the rural population, such as job, income, education level, land surface, and forest type. These factors also serve as an indicator of the importance to the forest by local farmers (e.g. respondents with a low income level would be more likely to depend on forest resources for subsistence). The survey is divided into several sections that focus on different aspects. Section 1 relates to the general properties of the household such as educational background, land ownership, land size, and net income. Section 2 is orientated to assess the perception of landowners towards the natural forest by including a variety of question such as: how do you define the forest? Do you have any knowledge of which forest species are on your land? Do you think that natural forests serve a particular function? Where did you learn about these functions? Do you think that forests have an economic (monetary) value? How important is the forest for your livelihood? Are there any negative characteristics of the forest that you would like to mention? Overall, section 2 is dedicated to the value that farmers place on the forest. In section 3, the survey evaluates the uses of the forest by farmers, focusing on the benefits and products obtained from the forest along with their related economic value, and how much the forest contributes to the overall annual income of the household. Section 4 is oriented towards conservation and protection programs, assessing the participants' understanding of such programs and their willingness to participate in the programs. Section 5 is dedicated to the participants' characterization of their forest land, such as forest regulations, opinions, and experiences with law enforcement, and expected future trends.

5.4 Results

5.4.1 Demography

Interviews for this study were conducted with the designated head of the household. Approximately 87% of the respondents were males, predominantly between 40 and 55 years of age. Most interviewees had a primary or secondary school education (Figure 5-4). The proportion of respondents with primary education slightly decreased as farm size increased, varying from 67% (for small-scale farmers) to 40% (for large-scale farmers). Secondary school, however, differs from the previous trend where most respondents were medium scale-farmers (29%) and large-scale farmers (24%). The largest proportion of farmers with a lower education level was found in the small-scale farmers group, which accounted for 17% of interviewees without a school education. Conversely, a higher education (university level) is more common among large-scale farmers, who comprised 28% of the respondents in this category. Household ownership varies between Colons (Brazilians) and Paraguayans. Figure 5-5 shows a gradient trend: Paraguayan ownership tends to decrease with larger farm size. About 88% of the small-scale farmers interviewed were Paraguayans, whereas 87% of large-scale farmers were Colons.

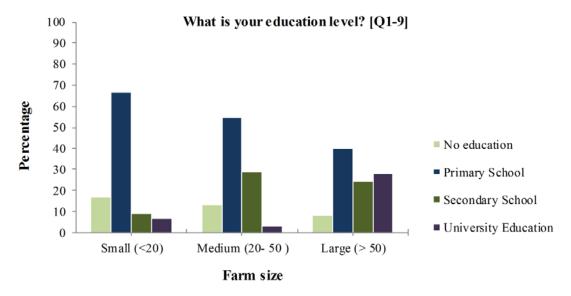


Figure 5-4. Education level according to farm size of respondents [Q1-9].

Household size varied between one and 11 members, with an average of three to five family members. When asked about their main occupation, almost 94% considered themselves to be farmers, whereas a smaller percentage (6%) held jobs in governmental institutions or owned grocery stores in addition to farming. The interviewed farmers focused mainly on soy bean production (large-scale farms), cattle (medium-scale and small-scale farms), mate tea (small-scale farms), and subsistence agriculture (small-scale farms). The average land area owned by the farmer groups is 750 ha for large-scale

farmers, 27 ha for medium-scale farmers and 9 ha for small-scale farmers. Interviewees were asked for their average annual salary, not taking into consideration the income source. Answers were given in Guaranies (PGY) and converted into USD. For the purpose of this study, five different categories were established, ranging from less than \$1,000 USD to over \$50,000 USD.

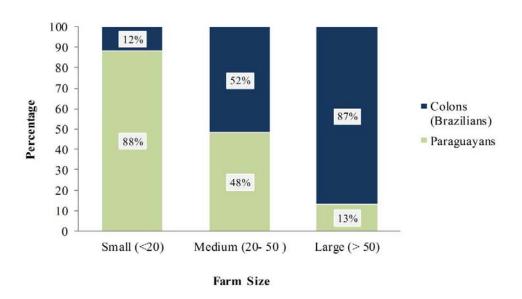


Figure 5-5. Household ownership according to farm size of respondents [Q1-6].

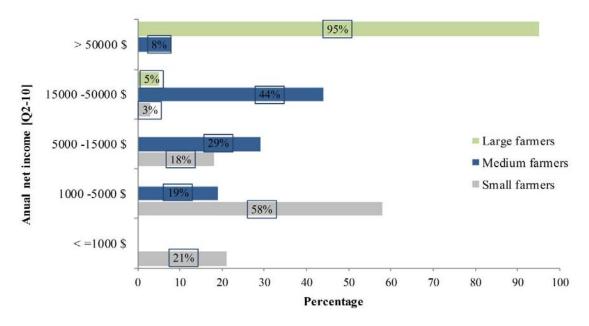


Figure 5-6. Income distribution according to farm size of respondents.

Results in Figure 5-6 show that land ownership is broadly proportional to annual salary. In general, over 34% of households have an income below the annual rural wage per capita (around \$6,500 USD estimated by the Direction of Census and Statistics from Paraguay (DGEEC, 2002)), when considering that household sizes average three to five members in the region. Small-scale farmers had the lowest income, with 79% of the respondents in the range of \$250–\$5,000 USD per year. Moderate to high incomes were reported in the medium-scale farmers' group with incomes ranging from \$11,000 USD–\$81,000 USD for 81% of the respondents. Large-scale landowners had the highest annual income, accounting for 95% of the interviewees and with profits above \$50,000 USD. They reached this level of income principally from large-scale mechanized farming (mostly soy bean production).

5.4.2 Understanding of natural forest perception in households

In general, there is no clear definition of a forest. Most interviewees used either a single or multiple functions of a forest to characterize it. Approximately 64% of the respondents referred to the forest as a natural area that needs to be conserved. The majority of the respondents (95%) understood the importance of the forest for water cleansing, biodiversity conservation, erosion control, cultural heritage, and recreational purposes, and to provide natural resources (such as medicinal plants, firewood, and construction wood). The forest functions described here were not recognized by less than 4%. When asked about how they learned these functions, almost 43% of the respondents stated "from personal experience" and 38% indicated "from teachers or professors". With regards to the economic value of the forest, almost 95% agreed that the forest had an economic value, but stated that it did not contribute actively to their net income (according to 71% of the respondents).

Are any negative aspects of the forest that you would like to mention? [Q3-9]

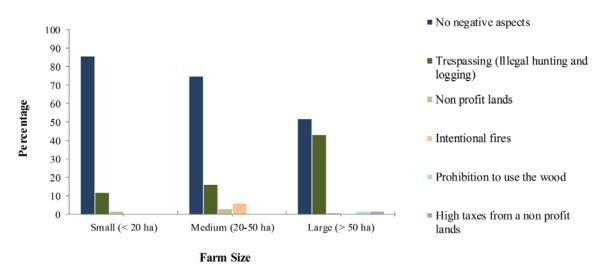


Figure 5-7. Negative aspects of forest according to farm size.

When asked about the negative characteristics of a forest, 30% of the respondents pointed out certain conflicts caused by the presence of natural areas. Figure 5-7 shows that trespassing, either because of illegal logging or hunting, is a major threat reported by all farmers' groups; the larger the farm, the higher the rate of trespassing.

5.4.3 General uses of forest in households and forest related income

Overall, 79% of landowners stated that they frequently benefited from the forest, and 92% considered the forest to be important for their livelihoods. A more in-depth analysis (Figure 5-8) revealed that 97% of small landowners indicated that they were highly dependent on the forest. Medium-scale farmers, however, showed less dependence on forest resources (Figure 5-8), although 77% stated that they still use these resources. Unlike the previous groups, 56% of large-scale farmers claimed that they did not use the forest, whereas the remaining 44% stated that they made some use of it, but not intensively. Figure 5-9 shows the types of uses for the forest, and about 93% of small-scale farmers stated that they use the forest especially for collecting firewood. However, a decreasing trend is observed in the group of medium- and large-scale farmers, where the extraction of firewood is 55% and 28%, respectively (Figure 5-9). Similar tendencies were seen in the use of the forest for construction wood. While 83% of small-scale farmers used the forest as a source of wood for construction, this use is less frequent among medium- and large-scale farmers (45% and 19% of the respondents, respectively). Small land owners showed a high reliance on forest products, which can be attributed to the lack of sufficient income (Figure 5-9).

100 3% 90 26% 80 56% 70 Percentage 60 No 50 97% Yes 40 77% 30 44% 20 10 0 Small (<20) Medium (20- 50) Large (> 50)

Farm Size

Do you use the forest for any purpose? [Q4-1]

Figure 5-8. Utilization of forest (yes /no) according to farm size.

For example, as seen in Figure 5-3 A and B, most small households own houses built from wood extracted from the forest. Additionally, harvesting firewood appears to be required by small-scale farmers, and 90% of these farmers depend on firewood for subsistence proposes (cooking). In contrast, medium- and large-scale farmers do not rely as much on forest products; most of them live in permanent homes with access to electricity and gas. Although they still harvest wood from the forest, they do so to produce wooden poles for fences or wooden barns for raising cattle. Unlike small-scale farmers, large land owners (41% in this category) considered the forest's main value to be recreational, while 12% acknowledged the agroforestry option, and only 5% mentioned harvesting medicinal plants.

Figure 5-9 shows that 48% and 39% of small landowners use the forest for forest farming and medicinal proposes, respectively. Most farmers engaging in forest farming (either large- or medium-scale farmers) do so for mate tea production as an additional source of income, while harvesting medicinal plants is mostly used for self-consumption. Farmers were further asked if they think that harvesting for construction or fuel was legal: 71% of respondents thought it was allowed; only 23% were fully aware that it was illegal and over 6% did not know. This suggests that most of the harvesting that is being carried out happens with the (erroneous) understanding that it is permitted. Thus, 70% of the harvesting is being done by small-scale land owners, of whom 78% do not possess any knowledge of environmental regulations. When asked how much more of their yearly income would have to be designated for firewood if the forest was not available, answers varied from \$18–\$4,000 USD, with an average of \$476 USD. For wood supplied for the purpose of construction, the estimated replacement cost if no free-of-charge resources were available fluctuated from \$36–\$7,000 USD (with a mean of \$1,553 USD).

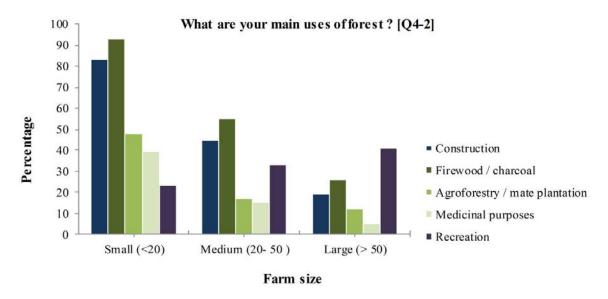


Figure 5-9. Main uses of the forest according to farm size.

Taken together, this amount would be equivalent to 46% of the income of the annual rural wage (\$6,500 USD according to the DEGEEC 2002). Farmers were also asked how much forest-related products contribute to their annual earnings. Interviewees were able to choose between four categories: all of it, more than 50%, between 50% and 30%, or none of their household income could be attributed to the forest. Because the category "all of it" was not selected by any of the respondents, Figure 5-10 only shows the remaining three categories. In general, 73% of the respondents stated that forest-related products do not contribute to their income. Figure 4-10 shows that small-scale famers are the group with the highest dependency on the forest, with 40% of the respondents claiming that forestrelated products contributed between 30% and 50% of their annual income. Most mediumscale farmers (22%) had profits from the forest that were in the 30-50% range, because their earnings were principally from agroforestry practices and mate production. Additionally, Figure 5-10 presents large-scale farmers (10%) as the group that profits the most from the forest, claiming that the forest contributes to over 50% of their annual income. However, this trend may be because the respondents were in charge of protected areas where the economy is largely depended on tourism. Farmers were asked to estimate the worth of 1 ha full of forest. Interviewees could freely state a figure, without any ranges given. No clear pattern was seen among farm sizes. Answers ranged from \$12,000-\$15,000 USD, with an average of \$13,671 USD. Some farmers frequently stated that 1 ha full of forest would not be attractive to purchase at this time, because the current environmental regulations prohibit the transformation of forest land into land for other uses. Profits obtained from forest-related products cannot be compared to the ones from agricultural lands (soy bean production) in terms of revenue on the national/international market. When landowners were asked if they thought that cutting down forests would reduce their income, 75% of small-scale farmers agreed, whereas 56% and 74% of medium- and large-scale famers disagreed, respectively.

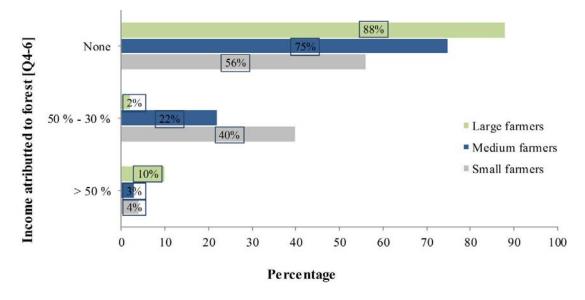


Figure 5-10. Percentage of household income attributed to forest related productst according to farm size.

5.4.4 Perception of forest protection and conservation programs

To understand perceptions about preserving the BAAPA, farmers were asked if the natural forest should be protected. Overall, positive feedback was obtained, with 98% of the respondents showing their support for protecting natural areas. Landowners were further asked if they would consider reducing forest lands to increase agricultural productivity: over 84% disagreed by highlighting the importance of forests for their livelihoods. Additionally, 91% of farmers claimed that if the forest disappeared it would have a negative impact on the environment and associated natural resources, such as water reservoirs, and local fauna. Following the set of questions, farmers were further asked if they considered that it would be better if more trees were planted. Responses varied by owned land size (see Figure 5-11). Strong support towards reforestation was seen among smallscale (95%) and medium-scale (78%) farmers, but 48% of large-scale farmers agreed, as long as their current agricultural crop lands would not be converted into forest. However, 29% of the overall respondents indicated that reforestations could not take place because all their lands were covered by crops. Since the region was recently affected by extreme weather events, landowners were asked what the importance of preserving the forest to reduce erosion or for protection against storms meant to them. The majority of small-scale (86%) and medium-scale (70%) farmers agreed that a decrease in forest land on their property would increase the risk of erosion, while 59% of large-scale famers claimed that erosion can be controlled by "good agricultural practices", which are independent of the presence of forest. People were further asked if the forest provided any kind of protection for their crops. Generally, over 77% of landowners believed that the forest serves as a barrier against soil erosion or that it reduces the damage caused by intensive rain. However, there is a large group of landowners (23%) who do not acknowledge the forest as a means of protection, particularly large-scale farmers (39%).

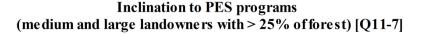
Inclination to reforestation programs [Q12-1]



Figure 5-11. Predisposition to reforestation programs according to farm size.

This trend is not surprising because for large scale soy production, forests are not considered to be relevant (according to the respondents), either to enhance the production itself or as a mean of protection against pests and diseases. People were also asked if they believe that extreme climate events were related to the disappearance of the forest. While the majority of small-scale (90%) and medium-scale (69%) farmers agreed, 68% of large landowners did not agree. The respondents claimed that during the 1970s, similar events occurred in the region, when the area was still covered entirely by forest.

With regards to conservation programs, farmers were asked if they ever received information concerning the sustainable use of forest and natural resources. Overall, 60% of respondents confirmed their involvement in workshops or programs, but large-scale farmers had the highest attendance (67%). When the respondents were asked about their main motivation, 56% of the respondents selected "improve the environment" as their main motivation, 33% stated that they wanted to "increase their income", and 11% indicated "to be alienated by current environmental regulations". Based on the results, farmers appear to be highly environmentally conscious. Moreover, 68% of the respondents indicated that to date, they are still using the information they acquired in the programs or workshops to protect water resources, agroforestry systems, and forest farming. People were asked about their knowledge of the PES and the possibility that they would use their forest lands in the program. During the interview, "understanding of the PES program" was acknowledged when respondents had some knowledge of the basic tenets of the program. The large-scale landowners group had a higher percentage of respondents (46%) who were aware that the PES program existed compared with medium-scale (20%) and smallscale (11%) farmers. Figure 5-12 shows the willingness of farmers to include their properties in the PES program.



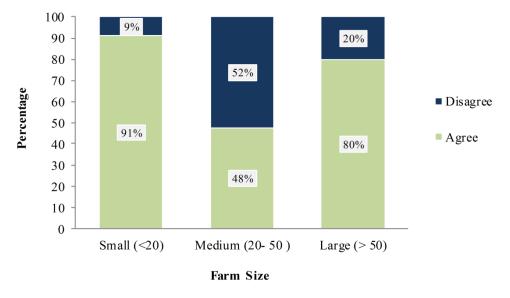


Figure 5-12. Predisposition to PES programs according to farm size.

According to PES law, only properties with more than 20 ha must fulfill the regulations of the 422/73 law (maintaining more than 25% of their property as natural forest) to benefit from the program. Small landowners (<20 ha) are exempt from the 422/73 law. Thus, any remnant of natural forest can be considered for environmental credits as long as they conform to the requirements set by the Ministry of Environment of Paraguay (SEAM). As presented in Figure 5-12, strong support for the program was shown among small-scale (91%) and large-scale (80%) farmers.

5.4.5 Perception of the general state of the forest and expected future trends

Over the last part of the survey, the questions were intended to understand how farmers perceive the status of the forest and which notable challenges the BAAPA is likely to face in the future. When asked about the state of the BAAPA, 57% of the respondents indicated that they lacked knowledge concerning the rapid disappearance of the eco-region. Responses among different farmer groups were compared, and large-scale landowners (60%) seemed to be more familiar with the current state of the BAAPA, whereas 77% of small-scale farmers lacked knowledge about the status of the overall eco-region. Additional questions were asked about environmental laws. Similar to the previous section, understanding of environmental regulations was defined as when respondents were aware of any of the current environmental laws in the country (e.g., afforestation and deforestation laws, water courses regulations, and penalties for breaching the environmental legislation). According to our analysis, medium-scale (80%) and large-scale (96%) farmers had a higher percentage of respondents with some knowledge of environmental laws compared with small-scale farmers (22.4%). However, this trend could be because farmers who own more land (medium-scale and large-scale) are engaged in more activities related to environmental permissions and transactions as a result of the size of their property, which might be affected by new regulations and laws.

When farmers were asked for their opinion on current environmental regulations, more than 80% of the respondents indicated their satisfaction with the existing legislation. However, farmers claimed that a high level of corruption was seen among national authorities who were responsible for law enforcement, which compromised the conservation of natural areas. People were also asked the state of their own forest and the future of the BAAPA. Figure 5-13 presents the farmers' perception of the status of their own forest. The amount of forest left intact increased along with the size of the properties (Figure 5-13). Degraded forest, however, seems to be the most common land category for all groups. Distinct from intact forest, bush lands appears to be more common on smaller farms and decreases as farm size becomes larger. Bush lands in the BAAPA region are commonly known as "capuerones", or lands covered by bamboo, bushes, and weeds, that has no economic value. All farmers groups referred to their forest as "degraded" when no valuable species of considerable height and diameter (over 10 m high and 30 cm of breast height (DBH)) were found on their land. Intact forest, however, was defined as a forest which has not been disturbed over the last decades and which had a high frequency of valuable tree species that still dominated the upper canopy. Finally, when farmers were asked about the future of the BAAPA over the next 10 years, 61% of the respondents believed that the forest cover would continue to decrease.

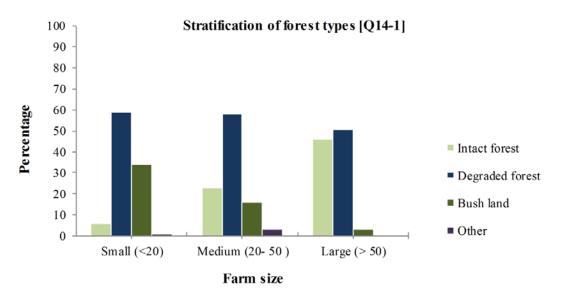


Figure 5-13. (a)-(c) Stratification of forest type according to farm size (represented in percentages) [Q14-1].

5.5 Discussion

The value given to the forest and the services provided is a topic of significant importance, but it has not been well studied (Lamarque et al., 2011). If the objective is to implement successful environmental policies that are intended to lead to the sustainable use and conservation of natural resources, local users from the forest must be involved (Sodhi et al., 2009; Casado-Arzuaga et al., 2013). Therefore, their opinions, preferences, and tendency towards conservation initiatives must be understood (Casado-Arzuaga et al., 2013).

The present study focuses on understanding how the BAAPA's ecosystem services are being perceived by different farmers' groups and to determine the influence of these groups on forest conservation. Throughout the present study, a social dependence on the services provided by the forest was observed. Farmers depend directly on the ecosystem for subsistence. However, their level of reliance varies according to farm size; less dependency was seen as farm size increased. For small-scale farmers, dependence on the forest is closely related to their income level. For example, a small-scale farmer who owns only 5 ha of land and is a government employee could earn up to \$5,000 USD per year (DGEEC, 2002) without exploiting the forest for subsistence purposes. However, a small-scale farmer with 18 ha of land and no other source of income can earn less than \$1,000 USD per year (DGEEC, 2002), thus depending heavily on the forest for subsistence. However, among the interviewees, few farmers had jobs in governmental institutions (e.g., professors, accountant assistant, nurses) or private companies (e.g., technical coordinators, salesman, and administrators). Similar results were observed in several studies such as Hartter (2010), Balvanera et al. (2012), Casado-Arzuaga et al.

(2013), and Kuenzer et al. (2013), where reliance on the ecosystem differed with the source of income (major job type) and the type of ecosystem analyzed.

The survey identified three main categories of ecosystem services used by the respondents: provisioning services (collecting firewood, timber for construction, medicinal plants, and understory crops), cultural services (recreation), and regulatory services (erosion control and water cleansing) (Figure 5-1) (Carpenter, 2005). Provisioning services appear to be more significant for small-scale and medium-scale farms, whereas cultural services are more important to large-scale landowners. The present trend appears logical because the income level among the different farmers' groups had a large variation, and thus, the reliance on forest resources for daily subsistence also differed. For example, whereas firewood and timber are essential for food and shelter among small-scale farmers, forest goods for medium-scale and large-scale farmers would be better described as an additional source of income. Large-scale farmers used forest resources much more sparingly than did the other classes of farmers. However, this restraint in resource use is related to the constant pressure exerted on the farmers by environmental authorities. Large-scale farmers perceive that they are constantly been pursued by local authorities who demand payment in exchange for permission to use the forest, whereas small-scale farmers are allowed to use the forest without restriction. However, according to forest law 542 article 25, "all landowners (no exception concerning farm size) who want to benefit from the forest must obtain a permit issued by the SEAM" (MAG, 2002).

The forest's regulatory services seem to be more important to small-scale and medium-scale farmers, especially for erosion control and water retention. Large scale-farmers, however, do not see the relevance of the forest to these services, stating that soil conservation can be achieved equally well by implementing good agricultural practices (e.g., direct seeding system). An additional service, primarily identified by small-scale farmers, consists of the ability of the forest to provide the necessary ecological conditions for forest farming (mate production mostly). Despite this farming practice being common only among small-scale farmers, forest farming was shown to be profitable when diversification of the production is needed to generate additional income (Montagnini et al., 2011). For cultural services, large-scale farmers use the forest primarily for recreational purposes, which could be related to their fear of environmental authorities penalizing them for other uses (as described above).

Overall trends in the percentage of income obtained from forest resources indicate that forest products mostly do not contribute to the annual household income. The observed trend is consistent with the large majority of farmers who consider forest products to be insufficient (in monetary terms) to secure their subsistence livelihoods. Especially for small-scale farmers, this tendency can be attributed to their lack of proper land management. Thus, natural resources have been degraded to the point where only a few products can be obtained, which are used solely for self-sufficiency. Additionally, small-scale farmers tend to lease their properties (between \$700 and \$800 USD per ha per year (according to the interviewees)) to large soybean producers, leaving only a small share of land for their own crops. Depending on the global market and production (per ha per year), a soy bean producer can earn up to \$2,100 USD per ha per year (MAG, 2008). Unlike soy crops, forest products (from natural areas) in the country do not have a stable market,

which hinders proper commercialization of the products (according to the respondents). When farmers were asked how much 1 ha full of forest was worth, figures given by the respondents were according to actual price of the land itself in the region (based on the National Service of Cadastral Data from Paraguay (SNC)), independent of the percentage of forest cover on their property. Currently, most of the interviewees perceive that 1 ha of soy crops holds a higher economic value than 1 ha of natural forest.

All farmers' groups (especially small-scale farmers) showed a strong interest in for the PES 3001/06 law, even though their knowledge of the details of the program was limited. Study cases from Brazil and Costa Rica demonstrated that, at least for small land owners, PES programs presented positive results to alleviate poverty (Wunder et al., 2008). However, to date, only a few landowners have registered their forest lands, citing the many regulations and large amount of paperwork involved in obtaining the required certificate. Similar constraints were found in Costa Rica and Mexico by Porras et al. (2013) and WWF (2015b), who showed that administrative issues discourage the inclusion of properties in the PES program. However, many respondents mentioned that all natural resources should be preserved because ecological resources must be protected, and therefore, there was no need to compensate the stakeholder for following the law. The same group of respondents referred to the PES program as being unfair; for them, every farm should contribute their share for the well-being of the environment and not just acquire certificates to be in compliance with the law. On the other hand, a small amount of farmers considered that payments established for 1 ha of forest in the region is not sufficient. The cost of protecting the forest itself (e.g., construction of fences, monitor the area, administrative cost to acquire the certificates) is much higher than the annual payments fixed by the PES program. Comparable outcomes were obtained from studies conducted in Brazil (Eloy et al., 2012; Wunder et al., 2008) where the cost opportunity of the land was compared with the low economic return from PES (Eloy et al., 2012 and Wunder et al., 2008). In general, better promotion of PES among farmers is needed, with a special focus on farmers with environmental liabilities (possible buyers) and farmers with large portions of forest cover (certificate owners). Moreover, the bureaucratic process and all administrative issues have to be simplified to increase the appeal for forest owners to participate.

Results of the survey also revealed a high level of environmental awareness among the respondents. Some properties (large-scale soybean producers) maintained forest reserves up to 300 ha beyond the area required by the law (>25% of the land), without receiving any kind of compensation. However, a higher percentage of farmers with environmental liabilities (lack of riparian forest or necessary forest cover) were observed on site. Several stakeholders stated that restoring the forest on their property was difficult, because most of their lands were already cultivated; to them, the forest represented a restriction to the expansion of agricultural areas. Additionally, misconceptions about forest laws were observed. For example, according to the forest law (422/73), a 25% forest cover is required for properties larger than 20 ha (without considering riparian forest), and several stakeholders counted the forest along the riverbanks in their total.

This results in an overestimation of the percentage of natural forest area on their land, which leads to a disagreement with the environmental authorities about when reforestations activities should be conducted to fulfill the environmental regulations.

Although the results showed stakeholder compliance with existing environmental laws, these laws, such as the 4241 law (riparian forest buffer) and the 542 law (forest resources), were not fully understood (MAG, 2002).

In the last part of the survey, farmers were asked about the future of the forest. A belief common to all stakeholders was that forest cover in the BAAPA would decrease over the next 10 years. The following statement is consistent with studies such as Hansen et al. (2013) and Da Ponte et al. (2015, 2016), which showed that the loss of forest cover in the BAAPA continues even when deforestation laws are in place. The level of corruption among environmental authorities was mentioned by all farmers' groups as the main factor obstructing forest preservation. In addition, a strong conflict of interest between farmers' groups was observed during the survey. Whereas small-scale farmers blame the large-scale farmers for cutting down the forest to expand their monoculture, large stakeholders blame small-scale farmers for trespassing, setting fire to their forests, illegal logging, and hunting. However, during the survey, few large-scale farmers admitted their previous mistake of cutting down the forest, defending themselves by saying that "they did not know the harm they were doing to the environment".

The responses derived from the survey might have some bias. First, the ministry of environment in Paraguay is currently concentrating its efforts on establishing a stronger enforcement of environmental laws in rural areas. Therefore, large-scale farmers might more conservatively answer questions about the condition of their forest, the use of forest resources, and general perceptions, to discourage further legal action by the government. The diversity of the interviewer's background could also have affected the responses in the survey, particularly within the group of farmers interviewed by WWF technicians. The constant pressure exerted by NGOs toward the enforcement of environmental regulations and conservation of natural resources, might have misled the true nature of the survey itself. Thus, WWF technicians could not have been perceived as neutral entities, which may have caused some bias in the responses. Finally, the distribution of the samples was affected by extreme weather events, making it difficult to access properties and properly cover the study areas. Thus, Figure 5-2 shows a clustering of the samples especially within the Tavapy district and the districts that are within the *Ñacunday* watershed.

5.6 Conclusions

The goal of this study was to provide a comprehensive analysis of the perception and the value given by local landowners to the BAAPA's ecosystem services. Interviews were conducted individually with the designated representatives of 277 households distributed randomly among the ITAIPU and Ñacunday watersheds and the Tavapy district, including the departments of Alto Parana and Canindeyú. The total study area covered 1,250,000 ha and included 42,490 households with 279,328 inhabitants.

The forest provides a variety of supplies such as firewood, timber, ecologic conditions for forest farming, medicinal plants, erosion control, and recreational areas. However, because of the rapid expansion of large mechanized agriculture, forest lands in the BAAPA region have been disappearing rapidly. In a socio-economic survey undertaken in January 2016, a variety of topics were covered regarding farm size, income, education, the

perception of the forest, the use of natural resources, and environmental awareness. The mean household income greatly differed according to farm size. In general, 79% of farmers used the forest for a variety of purposes. Moreover, the use of forest for firewood and timber plays an important role for the farmers. From the people interviewed, 52% used the forest for firewood or construction, without taking into consideration the current forest legislation. However, the extraction of wood has not been made completely illegal. Larger-scale farmers indicated their disagreement with the current local authorities, claiming that, unlike small-scale farmers, local authorities harassed them when they used the forest. Wood-related products from the BAAPA add up to an average of \$6,500 USD per year (46% of the annual rural wage) that farmers would have to spend if the forest was unavailable. However, according to 73% of farmers, forest products do not contribute to their annual net income. Among the farmers, small landowners presented the highest dependency on the forest, with 40% of respondents claiming that forest goods contributed up to 50% their annual income.

The household survey showed the correlation between the importance of the forest and farm size. Whereas small-scale farmers see the forest as an essential source of goods for subsistence, medium- and large-scale farmers placed more importance on its cultural and recreational services. In general, 84% of the respondents considered the forest to be important for their livelihood and 91% claimed that if all the forest were logged, it would have a big impact on the environment. It can be concluded that farmers understand the importance of the forest as a functional ecosystem that offers a variety of services and plays a significant role on the equilibrium of the environment. However, products obtained from natural forests are not seen as a profitable source of income. Soy bean production still remains the most lucrative activity in the region.

Fifty-two percent of large-scale farmers felt skeptical of restoration programs because these programs could interfere with their former crops. PES programs were seen as a suitable alternative for almost 73% of the respondents, either as a way to purchase certificates or to register their lands. Farmers who did not agree with the PES program (27%) frequently mentioned the lack of environmental responsibility from other farmers or neighbors, who were only interested in solving their environmental liabilities by purchasing environmental certificates. Thus, PES still requires further promotion (so that farmers have a better understanding of the concept) and a streamlined administrative processes to facilitate the procurement of environmental certificates. Establishment of pilot farms demonstrating successful cases of the program could increase forest owners' interest. Additionally, stratification of the payment levels should be considered, based on the type and quantity of services provided. Although the value of the PES certificates in Paraguay varies according to the relevance of the ecoregion, further environmental criteria would offer valuable assets for farmers to increase the remuneration from PES. Generally, over 70% of farmers possessed degraded forest or bush land.

Large-scale farmers held the largest remnants of intact forest, mostly because they applied the "Zero Deforestation Law" (2524/04). In general, 61% of the farmers indicated that the forest cover would decrease over the coming 10 years, mainly because of weak law enforcement and corruption among the environmental authorities.

The results of this questionnaire provided insight into the differences in perception and usage of the forest among the distinct farmers' groups. Further studies could analyze the obtained information from the field in combination with remote sensing data. Responses could be validated by studying the dynamics of the forest cover from the farms visited (based on cadastral data) in combination with answers on perception and uses of forest services. Further decision-making for management of natural resources based on ES should consider the outlook of the rural population, and also strive to satisfy the needs of the different occupational groups in the region. Targeting priority areas for conservation and landowners who are likely to include their lands in environmental programs could ensure that conservation program goals are achieved over time.

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5 Forest Cover Loss in Paraguay and perception of Ecosystem Services: a Case Study of the Upper Parana Forest

CHAPTER 6

6 Assessing Forest Cover Dynamics and Forest Perception in the Atlantic Forest of Paraguay, Combining Remote Sensing and Household Level Data

Abstract

The Upper Parana Atlantic Forest (BAAPA) in Paraguay is one of the most threatened tropical forests in the world. The rapid growth of deforestation has resulted in the loss of 91% of its original cover. Numerous efforts have been made to halt deforestation activities, however farmers' perception towards the forest and its benefits has not been considered either in studies conducted so far or by policy makers. This research provides the first multi-temporal analysis of the dynamics of the forest within the BAAPA region on the one hand, and assesses the way farmers perceive the forest and how this influences forest conservation at the farm level on the other. Remote sensing data acquired from Landsat images from 1999 to 2016 were used to measure the extent of the forest cover and deforestation rates over 17 years. Farmers' influence on the dynamics of the forest was evaluated by combining earth observation data and household survey results conducted in the BAAPA region in 2016. Outcomes obtained in this study demonstrate a total loss in forest cover of 7500 km2. Deforestation rates in protected areas were determined by management regimes. The combination of household level and remote sensing data demonstrated that forest dynamics at the farm level is influenced by farm type, the level of dependency/use of forest benefits and the level of education of forest owners. An understanding of the social value awarded to the forest is a relevant contribution towards preserving natural resources.

6.1 Introduction

Tropical Deforestation in the tropics today continues inexorably with severe implications for biodiversity conservation, climate regulation and ecosystem services such as carbon storage. The rapid expansion of the agricultural frontier, cattle ranching and illegal logging has converted the world's last remnants of tropical forest into isolated patches endangering their continuity (Carlson and Mitchell, 2011). Between 1999 and 2005, 69 million ha of forest have been lost in Latin America accounting for almost 7% of the forest cover of the continent (Tejaswi, 2007). Despite the fact that its speed has declined in comparison to previous years (WWF, 2008), deforestation still remains a concern.

The latest studies conducted on a global level identified Paraguay as one of the countries in Latin America with the highest deforestation rates (Hansen M., Sethman S. and Potapov, 2010). The continuous anthropological pressure on natural resources has led to

the loss of 90% of the forest cover in the eastern region of the country, where the Atlantic Forest is located (Fleytas, 2007). The Atlantic Forest encompasses 15 ecoregions and a total area of 471,204 km² (Bitetti Di, M.S., Placci, G., and Alves, 2003). The ecoregion is considered to be a biodiversity hotspot, due to the presence of numerous endemic species that are unique in the world (Mayers N. 1988; Mittermeier et al. 1999; Myers et al. 2000 and Olson 2002). Even though the portion of the Atlantic Forest (also known as the Upper Parana Forest (BAAPA)) within Paraguay only represents a small share of the complete geographic extension of the ecoregion, it has been recognized as a highly diverse ecosystem (Catterson, 2004). According to Huang et al. (2007), the BAAPA forest cover decreased around 50% of its original cover between 1973 and 2000, in less than 30 years (Carlson and Mitchell, 2011). Latest studies (Fleytas, 2007; Bitetti et al., 2003; Mayers, 1988; Mittermeier et al., 1999; Myers et al., 2000; Olson, 2002; Catterson and Fragano, 2004; Huang et al., 2007; Hutchison and Aquino, 2011) estimated that only 10% of its original cover remains. One of the major drivers of deforestation in the region is the expansion of mechanized agriculture and a lack of economic opportunities for forest owners (Grossman, 2012; Kernan et al., 2010). Economic alternatives to service wood production (e.g., construction wood, fire woods and charcoal) are limited for the local population. As a result, it is tempting for small-scale farmers to lease their lands to large companies that produce exclusively monocultural crops such as soy beans and maize (Valiente and Gerard, 2016). A common perception among farmers in the region is that one ha of soy crops simply holds a higher economic value than one ha of native forest. In addition, the low economic compensation that can be obtained for forest products cannot compete with the high levels of income generated by agricultural exports (Da Ponte et al., 2017a).

Over the past decades, several governmental institutions, e.g., Forest National Institute (INFONA) and international organizations (e.g., Food and Agriculture Organization of the United Nations (FAO), the World Wildlife Fund (WWF) and the United States Agency for International Development (USAID)), have used remote sensing data to assess deforestation in the BAAPA. Nevertheless, despite the existence of numerous deforestation reports, major parts of the spatial analysis are kept in clusters and some even considered sensitive information (Da Ponte et al., 2015). According to Da Ponte et al. (2015), only few scientific studies have provided a systematic analysis of forest cover change in the BAAPA region (Huang et al., 2007; Huang et al., 2009; Da Ponte et al., 2017b). These studies estimated the dynamics of the forest cover and forest structure by implementing solely bi-temporal analysis based on Landsat images spanning the years 1970 to 2001 and 2003 to 2013, respectively. Even though the discussed studies successfully identified deforestation processes and patterns with remote sensing techniques, no attempts were made to understand the underlying drivers of change or the effectiveness of conservation policies. No ground information that could capture local circumstances (e.g., uses of natural resources, farm types and cultural characteristics) between forest owners has been included in past analysis. For instance, recent studies conducted in the BAAPA (Da Ponte et al., 2017a; Bragayrac E., 2014) have demonstrated that farmers' perceptions of the importance of the forest vary according to farm types. Farmers with less economic resources depend more heavily on the forest, whereas larger farmers consider the forest's main value to be recreational/cultural.

Hence, it is to be expected for small-scale farmers to present a higher percentage of farms exhibiting a decrease in their forest cover. In order to address these shortcomings, in this study, a dense set of Landsat imagery is applied on the one hand to provide the first multi temporal analysis of forest cover change in the BAAPA region (to the knowledge of the authors) between the years 1999 and 2016. On the other, remote sensing and household level data are combined to understand how farmers' perceptions of the forest affects conservation practices at the farm level. The goal of this study is to measure the influence of farmer's educational background on the dynamics of the forest, how changes in deforestation frequency differ according to farm type (small, medium, and large), how farmers' dependency on natural forest resources influences changes in the forest cover, and the impact farmers' participation in conservation programs has on preservation. The outcomes obtained in this study provide useful information when contemplating the importance of social involvement in land-use planning.

6.2 Data and Methods

6.2.1 Study area

This study was conducted in the Upper Parana Atlantic Forest of Paraguay (BAAPA), located in the eastern region of the country. The ecoregion comprises portions of ten departments, resulting in a total area of 86,000 km² (see Figure 6-1) (DGEEC, 2003). Almost 50% (over 3 million inhabitants) of the country's population is located within the boundaries of the BAAPA (DGEEC, 2003). The areas of highest population density in the ecoregion are located in the east (Ciudad del Este) and south (Encarnación), whereas in the north the population decreases (DGEEC, 2003). The climate in the Atlantic Forest is characterized by frequent rainfalls that fluctuate between 1300 to 1800 mm per year. The temperature in the region varies greatly between seasons. During summer months (December-March), the temperature can increase up to 42 °C, while over winter (May-August), it can decrease down to 0 °C. Most of the diverse biological richness of the BAAPA is distributed in the ecoregions of the Montane Forest in the North (Amambay), the central forest in the south and the Upper Parana forest in the southeast (Catterson and Fragano, 2004). Although forest cover represents a significant portion of the natural vegetation in the ecoregion, the severe pressure from anthropological activities has degraded the forest with only a few remaining fragmented patches (Huang et al., 2007 and Huang et al., 2009).

Prior to 1940, the BAAPA forest covered over 55% of the eastern region of the country (accounting for almost 9,000,000 ha). Nevertheless, uninterrupted deforestation practices resulted in the loss of 90% of its original cover (Fleytas, 2007). Currently, 90% of the country's soy bean production on 3 million ha is located within the boundaries of the BAAPA region (MAG, 2010). According to studies such as Huang et al. (2007, 2009), causes of deforestation were related to the long-established perception of the forest as unproductive lands, the rapid expansion of the agricultural frontier and the unsustainable use of natural resources. By the year 2000, almost two-thirds of the Paraguayan Atlantic Forest was lost, with an annual average deforestation rate of 2000 km².



Figure 6-1. (a) Overview of the study area (Base layer provided by Natural Earth Community and Conservation international (Patterson and Kelson, 2006; Mittermeier, 2004)). (b) Paraguay and the Upper Parana Atlantic Forest (BAAPA) location (source: adapted from Natural Earth Patterson and Kelson, 2006)). (c) Household distribution within selected study areas.

The government introduced reforestation programs in the late 1990s (incentives to forestation and reforestation law 536/96) to diminish the damage done in the BAAPA, yet unfortunately, these did not obtain remarkable results.

The lack of clear regulations and financial support discouraged land owners from introducing further lands into the program (UN-REDD, 2010). By 2003 at the latest, Paraguay had become the country with the second highest deforestation rate in the world (WWF, 2013). In response, the Paraguayan government approved in 2004 the "Zero Deforestation Law (2524/04)" for a period of two years, which prohibited the conversion of any parts of the Atlantic Forest in eastern Paraguay (Hutchison and Aquino, 2011; Kernan et al., 2010). According to reports from the World Wildlife Fund (WWF, 2013), deforestation rates decreased drastically as a result, slowing by over 90% from 2002 (110,000 ha of forest loss per year) to 2009 (8000 ha of forest loss per year).

6.2.2 Landsat image acquisition and pre-processing

For this study, Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 8 Operational Land Imager (OLI) data were acquired between the reference years of 1999 and 2016. Taking into consideration the high temporal and spatial resolution of the Landsat images, the sensor was considered the most suitable for this research. As presented in Table 6-1, a total of 2775 terrain corrected (L1T) images with less than 30% cloud cover were obtained from the United States Geological Survey (USGS) archives. In order to decrease any possible noise and data gaps resulting from clouds and further atmospheric distortions, the number of satellite images to be used per classification was increased by considering data of two years for each map.

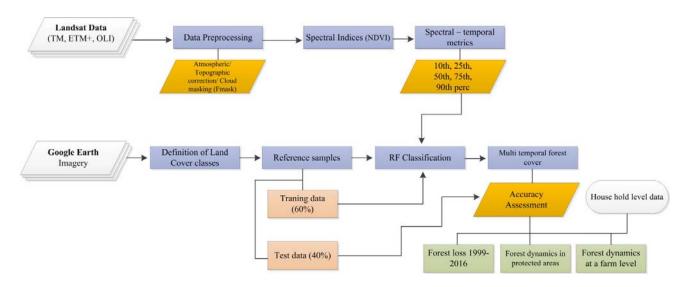


Figure 6-2. Workflow of remote sensing data processing and classification procedures (source: adapted from Mack et al. (2017).

This permitted to obtain a denser temporal coverage from the study region. Similar to Wohlfart et al., (2017), Knauer et al., (2017) and Gebhardt et al., (2014), the FMASK (Function of mask) algorithm was applied over the Landsat images to identify and mask pixels classified as clouds shadows or no data (see Figure 6-2). The FMASK algorithm was developed to automatically detect and mask clouds, cloud shadows and snow from Landsat images by taking the spectral and textural features into consideration based on probabilistic scores (Zhu and Woodcock, 2012). Atmospheric corrections were performed with ATCOR-3 (Richer and Schläpfer, 2016) for each Landsat scene to obtain physically comparable surface reflectance information, while also integrating topographic corrections by incorporating slope and elevation information from the Shuttle Radar Topography Mission.

Table 6-1. Landsat data and number of processed scenes used in this study.

Sensor	Path/Row	Acquisition dates	Number of Scenes	Total	
	224/77	07/1999 -11/2011	116	930	
	224/78	04/1999 -11/2011	108		
	224/79	01/1999 -11/2011	106		
Landsat 5 TM	225/76	01/1999 -11/2011	112		
	225/77	01/1999 -11/2011	118	300	
	225/78	01/1999 -11/2011	121		
	225/79	01/1999 - 9/2011	127		
	226/76	02/1999 -10/2011	122		
	224/77	08/1999 - 07/2016	190		
	224/78	08/1999 - 08/2016	177 188		
	224/79	09/1999 - 08/2016			
Landsat 7 ETM +	225/76	07/1999 - 07/2016	198	1514	
Lundsat 7 L TW	225/77	07/1999 - 08/2016	197	1014	
	225/78	07/1999 - 08/2016	194		
	225/79	10/1999 - 08/2016	179		
	226/76	08/1999 - 08/2016	191		
	224/77	05/2013 - 08/2016	43 40 42 44	331	
	224/78	05/2013 - 08/2016			
	224/79	07/2013 - 08/2016			
Landsat 8 OLI	225/76	04/2013 - 07/2016			
Lanusal o OLI	225/77	04/2013 - 07/2016	41	JJ 1	
	225/78	04/2013 - 07/2016	45		
	225/79	04/2013 - 07/2016	43		
	226/76	04/2013 - 08/2016	33		

6.2.3 Spectral-temporal Landsat time-series metrics

The use of continuous spectral-temporal metrics not only has proven to solve problems related to data gaps (a consequence of clouds), but also has been applied extensively as a reliable approach for separating land cover/use classes (Griffiths, et al., 2014; Hansen, et al., 2014; Müller et al., 2016; Mack et al., 2017). A variety of different spectral-temporal metrics were estimated based on bi-annual Landsat stacks, characterizing different land cover classes for the most prominent phenological information. The procedure follows the approach as described in Mack et al. (2017) and Wohlfart et al. (2017). The lack of temporal regularity of Landsat acquisitions constrains the direct quantification of phenological metrics. Therefore, several bi-annual spectral-temporal metrics were computed from the Landsat scenes in order to obtain proxies for seasonal information. For this study, several statistical image metrics were derived (percentiles of 10, 25, 50, 75, 90%) from Landsat (TM, ETM+, and OLI) observations based on the reflectances of the five bands (blue, green, red, near infrared and short-wave infrared). For each band and index, multi-year percentile differences (90% minus 10% and 75% minus 25%) were calculated. As described in Mack et al. (2017) interannual minimum and maximum were neglected in order to decrease noise and further outliers. In addition, Normalized Vegetation Index (NDVI) percentiles were computed. Hence, a total of 35 multi-temporal spectral features were considered as input variables in the classifications.

6.2.4 Estimation of forest cover between years 1999-2016

Forest / non-forest maps were produced for every year between 1999 and 2016, employing a random forest (RF) (Breiman, 2001) classifier to generate inter-annual thematic change maps based on spectral-temporal metrics (see Figure 6-2). For each reference year, training samples were randomly collected over the BAAPA area, resulting in a set of at least 100 homogeneous training polygons (as suggested by Congalton and Greene (2008)) for each of the five land cover/use classes forest, croplands, grasslands, urban areas, and water. Training and validation samples were well distributed over the study area to obtain the most representative coverage of land cover/uses in the region. Following the procedures of Wohlfart et al. (2016), visual interpretation of very-high-resolution images (acquired from the historical imagery function of Google Earth between 1999 and 2016) was performed to define the classes of the training and validation samples. The interpretation was based not only on the image interpretation but also on local expert knowledge of the area.

The RF algorithm has been increasingly applied to conduct land cover mapping due to its performance, user friendliness and computer proficiency (Pal, 2005; Gislason et al., 2006; Schneider, 2012). RF is a decision tree algorithm which selects random subsets of learning samples and of variables to build multiple (default value of 500) independent decision trees. Models were built and adjusted using the statistical software R (version 3.3.1) using its random forest package (Liaw and Wiener, 2002). The pixel-wise classification applies the majority vote rule from aggregated decision trees to determine the final category. In this study, RF models with 500 independent trees were built for each two-year composite, resulting in a total of 8 individual models.

Default values for the mrty parameters were used, which traditionally is \sqrt{p} , where the number of predictors in the dataset is represented by p.. In order to train the RF classifier, 60% of the reference dataset served as the training input, and the remaining 40% of the samples as the verification set. The quality of each classified image was described through overall accuracies, producers' and users' accuracies, and Kappa coefficients derived from the error matrix (Lillesand et al., 2008). Finally, a non-forest mask was generated by grouping all non-classes. Forest patches with an area smaller than 0,5 ha were excluded from the analysis, considering the forest definition established by FAO (FAO, 2010). In order to analyze the long-term differences of forest dynamics between protected areas (of different ownership) a long-term (bi-temporal) analysis of change was conducted by comparing forest classifications results for the reference years of 1999-2000 and 2015-2016.

6.2.5 Household survey data

For this study, a household socio-economic survey (277 households) was conducted in the BAAPA region (see Figure 6-1c) in January 2016 over a period of one month. Due to the large size of the BAAPA region, three sample areas were chosen to conduct the survey; the ITAIPU watershed dam (10,000 km²) located in the north, the Nacunday watershed (2,500 km²), and the Tavapy district (436 km²) situated in the South (see Figure 6-2(c)). Respondents were stratified according to the size of their farm, following the categorization applied by the Ministry of Agricultural of Paraguay in its rural censuses (PNUD, 2010). Farmers with land size < 20 ha represent the small-scale farmers group; farmers with land sizes of 20-50 ha represent the medium-scale farmers group; and farmers with land size > 50 ha represent large-scale farmers. In general, the survey focuses more on aspects of the rural population (e.g., job, income, education level and land size) and their relationship with the forest (e.g., how they define "a forest,", their knowledge of its functions, and its importance for their livelihood), their use of forest resources and services (e.g., firewood, construction and forest farming) and conservation programs (e.g., understanding and participation in such programs). For further detail information on the (conducted) household surveys methods and results, the interested reader is referred to Da Ponte et al. (2017).

6.2.6 Combining household and remote sensing data

Using cadastral information, long-term forest cover change results for the reference years 1999–2000 and 2015–2016 were correlated to responses acquired from the field survey. For 106 of the interviewed farmers, cadastral data was obtained from the Paraguayan National Cadastral Service (SNC). Further, information was acquired on site during the field campaigns by measuring the limits of 39 farms while it was feasible to do so; for small-scale farms in particular, the topographic and weather conditions needed to be appropriate for doing so. This resulted in a number of 145 farms where both household survey and cadastral information was available for our comparative study.

This sample size can be considered representative of the study region, since according to Yamane's equation (1967), 100 samples are required to achieve a sampling accuracy of approximately 90%. See Equation 1:

$$n = N / [1 + N(e)2],$$
 (1)

where: n represents the samples needed; N (145 households) refers to the sample population; and e the sampling error (10%).

Changes in forest cover at farm level were assessed by applying bi-temporal change detection analysis stratifying the changes into three categories: "forest loss," "forest gain" and "no significant changes". A farm was considered to fall into the category "no significant changes" if variations in forest cover occurred between 1 and 4 pixels (0, 36 ha).

6.3 Results

6.3.1 Forest classification accuracy

In general, classification accuracies obtained from Landsat images between the years 1999 and 2016 fluctuated from 85% to 93%, with Kappa coefficients ranging from 0.82 to 0.91 (see Table 6-2). The Landsat data set from 2001–2002 exhibited the highest accuracy, of which 94% of the pixels were classified correctly as forest. On the other hand, the lowest accuracy values were seen in the 2015–2016 Landsat data sets, obtaining 88% and 87%, respectively. The lower classification values could be attributed to high spectral similarities between forest areas and dense crop fields (e.g., soybean and maize plantations).

Table 6-2. Classification accuracies for each time step from 1999 to 2016.

Time period	Overall	KAPPA	Producers Accuracy Forest	Users Accuracy Forest	Producers Accuracy non- Forest	Users Accuracy non-Forest
1990/2000	89.04%	0.85	90.15%	89.12%	89.87%	88.10%
2001/2002	93.06%	0.91	94.13%	92.28%	92.86%	93.18%
2003/2004	85.71%	0.82	86.74%	85.95%	84.67%	85.13%
2005/2006	92.86%	0.90	93.75%	92.67%	92.88%	91.43%
2007/2008	91.69%	0.89	93.09%	90.43%	91.15%	92.24%
2009/2010	91.03%	0.87	91.15%	91.08%	89.87%	91.02%
2011/2012	92.35%	0.89	94.88%	93.45%	90.72%	91.23%
2013/2014	92.13%	0.89	92.78%	92.52%	91.36%	91.75%
2015/2016	87.36%	0.83	88.40%	87.78%	87.04%	86.26%

6.3.2 Forest loss rates

In 1999/2000, over 31% (27,000 km²) of the BAAPA area was covered by forest. As presented in Table 3 and Figure 6-3, the largest forest areas in the region were located in the departments of Canindevú and San Pedro, accounting for more than 48% (over 10,000 km²) of the total forest area in the BAAPA. The lowest levels of forest coverage were found in the departments of Paraguarí, Guairá and Concepción, together accounting for only 9% of the forest cover (around 2500 km²). In the years 2001/2002, the forest cover in the BAAPA decreased to 29%, equivalent to 630 km². The departments of Canindeyú, San Pedro and Alto Parana exhibited the highest relative forest loss of 79%, with more than 500 km². In 2003/2004, deforestation rates increased drastically. Almost 9% (2300 km²) of the forest was being depleted, nearly four times as much as in previous years. Similar to the trends above, the highest rates of deforestation were concentrated in the departments of Canindeyú, San Pedro, and Alto Parana, together totaling over 56% (around 1300 km²) of the area loss. Following the year 2004, rates of deforestation gradually decreased from 4.9% (1200 km²) from 2005/2006 down to 2.5% (549 km²) between 2011 and 2012, before increasing again slightly in 2015/2016 (2.9%). Overall, by the year 2016, more than 27% (7500 km²) of forest cover was lost since 1999, at an annual deforestation rate of 1.5% (442 km²) over the entire BAAPA area.

Table 6-3. Forest cover and forest cover loss in the BAAPA region from 1999 to 2016.

Department	Forest cover (1999– 2000 km²)	%	Forest cover (2001– 2002 km²)	%	Forest cover (2003– 2004 km²)	%	Forest cover (2005– 2006 km²)	%	Forest cover (2007– 2008 km²)	%
Alto Paraná	3336	12.3	3210	11.8	2856	10.5	2747	10.1	2709	10.0
Amambay	2414	8.9	2371	8.7	2353	8.7	2144	7.9	1998	7.3
Caaguazú	3113	11.5	3069	11.3	2801	10.3	2658	9.8	2649	9.7
Caazapá	2172	8.0	2169	8.0	1901	7.0	1801	6.6	1787	6.6
Canindeyú	5812	21.4	5602	20.6	5036	18.5	4889	18.0	4692	17.3
Concepción	1246	4.6	1236	4.5	1084	4.0	1027	3.8	940	3.5
Guairá	916	3.4	891	3.3	862	3.2	860	3.2	856	3.1
Itapúa	3086	11.4	3084	11.3	2833	10.4	2802	10.3	2730	10.0
Paraguarí	357	1.3	324	1.2	347	1.3	335	1.2	327	1.2
San Pedro	4735	17.4	4570	16.8	4124	15.2	3728	13.7	3383	12.4
Total	27,187	100	26,526		24,197		22,991		22,071	
	Forest		Forest		Forest		Forest			
Department	cover (2009– 2010 km²)	%	cover (2011– 2012 km²)	%	cover (2013– 2014 km²)	%	cover (2015– 2016 km²)	%	Total Forest loss (km²)	%
Department Alto Paraná	(2009–	9.8	(2011–	9.6	(2013-	9.6	cover (2015–	9.3	Forest	24.2
•	(2009– 2010 km²)		(2011– 2012 km²)		(2013– 2014 km²)		cover (2015– 2016 km²)		Forest loss (km²)	
Alto Paraná	(2009– 2010 km²) 2664	9.8	(2011– 2012 km²) 2609	9.6	(2013– 2014 km²)	9.6	cover (2015– 2016 km²)	9.3	Forest loss (km²)	24.2
Alto Paraná Amambay	(2009– 2010 km²) 2664 1946	9.8 7.2	(2011– 2012 km²) 2609 1911	9.6 7.0	(2013– 2014 km²) 2598 1827	9.6 6.7	cover (2015– 2016 km²) 2528 1808	9.3 6.7	Forest loss (km²) 808 606	24.2 25.1
Alto Paraná Amambay Caaguazú	(2009– 2010 km²) 2664 1946 2548	9.8 7.2 9.4	(2011– 2012 km²) 2609 1911 2487	9.6 7.0 9.1	(2013– 2014 km²) 2598 1827 2434	9.6 6.7 9.0	cover (2015– 2016 km²) 2528 1808 2322	9.3 6.7 8.5	Forest loss (km²) 808 606 791	24.2 25.1 25.4
Alto Paraná Amambay Caaguazú Caazapá	(2009– 2010 km²) 2664 1946 2548 1768	9.8 7.2 9.4 6.5	(2011– 2012 km²) 2609 1911 2487 1768	9.6 7.0 9.1 6.5	(2013– 2014 km²) 2598 1827 2434 1732	9.6 6.7 9.0 6.4	cover (2015– 2016 km²) 2528 1808 2322 1639	9.3 6.7 8.5 6.0	Forest loss (km²) 808 606 791 533	24.2 25.1 25.4 24.5
Alto Paraná Amambay Caaguazú Caazapá Canindeyú	(2009– 2010 km²) 2664 1946 2548 1768 4427	9.8 7.2 9.4 6.5 16.3	2609 1911 2487 1768 4278	9.6 7.0 9.1 6.5 15.7	(2013– 2014 km²) 2598 1827 2434 1732 4091	9.6 6.7 9.0 6.4 15.0	cover (2015– 2016 km²) 2528 1808 2322 1639 3904	9.3 6.7 8.5 6.0 14	Forest loss (km²) 808 606 791 533 1908	24.2 25.1 25.4 24.5 32.8
Alto Paraná Amambay Caaguazú Caazapá Canindeyú Concepción	(2009– 2010 km²) 2664 1946 2548 1768 4427 916	9.8 7.2 9.4 6.5 16.3 3.4	2609 1911 2487 1768 4278 901	9.6 7.0 9.1 6.5 15.7 3.3	(2013– 2014 km²) 2598 1827 2434 1732 4091 890	9.6 6.7 9.0 6.4 15.0 3.3	cover (2015– 2016 km²) 2528 1808 2322 1639 3904 876	9.3 6.7 8.5 6.0 14 3.2	Forest loss (km²) 808 606 791 533 1908 370	24.2 25.1 25.4 24.5 32.8 29.7
Alto Paraná Amambay Caaguazú Caazapá Canindeyú Concepción Guairá	(2009– 2010 km²) 2664 1946 2548 1768 4427 916 834	9.8 7.2 9.4 6.5 16.3 3.4 3.1	(2011– 2012 km²) 2609 1911 2487 1768 4278 901 816	9.6 7.0 9.1 6.5 15.7 3.3 3.0	(2013– 2014 km²) 2598 1827 2434 1732 4091 890 806	9.6 6.7 9.0 6.4 15.0 3.3 3.0	cover (2015– 2016 km²) 2528 1808 2322 1639 3904 876 805	9.3 6.7 8.5 6.0 14 3.2 3.0	Forest loss (km²) 808 606 791 533 1908 370 111	24.2 25.1 25.4 24.5 32.8 29.7 12.1
Alto Paraná Amambay Caaguazú Caazapá Canindeyú Concepción Guairá Itapúa	(2009– 2010 km²) 2664 1946 2548 1768 4427 916 834 2705	9.8 7.2 9.4 6.5 16.3 3.4 3.1 9.9	2609 1911 2487 1768 4278 901 816 2700	9.6 7.0 9.1 6.5 15.7 3.3 3.0 9.9	(2013– 2014 km²) 2598 1827 2434 1732 4091 890 806 2678	9.6 6.7 9.0 6.4 15.0 3.3 3.0 9.9	cover (2015– 2016 km²) 2528 1808 2322 1639 3904 876 805 2634	9.3 6.7 8.5 6.0 14 3.2 3.0 9.7	808 606 791 533 1908 370 111 452	24.2 25.1 25.4 24.5 32.8 29.7 12.1 14.6

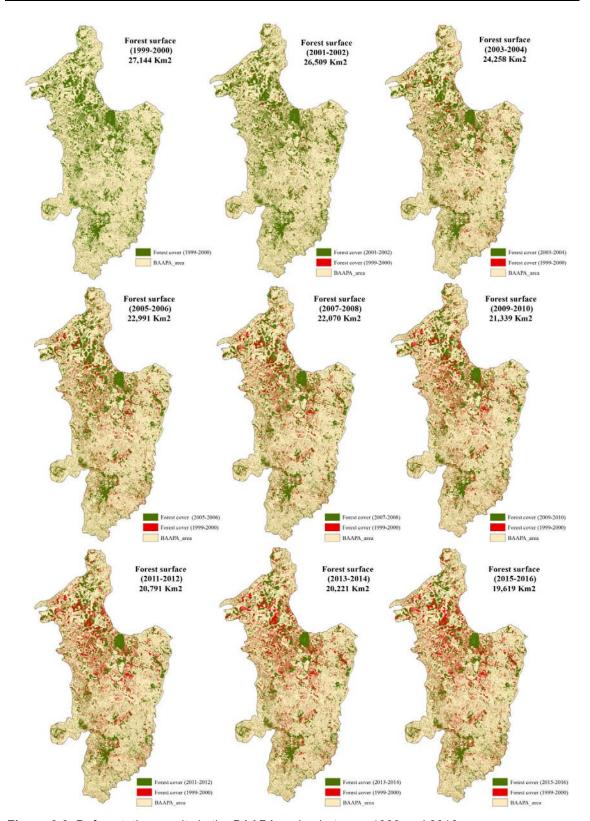


Figure 6-3. Deforestation results in the BAAPA region between 1999 and 2016.

The lowest deforestation rates were shown in the departments of Guairá (12.1%) and Paraguarí (2.4%) accounting for 1.5% (120 km²) of the total area deforested. In contrast, the departments of San Pedro and Canindeyú consistently evidenced the highest losses, with a total forest cover loss of 41% and 33%, respectively.

Figure 6-4 reveals a clear pattern concerning the effectiveness of the protecting reserves based on their style of governance (ownership). For instance, each protected area owned by a governmental entity (Gov) showed a decrease in total forest cover. The highest deforestation rates were found in the National Parks of Cerro Corá (4.5%), Ybytyryzú (3%) and San Rafael (2.9%), totaling almost 30 km2. In contrast, each natural reserve under ITAIPU-IT (binational hydroelectric dam (partially owned by the government)) management exhibited increments on their forest cover, with natural restoration rates (natural reforestation) varying between 1% (in the Yvytyrokai) and 69% (Biological Reserve Mbaracayú). As for protected areas privately owned (Prv) (e.g., Mbaracayú and Morombí), no clear trend was found. While the Mbaracayú reserve exhibited a small increase in forest cover, (0.8%), the Morombí reserve, by contrast, presented the highest deforestation rates (4.7%) among all the protected areas in the BAAPA region.

Forest cover dynamics within protected areas

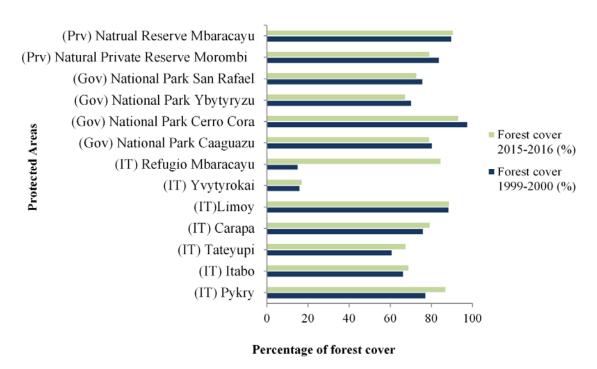


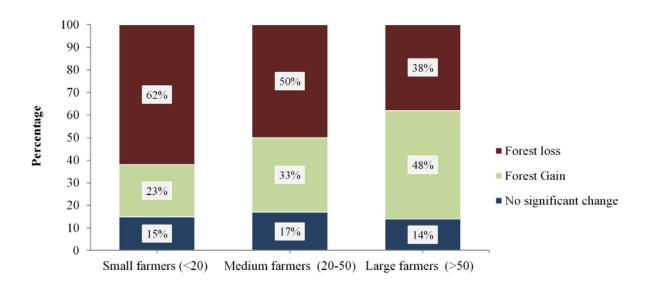
Figure 6-4. Comparison of forest dynamics between protected areas based on the type of ownership: Prv. (Private ownership), Gov. (Governmental ownership) and IT (Owned by the ITAIPU hydroelectric dam).

6.3.3 Forest cover change and household survey

6.3.3.1 Demography and Influence on forest dynamics

All interviews were conducted with the designated head (by the families) of each household. The vast majority of respondents were males (around 85%) with an age between 30 and 62 years. Ownership was mixed between Paraguayans and Colons (Brazilians), with the Paraguayans tending to own the smaller farms (82% Paraguayans), and Colons larger ones (83% Colons). The principal occupation of 91% interviewees was farmer, while a small share (9%) occupied positions in governmental institutions in addition to farming activities. Respondents' main agricultural activities were soy bean production (mainly large-scale farmers), cattle ranching (mostly medium-scale and small-scale farmers) and subsistence agriculture (small-scale farmers in particular). When analyzing the dynamics of the forest at the farm level, Figure 6-5 shows that forest loss/gain are closely related to farm size. For instance, the majority of forest loss (62%) occurred on small-scale farmers' properties. The percentage of farmers experiencing deforestation gradually decreases with an increased farm size, declining from 50% for medium-scale to 38% for large-scale farmers groups. Forest gain, on the other hand, is more common among large-scale farmers, accounting for 48% of the interviewees. On the contrary, small scale farmers exhibited the lowest percentage (23%) of respondents with an increment in their forest cover. Hence, when farm sizes increase, the percentage of farms showing forest cover gain increases as well.

Forest dynamics according to farm type



Farm types

Figure 6-5. Dynamics of the forest stratified by farm type.

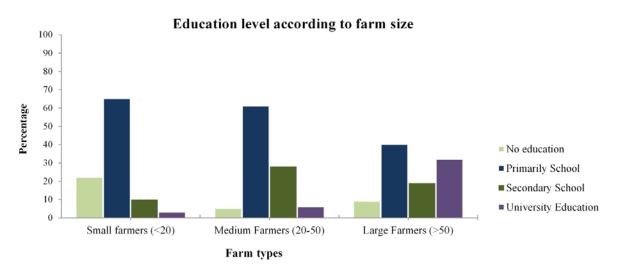


Figure 6-6. Education level according to farm size of the respondents

Figure 6-6 presents the distribution of the education level between farm types. Basically, education level increases slightly as farm sizes increases. The majority of farmers with higher education (a university degree) is found among the large-scale farmers group (32%). Small-scale farmers more frequently reveal lower levels of education, with 22% of the respondents having no school degree. Notwithstanding, a primary school education remains the most common level of education among all farm types with 65% (small-scale farmers), 61% (medium-scale farmers) and 40% (large-scale farmers) of respondents, respectively. Figure 6-7 presents strong tendency between a farmers' education level and the dynamics of the forest on their parameters

Forest dynamics according to education level

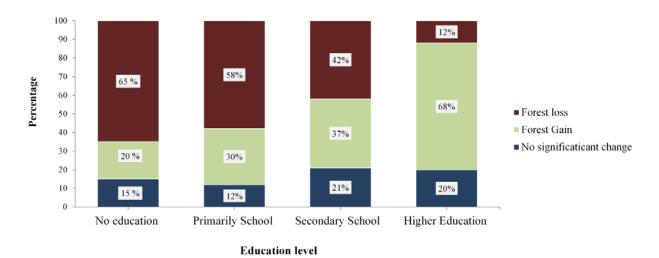


Figure 6-7. Dynamics of the forest based on the education level of the respondents.

The highest percentage of farmers exhibiting forest loss is found in the group with no school degree. This tendency gradually decreases as education level increases, down from 65% in the group with no formal education to 12% in the group with a college education. Furthermore, farmers with higher education (University degree) most commonly saw gains of forest cover on their property. This tendency decreases with decreasing education level, dropping from 68% (higher education) to 20% (no education).

6.3.3.2 Uses of forest benefits and influence on the forest cover

To capture the level of dependency on forest benefits by different farm types, interviewees were asked which products they obtained from the forest and how important they were to them. A total of 68% of the farmers remarked that they frequently benefited from the forest, and 92% stated that forests are very important for their livelihood. A deeper analysis of the results revealed a higher dependency of forest products among small (97%) and medium-scale (78%) farmers, whereas large-scale farmers (44%) stated that they made use of the forest but not as intensively.

The high reliance on forest products and services, in particular among the small-scale farmers group, can be attributed to a lack of other sufficient financial resources. Figure 6-8 presents the different uses of the forest according to farm type. Over 88% of the small-scale farmers group admits collecting firewood from the forest. A total of 94% of this group stated that their main use was for subsistence, in particular cooking. On the other hand, only 40% of medium and 18% large-scale farmers claimed a certain level of dependency, in clear contrast to the above. Small (73%) and medium-scale (44%) farmers were more reliant on forest wood for construction (e.g., households, barns and fences construction) than large-scale farmers (16%).

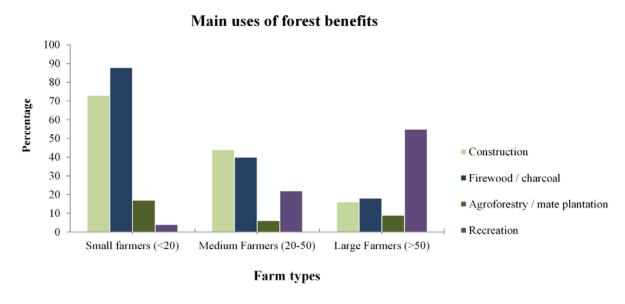


Figure 6-8. Main uses of forest related products based on farm type.

In rural areas, the vast majority of small households (in particular within the group of smallscale farmers) own houses that are built with wood from the forest, while medium- and large-scale farms often present permanent homes. When asked about the cultural value of the forest, around 55% of large-scale farmers considered the forest's main value to be recreational. However, this inclination is less frequent among medium- and small-scale farmers, of which only 22% and 4%, respectively, held the same opinion. Figure 6-9 presents how the forest cover of each farm group is affected by the use of forest benefits and products. For this analysis, the percentage of farmers that acknowledged the use of the forest for any purpose (e.g., construction, firewood, agroforestry and recreation) and the spatial information from the forest cover of each farm was considered. When analyzing the small-scale farmers group, 60% of the respondents presented forest loss, whereas only 26% and 14% showed forest gain or non-significant changes. Similar trends were observed among medium-scale farmers, among whom a high percentage of respondents (58%) presented a decrease in their forest cover, in comparison to the ones showing increments (35%) or no changes (7%). In contrast, a much higher proportion of the largescale farmer's group (53%) revealed forest gain.

Overall trends disclose a correlation between the uses of forest by different farm groups and their influence on the forest cover. Whereas small- and medium-scale farms evidenced high rates of deforestation, large-scale farmers demonstrated more sustainable use of the natural resources. However, it is important to mention that main uses of forest benefits differed among farm groups, which could have an impact on the forest cover itself. As described previously, small- and medium-scale farmers exhibited a higher tendency to use the forest as a source of firewood and construction-wood, whereas large-scale farmers were more inclined to use the forest for recreational proposes.

Forest dynamics based on the use of the forest

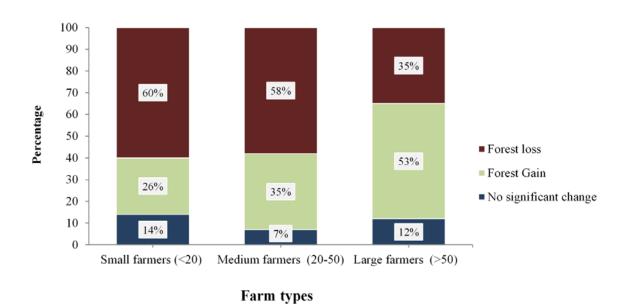


Figure 6-9. Dynamics of the forest cover based on the level of dependency.

6.3.3.3 Conservation programs and forest cover change

To comprehend landowner's perception about the willingness to conserve forests, farmers were asked if natural areas should be protected. In general, positive responses were obtained, with 99% of farmers expressing their support for protecting forests. Additionally, 88% of the farmers remarked on the importance of the forest and the negative effects of a disappearing forest, in particular on the prevailing natural resources, flora and fauna and water reservoirs. Overall, the interviewed farmers exhibited high degrees of environmental awareness.

Furthermore, 54% of respondents reported participating in environmental programs such as the Payment for Ecosystem Service (PES) program, reforestation programs and water courses protection programs. Particularly large-scale farmers (65%) participated in such programs followed by medium (47%) and small-scale (45%) farmers' groups. To understand the influence of conservation programs on forest dynamics, respondents' participation in environmental programs/workshops was reflected by the variations of the forest cover in each farm. Overall, results also highlighted that sustainable use of the forest was related with program participation. Of the group that reported not participating in any environmental workshops or conservation programs, 73% evidenced forest loss and only 9% an increase in forest cover. On the contrary, the fraction of properties experiencing forest loss decreased to 48% among participants in environmental programs, and the fraction of farmers with forest gains increased to 41%. When analyzing the results at a farm type level, small-scale farmers presented similar tendencies to the ones described above (see Figure 6-10). The percentage of famers exhibiting forest loss decreased from 73% to 48% for respondents involved in conservation/workshops programs.

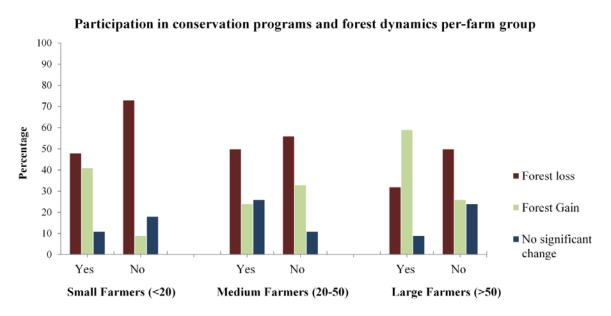


Figure 6-10. Relationship between conservation programs and forest cover change per-farm type.

Additionally, forest cover increase was found among farmers with environmental education, accounting for 41% of the respondents in this group. Large-scale farmers revealed different patterns from the ones described previously. The group of respondents which attended workshops was higher among farmers with increases in their forest cover (59%) in comparison to the ones exhibiting forest loss (32%) in the same group. Trends among the non-participant group resemble the ones shown for small- and medium-scale farmers, where farmers exhibiting forest loss (50%) dominated. Overall, results revealed a clear pattern where environmental education has an influence on the dynamics of the forest. Farmers with environmental knowledge tend to experience less forest loss.

6.4 Discussion

6.4.1 Forest cover change analysis

The dynamics of the BAAPA forest and the perception of its benefits is a topic of great importance which has not been adequately studied so far. When analyzing changes of the forest cover, most studies were based solely on remote sensing (Hansen et al., 2010; Hansen et al., 2013; Huang et al., 2009) or field survey data (Da Ponte et al., 2017). To the knowledge of the authors, no research has combined both information types in the region. If the objective is to preserve natural resources, it is important to understand not only the historical distribution of the forest, but also the landowners' perceptions of it (Sodhi et al., 2009; Casado et al., 2013). In a first part, the present study focuses on how the forest cover has been changing over the last 17 years, using a multi-temporal analysis approach. For this purpose, changes in the forest cover were assessed by applying a RF classifier using spectral temporal metrics derived from a dense set of Landsat Imagery (TM, ETM+ and OLI/TIRS). In a second part, this study examines how different farmer groups perceive the forest and how their perceptions influence its dynamics, integrating remote sensing and household level data.

Overall, change detection results revealed a total forest cover loss of 7500 km² (almost 28% of its original cover) between 1999 and 2016. However, in comparison with studies conducted for the previous years, a decreasing trend in deforestation rates is observed. Huang et al. (2007 and 2009) demonstrated that between 1989 and 2000, the BAAPA forest lost almost 40% (over 13,500 km²) of its original cover, a figure nearly two times higher than deforestation figures found in this research. Inconsistencies with other studies regarding deforestation rates were found. For example, Da Ponte et al. (2017) analyzed changes in the BAAPA forest between the years 2003 and 2013 based on Landsat images (OLI and ETM+). The study reported a total forest cover loss of 37% (around 33,039 km²) by the year 2003 and 30% (over 26,966 km²) in 2013. The present research, however, revealed lower forest coverage for the same period, of 28% (24,197 km²) and 23% (20,221 km²), respectively. Differences between findings could be related to sensors applied, input data (e.g., percentiles, vegetation indexes) and definition of forest. Similar trends were observed when comparing classification results with the ones obtained by the National University of Asuncion - UNA. For the year 2011, the UNA found natural forest coverage of 20% in the BAAPA, or almost 17,500 km2 (Rajelada et al., 2013).

Results from this study presented higher forest coverage values (around 23% (20,000 km²)) for the same period. It is worth noting that both studies assessed changes in the forest cover by applying bi-temporal-approaches considering only single scenes. Further spectral features such as percentiles derivation, vegetation indices, and a dense set of Landsat imagery were excluded from the analysis. The described data was already proven to be essential to achieving higher accuracy in land cover predictions and change detection assessment (Wohlfart et al., 2017; Müller et al., 2016).

A detailed analysis of the time series indicates that deforestation rates seem to increase abruptly between the years 2002–2004 (almost four times higher than previous years) and gradually decrease again until the years 2015–2016, where slight increase is once again observed. This trend can be attributed to the Zero Deforestation Law (N°2524/04) established in the year 2004, which banned the conversion of forest lands for other purposes (Hutchison and Aquino, 2011). According to farmers interviewed during the field survey, the Zero Deforestation Law was anticipated by rural communities and large landowners, who increased their deforestation activities before the deforestation law took effect.

A clear difference in the effectiveness of conservation programs under different forest management regimes is observed. For instance, every natural reserve owned by the Government-Gov presented a certain degree of forest loss within their boundaries. Reserves managed by the ITAIPU-IT hydroelectric, on the other hand, showed increases in forest cover, in some cases up to 71% of its total area (e.g., Mbaracayu reserve). ITAIPU is a binational hydroelectric company owned by the Paraguayan and Brazilian government. They invest economic resources to protect natural areas, but solely in areas located directly in their watersheds (as a part of their environmental mitigation program). Subsidies given directly by the government, in contrast, are rather scarce. According to several national environmental institutions (e.g., Guyra Paraguay, WWF, Fundacion Moises Bertoni), further support to protecting natural forest areas is needed. Until today, there still remains a strong weakness in the enforcement of environmental laws, policies and proper criteria to include stakeholder's needs and concerns when implementing conservation programs (Gonzales and Rivadeneira, 2004).

6.4.2 Household survey and remote sensing data

The analysis of forest cover change at the farm level in combination with results derived from field surveys permits comparing variations in forest surfaces along with the influence of change by different farm groups. Overall, results revealed a clear difference in the dynamics of the forest cover between farm types. In general, a higher proportion of small-scale farms presented forest loss compared with medium- and large-scale farmers. Similar tendencies were found in several reports from Peruvian environmental agencies (e.g., Ministry of Environment and Ministry of Agriculture and Irrigation) that tag small-scale farmers as the principal responsible group for over 90% of the deforestation activities that occurred in the Peruvian Amazon (Ravikumar, 2017). However, it is important to clarify that the total area of forest loss between farm types was not considered in this study.

Therefore, even though small-scale farmers were shown to be the farm group most responsible for deforestation activities, the total forest area loss might not be as high compared to medium- and large-scale farmers. This study also analyzed the influence of education level on deforestation tendencies in the BAAPA. The percentage of farmers exhibiting forest loss decreases as education levels increase. Comparable trends were found among the Amerindian farmers in Honduras, where forest clearings tended to decline as education levels increased (Godoy et al., 1998). Additionally, according to Turner II et al. (2004), a higher level of education could imply a better management of natural resources and a decrease in pressure on the forest.

A clear correlation was observed between the various farm types and differing ways of using the forest. In general, results show a higher percentage of small- and medium-scale farmers demonstrating forest loss. The present trend is consistent with the results obtained in the 2016 field survey, which revealed a high dependency on forest benefits (in particular construction wood and fire-wood) by the same farm types. The extraction of forest goods without considering any concept of sustainability or management plans could greatly influence its continuity (Hutchison and Aquino, 2011). Similar to the trends discussed above, a correlation between the tendencies found among large-scale farmers and results obtained in the 2016 survey was observed. The majority of large-scale farmers stated that their main use of the forest was recreational; correspondingly, their properties did not show evidence of intense harvesting. Results in our study demonstrated not only that large-scale farms presented the lowest percentage of respondents exhibiting forest loss, but also that the same group showed the highest percentage of respondents with increases in their forest cover. However, it is important to remark that the level of use of forest goods is highly associated with the level of income and daily subsidence needs (housing and cooking in particular), from each farm group. According to the main results obtained in the survey, the level of reliance on forest products varies with farm size; dependency on the forest tends to increase as farm size decreases. Whereas medium- and large-scale farmers are inclined to see the forest as an additional source of income, small-scale farmers, on the contrary, rely directly on forest products for subsistence.

Lastly, this study related the influence of environmental education on the variation in forest cover between farm types. The properties of farmers that participated in environmental programs/workshops were less likely to exhibit forest loss. However, at least for small- and medium-scale farmers, the percentage of farms showing forest loss was overwhelming. Large-scale farmers presented different trends, the majority of farms demonstrating increases in forest cover, which can be related to their increased participation in environmental programs. Finally, it is important to take notice of certain biases on the input data that might have influenced the outcomes of this study. Firstly, the responses of the survey could have been influenced by the background of the interviewer, problems with environmental authorities and personal thoughts over the nature of the research itself. The present study combined remote sensing data with the available cadastral information for the area as far as possible. However, since most of the cadastral data was not accessible (in particular for small-scale farmers), field measurements relied on the knowledge of the farmer regarding the boundaries from their farm.

Lastly, the distribution of the samples was dependent on the cadastral information; therefore, the representation for the study area could have been biased.

6.5 Conclusions

The results of this study provided a description of deforestation trends over the BAAPA region between 1999 and 2016. The correlation of household and remote sensing data permitted the obtainment of relevant information with regards to farmers' influence on the dynamics of the forest at the farm level. Based on the major findings and discussions in this study, the main conclusions are described as follows:

- Results of the forest change detection analysis based on Landsat imagery revealed a total forest cover loss of almost 7500 km2 between the years 1999 and 2016, which represents almost 27% of its cover.
- The outcomes of the time series analysis presented a drastic increase in deforestation rates between the years 2001–2002 and 2003–2004, almost four times the deforestation rates observed for previous years (2300 km2). According to local farmers, the present trend could be attributed to the upcoming Zero Deforestation Law in the country, which influenced the rapid deforestation before the law was applied.
- Forest cover change analysis in protected areas demonstrated a clear difference between their effectiveness. Whereas protected areas under the ITAIPU hydroelectric management regime presented increases in forest cover, protected areas managed by the Government, on the contrary, showed a decrease in their forest cover in each of the reserves.
- According to the 145 households interviewed, forest dynamics at the farm level is related to farm types. While the frequency of farmers presenting forest loss increases as farm sizes decreases, forest gains, on the contrary, increase as farm sizes increases as well.
- Education level has been shown to have an influence on the dynamics of the forest
 at the farm level. Overall, results demonstrated that, as education level increases,
 the percentage of famers exhibiting forest loss decreases. When considering forest
 gain, on the other hand, a higher percentage of farms with increases in forest cover
 can be found among the group with higher education.
- The level of dependency on forest products by different farm groups affects the status of their forest. Higher levels of dependency resulted in a higher percentage of farmers presenting forest cover loss.
- Environmental programs provide a certain degree of influence on changes in the forest cover at the farm level. Among the groups participating in environmental

programs and workshops, a lower percentage of respondents showed forest loss on their properties than for comparable groups that did not attend the workshops.

Further studies could make use of higher resolution imagery to increase the accuracy of the results, in particular when considering an assessment of forest cover change at the farm level. In addition, absolute values of deforestation between farm types should be addressed in future studies to assess what the actual impact of different farm types on the forest cover is. Moreover, it would be interesting to consider additional dynamic information on the state of the forest (such as yearly forest degradation and regeneration rates) which would add more information with regards to the pressure exerted by different farm types on forest resources. The use of multi-temporal information, along with ground data, are key components to designing and supporting conservation strategies and policies. It is crucial to consider not only the outlook of rural population but their influence on the behavior of natural resources over time, as well.

6.6 References

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6 Assessing forest cover dynamics and forest perception in the Atlantic Forest of Paraguay, combining remote sensing and household level data

CHAPTER 7

7.1 Synthesis and outlook

The overall objective of this dissertation was to investigate almost two decades of tropical forest dynamics in the BAAPA eco-region. This thesis provides the first multi-temporal analysis of the BAAPA forest cover for a period of 17 years. Based on a novel approach, this research combined two data types to understand the level of influence of farmers' activities on dynamics of the BAAPA. The focus of this research was to provide a consistent delineation of the current BAAPA cover status, with a particular focus on forest conservation.

The BAAPA forest has been transformed drastically over the last decades, becoming one of the most endangered rain forests in the world; however, few scientific studies have been performed in the ecoregion. After the 1950s, the rapid advance of the agricultural frontier and urbanization increased deforestation practices in the ecoregion considerably. Despite the existence of numerous deforestation reports and monitoring programs, proper scientific environmental data in the ecoregion remains scarce. Additionally, several policies were implemented to halt deforestation activities in the region; however, their long-term impact on the forest remains understudied. Although farmers' perception of forest resources is a key component to understanding the drivers of change in the BAAPA, no previous studies have addressed this research gap. Therefore, there is an urgent need to characterize longterm differences and dynamics patterns in the ecoregion. The comprehensive data provided in this analysis delivers relevant information to understand the reasons behind the drastic changes that occurred in the BAAPA over the past decades. Application of earth observation data and remote sensing approaches was shown to be a relevant tool to generate the necessary information to comprehend the insights of the dynamics occurring in the forest cover.

Core objectives in this dissertation are presented in four main chapters. In the following section, each objective formulated in Chapter 1 is discussed and summarized in the form of short statements contributing to the main research focus of this thesis.

Objective 1: "Provide a comprehensive review on all the studies that have applied earth observation data to assess forest disturbances in Latin America"

In Chapter 3, a detailed review of the use of earth observation data to assess changes in tropical forest cover in Latin America was provided. Several different approaches were used to obtain a diverse range of products. For example, global forest assessments became available in the early 1990s based on coarse resolution imagery (MODIS, AVHRR, or MERIS) with a spatial resolution varying from 1 km to 300 m (9% of the reviewed studies). More recently, changes in detection processes permitted the generation

of higher resolution products based on Landsat and ALOS PALSAR data, allowing global forest maps to be produced with up to 25-m resolution. Around 65% of the studies reviewed were conducted at the local scale using medium resolution data (Landsat imagery). Most articles reviewed (95% of the studies) focused on the detection deforestation and degradation activities, underlying patterns of change, drivers, and hotspots. Landsat was the most frequent sensor used (over 48% of the studies). Sensors such as ASTER, CBERS, IKONOS, QuickBird, and SPOT (around 15% of the articles reviewed) were incorporated less frequently, serving mostly to fill data gaps not covered by Landsat images. Similar to EO described above, the application of radar data (ERS-1/ERS-2, JERS-1, SIR-C/X, ALOS PALSAR, RADARSAT 2, and COSMO Sky Med) was rather rare, and concentrated mainly over the Brazilian Amazon.

For change detection methods, the approaches reviewed varied according to the type of process assessed (deforestation or degradation) and the objectives of the research. Generally, change detection studies featured a comprehensive procedure involving thoughtful consideration of each step, definition of the research objectives, identification of the suitable earth observation data, processing of satellite imagery, identification of change detection method, and evaluation of the results. Overall, deforestation products were obtained based on manual interpretation, thematic maps, or continuous variables (e.g. vegetation indexes, subpixel vegetation fractions, continuous fields of tree cover, PCA components, or TC metrics) and bi-temporal or multi-temporal (in almost 95% of the studies) and real-time series analysis (less than 5% of the articles). Conversely, analysis of degradation presented more difficulties. Because there is no standardized definition of degradation, degradation processes are confused with natural disturbances (e.g. season changes or wind throws) and the short period of time required to map the disturbance, and many studies have struggled to provide a standardized detection technique. However, inclusion of continuous variables and textural metrics has improved the detection logged areas up to three years after the actual disturbance event. Finally, for spatial distribution of the areas of interest in the studies, a large percentage (almost 72%) of the reviewed articles were conducted in Brazil, primarily over the Amazonian region. However, other forested regions in Latin America that are equally affected by deforestation and degradation activities remain without proper scientific studies. The case study from Paraguay included in this review serves as an example of how forest areas that are ecologically equally as important as the Amazonian region were completely devastated, yet primarily ignored by international scientific journals.

The continuous expansion of the agricultural frontier, illegal logging activities, and the constant demand for natural goods threaten the continuity of the tropical forest. To meet these challenges, there is an urgent need to develop methods and approaches in the field of remote sensing observations. This would simplify the implementation of environmental laws and conservation programs orientated toward protecting the last remnants of natural forest on the continent.

Objective 2: "Detect and characterize changes in the Paraguayan Atlantic Forest ecoregion between 2003 and 2013"

The BAAPA forest has been identified as one of the most threatened rain forests in the world. However, only few scientific investigations have been addressed for this region. The last study conducted in the BAAPA was performed in 2009, analyzing forest cover changes between the years 1970 to 2001. This thesis provides a novel comprehensive analysis on detection and characterization of forest cover loss in the Paraguay's Atlantic, spanning the years 2003 to 2013. This research provides a detailed assessment of spatial patterns of deforestation, effectiveness of protected areas, fragmentation level of the forest, identification of critical areas for biodiversity conservation, and connectivity between these areas. For this purpose, Landsat ETM+ and OLI/TIRS imagery was used to map the forest cover for the years 2003 and 2013 based on a threshold classification approach, achieving overall accuracies of 83% and 95%, respectively.

Overall, results obtained from the change detection analysis revealed a total forest loss of 6000 km² between 2003 and 2013, resulting in an annual deforestation rate of 1.8%. Outcomes produced from this research show the effectiveness of protected areas to preserve the forest. Generally, deforestation rates vary between 3% and 4% inside the reserves. However, deforestation rates increase abruptly outside the border of such areas. Consequently, the main forest areas in the region are turned into isolated patches, compromising their biodiversity. This tendency reveals a remarkable pressure on areas protected from anthropologic activities. Thus, law enforcement strategies need to be developed to successfully protect these forest sites.

For fragmentation of the forest cover, general results demonstrated an increase in the fragmentation level in large patches. Overall, forest cover loss resulted in a decline of the total core area, an increase in the number of patches, and a decline in the mean patch size. General outcomes demonstrate a low connectivity between the few intact forest areas for nature conservation. Large forest areas are often interspersed with several large gaps between neighboring patches, resulting in numerous forest islands throughout the BAAPA landscape.

Results obtained from this thesis demonstrate that the novel combination of different GIS and remote sensing approaches provide relevant information to achieve the sustainability of forest resources in the region, along with protecting the biodiversity within these areas.

Objective 3: "Study how farmers in the BAAPA perceive and benefit from the services provided by the forest and understand their influence on forest conservation"

The perception of forest benefits is a topic of significant importance that has not previously been analyzed in depth. With the objective to understand the reasons behind the changes occurring in the forest, it is essential to identify the level of importance given by farmers to their own natural resources. Thus, chapter five presents comprehensive results on how the services derived from the forest are perceived by different farmers' groups (small, medium, or large), and analyzing their influence on forest conservation. In this context, an extensive socio-economic survey was conducted, and more than 270 farmers spread over an area of 12,500 km² in the BAAPA region were interviewed over a period of 1 month in 2016. The survey developed comprised over 117 questions covering a vast diversity of topics related to general aspects of the household (e.g. job, education, income level, and land size), the

participants' perception of the forest and its benefits (e.g., definition of forest, importance for their livelihood, usage and level of dependency on forest resources (e.g., firewood, construction, timber production)) and finally their view on environmental laws and conservation programs. Land owners were stratified according to their farm size (based on the stratification format from the Ministry of Agriculture of Paraguay) as follows: "small farmers", with a land size <20 ha; "medium farmers" with land sizes varying between 20 and 50 ha, and "large farmers" with lands above 50 ha (mainly soy bean producers).

The survey results illustrate that the level of dependency on the services provided by the forest differs among farm groups. Farmers with small land sizes present a higher reliance on forest resources than medium- and large-scale farmers. Whereas a large percentage of small scale-farmers depend directly on the forest for subsistence, (firewood and construction in particular), medium and large farmers consider the forest to have cultural and recreational value. Furthermore, the obtained outcomes show that the high level of dependence presented by small-scale farmers was closely related to their income level. For example, whereas a small-scale farmer with a governmental position (e.g. teacher, secretary,) could earn as much as \$5,000 USD per year (*DGEEC*, 2002) without disturbing the forest, a land owner whose source of income depends directly on farm products sometimes earn below \$1,000 USD, and thus they rely on the forest for subsistence much more intensively. In summary, farmers have a high level of understanding about the importance of the forest and the necessity to preserve its natural resources. Over 84% of the farmers remarked on the importance of the forest for their livelihood and over 91% stated that they believe the forest should be protected.

With regards to ongoing conservation programs in the country, results from the field survey revealed a high preference for the program "Valuation and Retribution of Ecosystem Service Law 3001/2006" (PES 3001/2006" (73% of the respondents) in comparison to the "Reforestation Incentives" program (27% of the respondents). A large number of respondents stated that reforestation activities could compromise their current crop production, thus substantially limiting their source of income. PES, however, presents a suitable option for large scale farmers with environmental difficulties. PES is an economic retribution that farmers can obtain by obtaining environmental certificates for their forested lands. Land owners with environmental obligations can acquire such certificates without compromising their current land use and being alienated with the law. However, 90% of the respondents stated that they believe the level of corruption in the country does not permit proper implementation of any such regulations to preserve the forest.

Results from the survey provide a comprehensive understanding of differences in perception of forest benefits and services by distinct groups of farmers. When considering policies and management plans for nature conservation, the outlook of the rural population should be taken into account. By focusing on hotspot areas that need to be preserved, rural communities or individual farmers with a high level of environmental awareness would ensure that conservation programs goals are attained over time.

Objective 4: "Generate the first multi-temporal analysis of changes in the BAAPA forest between the years 1999 and 2016"

Based on the outcomes obtained in chapter 4, the present investigation extends the temporal resolution of the analysis to a timeframe of 17 years, presenting the first multitemporal analysis of changes that occurred in the BAAPA forest. This study offers a novel approach to quantify forest loss in the eco-region and provides a comprehensive analysis on how different management regimes have an impact on the effectiveness of protected areas. For this purpose, a dense set of Landsat imagery from the sensors TM ETM + and OLI/TIRS was acquired for the years 1999 to 2016. Changes in the forest cover were estimated using a RF classifier based on spectral temporal metrics and vegetation indices derived from the acquired Landsat images. Accuracy of the forest classification products varied between 85% and 93%. The results indicated a total forest cover loss of 7,500 km² in the BAAPA region overall, resulting in almost 28% of its original cover between the years 1999 and 2016. When considering a detailed analysis of the time series outcomes, deforestation rates appear to increase drastically between the years 2002 and 2004 (nearly four times higher than preceding years (over 2,300 km²)) and progressively decrease until the years 2015-2016, where a minor increase was detected again. The observed trend could be attributed to the "Zero Deforestation Law" (N°2524/04) incorporated by the Paraguayan government in 2004, which "prohibited the conversion of forest lands to other land purposes" (Hutchison and Aquino, 2011). Based on results obtained from the field survey conducted in 2016, farmers were aware of the upcoming deforestation law and increased the rate of their deforestation activities before the law was enacted and enforced.

With regards to the effectiveness of designating protected areas, a clear difference was identified among the different management regimes implemented. For example, all protected areas managed by the government experienced some degree of loss in forest cover. Reserves owned by ITAIPU Hydroelectric Company, however, showed increases in forest cover of up to 71% of the total area in some cases (e.g., Mbaracayu reserve). The ITAIPU Hydroelectric Company is a binational company owned by the Brazilian and Paraguayan government. The vast economic resources of ITAIPU permits the successful implementation of environmental programs aimed at preserving natural areas concealed directly within the boundaries of their watershed. Subsidies from the government, however, are rare. Environmental institutions (e.g., Guyra Paraguay, WWF, Fundacion Moises Bertoni) in the country continuously highlight the lack of support given by the government to protect natural resources. To date, the country still has weak law enforcement in areas concerning environmental policies and appropriate criteria to integrate stakeholder necessities when applying conservation programs.

Objective 5: "Analyze how land owners perception towards to the forest influences its dynamics at a farm level"

When analyzing changes in the forest cover, most studies conducted for the region did not consider how land owners perceive their own forest and how this perception affects its conservation. Based on results obtained previously in this thesis, there is a clear understanding that the BAAPA forest cover has decreased greatly over the last decade, but to what degree are forest owners responsible for these changes? The present research follows the outcomes obtained in the previous chapters (4 and 5) by combining

remote sensing data with the main results of the field survey conducted in the 2016. The objective of this investigation was to analyze how the BAAPA forest cover has been changing at the farm level over the 17-year period (between 1999 and 2016) and how these changes relate to farmers' perceptions towards their own forest. To achieve this objective, forest masks obtained for the years 1999 and 2016 (already described in objective 4) were combined with cadastral data from each of the farmers interviewed.

Generally, new findings from this research show a clear difference in the dynamics of the forest cover between farm groups. The small-scale farmers' group's properties, for example, showed some degree of forest loss more frequently than medium and large-scale farmers. Conversely, increases in forest cover were more frequent on medium and large-scale farms. This tendency relates to the results found in objective 5, where small scale farmers had a higher level of dependency on forest resources than land owners with larger land sizes. However, the total area deforested between farm groups was not considered in this analysis. Thus, while small-scale farmers can be viewed as the farm group most responsible of deforestation activities in the region, the total area deforested by them is less relevant than that of medium and large-scale farmers.

Moreover, this research studied the influence of education level on the dynamics of the forest in the BAAPA. General results identified that a higher percentage of the properties belonging to farmers with no educational background showed forest loss compared with the others. As education level increases, the percentage of farms showing forest loss also decreases. However, forest gains are more common among farmers with higher education. This trend tends to decrease as the education level decreases. Based on results obtained from the household survey, a higher percentage of small-scale farmers are also in the group with a lower education. Therefore, the two results are correlated.

Finally, the influence of environmental education on changes in the forest cover was analyzed in the different groups. Forest loss was less frequent in farmers' groups where their members attended environmental programs or workshops. The perception of the forest and the importance of the sustainably using natural resources appears to have a good effect on the rate of deforestation activities at the farm level. Overall, it can be concluded in this chapter that forest dynamics in the BAAPA are dependent of farm size, educational background, and environmental awareness.

The use of multi-temporal information in combination with ground data provides novel information for developing and supporting strategies/policies intended to preserve the forest. Therefore, it is important to consider both the rural population's outlook and how their activities have an impact on the natural resources over time.

7.2 Overall conclusions

General conclusions demonstrate the intense dynamics that were present in the BAAPA forest over the last decades. Although deforestation rates have been systematically decreasing after 2004, forest cover loss continued inexorability. The high level of corruption in the country along with a lack of proper environmental law enforcement has led to the disappearance of more than 27% of its original cover in 17 years. A clear

example was observed in 2004, when a Zero Deforestation law was established as a desperate measure to halt any deforestation activity in the region. Instead, the law increased the rates of deforestation up to four-times higher than previous years. Results of this investigation defined the BAAPA as a highly fragmented forest, with only a few isolated remnants separated from each other. Consequently, local fauna, which tends to migrate between areas, remains enclosed, which endangers their continuity. Thus, environmental laws in the country should consider both the reserve itself and integrated conservation programs to preserve the forest in its surroundings.

On the other hand, outcomes from this investigation have shown that protected areas are a suitable measure to preserve the last remnants of natural forest in the region. However, some of these areas still experience forest loss inside its boundaries (up to 4.5% of its original cover), particularly when managed by the government. On the contrary, every reserve managed by private companies has experienced an increase in forest cover. As observed, there is notable lack of interest from governmental institutions to properly protect natural reserves. As long as the government does not provide sufficient economic support for the protection of natural resources, the integrity of the protected areas will remain threatened.

Lastly, as demonstrated in this thesis, there is a high level of environmental awareness among the rural population in the BAAPA. When integrating environmental laws or conservation programs, their outlook and needs must be considered to ensure the effectiveness of such initiatives. For example, while small-scale farmers require the forest as a means of subsistence, medium and large-scale farmers support fair environmental laws.

Overall, there is still much work ahead to reverse the current situation in the country. Unless the government stops prioritizing agricultural exports over natural resources, deforestation activities will continue dominating the eco-region.

7.3 Outlook: further opportunities and challenges with respect to remote sensing, based on forest monitoring in the BAAPA region

Currently, there is an urgent need for accessible and reliable information regarding the status of world's tropical forests among the scientific community, environmental institutions, and governmental entities. Despite the latest developments in remote sensing approaches and technologies, the produced data seems unable to fulfill the constant demands for information regarding spatial resolution, temporal extent, and accessibility. For example, as described in this dissertation, the BAAPA forest has been changing constantly over the last decades. However, no monitoring systems have been introduced by the government to detect these disturbances. Conversely, other countries in Latin America such as Brazil have introduced governmental programs or monitor forest disturbances within 15 days, based on MODIS and CBERS sensors.

However, implementation of such monitoring programs requires large amounts of data and economical resources, which unfortunately several countries in Latin America do not possess.

Additional research should be conducted in the BAAPA forest, using consistent information from the region. For example, fragmentation assessments should be conducted based on concrete information regarding particular species in the eco-region. Because most of the information is still missing for the country, most research applies a standardized assumption to conduct the analysis. Therefore, the results might not provide the most appropriate representation of the region, for example, to identify priority areas for conservation of the local fauna. Further research should be performed to study the ecology of the species and animal behavior in the country. Inclusion of different research areas provides a valuable asset to achieve the proper representation of the eco-region. Additionally, further studies could incorporate a detailed analysis with regards to different land uses and forest classes. When considering landscape metrics at a class level, the relationships among different land uses and forest density can be estimated, and thus the interactions between the classes can be derived.

On the other hand, when considering the inclusion of field survey data (particularly from rural areas) in studies, it is important to note the bias from the outcomes. For example, the Ministry of Environment in Paraguay is focusing its current efforts on the enhancement of environmental laws in rural areas. Thus, land owners might have felt pressured to answer questions concerning environmental topics. As a recommendation, interviews should be conducted by local habitants or community leaders so farmers would feel more comfortable responding to certain questions concerning sensitive environmental topics. Additionally, the sample distribution should be stratified on the form to integrate most rural communities within the study area.

Finally, this research combined outcomes obtained from remote sensing analysis with cadastral information to understand how farmers' activities and perceptions towards the forest has an effect on its dynamics. However, because of the lack of cadastral data in some areas (particularly for the group of small-scale farmers), field measurements were conducted to estimate the boundaries of the farms. As a consequence, some uncertainties with regards to the accuracy of the results could arise. Consequently, it is recommended to conduct further studies based only on certified lands, such as farms with proper cadastral information issued by the National Department of Census and Statistics (DGEEC). Additionally, the use of absolute deforestation values could provide a better understanding of the actual impact caused by different farm types on the forest cover. Future investigations could increase our understanding of additional forest dynamics information (e.g. forest degradation and regeneration rates). The proposed research could enhance considerably the understanding of the real impact of farm types on forest resources.

Overall, the use of remote sensing information is entering a new phase, where a large variety of sensors continuously acquire data from the earth's surface. Higher temporal and spatial resolution would deliver additional information and could serve as starting point for the development of further methods and approaches for forest cover change analysis. For example, the ESA Sentinel 1 radar satellite has provided all-weather day and night imagery since 2014, with a cycle 12 days. On the other hand, the Sentinel 2 optical sensor

(available since 2015) would provide imagery at 10-m resolution every 10 days. The use of a proper integrated database, where remote sensing and field survey information could generate essential information, is a further step toward developing strategies and polices aimed at the conservation of natural resources.

Statement of authorship

I hereby certify that I have authored this Dissertation entitled "Assessment of forest cover dynamics in Paraguay, a case study of the Upper Parana Atlantic Forest" independently and without undue assistance from third parties. No other than the resources and references indicated in this thesis have been used. I am aware that violations of this declaration may lead to subsequent withdrawal of the degree. The work has not previously been presented in the same or a similar format to another examination body in Germany or abroad.

I confirm that I acknowledge the doctoral regulations of the Faculty of Mathematics and Natural Sciences of Kiel University.

München, 2018

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