Policy options to reduce deforestation in the Bolivian lowlands based on spatial modeling of land use change

Dissertation
zur Erlangung des mathematisch-naturwissenschaftlichen Doktorgrades
"Doctor rerum naturalium"
der Georg-August-Universität Göttingen

vorgelegt von
Robert Christian Müller
aus Heidelberg

Göttingen 2011

Referent: Prof. Dr. Gerhard Gerold
Korreferent: PD Dr. Rüdiger Schaldach
Zweiter Korreferent: Dr. Daniel Müller
Tag der mündlichen Prüfung:

Diese Dissertationsschrift ist kumulativ angelegt. Die folgenden drei Publikationen werden direkt wiedergeben:

1. Müller R, Müller D, Schierhorn F, Gerold G (2011): Spatiotemporal modeling of the expansion of mechanized agriculture in the Bolivian lowland forests. Applied Geography 31(2): 631-640.

2. Müller R, Müller D, Schierhorn F, Gerold G, Pacheco P (2011): Proximate causes of deforestation in the Bolivian lowlands – an analysis of spatial dynamics. Regional Environmental Change: DOI: 10.1007/s10113-011-0259-0 (online bereits erschienen).

3. Müller R, Pistorius T, Rohde S, Gerold G, Pacheco P (eingereicht): Policy options to reduce deforestation based on a systematic analysis of drivers and agents in lowland Bolivia. Eingereicht bei Land Use Policy.

Summary

Tropical deforestation represents one of the most urgent environmental problems of our time; it contributes heavily to climate change, causes immense losses of biodiversity and endangers important environmental services. Bolivia is among the countries with the highest deforestation rates in the world. In light of the current international efforts to reduce deforestation within the framework of REDD, effective and efficient country-specific policy options need to be identified to make progress on the ground. A prerequisite for the prioritization of such policy options is a detailed understanding of the complex processes driving deforestation. Spatial models can contribute valuable information to this end. They can provide quantitative evaluations of hypothesized drivers of deforestation in the past and also generate scenarios that represent probable developments in the future. This study applies spatially explicit regression models as a key instrument for the systematic identification of specific policy options suitable for mitigating the expansion of the main forest-depleting land uses. The entire study is based on Bolivia as a model country.

The expansion of mechanized agriculture in the department of Santa Cruz is analyzed as a first case study. Soybean production has converted this area into one of the hotspots of deforestation in the entire Amazon. A logistic regression model covering five time steps (1976, 1986, 1992, 2001 and 2005) identifies the main determinants of the expansion of mechanized agriculture and explores the development of their effects over time. It shows that – while deforestation dynamics have been generally stable over time – there is a tendency of increased penetration into the more humid Amazonian forests in northern Santa Cruz, a development that is also known from Brazil. The model's results are thoroughly validated, including a comparison between projected and observed deforestation patterns and the investigation of hidden correlations between independent variables. The case study shows that logistic regression is a suitable tool for the purposes of the entire study, provided that careful evaluations and plausibility checks of the model outputs are conducted.

In a subsequent analysis covering the entire Bolivian lowlands, three main proximate causes of deforestation are identified: mechanized agriculture was responsible for 54% of deforestation between 1992 and 2004, followed by cattle ranching with 27 %, and small-scale agriculture with 19%. A multinomial logit model is applied to analyze the determinants of each of these proximate causes of deforestation. The results suggest that the expansion of mechanized agriculture occurs mainly in response to good access to export markets, fertile soil and intermediate rainfall conditions. Increases in small-scale agriculture are mainly associated with a humid climate, fertile soil and proximity to local markets. Forest conversion into pastures for cattle ranching occurs mostly irrespective of environmental determinants and can mainly be explained by access to local markets. Land use restrictions, such as protected areas, seem to prevent the expansion of mechanized agriculture but have little impact on the expansion of small-scale agriculture and cattle ranching. An analysis of future deforestation trends reveals possible hotspots of future expansion for each proximate cause and specifically highlights the possible opening of new frontiers of deforestation due to mechanized agriculture in the areas of Puerto Suarez and San Buenaventura. The quantitative insights of the model are substantiated with a qualitative analysis of historical processes that have shaped land use patterns in different zones of the Bolivian lowlands to date. Whereas the quantitative analysis effectively elucidates the spatial patterns of recent agricultural expansion, the interpretation of long-term historic drivers reveals that the timing and quantity of forest conversion are often triggered by political interventions and historical legacies.

In a third analysis, a systematic approach is developed in order to prioritize policy options for effective and efficient deforestation reduction, making use of the model outputs, among other things. Again, Bolivia is taken as a model country. The derivation of policy options is based on analyses of the spatial and economic potential of agricultural expansion, the expected costs of deforestation reduction, and the current legal and political framework in Bolivia. All analyses focus on the three proximate causes of deforestation; and specific policy options are discussed for these types of land use. It is concluded that, although mechanized agriculture caused more than half of all past deforestation in lowland Bolivia, cattle ranching activities should be targeted as a priority since their expansion threatens forests in many different locations and improvements could be achieved at relatively low costs. Enforcing legislation while strengthening institutions on both national and local levels is of utmost importance for the reduction of the expansion of all three land use categories. Specific measures should aim at giving an advantage to more efficient production on existing farms over the expansion into forested areas. In this context, a higher legal fee for deforestation has potential to mitigate forest conversion due to mechanized agriculture and cattle ranching farms, while a removal of subsidies for agro-diesel may specifically reduce the expansion of mechanized agriculture. Such measures could be complemented by a support for higher production efficiency, such as better access to fertilizer and techniques allowing increased cattle stocking densities. The expansion of small-scale agriculture seems to be difficult to control, due to the large number of agents; measures should focus on mitigating the encroachment into areas with land use restrictions, fostering more sustainable and space-efficient agricultural practices, as well as off-farm employment.

Models of deforestation are found to be important analytical tools for a better understanding of the processes leading to deforestation; they can render important information for the development of policy options to combat deforestation. Further investigations may explore the possibilities of building more complex scenarios by adding dynamic elements that are contained in some existing land use modeling frameworks. In the outlook of this study, the mapping of opportunity costs of forest conservation is shortly introduced as a promising possibility of generating scenarios based non-spatial factors such as prices of agricultural goods. It is however concluded that, for practical applications, it seems reasonable to keep the transparency of models as high as possible in order to allow for constant plausibility checks of the model outputs.

The study concludes that more research is needed to identify and evaluate suitable policy options to reduce deforestation on the ground. In the discussion on REDD, only little attention seems to be given to the development of mitigation strategies for large forest clearings driven by corporate agents and large cattle farms. This may be due to a certain prevalence of traditional approaches to biodiversity conservation within selected conservation areas and an unjustified focus on smallholders. Also the strong focus on market-based solutions may be questionable; according to this study it would be more appropriate to directly support the governments of tropical countries to implement the most promising measures. It may also be important to target existing markets that drive deforestation, i.e., global markets for beef, soybean, palm oil and tropical timber stemming from clear-cuts.

Resumen

La deforestación de bosques tropicales es uno de los mayores problemas ambientales de nuestros tiempos; contribuye al cambio climático, causa grandes pérdidas de biodiversidad y pone en peligro importantes servicios ambientales. Bolivia es uno de los países con las más altas tasas de deforestación en el mundo. En busca de soluciones a este problema, especialmente en el contexto de REDD, es importante identificar posibles medidas concretas para lograr una efectiva y eficiente reducción de la deforestación. Para esto, se necesita entender los procesos que llevan a la conversión de bosques. Modelos espaciales pueden contribuir insumos importantes para este objetivo, mediante una evaluación cuantitativa de factores de influencia y la generación de escenarios futuros. Este estudio aplica modelos espaciales de regresión logística como una herramienta clave para la identificación sistemática de medidas concretas que puedan ayudar a mitigar la expansión de actividades agrícolas hacia bosques tropicales. El estudio analiza la deforestación en Bolivia como un escenario ejemplar.

Como primer estudio de caso, se analiza la agricultura mecanizada en el departamento de Santa Cruz. La expansión del cultivo de la soya convirtió a esta región en uno de los centros de deforestación a nivel de toda la Amazonía. Un modelo de regresión logística que cubre cinco observaciones en el tiempo (1976, 1986, 1992, 2001 y 2005) identifica los factores que influenciaron la expansión de la agricultura mecanizada, así como sus efectos sobre la misma. Si bien las dinámicas de deforestación muestran cierta estabilidad en el tiempo, se puede identificar una tendencia de extensión hacia los bosques amazónicos en el norte de Santa Cruz – un fenómeno que también ocurre en Brasil.. Se realiza una validación detallada de los resultados del modelo, incluyendo una comparación de la deforestación proyectada con la situación real, así como la investigación de correlaciones escondidas entre variables independientes. El estudio de caso muestra que la regresión logística es una herramienta apta para el estudio en total, bajo la condición de realizar evaluaciones detalladas así como pruebas de plausibilidad.

En un siguiente análisis que cubre todas las tierras bajas de Bolivia se identifican tres causas directas de deforestación: La agricultura mecanizada causó 54% de la deforestación entre 1992 y 2004, seguido por la ganadería con 27% y la agricultura a pequeña escala con 19%. Con un modelo logit multinomial se analizaron los factores de influencia para cada una de estas causas directas. Los resultados muestran que la agricultura mecanizada expandió mayormente donde hay un buen acceso a los mercados de exportación, suelos fértiles y lluvias moderadas. La expansión de la agricultura a pequeña escala se asocia con un clima húmedo, suelos fértiles y un buen acceso a mercados locales. La conversión de bosques a pastizales para la ganadería muestra poca dependencia de factores ambientales y se puede explicar principalmente por el acceso a mercados locales.

Restricciones de uso de suelo, como áreas protegidas, parecen ser efectivas en la prevención de la agricultura mecanizada pero tienen poco impacto sobre la expansión de la agricultura a pequeña escala y la ganadería. Un análisis de tendencias futuras de deforestación identifica posibles focos de una futura expansión para cada una de las causas directas de deforestación. Se destaca la posible apertura de nuevas fronteras de agricultura mecanizada en las zonas de Puerto Suárez (sureste) y San Buenaventura (noroeste). Para complementar los resultados cuantitativos del modelo, se realiza también un análisis cualitativo de procesos históricos que han formado los patrones de uso de suelo en diferentes partes de las tierras bajas. Mientras el análisis cuantitativo es útil para entender los patrones espaciales de la expansión agrícola reciente, parece que los momentos y las cantidades de

deforestación se explican mejor por la interpretación de factores históricos, como por ejemplo la implementación de programas políticos.

En un tercer análisis se desarrolla un método sistemático para priorizar medidas concretas de reducción de deforestación. Se utilizan, entre otros, los resultados de la modelación. También en este análisis, Bolivia es seleccionada como país ejemplar. Para la identificación de medidas concretas, se analiza el potencial espacial y económico de la expansión agrícola, los posibles costos de una reducción de deforestación así como el marco político y legal correspondiente. Todos los análisis enfocan las tres causas directas de deforestación y se discuten medidas concretas de mitigación específicamente para cada una de las tres categorías de uso de suelo. Se concluye que es prioritario mitigar la deforestación causada por la ganadería, que amenaza prácticamente a todos los bosques accesibles y que podría ser reducida a costos relativamente bajos. La aplicación consecuente de las leyes existentes, así como el fortalecimiento de instituciones correspondientes a nivel nacional hasta local tiene gran importancia para lograr una reducción de la expansión de todas las tres categorías de uso de suelo. Medidas específicas deberían apuntar a dar ventaja a una producción más eficiente en campos existentes sobre la expansión hacia áreas todavía con bosque. En este contexto, se debería elevar el costo legal de la deforestación lo que podría reducir la expansión de la agricultura mecanizada y de la ganadería. La abolición de los subsidios de diesel podría ser especialmente efectiva en cuanto a la agricultura mecanizada. Tales medidas podrían ser complementadas por un apoyo técnico para aumentar la eficiencia de la producción, por ejemplo, por un mejor acceso a fertilizantes o mediante técnicas que permiten una mayor carga animal en la ganadería. El control de la expansión de agricultura a pequeña escala parece más difícil, debido al gran número de actores y sus contextos locales. Sería importante mitigar la invasión en áreas con restricciones de uso, promover prácticas más eficientes y sostenibles de agricultura y mejorar la oferta de empleos no agrícolas.

Modelos de deforestación se constituyen en importantes herramientas analíticas para entender los procesos de deforestación y pueden dar importantes insumos para la formulación de políticas públicas para su combate. Investigaciones futuras podrían explorar las posibilidades de modelar escenarios mas complejos con la integración de elementos dinámicos que ya son parte de algunos programas existentes para modelar el uso de suelo. En la última parte de este estudio, se introduce el mapeo de costos de oportunidad de conservación de bosques como una posibilidad de generar escenarios basados en factores no espaciales, tales como precios de productos agrícolas. Sin embargo, para aplicaciones prácticas, parece importante buscar a mantener los modelos lo más transparente posible para facilitar frecuentes pruebas de plausibilidad de los resultados.

Se concluye también que se requiere de más investigación orientada a identificar y evaluar posibles medidas concretas para reducir la deforestación. En el marco internacional de las discusiones sobre REDD, parece que se presta poca atención al desarrollo de estrategias para mitigar grandes desmontes causados por actores agroindustriales o grandes estancias ganaderas. Esto podría explicarse por cierta prevalencia de conceptos tradicionales de conservación y un enfoque no justificado en pequeños agricultores. También se puede cuestionar la importancia que se da a mecanismos de mercado para reducir la deforestación. Según este estudio, parece más apropiado apoyar a los gobiernos de países tropicales de manera directa en la implementación de las medidas que se ven como más prometedoras. Asimismo, puede ser importante trabajar con mercados existentes que fomentan la deforestación, tales como los mercados globales de carne de res, soya o aceite de palma.

Zusammenfassung

Tropische Entwaldung ist eines der dringendsten Umweltprobleme unserer Zeit. Sie ist einer der wichtigsten Treiber des Klimawandels und führt zu hohen Verlusten von Biodiversität und Ökosystemdienstleistungen. Bolivien ist eines der Länder mit den höchsten Entwaldungsraten weltweit. Im Rahmen der weltweiten Bemühungen zur Lösung dieses Problems unter dem REDD-Mechanismus ist es wichtig, konkrete und länderspezifische Handlungsoptionen für eine effektive und effiziente Entwaldungsreduktion zu identifizieren. Eine wichtige Voraussetzung dafür ist ein tiefgehendes Verständnis der komplexen Prozesse, die zu Entwaldung führen. Räumliche Modelle können hierfür wertvolle Informationen liefern, indem sie mögliche Einflussfaktoren in der Vergangenheit auswerten und Szenarien über künftige Entwicklungen generieren. In dieser Arbeit wird die logistische Regression als Schlüsselinstrument für eine systematische Identifikation von Handlungsoptionen angewendet, um die Ausbreitung der wichtigsten waldersetzenden Landnutzungsaktivitäten einzudämmen. Die gesamte Arbeit untersucht das bolivianische Tiefland als Modellregion.

In einer Fallstudie wird zunächst die Expansion der mechanisierten Landwirtschaft im Department Santa Cruz untersucht. Der großflächige Soja-Anbau macht diese Region zu einem der Brennpunkte der Entwaldung in Südamerika. Ein logistisches Regressionsmodell über fünf Beobachtungszeitpunkte (1976, 1986, 1992, 2001 und 2005) identifiziert die wichtigsten Einflussfaktoren für die Ausbreitung der mechanisierten Landwirtschaft und analysiert ihre Wirkung über die Zeit. Es zeigt sich, dass die übergeordnete Entwaldungsdynamik über die Zeit stabil blieb, wobei es jedoch eine Tendenz zum Vordringen in die amazonischen, feuchteren Wälder im Norden von Santa Cruz gibt; eine analoge Entwicklung ist auch aus Brasilien bekannt. Die Modellierungsergebnisse werden genau validiert; dafür werden projizierte mit tatsächlichen Entwaldungsmustern verglichen und versteckte Korrelationen zwischen unabhängigen Variablen aufgedeckt. Die Fallstudie zeigt, dass die logistische Regression ein geeignetes Werkzeug für die weitergehenden Studien ist, unter der Voraussetzung, dass sie von sorgfältigen Evaluierungen und Plausibilitätschecks begleitet wird.

In einer Folgeanalyse werden die drei wichtigsten direkten Ursachen für Entwaldung im gesamten bolivianischen Tiefland identifiziert: Mechanisierte Landwirtschaft war für 54% der Entwaldung zwischen 1992 und 2004 verantwortlich, gefolgt von Rinderzucht mit 27% und kleinbäuerlicher Landwirtschaft mit 19%. Mithilfe eines multinomialen Logitmodells werden die Einflussfaktoren dieser drei Landnutzungsformen analysiert. Die Resultate zeigen, dass die Expansion der mechanisierten Landwirtschaft hauptsächlich mit einem guten Zugang zu den Exportmärkten, fruchtbaren Böden und moderaten Niederschlagsbedingungen im Zusammenhang steht. Die Ausbreitung der kleinbäuerlichen Landwirtschaft ist mit einem eher feuchten Klima assoziiert, außerdem mit fruchtbaren Böden und einem guten Zugang zu lokalen Märkten. Die Umwandlung von Wald in Weideland zeigt nur geringe Korrelationen mit Umweltfaktoren und lässt sich am besten mit dem Zugang zu lokalen Märkten erklären. Landnutzungsrestriktionen, etwa Schutzgebiete, scheinen die Expansion von mechanisierter Landwirtschaft zu verhindern, zeigen aber wenig Wirkung in Bezug auf kleinbäuerliche Landwirtschaft und Viehzucht. Eine Analyse von zukünftigen Entwaldungstendenzen zeigt die wahrscheinliche künftige Ausbreitung jeder der drei Landnutzungsformen und identifiziert insbesondere zwei mögliche neue Expansionsgebiete der mechanisierten Landwirtschaft bei Puerto Suarez und San Buenaventura. Die quantitativen Modellierungsergebnisse werden ergänzt durch eine qualitative Analyse historischer Prozesse, die die Landnutzungsmuster in verschiedenen Teilen des bolivianischen Tieflands geformt haben. Während

die quantitative Analyse die neueren räumlichen Entwaldungsdynamiken gut erklären kann, scheinen die Zeitpunkte von Entwaldungsereignissen vor allem durch historische Faktoren und politische Interventionen bestimmt zu werden.

In einer dritten Analyse wird – wieder am Beispiel Boliviens – ein systematischer Ansatz zur Identifikation von Handlungsoptionen entwickelt, wobei die Modellierungsergebnisse ein wichtiges Element bilden. Die Ableitung von Handlungsoptionen basiert auf dem räumlichen und ökonomischen Potenzial landwirtschaftlicher Expansion, auf den erwarteten Kosten einer Entwaldungsreduktion sowie auf den aktuellen rechtlichen und politischen Rahmenbedingungen in Bolivien. Alle Analysen beziehen sich auf die drei direkten Ursachen von Entwaldung; für diese Landnutzungsformen werden spezifische Handlungsoptionen diskutiert. Die Eindämmung der Viehwirtschaft zeigt sich trotz des höheren Entwaldungsanteils der mechanisierten Landwirtschaft als Priorität, da die Umwandlung in Weideland für nahezu alle zugänglichen Wälder eine Bedrohung darstellt und da eine Reduktion zu relativ geringen Kosten möglich sein sollte. Eine schärfere gesetzliche Kontrolle sowie die Stärkung von zuständigen Institutionen auf nationaler und lokaler Ebene sind von höchster Bedeutung für die Reduktion aller drei Entwaldungstypen. Spezifische Maßnahmen sollten eine effizientere Produktion auf bereits genutzten Flächen gegenüber dem Vordringen in bewaldete Gebiete attraktiver machen. In diesem Zusammenhang könnten höhere Gebühren für legale Entwaldung die Ausbreitung von mechanisierter Landwirtschaft und Viehwirtschaft eindämmen. Auch eine Rückführung der Diesel-Subventionen dürfte die Expansion der mechanisierten Landwirtschaft bremsen. Solche Maßnahmen sollten durch die Förderung einer höheren räumlichen Produktionseffizienz ergänzt werden, etwa durch verbesserten Zugang zu Dünger oder technische Beratung und Unterstützung für höhere Bestockungsdichten. Die Ausbreitung der kleinbäuerlichen Landwirtschaft scheint aufgrund der hohen Zahl von Akteuren schwerer kontrollierbar zu sein; wichtig wäre es aber, das Eindringen in Schutzgebiete zu verhindern und effizientere und nachhaltigere Anbauformen sowie auch Arbeitsplätze außerhalb der Landwirtschaft zu fördern.

Die Entwaldungsmodellierung zeigt sich als wichtiges analytisches Werkzeug zum Verständnis der zugrunde liegenden Prozesse; sie kann wichtige Informationen zur Ableitung von Handlungsoptionen liefern. Zukünftige Forschung könnte die Möglichkeiten von komplexeren Szenarien durch die Integration dynamischer Elemente ausloten; entsprechende Möglichkeiten sind in bestehenden Modellierungsprogrammen angelegt. Im Ausblick dieser Arbeit wird außerdem die Technik des Kartierens von Opportunitätskosten des Waldschutzes vorgestellt: Sie ermöglicht Szenarien auf der Basis von nicht-räumlichen Faktoren, etwa von Preisen landwirtschaftlicher Produkte. Für die praktische Anwendung von Modellen scheint es allerdings wichtig zu sein, eine hohe Transparenz zu wahren, um regelmäßige Plausibilitätschecks zu ermöglichen.

Es besteht weiterer Forschungsbedarf zur Identifikation geeigneter Handlungsoptionen für eine effektive und effiziente Entwaldungsreduktion. In der Diskussion um REDD scheint die Bekämpfung der Entwaldung durch industrielle Landwirtschaft und große Rinderfarmen nur eine untergeordnete Rolle zu spielen. Dies könnte im Vorherrschen traditioneller Naturschutzkonzepte begründet sein sowie in einem ungerechtfertigten Fokus auf Kleinbauern. Auch der Schwerpunkt auf marktbasierten Lösungsansätzen scheint fragwürdig; nach den Ergebnissen dieser Arbeit könnte die direkte Unterstützung der Regierungen von tropischen Ländern bei der Umsetzung der erfolgsversprechendsten Maßnahmen zielführender sein. Des Weiteren scheint es wichtig, bei existierenden entwaldungsrelevanten globalen Märkten anzusetzen, etwa beim Handel mit Agrarrohstoffen wie Soja, Rindfleisch, Palmöl oder Tropenholz aus Kahlschlägen.

Acknowledgements

This thesis was prepared within the DFG-funded research project "Landnutzung, Entwaldung und Naturschutz in Bolivien – Analyse und modellgestützte Prognose zukünftiger Entwicklungen" at the Department of Landscape Ecology at the Geographical Institute of the University of Göttingen.

I would like to thank Prof. Dr. Gerhard Gerold for supervising this thesis and for his valuable support and his confidence from the first moment on. I also want to thank my co-referees Dr. Rüdiger Schaldach and Dr. Daniel Müller. Daniel accompanied me throughout the work on this thesis and greatly helped me with his knowledge on deforestation models; I also want to thank him for his diligence and patience as a co-author. I am also grateful to my co-authors Pablo Pacheco and Till Pistorius for their valuable contributions and their endurance during the long process from the early ideas to the final manuscripts. A special thank goes to Florian Schierhorn who – apart from being co-author – supported me greatly when he was writing his diploma thesis in the initial stage of the project. Thanks also to Sophia Rohde and Moritz Maneke who helped me during the work on their theses, and to the current and former colleagues at the Geographical Institute, particularly Jens-Peter Krüger, Stefan Erasmi and Jürgen Böhner; and to Dorothea Röckl for her patience and support with administrative issues.

This work would never have been possible without the support of many partners and friends in Bolivia. I am grateful to the Museum of Natural History Noel Kempff Mercado in Santa Cruz and to Conservation International Bolivia for sharing the extensive data set on deforestation. I am also particularly grateful to FAN Bolivia, especially to the team of the "Ciencias" department, not only for all the help during the work on this thesis, but also for manifold support and friendship during the last 10 years; I particularly want to thank Natalia Araujo. In this context I am also thankful to Pierre Ibisch and Christoph Nowicki who introduced me into biodiversity and conservation in Bolivia. I also thank Jörg Seifert for the cooperation with the environmental services department of FAN. Thanks a lot also to Fundación Natura Bolivia for the fruitful cooperation on deforestation studies in El Choré and TIPNIS, in particular to Maria Teresa Vargas and Anita Guerra. I would also like to mention the following Bolivian institutions and individuals who helped me with data and by sharing experiences: the team of the former Superintendencia Forestal, especially Rolf Wachholtz and Maurizio Forno, Juan Carlos Gutiérrez from Centro de Investigación y Promoción del Campesinado (CIPCA), Ismael Gonzales and Mariselva Viera from CIAT Santa Cruz, the team of Fundación para la Conservación del Bosque Seco Chiquitano (FCBC), Prof. Dr. Alejandro Guaman, Juan Carlos Ledezma, Clea Paz, the staff of the Cámara Agropecuaria del Oriente (CAO) in Santa Cruz, SERNAP, LIDEMA, CEPAC, Cecilia Ayala from Conservation Strategy Fund, the team of the Oficina de Desarrollo Limpio in 2010 and the team of the ABT in Cobija, Pando.

Muchísimas gracias also to my Bolivian friends who supported me in many ways during my time in this fascinating country and with whom I shared wonderful experiences during many field trips, particularly Gustavo Mariaca, Jeyson Miranda, José Mercado, Mauricio Ballesteros, Inka Montero, Juan Carlos Montero and Stefan Kreft. Stefan Kreft and Juan Carlos Montero, together with James Johnson, also reviewed parts of the study and contributed valuable comments.

A thousand thanks to all of you and to all the other people who have not been mentioned in person here!

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Road from La Paz to the lowlands (Picture: Juan Carlos Montero)

1 Introduction

1.1 General introduction and objectives of the study

The mitigation of tropical deforestation constitutes one of the major environmental challenges of our times. The conversion of tropical forests to agricultural uses and degraded land makes up about 20% of anthropogenic climate change (IPCC 2007) and is a major global cause of the loss of biodiversity and declining ecosystem services (Millennium Ecosystem Assessment 2005; Myers et al. 2000; Sampaio et al. 2007). Approximately 50% of tropical deforestation occurs in the Amazon (FAO 2010). Bolivia, which shares a part of the Amazon, is among the 10 countries with the highest absolute annual forest loss (FAO 2011), ranked fourth in terms of deforestation rates (Maplecroft 2011). In order to reduce tropical deforestation, there is a need for a better understanding of the drivers and processes behind it (Geist and Lambin 2002) and to take these as a basis for the development of strategies to reduce deforestation within different ecological and socioeconomic contexts. Bolivia is a suitable model country for the investigation of deforestation processes and possible solutions; its forests are threatened by different agricultural and land uses (see Figure 1.1) associated with diverse agents (Killeen et al. 2008) and suitable spatial data for the analysis are available.

Deforestation modeling constitutes an important tool for analyzing and understanding deforestation dynamics. Due to progress in remote sensing techniques, there has been a steady improvement of tropical deforestation modeling over the last 20 years. A number of international programs have been founded, including the *Land Use and Cover Change* (LUCC) project, which is part of the *International Geosphere-Biosphere Programme* (IGBP) and the *International Human Dimensions Programme on Global Environmental Change* (IHDP) (Lambin and Geist 2006), and the *Land Cover Land Use Change* (LCLUC) program of the NASA (2009). Important reviews on studies in the field of deforestation modeling have been prepared by Kaimowitz and Angelsen (1998), Agarwal et al. (2002), Heistermann et al. (2006), Matthews et al. (2007), Verburg et al. (2004) and Walker (2003). Also in the context of REDD (Reducing Emissions from Deforestation and Degradation, Miles and Kapos 2008), deforestation modeling is an important task for determining baseline scenarios of deforestation reduction (Brown et al. 2007; Clark Labs 2010).

To date, there are a variety of different approaches available for modeling deforestation, including logistic regression (Chomitz and Gray 1998), machine learning based algorithms, e.g., neural networks (Pijanowsky et al. 2006) and cellular automata (Manson 2006). Apart from purely spatial models, integrated models have also been developed to allow for the dynamic modeling of deforestation under the consideration of a broad variety of economic and agricultural data (e.g., Schaldach et al. 2011; Verburg and Overmars 2009). In this study, existing concepts of deforestation modeling shall be applied and further developed as practical tools to better understand tropical deforestation and to define mitigation strategies. It is intended to keep models as transparent and simple as possible while constantly subjecting modeling concepts and outputs to plausibility checks by discussing them in the broader context of deforestation processes on the ground.

The urgency of the tropical deforestation problem indicates the serious need for developing suitable mitigation strategies. The REDD mechanism, which developed over the past few years within the framework of the Kyoto protocol, constitutes the major effort of the international community to reduce deforestation (Miles and Kapos 2008; Santilli et al. 2005). Though the goal of the international negotiations on REDD - a systematic international compensation scheme for tropical countries that achieve sustainable deforestation reduction – is still far from being reached, there is already a significant amount of funding available from international sources, such as the Forest Carbon Partnership Facility (FCPF, managed by the World Bank, FCPF 2011), and mainly European governments (e.g., Norway, Germany and others, Physorg 2010). At the same time, REDD projects represent the fastest-growing project category on the voluntary carbon market in terms of the volume of carbon credits traded (Peters-Stanley et al. 2011). But most studies and negotiations on REDD target institutional and financial issues and aspects of monitoring and verification of deforestation while there is still little discussion on concrete measures to reduce deforestation on the ground. (This phenomenon is discussed in detail in Section 6.2). There are currently 14 countries receiving direct support from the UN-REDD program and most of them have drafted national REDD programs. These national programs, however, tend to focus on institutional matters and contain rather generalized and anecdotic information on drivers of deforestation and possible mitigation measures (UN-REDD 2011a). Only few attempts to systematize possible policy options for deforestation reduction have been made. A preliminary list of possible policy options has been prepared in the context of negotiations on REDD (UNFCCC 2006). This list is mainly based on Kaimowitz et al. (1998) and distinguishes between policies and positive incentives; the list has not been updated until 2011. Angelsen (2009) presents a short review of policy options from an economic point of view. Fearnside (2003) evaluates the effectiveness of policies aimed at reducing deforestation in Brazil in the late 1990s. The present study seeks to contribute to the identification and prioritization of concrete measures to reduce deforestation, based on a systematic and quantitative investigation of the underlying processes.

Objectives

As its ultimate objective, this thesis aspires to contribute to the identification of policy options for an effective and efficient reduction of tropical deforestation. In order to do this, it is sought to achieve a detailed understanding of the processes leading to tropical deforestation, with a special emphasis on analyzing the spatial dynamics of the expansion of the main forest-depleting land uses. Spatially explicit models of deforestation shall therefore be studied and applied. The entire study is based on Bolivia as a model country.

The study consists mainly of three investigations that pursue the following specific objectives:

a) The first investigation explores the suitability of logistic regression as a tool for modeling deforestation in a case study.

b) The second investigation tries to achieve a better understanding of land use change in lowland Bolivia based on a quantitative regression analysis and a qualitative analysis of historical changes in land use trends.

c) The third investigation intends to develop a systematic approach to identify and specify policy options for effective and efficient deforestation reduction.

Figure 1.1 Forests and Deforestation in Bolivia. Pictures: Juan Carlos Montero and Author.

A – C: Amazonian forest and impacts of mechanized agriculture north of Santa Cruz de la Sierra

D – F: Smallholders and shifting cultivation in the northern Amazon, Pando

G: Cattle ranching in the Northern Bolivian Amazon

H: Degrading pasture north of Santa Cruz

1.2 Structure of this thesis

This document consists of three articles for peer-reviewed international journals that have been prepared in the context of the doctoral study, framed by the present introductory chapter, a short synthesis, and an outlook chapter. Only small formal changes have been made to the journal articles.

In the last section of the present chapter, an introduction into spatial deforestation modeling is given with special emphasis on logistic regression and a justification for the choice of this method as main modeling approach. The description of the study area is not included in the introductory chapter since it is part of Chapter Two (which describes the area around Santa Cruz de la Sierra) and Chapter Three (which describes the entire Bolivian lowland).

Chapter Two scrutinizes the method of logistic regression for deforestation modeling; in a case study, the expansion of mechanized agriculture around the city of Santa Cruz is modeled, focusing on the consistency of model outputs over subsequent periods of time and possible biases caused by the correlation of independent variables. Moreover, model outputs are evaluated by a comparison between projected and observed deforestation.

Corresponding journal article:

- Müller R, Müller D, Schierhorn F, Gerold G (2011): Spatiotemporal modeling of the expansion of mechanized agriculture in the Bolivian lowland forests. Applied Geography 31(2): 631-640.

Chapter Three applies the methods that have been tested in the previous chapter and sets the basis for the derivation of policy options in Chapter Four. The central land use model is constructed, including the definition of the three main proximate causes of deforestation in Bolivia, i.e., mechanized agriculture, small-scale agriculture and cattle ranching. Model outputs are thoroughly discussed in the context of the land use history in different regions of the Bolivian lowlands.

Corresponding journal article:

- Müller R, Müller D, Schierhorn F, Gerold G, Pacheco P (2011): Proximate causes of deforestation in the Bolivian lowlands – an analysis of spatial dynamics. Regional Environmental Change. DOI: 10.1007/s10113-011-0259-0 (already available online).

In Chapter Four, a systematic approach is developed in order to prioritize policy options for effective and efficient deforestation reduction, again taking Bolivia as an example. The derivation of policy options is based on analyses of the spatial and economic potential of agricultural expansion, the expected costs of deforestation reduction, as well as the current legal and political framework in Bolivia. All analyses focus on the three proximate causes of deforestation defined in Chapter Three; policy options are specifically discussed for these proximate causes of deforestation.

Corresponding journal article:

- Müller R, Pistorius T, Rohde S, Gerold G, Pacheco P (submitted): Policy options to reduce deforestation based on a systematic analysis of drivers and agents in lowland Bolivia. Submitted to Land Use Policy.

Chapter Five provides a synthesis of the previous three chapters.

Chapter Six contains an outlook and includes some examples of additional and complementary analyses, including the generation of deforestation scenarios by logistic regression and the mapping of opportunity costs of forest conservation. Further research needs are discussed both for deforestation models and for the definition of policy options to reduce deforestation; the latter is discussed in the context of the current international negotiations on REDD.

Chapter Six is partially based on four additional publications that have been prepared in the context of this doctoral thesis:

- Müller R (2009): Reserva Forestal El Chore: Análisis de deforestación y estrategias para reducirla. Fundación Natura Bolivia, Santa Cruz de la Sierra, Bolivia.
- Müller R (2011): Possibilities to reduce tropical deforestation by carbon funding – general reflections and examples from Bolivia. In: Hansjürgens B, Antes R, Schrunz M (eds.): Permit Trading in Different Applications. Routledge, London.
- Müller R (in press): Proyección de la deforestación en el TIPNIS. In Vargas M (ed.): Compensación por servicios ambientales de carbono. Una alternativa para reducir la deforestación en el TIPNIS. PIEB. La Paz, Bolivia.
- Müller R, Schierhorn F, Rohde S, Gerold G (in press): Landnutzungsänderungen und Entwaldung im bolivianischen Tiefland – Analyse von Einflussfaktoren, räumliche Modellierung und Entwicklung von Szenarien. In: Coy M, Neuburger M (eds.): Global Change: Herausforderungen für Lateinamerika. Proceedings of the Annual Conference of the Society of German Geographers, Geographical Institute, Innsbruck University.

1.3 Deforestation modeling – why and how?

The motivation for this study originated from the author’s work in different programs concerning spatial planning of biodiversity conservation in Bolivia (Müller et al. 2003; Ibisch et al. 2006; Ibisch et al. 2007; Araujo et al. 2010). In this context, detailed and systematic analyses have been developed to identify priority areas for biodiversity conservation on the national level, i.e., to answer the question of *what* to protect; while the question of *against* what to protect has only been addressed in a superficial way. Since in Bolivia, as well as in many other tropical countries, the main threat to biodiversity consists of the conversion of forests to agriculture (Geist and Lambin 2002), a systematic analysis of deforestation emerged as a useful task. Modeling is a suitable approach for such systematic analyses. Since a strong focus is put on understanding the processes leading to deforestation, models are primarily regarded as analytical tools. In accordance with the objective of the present study, the models developed within this thesis should be applicable for four main purposes (see also Lambin 1997):

1) Improved understanding of processes leading to deforestation
2) Verification and falsification of hypotheses on potential drivers of deforestation
3) Generation of simple scenarios and predictions
4) Definition and discussion of possible policy options

During the work on deforestation models, two important constraints are to be kept in mind:

a) The accuracy of a model can never be better than the accuracy of the data used as inputs.
b) There will always be a trade-off between the complexity and transparency of models.

In particular the first two purposes and both constraints are seen as arguments in favor of empirical and transparent methodologies. A focus is put on spatial modeling. The expansion of land use into forests is a spatial phenomenon which is measured in spatial units, and the spatial expansion is probably the aspect of deforestation that is best-documented due to remote sensing techniques and thus offers the best possibilities for systematic analyses. Though there are also models focusing on non-spatial aspects of deforestation (see e.g., Kaimowitz and Angelsen 1998), such aspects are not evaluated by models in the present study but are assessed qualitatively and systematically in the context of analyzing possible policy options (see Chapter Four).

In the following sections, examples are given of factors triggering deforestation in Bolivia and assigned to loose categories. Thereby it shall be explored which parts of the processes leading to deforestation can be covered by spatial models and which factors have to be considered outside the modeling framework. It is also intended to illustrate the complexity of the processes leading to deforestation and to explain the high level of importance that is given to constant plausibility checks of the results in this study. The categories presented below are adapted from Müller et al. (in press) with reference to Geist and Lambin (2002), but without the pretension of formulating a self-contained system.

Non-exclusive categories and examples of factors that shape deforestation

Historical factors

The current pattern of deforestation is always a consequence of the past. But factors that used to be decisive in the past may have lost their relevance. Examples from Bolivia include the foundation of settlements in the Chiquitania region in eastern Bolivia by Jesuits in the 18th century with the purpose of evangelizing and settling down the indigenous population (Tonelli Justiniano 2004), the rubber boom in the Amazonian north of Bolivia (Gamarra Tellez 2004), and the construction of a railway from Santa Cruz to Trinidad, which was started and abandoned in the 1960s, but now offers access to smallholders to the El Choré forest reserve (Montes de Oca 2004; José Luis Vega López, personal communication).

Policies on land use

National policies often put restrictions on land uses in selected areas. A large part of the Bolivian lowlands is covered by protected areas, forest concession and indigenous territories, etc. (Figure 3.5). But the recent example of the Indigenous Territory and National Park Isiboro Sécure (TIPNIS) has shown that neither the protection status nor the ownership of indigenous peoples can automatically guarantee the conservation of an area. It was only strong protests that could finally oblige the government to abandon the plan of building a road across the area (BBC News 2011). The forest law regulates forest clearings in Bolivia, requiring land owners to get approval for land use plans on the private–property level. There is also an obligation to show the socioeconomic function of privately owned land which represents a perverse incentive to clear forests in order to justify ownership (see 4.2).

Political programs

Until the 1980s, governmental programs aiming at fostering the development of forested areas played in major role in the history of land use in Latin America (Rudel 2005), e.g., by donating land, providing cheap capital and constructing infrastructure. In Bolivia, settlements of colonists from the highlands were established in the Andean piedmont (in the regions of Alto Beni and Chapare) and in the northern parts of the Department of Santa Cruz (Sandoval et al. 2003). In Santa Cruz, land was also donated to foreign colonists, mainly Mennonites. Another example is the area of San Juan de Yapacaní north of Santa Cruz de la Sierra, where a Japanese colony was founded in the 1950s with support of the Bolivian government (Sandoval et al. 2003). The Japanese settlers specialized in rice production and are still leading in this field, which still shapes deforestation in this area now. In the area around Santa Cruz, the "Tierras Bajas" program largely supported the modernization of agriculture and construction of infrastructure in the early 1990s (Baudoin et al. 1995). Another example was the attempt to replace illegal coca plantations in the Chapare with alternative crops starting in the 1990s (Barrientos 2005). Since coca is an unbeatably space-efficient crop, such programs indirectly promoted deforestation.

Economic factors

Land use activities take place within a broader macroeconomic context. Particularly for the production of exported agricultural goods – in Bolivia mainly soybeans – world market prices and exchange rates become important factors in relation to deforestation. One related factor is the success of the Bolivian government in securing export markets: currently most soybean is sold under favorable conditions to Venezuela and Colombia (CADEX 2008). Available infrastructure and market access are important for virtually all types of agriculture in Bolivia, since even small-scale farmers generally sell an important part of their yield. Another important economic factor is access to capital. In the Bolivian agro-industry, Brazilian capital plays an important role; small-scale producers often depend on cooperatives or national agencies. The current high subsidy for diesel is another important economic factor leading to a significant cost reduction for mechanized agriculture in Bolivia (see 4.4.1).

Socio-cultural factors

Different ethnic groups tend to apply different forms of agriculture. Mennonites, for example, are known to be hard-working farmers in Bolivia. They tend to install a large number of small, connected fields that are cultivated very intensively (Killeen et al. 2008). In the northern Amazon in Bolivia, owning large numbers of cattle can guarantee a high social status as "ganadero," which can constitute a non-economic incentive to extend pastures. National migrants stemming from the highlands ("colonos") are by far the most important small-scale farmers in the lowlands; smallholders originating from the lowlands often prefer extractive activities like gathering Brazil nuts (Stoian and Henkemans 2000).

Geophysical factors

Geophysical factors such as climate, topography and soil fertility set the natural conditions for agriculture. In Bolivia, the best soils of the country are found in the Rio Grande floodplain east of

Santa Cruz, which is also the center of mechanized agriculture (see Chapters Two and Three for more details).

Technological progress and innovation

New agricultural technologies have the potential to boost agriculture as well as deforestation. The poor soils of the Precambrian shield in eastern Bolivia present a severe limitation to agriculture. In Brazil however, the state of Mato Grosso – mostly under similar conditions – is the center of soybean cultivation due to technologies that allow soybean production with a massive use of fertilizer and lime (Kaimowitz and Smith 2001). A similar "agricultural revolution" may also become a threat to the Chiquitano Dry Forest in eastern Bolivia, probably driven by Brazilian capital.

Other factors

There are many other factors that have great influence on deforestation but are hard to categorize, such as the fact that Bolivia is not officially free of the foot and mouth disease which limits the possibilities of exporting beef (Pacheco 2006a).

Possibilities of spatial modeling

The large variety of factors that influence deforestation illustrates the high complexity of the underlying processes. Of the different factors mentioned above, only those that can be represented in maps may be used in spatial models. Such factors mainly include geophysical factors and also some factors referring to land use policies (e.g., protected areas) and economic factors, such as the access to markets. Therefore, spatial models face clear limitations; but at the same time, the concentration on spatial factors keeps models homogeneous and relatively simple. A representation of all factors in the form of standardized maps allows for statistical evaluations of possible determinants of deforestation based on large datasets. Maps are generally divided into raster cells. Heistermann et al. (2006) differentiate between geographic models, which are similar to spatial models, and economic models. The latter analyze non-spatial economic data, e.g., in the form of economic equilibrium models such as FASOM (Adams et al. 2005). Deforestation is often just one of many outputs in such models. They tend to be highly complex due to manifold interdependencies between the factors (e.g., because demand elasticities influence prices which influence production, etc.).

Integrated land use models attempt to combine spatial and non-spatial components, the latter mainly being economic factors (Heistermann et al 2006). Examples are Dyna-CLUE (Verburg and Overmars 2009) or LandSHIFT (Schaldach et al. 2011). In integrated models, the spatial component usually forms a separate module that can also be run independently from the integrated model. The output of the spatial component of deforestation models is generally a map of propensity of deforestation, i.e., a map that indicates spatially differentiated probabilities of forest conversion. Such maps are suitable to estimate which parts of a studied area will probably be deforested first. Eastman (2005) calls them "soft predictions".

In order to generate defined scenarios of future deforestation, the quantity of expected deforestation must also be known. This is generally done in separate analyses that determine a "demand for deforestation" (Verburg and Veldkamp 2004), e.g., the demand for products produced at the expense of forests. For this purpose, different methodologies are applied (see Verburg and Overmars 2009), including simple trend analysis (Pontius and Malanson 2005), simple demand models (Sohl et al. 2007) and complex multi-sectoral economic equilibrium models (e.g., Rosegrant et al. 2008). An example for a sigmoid trend analysis (Müller 2009) is presented in Section 6.1.1. Since the demand for deforestation depends on complex macroeconomic processes, there is always a high degree of uncertainty in projections of the demand for deforestation – just as in predictions of commodity prices or stock markets. The demand for deforestation is then generally allocated to a map of deforestation propensity which leads to a concrete scenario of deforestation – or a "hard prediction" according to Eastman (2005). Apart from spatially different deforestation propensities, the allocation process can also consider additional rules such as neighborhood relations. Examples of this are found in modeling frameworks such as CLUE-S (Verburg and Veldkamp 2004), Dinamica EGO (Soares-Filho et al. 2009) and LandSHIFT (Schaldach et al. 2011). These modeling frameworks also allow for dynamic simulations of land use change, i.e., different prediction maps can be produced in subsequent time steps of which each uses input data generated by the former.

Since in the present study, the focus is on spatial, empirical analyses, a main purpose of modeling here is the generation of maps of deforestation propensity. A variety of approaches are available for this purpose (Table 1.1). With the exception of cellular automata, all these approaches are empirical[1] since they generate rules to derive spatial propensities of deforestation based on a comparison of observed deforestation and hypothesized determinants. These approaches differ in the methods and show specific advantages as well as disadvantages.

Logistic regression models allow for high transparency; the interpretation of regression coefficients enables differentiated testing of hypotheses and quantitative evaluations of independent variables. Due to the regression technique, which is analogue to multiple linear regression, the regression coefficients of an independent variable can vary if other variables are changed, included or excluded, i.e., models account for possible interactions between independent variables. This can avoid possible biases, but it also implies that the set of analyzed variables should not omit important determinants of deforestation. One example would be the effectiveness of a protected area that is situated in a zone with low suitability for agriculture: if the protected area is evaluated independently from other variables, its modeled effectiveness in reducing deforestation may appear to be high. An inclusion of other variables representing agricultural suitability might, however, reduce the modeled impact of protected areas.

Neural networks show a strong performance in terms of calibration accuracy in comparative studies (Eastman 2005). But since no regression coefficients are generated, the possibilities of evaluating the impacts of individual variables are very limited, which also limits the possibility of comparing deforestation dynamics under different circumstances. Qualitative indirect evaluations are possible by running the model several times with different sets of variables.

Other empirical methods such as weights of evidence, analytic hierarchy processes and the method applied in GEOMOD (Pontius and Malanson 2005) evaluate independent variable one-by-one or pair-wise, without accounting for complex interactions. This leads to a high degree of simplicity, but also implies a risk of misinterpretation (e.g., in the example of the protected area described above).

Cellular automata allow for running simulations with a high temporal resolution, including complex feedbacks in space and time. At the same time, models quickly become highly complex even with simple input data which makes it difficult to check for the plausibility of outputs. Rules of interaction

---

[1] Overmars et al. (2007) distinguish between inductive approaches that are analogue to empirical approaches, and deductive approaches where there first is a theory which is then evaluated by observed data.

of neighboring grid cells often have to be set based on non-empirical criteria such as expert judgment, which can be a cause of uncertainty and reduce verifiability. Cellular automata always contain a dynamic component that cannot be separated from the spatial component.

Another method of spatial deforestation modeling is the direct mapping of the modeled profitability of forest-depleting land uses, i.e., the opportunity costs of forest conservation (Vera Diaz et al. 2007). This method is deductive in the sense that observed deforestation patterns are not evaluated; it is, however, based on empirically observed economic input data, such as spatially differentiated costs and revenues of agricultural production. Examples of opportunity-cost mapping are given in the outlook (Chapter Six).

Table 1.1 Different approaches for spatial modeling of deforestation. Source: Author, based on the sources indicated in the table, as well as Eastman (2005).

Approach	Examples	Method	Advantages	Disadvantages
Logistic regression (empirical)	Chomitz & Gray (1998), recommended for CLUE-S (Verburg and Veldkamp 2004)	Multiple linear regression after logistic transformation of the dependent categorical variable	Transparent and verifiable, accounts for interaction between independent variables	Rather static, sensitive to the selection of independent variables
Neural networks (empirical)	LCM (Clark Labs 2009), LTM (Pijanowski et al. 2006)	Iterative process of machine learning	Achieves high goodness of fit of calibration	Low transparency („black box“), no quantitative interpretation of coefficients
Simplified empirical approaches: a) Weights of evidence b) Analytic hierarchy process c) Method applied in GEOMOD	a) Dinamica EGO (Soares-Filho et al. 2009) b) LandSHIFT (Schaldach et al. 2011) c) GEOMOD (Pontius and Malanson 2005)	Potential determinants are analyzed one by one or pair wise	Simple and transparent	No or little accounting for interaction between independent variables
Cellular automata (mostly deductive)	(e.g., Manson 2005)	Dynamic process based on neighborhood functions	Dynamic modeling, accounts for spatial interaction	Very complex, rules defined on rather subjective criteria, no quantitative interpretation of coefficients

In the present study, logistic regression is chosen as a modeling approach since the analysis of regression coefficients allows quantitative interpretations of the modeled effects of independent variables, and also because this approach is highly transparent and accounts for interaction between variables.

Logistic regression in land use modeling

In the following section, basic concepts of logistic regression are explained, mainly based on Menard (2002) and Long and Freese (2006); parts of the explanations are taken from Müller et al. (in press). Thereby, an introduction into the main modeling method applied in this study is given[2]. Any modeling approach relies on certain assumptions. A common assumption for land use modeling is the tendency of land use agents to maximize the land rent (Chomitz and Gray 1996) by choosing the most profitable agricultural land use (e.g., the most suitable crop). Von Thünen (1990/orig: 1826) analyzed market access as a spatial factor deciding on land rent and corresponding land use decisions. Ricardo (2002/orig: 1817) assumed varying soil qualities as a spatial factor triggering differentiated land use. The first selection of independent variables to be tested in empirical approaches, such as regression analysis and neural networks, generally considers factors that are supposed to influence the profitability of agricultural land use, which represents a deductive component within these empirical models.

In a spatial regression analysis, observed deforestation as a binary dependent variable is related to hypothesized determinants of land use decisions as independent variables, within discrete land units that are generally represented by raster cells (see Figure 1.2; Kaimowitz and Angelsen 1998; Verburg et al. 2004). The regression analysis thereby investigates correlations without directly analyzing causal relations.

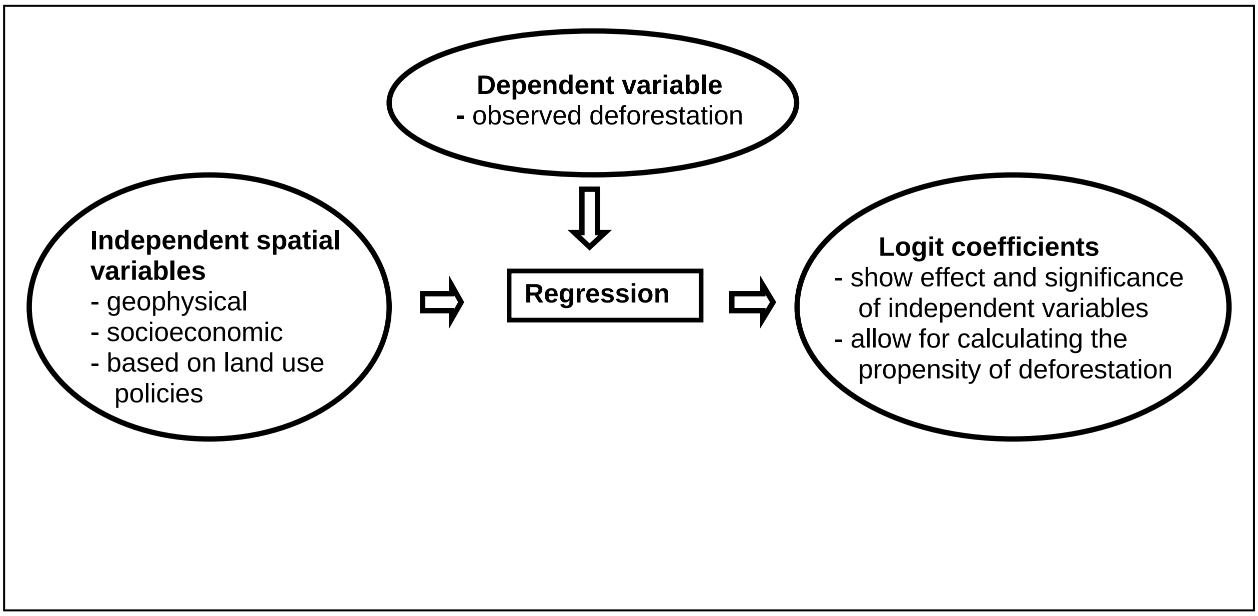


Figure 1.2 Schematic representation of a spatial logistic regression model on deforestation (adapted from Müller et al., in press).

Since the dependent variable is binary (forest – non forest), a transformation is required to enable the application of regression techniques. In logistic regression, the proportion of a state of the binary dependent variable (percentage of deforested cells), ranging from 0 to 1 (or 0 to 100%), is first

---

[2] Chapters Two and Three only contain general descriptions of the principles of logistic regression.

transformed to “odds”, i.e., the ratio of the probability and counter probability[3]. The range of odds values is from zero to infinity. The natural logarithm of the odds is called “logit”. Logits range from $-\infty$ to ∞ and allow for regression in analogy to multiple linear regression, generally by maximum likelihood estimation (see e.g., Menard 2002). Figure 1.3 illustrates the logistic transformation.

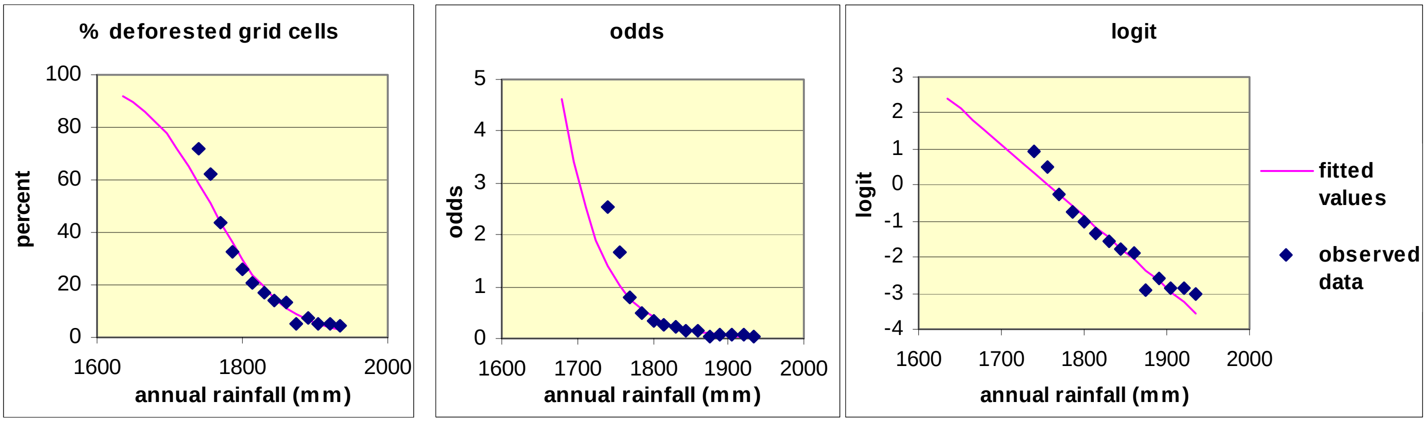


Figure 1.3 Logistic transformation illustrated on an example of deforestation in the El Choré forest reserve (adapted from Müller 2009).

The formula of logistic regression can be represented as follows:

$$f(z) = 1/(1+e^{-z})$$

$$z = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k$$

where $f(z)$ refers to the probability of an outcome (e.g., deforestation), and z to the combined contribution of all independent variables. β_0 is a constant, β_i is the regression coefficient of the variable x_i and k is the number of independent variables.

An interpretation of the modeled regression coefficients allows for inferences of the direction and strength of the impact of an independent variable. The significance of the effect of a variable is expressed by z-statistics (Long and Freese 2006). In case of a categorical dependent variable with more than two outcome categories – e.g., forest, agriculture and pasture – different logistic regressions are performed against one base outcome (generally forest). The corresponding model is called *multinomial logistic regression model* (see Chapter Three). Further details on the logistic regression, particularly on the interpretation of regression coefficients and the detection of possible biases, can be found in Chapter Two.

---

[3] One example: the odds of a probability of 75% are equal to 3 – 75% divided by 25%.

Chapter 2

Spatiotemporal modeling of the expansion of mechanized agriculture in the Bolivian lowland forests

Co-authors: Daniel Müller, Florian Schierhorn, Gerhard Gerold

Abstract

Since the 1980s, mechanized soybean production in Bolivia has caused extensive deforestation in the northeast of Santa Cruz de la Sierra in the eastern Bolivian lowlands. We analyze the spatial and temporal dynamics of deforestation due to mechanized agriculture with spatially explicit logistic regression models. Deforestation patterns are derived from the classification of Landsat imagery by Killeen et al. (2007) and include five time steps (1976, 1986, 1992, 2001 and 2005). We associate deforestation with geophysical and socioeconomic determinants. Our model controls for spatial autocorrelation and temporal dependencies, and we assess the robustness of the results for several model formulations.

The expansion of mechanized agriculture is concentrated in areas with favorable environmental conditions, good market access and close proximity to prior deforestation. While overall dynamics remained relatively stable over time, the expansion of mechanized agriculture between 2001 and 2005 became more tolerant to excessive rainfall and less dependent on fertile soils. This mirrors the increasing penetration of mechanized agriculture into humid and less fertile Amazonian rainforests in the northern portion of the study area. The map of deforestation probability substantiates these patterns and shows the highest propensities for future deforestation in the north. Our study demonstrates the value of spatial regression models to better understand the development of deforestation dynamics over a 30-year time span, and contributes to the formulation of policies that aim to reduce deforestation. Yet the results are sensitive to hidden correlations between independent variables, and we therefore advocate a careful evaluation of regression results for different model formulations.

2 Spatiotemporal modeling of the expansion of mechanized agriculture in the Bolivian lowland forests

2.1 Introduction

Deforestation is a major source of global carbon dioxide emissions (van der Werf et al. 2009), and the reduction of tropical deforestation is of global relevance for fighting climate change and conserving biodiversity (IPCC 2007; Venter et al. 2009). To mitigate tropical deforestation, it is important to understand the processes that trigger its spatial patterns. Empirical statistical deforestation models are an important tool in this respect, because they allow us to test assumptions and rank the importance of factors (Kaimowitz and Angelsen 1998; Verburg et al. 2006; Munroe and Müller 2007). Such models can also be applied for generating maps of imminent deforestation risks that identify areas under a particular threat of deforestation. Better knowledge of the determinants of deforestation and likely future hotspots can enhance the effectiveness of policies that target a reduction of deforestation (Chomitz and Gray 1996; Brown et al. 2007).

Bolivia still contains around 400,000 km^2 of intact tropical rainforests, which corresponds to 90% of its original tropical forest cover (Killeen et al. 2007). Yet deforestation is rapidly advancing at an annual rate of around 0.5%, and Bolivia is classified as a country at the forest frontier (Angelsen 2007). In this study, we focus on the area northeast of Santa Cruz de la Sierra in the eastern lowlands of Bolivia. The region is experiencing a steady expansion of mechanized cash crop production, mainly for the cultivation of soybean for export (Hecht 2005; Gerold 2007). We concentrate on mechanized agriculture and exclude other land uses such as cattle ranching and small-scale agriculture, since the former is by far the most important cause of deforestation in the study area (Killeen et al. 2008).

Most existing spatial statistical analysis of deforestation patterns only rely on one or two points in time (see examples in Verburg et al. 2004). This bears the risk of arriving at conclusions from snapshots that insufficiently reflect a region's historical dynamics. A longer time series of deforestation data allows us to generate more sophisticated and informative results (McConnell et al. 2003; Mertens and Lambin 2000; Mertens et al. 2004; Verburg et al. 2004). In this study, we estimate spatially explicit binary logistic regression models to analyze the effects of hypothesized drivers of deforestation in eastern Bolivia for the periods of 1976-1986, 1986-1992, 1992-2001, 2001-2005, and for the entire period of 1976-2005. Deforestation data are taken from Killeen et al. (2007). We interpret the temporal variations of the coefficients to best capture the patterns and processes of change.

The objective of this study is threefold: First, we seek to understand the spatial patterns of deforestation due to mechanized agriculture in the study area. Second, we explore the temporal evolution of deforestation dynamics to identify the key drivers that have shaped the expansion of mechanized agriculture during the last 30 years. Third, we aim to provide spatially explicit information that can inform policy-makers by identifying future deforestation hotspots. In this way, conservation efforts can be better-targeted to places where such action is most needed.

2.2 Methods and Data

2.2.1 Study area

The study area (Figure 2.1) represents the center of mechanized agriculture in Bolivia, and is located near the city of Santa Cruz de la Sierra, within the Department of Santa Cruz, one of nine administrative districts in Bolivia. The boundaries of the study area have been defined according to the boundaries of the department of Santa Cruz, clipped to 15°07’ to 19°08’ (southern latitude) and 60° to 64°18’ (western longitude); areas beyond the first Andean foothills above approximately 500 m meters above sea level were also excluded.

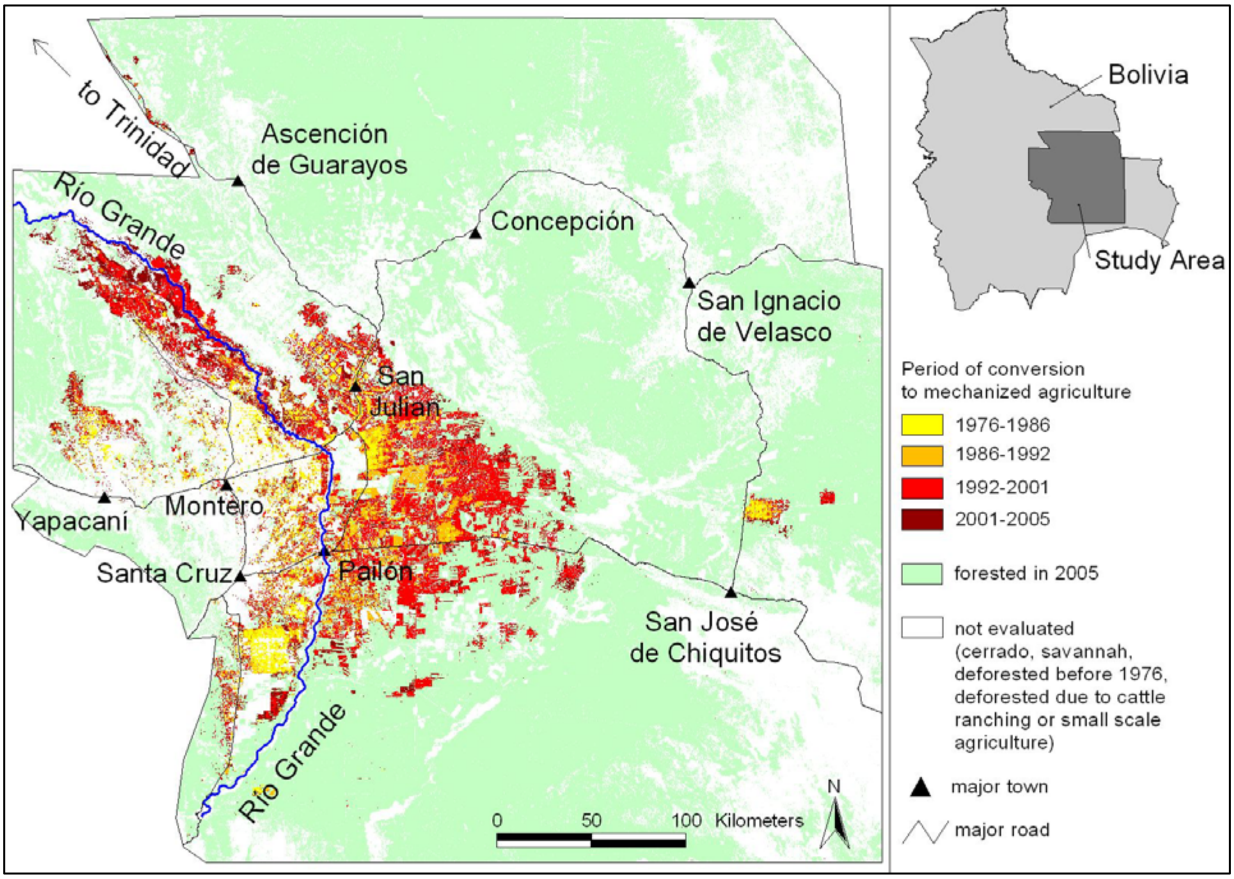


Figure 2.1 Expansion of mechanized agriculture in the study area. Source: adapted from Killeen et al. (2007) and Museo Noel Kempff and Prefectura de Santa Cruz (2008).

With approximately 1.5 million inhabitants, Santa Cruz de la Sierra is currently the largest and also the fastest-growing city in Bolivia and its economy is largely influenced by agro-industry. The study area enjoys favorable climatic and edaphic conditions for agriculture, and is located in the transition zone between Amazonian rainforests in the north, Chiquitano semi-deciduous forests in the east, and Chaco dry forest in the south (Navarro and Maldonado 2002). Traditionally, the zone is separated into the “integrated zone” north of Santa Cruz, which was developed from the 1970s onwards, and the “expansion zone” east of Santa Cruz beyond the Río Grande. The development of this latter zone began in the late 1980s (Gerold 2001; Hecht 2005). Mechanized agriculture, which occupied an area of approximately 15,000 km^2 in 2005, is responsible for around 70% of all forest clearings in the study area (Museo Noel Kempff and Prefectura de Santa Cruz 2008). The remaining 30% of the clearings are due to cattle ranching and manual agriculture. Until the 1970s, mainly sugar cane was produced for the national market in the areas close to Santa Cruz. Today, sugar cane is still an important crop, but oil seeds, predominantly soybeans, comprise the largest share of crops (CAO 2008). Settlements facilitated by Bolivian governments mainly between the 1950s and 1970s play an important role in the land use history of the area. In the south and east of the study area, Mennonites practice intensive mechanized mixed agriculture; Japanese settlements in the northeast of Santa Cruz specialize in industrialized rice cultivation; and national migrants from the Bolivian highlands partly apply mechanized agriculture in the area around San Julian (Killeen et al. 2008). In the 1970s and early 1980s, centrally-planned agricultural development took place with the purpose of import substitution, whilst in the 1990s, agricultural development mainly occurred in the context of structural adjustment policies. During this time, agricultural production became more and more driven by Bolivian and international corporations, and oriented itself towards exportation (Hecht 2005; Pacheco 2006a; Gerold 2007).

2.2.2 Logistic regression models

We choose a traditional regression framework, because our aim is to identify spatial patterns in the data and to understand temporal dynamics. Regression is very well suited to analyze such issues, to test for effects, and to rank the importance of the effects in a manner that is easy to understand (and to convey). Logistic regression is the most suitable regression tool here, since the dependent variable is binary. We thus estimate spatially explicit binary logistic regression models (e.g., Hosmer and Lemeshow 2000; Menard 2002; Mertens et al. 2004) for the expansion of mechanized agriculture. Regression coefficients indicate the direction and strength of the influence of the independent variables on the probability of deforestation due to mechanized agriculture (dependent variable). We present the results as raw coefficients, standardized coefficients and odd ratios. Standardized logit coefficients are used for graphical representation because they allow us to compare the relative effects of the various independent variables on a quasi-linear scale. We calculate standardized logit coefficients by multiplying the logit coefficient of a non-standardized independent variable with its standard deviation (e.g., Long and Freese 2006). This leads to results identical to standardizing the variable before starting the regression model, with the exception of the intercept.

Dependent variable

Deforestation due to mechanized agriculture at the pixel level serves as the dependent variable with “one” representing all pixels deforested, “zero” representing all pixels remaining forest, and “no data” for all other pixels, e.g., pixels under different land uses than mechanized agriculture. We excluded land uses other than mechanized agriculture for our study because these cause much less deforestation in the study area and follow different dynamics. A multinomial approach including other land uses would only be feasible for a single time step, since no comparable land use change maps with multiple land use categories are available. Deforestation data were taken from Killeen et al. (2007) and combined with a land use map provided by the departmental government of Santa Cruz (Museo Noel Kempff and Prefectura de Santa Cruz 2008). Killeen et al., (2007) distinguish between forest and non-forest areas for the entire Bolivian lowlands for the years 1976, 1986, 1992, 2001 and 2004, with a tolerance margin of one year. Within the study area, these authors evaluated 45 Landsat scenes from the MSS, TM and ETM+ sensors; the scenes were first classified in unsupervised classifications and then manually corrected. The resolution of the final product was resampled to 30 m, and final results were validated by aerial videography. Killeen et al. (2007) also define the classes of “Cerrado” and “deforestation in Cerrado”. We excluded these classes from the analysis because “Cerrado” refers to open woodland for which the definition and distinction of deforestation is difficult. The land use map (Museo Noel Kempff and Prefectura de Santa Cruz 2008) represents land use in 2005. The map has similar characteristics to the map presented in Killeen et al. (2007), and was prepared by the same institution (Museum of Natural History Noel Kempff Mercado in Santa Cruz). We used these data to select areas under mechanized agriculture from areas classified as "deforested" by Killeen et al. (2007), and to extend the time series by one year. Combining the map from Killeen et al. (2007) with the land use map thus results in data representing deforestation due to mechanized agriculture for the years 1976, 1986, 1992, 2001 and 2005 (Table 2.1). We assume that areas under mechanized agriculture in 2005 have been converted from forest and not from other land uses.

Table 2.1 Deforestation due to mechanized agriculture in the study area. Source: adapted from Killeen et al. (2007); Museo Noel Kempff and Prefectura de Santa Cruz (2008).

	Area deforested (km^2)[a]	Percent	Percent per year
Before 1976	2,563	2.16	not evaluated[b]
1976-1986	1,619	1.36	0.14
1986-1992	2,825	2.38	0.40
1992-2001	7,151	6.01	0.67
2001-2005	3,314	2.79	0.70

[a] Total forest area: 118,898km^2

[b] number of years not known

Model setup

We calibrated regression models for each period (as indicated in Table 2.1, excluding the time prior to 1976), as well as for the entire period from 1976-2005. We opted for a set of independent models rather than building an integrated model. An integrated model could consist of a multinomial logit model representing the different trajectories of forest cover change over the years (e.g., forest-forest-forest-agriculture, forest-forest-agriculture-agriculture etc., see Mertens and Lambin, 2000; Munroe et al. 2004). We decided against this option because it does not allow for the inclusion of variables that vary in time (*distance to prior deforestation* and *transportation costs*). We also investigated the sensitivity of the results to different sets of independent variables. To correct for potential spatial autocorrelation in the dependent variable, we computed models that only included non-neighboring grid cells and estimated the regressions with samples of every second and every third grid cell in both an east-west and north-south direction. All regression models were estimated with a spatial resolution of 200 m and 500 m. Neither the variation in the sampling frame nor a different spatial resolution led to considerable alterations of the results (deviations of coefficient values rarely passed 2%). Subsequently, we present the results with a spatial resolution of 200 m by 200 m and base them on all observations in the study area. We believe that this resolution is suitable for analyzing major changes over several years and providing inputs for land use planning on a departmental scale. We calculated the correlation coefficients for each pair of independent variables to assess multicollinearity between the independent variables (Menard 2002). We also computed variance inflation factors (VIFs, see Chatterjee et al. 2000) in every time step. Finally, we calculated maps representing the probability of deforestation due to mechanized agriculture by combining the regression coefficients with the values of independent variables. We also converted the map of deforestation probability into a map indicating which cells are expected to be deforested in the future, under the assumption that mechanized agriculture expands linearly.

Model validation

To evaluate the fit of the logistic regression, we calculated the pseudo R^2 for each model, whilst the significance of coefficients was measured by z-statistics (Long and Freese 2006). We further assessed the predictive accuracy of probability maps by calculating the area under the curve (AUC) of the receiver operation characteristics (ROC, Pontius and Schneider 2001). The AUC value validates continuous predicted probabilities against binary observations; it is independent from a fixed cut-off value. An AUC value of 0.5 indicates accuracy equal to a random model, while a value of one indicates perfect accuracy. We refrained from calculating Kappa indices, because Kappa does not distinguish between cells that are correctly classified as "1" and "0". Therefore, the index is problematic in the case of very unequal distributions of classes in the dependent variable, e.g., if only a very small percentage of all cells are deforested.

2.2.3 Independent variables

The independent variables encompass a variety of geophysical variables as well as distance to prior deforestation and transportation costs, the latter of which proxies market access. We selected these variables based on reviews of tropical deforestation studies (e.g., Kaimowitz and Angelsen 1998; Geist and Lambin 2002; Kirby et al. 2006), existing deforestation models for the Santa Cruz area (Kaimowitz et al. 2002; Mertens et al. 2004), and our field expertise in the study area (e.g., Gerold 2007). We further conducted extensive qualitative, on-the-ground investigations in the study area to verify the information content of the independent variables and to gain insights into the economic, social and political context of forest conversion. We conducted site visits, evaluated secondary statistics from the agricultural chamber CAO (2008), and interviewed representatives of relevant governmental and non-governmental institutions. For a correct representation of spatiotemporal dynamics, we use different layers for the dynamic variables *distance to prior deforestation* and *transportation costs*, illustrating the state of the variable at the beginning of each time step.

Land use restrictions such as protected areas or forest concessions were not used as independent variables, as there is virtually no overlap between such areas and the expansion of mechanized deforestation. This is arguably not due to efficient protection, but rather to the fact that such areas are located where environmental conditions are not suitable for mechanized agriculture (Nepstad et al. 2008).

Geophysical variables

Rainfall

The rainfall variables are based on a transformation of the interpolated mean annual precipitation (Conrad et al. 2006, see Figure 2.2). We transformed the rainfall data because intermediate values are preferable for cash crop production (see also Kaimowitz et al. 2002). Two variables were thus created to reflect two climatic influences that limit agricultural production potentials. First, *excessive rainfall* indicates the amount of annual rainfall that surpasses 1,700 mm in steps of 100 mm, i.e., an area with 1,800 mm rainfall receives a value of one, 1,900 mm rainfall corresponds to two, etc. Areas with precipitation below 1,700 mm receive the value of zero. Second, *drought risk* is proxied by the amount that rainfall is below 1,000 mm in steps of 100 mm, i.e., an area with 800 mm rainfall receives the value of two. Areas with precipitation above 1,000 mm are labeled zero. Specifications for both rainfall variables were chosen according to an analysis of crop distribution and average yields based on Bolivian agricultural statistics (Kemp 2006; CAO 2008). Locations where both precipitation variables are zero offer the most favorable rainfall conditions for cash crop production, particularly for soybean.

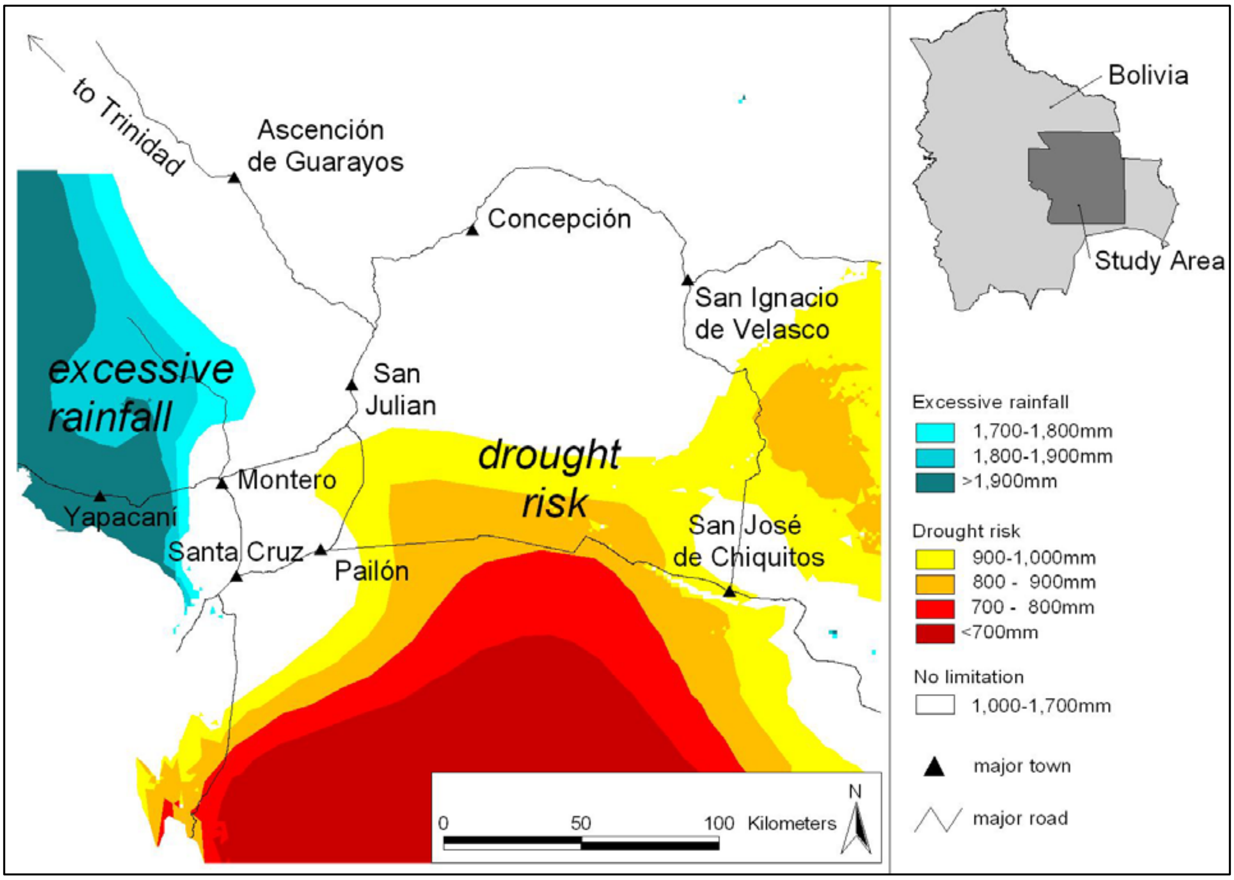


Figure 2.2 Mean annual rainfall in the study area. Source: adapted from Conrad et al. (2006).

Soil fertility

We derived two dummy variables that capture soil fertility in the study area, based on the three soil categories (see Figure 3.3). First, we defined the binary variable *precambrian soils*, which takes a value of one for poor soils of the Precambrian Shield in the eastern parts of the study area (Navarro and Maldonado 2002), and zero otherwise. Here, ferralitization and clay lixiviation formed mainly Ferralsols, Plinthosols and Acrisols (Gerold 2001) with low nutrient availability and low organic matter content. The area was identified using the geological map of Bolivia as a reference (Servicio Geológico de Bolivia 1978). Second, we created the variable *fertile soils*. Here, a value of "one" refers to alluvial soils in the area east of the Rio Grande and west of the Brazilian Shield, mainly Fluvisols with very high nutrient availability and organic matter content (Gerold 2001). The boundary to the west (Río Grande) was chosen based on expert knowledge (Gerold 2001; Gerold 2004), including the evaluation of an unpublished database containing 300 soil profiles (Krüger 2005; Conrad et al. 2006).

The northern limit of this area was drawn using the soil categorization of the land use plan of Santa Cruz (Prefectura de Santa Cruz – Consorcio IP/CES/KWC 1996) as a reference. Areas where both dummy variables are zero refer to alluvial soils with intermediate fertility in the northwestern part of the study area (Figure 2.2). Contrary to Mertens et al. (2004), we did not rely on the map of soil suitability included in the land use plan for Santa Cruz because of its coarse spatial scale and the fact that it combines several criteria including slope, risk of erosion and floods whose effects cannot be evaluated separately.

Slope

The slope for each grid cell in degrees was derived from the digital elevation model SRTM that has a resolution of 90 m (Shuttle Radar Topography Mission, USGS, 2004); these data were resampled to 200 m. Since the SRTM model registers vegetation height as soil level, slope values at the forest edge appear too high in flat areas. To avoid this bias, we merged all slope values from 0-5° into a single class (labeled “5°”). Higher values were grouped in steps of 1° ranging from 6° to 48°.

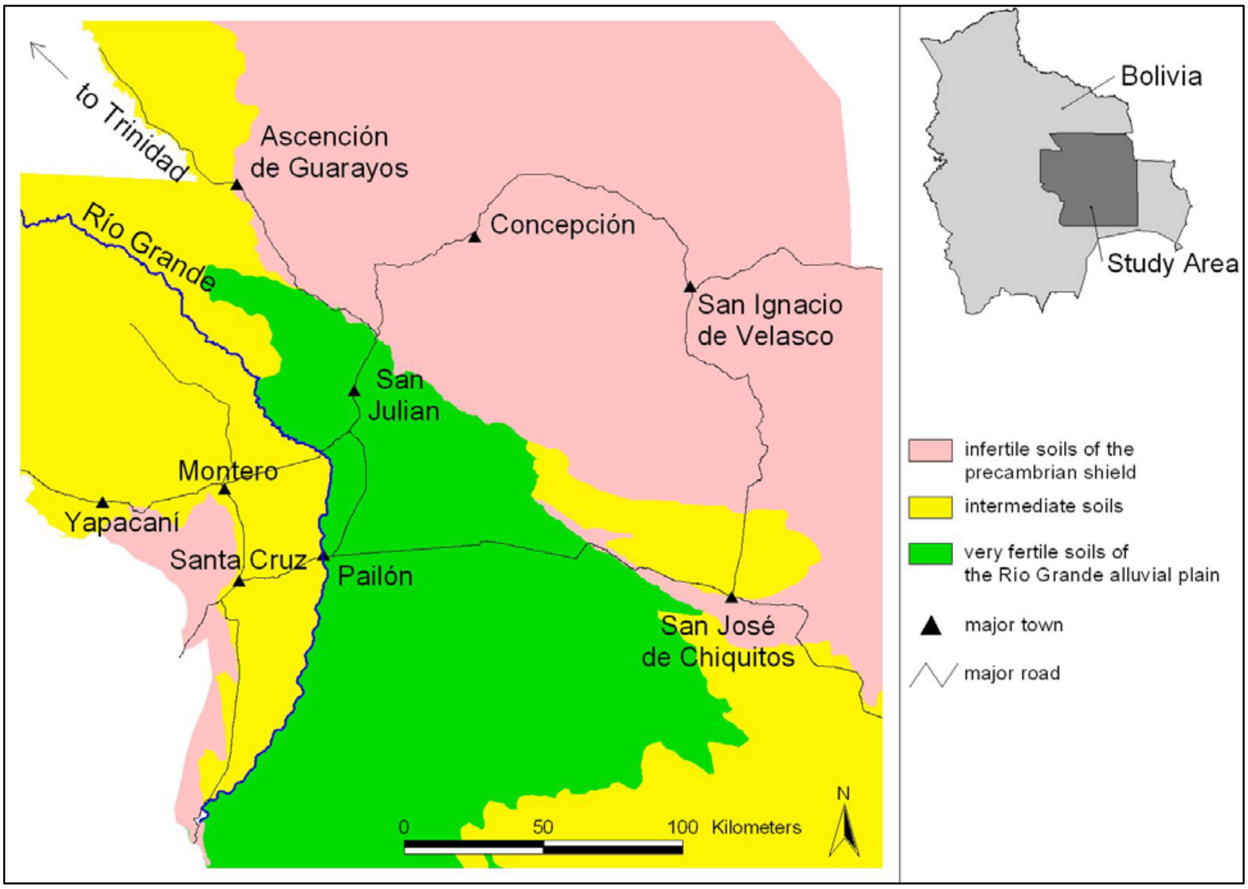


Figure 2.3 Soil fertility in the study area. Source: Authors.

Transportation costs

We calculated the average costs of transporting agricultural products to the main market for cash crops, which is the city of Santa Cruz. We used a road network generated from the official road map of the departmental authority of Santa Cruz (SEPCAM 2008), which allows us to distinguish between paved roads and dirt roads. The road network for former time steps was adapted with high resolution satellite imagery, from historic maps (e.g., from Prefectura de Santa Cruz – Consorcio IP/CES/KWC 1996), and based on interviews with experts who worked in the area in the 1970s and 1980s. Underlying transportation costs were applied in US$/t-km as 0.05 for paved roads, 0.10 for dirt roads, and 0.50 for land without such roads. The first two values were estimated with reference to CAF (2004), but the third value was assigned lower than in comparable studies (e.g., Vera Diaz et al., 2007) since we do not account for small local and private roads, which would reduce transportation costs. Transportation costs and roads may be endogenous to the clearing of forest for mechanized agriculture if roads are built with the purpose of opening up suitable undeveloped areas (Müller and Zeller 2002; Perz and Skole 2003). We assume that local and private roads are indeed likely endogenous, as these may be constructed with the purpose of developing a selected plot of land. Therefore, we only included roads maintained by the corresponding departmental or national authority (SEPCAM 2008). We calculated the transportation costs for the state of the roads at the beginning of each time step.

Distance to prior deforestation

Distance to prior deforestation was included as the logarithmic distance to the nearest plot that had been deforested due to mechanized agriculture in the previous time steps. We excluded plots with a surface smaller than 100 hectares, which are presumably insignificant for triggering the expansion of mechanized agriculture in a later time step. We used the logarithmic distance that generated a quasi-linear relation between the distance to prior deforestation and the logit of deforestation (Hosmer and Lemeshow 2000).

Potentially important determinants unable to be included

There exist possibly important factors influencing spatial deforestation patterns that are not included in the model. For example, flood risk and soil drainage could not be included in the analysis due to the unavailability of suitable data. We further suppose that (often informal) land tenure is an important factor, but data are unavailable because the consolidation of land rights is an ongoing process in the study area (INRA 2009). We also refrained from using the location of planned settlements (“colonies”), because the only available map is very imprecise compared to the scale of the modeled data set.

2.3 Results and Discussion

2.3.1 Dynamics of deforestation due to mechanized agriculture

We first evaluate the models covering the entire period between 1976 and 2005 to describe the general effects of the determinants of the expansion of mechanized agriculture (Table 2.2). All coefficients are significant at the 99% level and have the expected algebraic sign.

Precambrian soils reduce the probability of deforestation due to mechanized agriculture by a factor of 25 (odds ratio = 0.04), whilst on *fertile soils*, the expansion of agriculture is over four times more probable than elsewhere (odds ratio = 4.05). *Excessive rainfall*, *drought risk* and higher *slope* all reduce the profitability of mechanized agriculture, and thereby the probability of deforestation. An increase of *transportation costs* by one US$/t reduces the risk of deforestation by 5%. Increasing the distance to areas deforested before 1976 by one logarithmic step (i.e., multiplied by e = 2.72) decreases deforestation risks from mechanized agriculture by 64%. In sum, the spatial patterns of deforestation in the last 30 years were highly dependent on environmental conditions, market access and patterns of prior deforestation. These results are in line with Kaimowitz et al. (2002) and Mertens et al. (2004), who applied logistic regression to analyze deforestation in the whole department of Santa Cruz and identified distance to roads, distance to previously deforested areas and low soil suitability as the important drivers of deforestation. The findings also correspond to results of Amazon-wide studies evaluated by Kirby et al. (2006).

Table 2.2 Logistic regression results for deforestation between 1976 and 2005. Source: Authors

	Unit	Coefficient	Odds ratio	Standardized coefficient (for non-dummy variables)	z-statistics
Excessive rainfall	100 mm	-0.75	0.47	-1.25	-166.49
Drought risk	100 mm	-0.77	0.47	-1.36	-291.09
Fertile soils	1/0 (dummy)	1.40	4.05		200.29
Precambrian soils	1/0 (dummy)	-3.32	0.04		-219.32
Slope	degrees	-0.60	0.55	-0.56	-15.65
Transportation costs	US$/t	-0.05	0.95	-1.17	-181.84
Distance to prior deforestation	ln(km)	-0.45	0.64	0.56	-151.54
Constant	ln(km)	8.26			43.06

[a]All coefficients are significant at the 99% level. Number of observations: 2,966,253. AUC: 0.96. Pseudo R^2: 0.54

2.3.2 Temporal variations in deforestation determinants

We evaluate two models for each time step, one including *distance to prior deforestation* and one without this variable. We do so because we found that the inclusion or non-inclusion of this variable leads to significant changes in the coefficients of the rest of the variables (see discussion in 4.3, also Kaimowitz et al. 2002; Mertens et al. 2004). We interpret coefficients of the model including *distance to prior deforestation* and use the model without this variable to control for possible biases.

Coefficients of most independent variables were found to be rather stable across time in terms of their direction, magnitude, and significance (Figure 2.4). However, Figure 2.4 also reveals interesting temporal variations that can be connected with the context of the recent history of land use change in the study area (see e.g., Nagendra et al. 2003).

Excessive rainfall increases the risk of floods and pests. In the most recent period (2001-2005), *excessive rainfall* seems to be less inhibitive than before. This is in line with the expansion of mechanized agriculture to the northwestern part of the study area. Droughts negatively impacted yields towards the south in 1999 and 2001 (Kemp 2006; Pacheco 2006a), and representatives of the local agricultural chamber confirm that recently, farmers perceive droughts to be a higher risk than excessive rainfall and flood risk (CAO, personal communication). The coefficients for *drought risk* show a development which is complementary to *excessive rainfall*, i.e., if the former increase, the latter decrease.

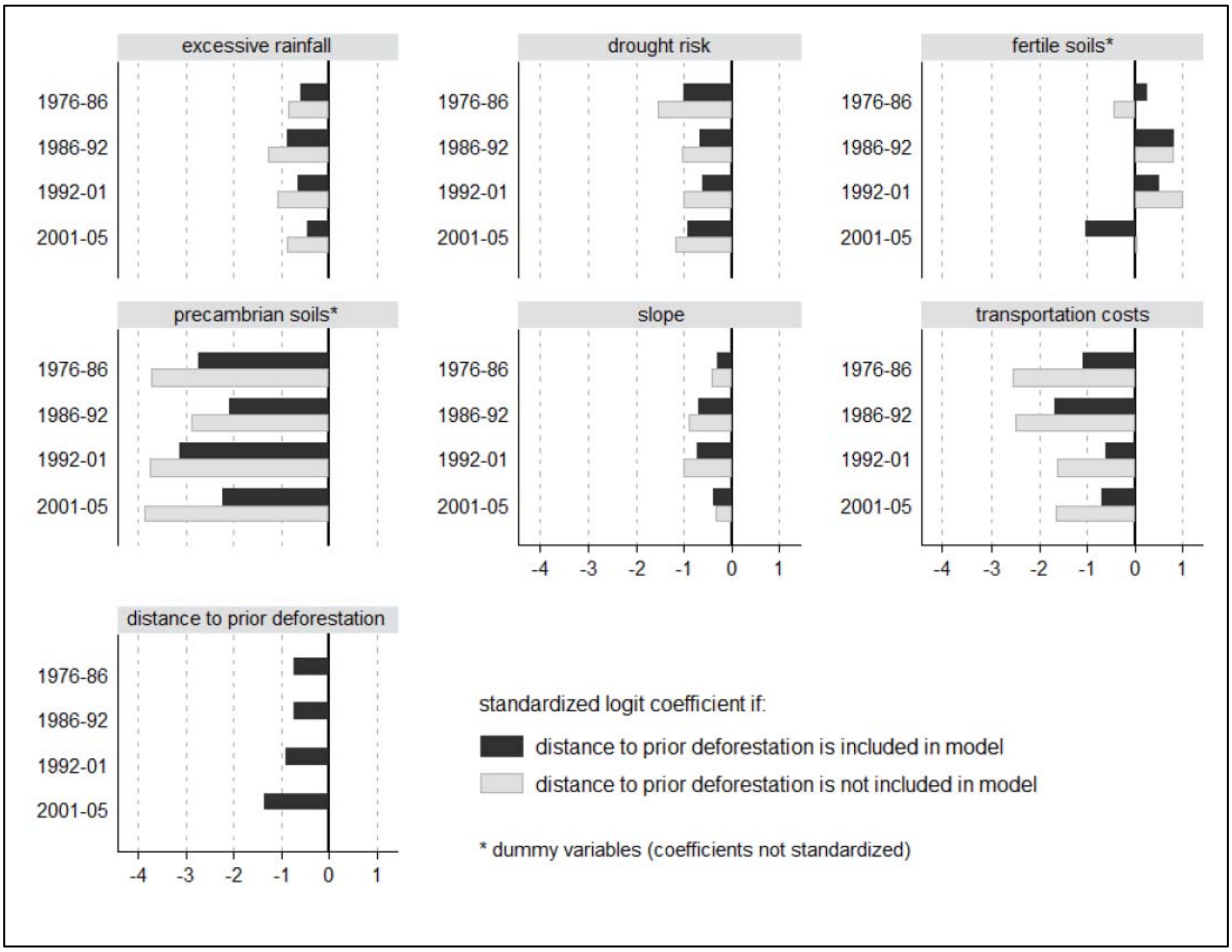


Figure 2.4 Standardized logit coefficients in the different time steps. Source: Authors.

The positive effect of *fertile soils* on deforestation due to mechanized agriculture first increases, and then decreases over time. The negative coefficient of the variable during the first period (1976-1986) is probably due to the fact that areas with high soil fertility east of the Rio Grande were not developed during that time. In the 2001-2005 model including *distance to prior deforestation*, the negative coefficient for *fertile soils* implies that fertile soils render mechanized agriculture less likely. On the contrary, the model without *distance to prior deforestation* shows a small positive coefficient, which seems more plausible. One reason for this discrepancy may be the correlation between *fertile soils* and *distance to prior deforestation* (see detailed explanation in the next section). The missing positive effect of soil fertility for the 2001-2005 period is probably due to the extensive conversion of excellent soils east of the Rio Grande between 1986 and 2001 (see Figure 2.1), leaving little area for further expansion in this region. The few patches that remain forested in this zone after 2001 are possibly more influenced by other limiting factors not included in our models, e.g., by specific forms of land tenure. Another probable reason for the recent expansion of mechanized agriculture onto soils of intermediate quality in the northern part of the study is the lower risk of droughts mentioned as part of the interpretation of the effect of *excessive rainfall*.

Coefficients for *precambrian soils* remain negative and stable over all periods, because their low fertility limits the profitability of cash crop production. In Brazil, however, such soils are heavily used for soybean production that applies advanced fertilizing technology (Kaimowitz and Smith 2001).

The influence of *slope* is negative throughout, but twice as strong in the second and third periods as in the first and last (Figure 2.4). This is in line with the fact that from 1986 to 2001, the expansion of mechanized agriculture was concentrated on the particularly flat alluvial plain of the Río Grande.

The effect of *transportation costs* to Santa Cruz is larger in the first two periods, when agricultural expansion concentrated on forested areas close to the city of Santa Cruz. But the higher investment of private capital in mechanized agriculture during the last two periods (Kaimowitz and Smith 2001) probably led to the endogenous construction of more small and private roads that are not included in the transportation proxy.

Distance to prior deforestation becomes more important as a driver over time, especially during the last period. This likely indicates that the agro-industry became more and more self sufficient in terms of infrastructure; i.e., private roads, silos or supply centers implemented by agricultural corporations attracted investments near already developed areas.

In summary, we find that until 1986, when mechanized agriculture was concentrated near Santa Cruz, environmental drivers had a weaker bearing on the expansion of mechanized agriculture. During the late 1980s and particularly in the 1990s, the area east of the Rio Grande, with its excellent soils, experienced massive agricultural expansion. In the most recent period (2001-2005) agriculture expanded into Amazonian forests in the north of the study area where lower soil fertility, higher amounts of rainfall, and lower drought risk prevail.

2.3.3 Validation of the results and sensitivity analysis

The overall model from 1976-2005 shows a better fit of the regression (measured by pseudo R^2), higher significance levels of coefficients, and mostly larger absolute values of coefficients than the four models covering single time steps (see supplementary material in Appendix A). This is likely due to the higher total deforestation in the overall model yielding more positive occurrences for the regression.

No serious multicollinearity between independent variables was detected in all models and the VIFs are well below 10 (Chatterjee et al. 2000). Pairwise correlation coefficients never exceeded 0.8, which is a critical threshold according to Menard (2002). The highest correlation coefficients in our dataset are between *transportation costs* and *distance to prior deforestation*, with 0.6 in the 2001-2005 period, and 0.76 in 1986-1992. Values above 0.5 are also found between *fertile soils* and *precambrian soils* (0.65-0.66 in the various models), and between *drought risk* and *fertile soils* (0.58-0.61).

There are significant differences between the models with and without *distance to prior deforestation* (see Figure 2.4). Without this variable, the absolute values of the logit coefficients of the other independent variables increase by an average of 50%. *Distance to prior deforestation* absorbs parts of the explanatory power of the remaining variables. We argue that it is inherently correlated with all other independent variables, because these also shaped the deforestation patterns in the prior time step

(Kaimowitz et al. 2002; Mertens et al. 2004). Hence, a variable capturing the distance to a prior land use change must be included and interpreted with great care in land use change models.

For models covering the years between 2001 and 2005, the coefficient for *fertile soils* changes sign (from -0.99 to 0.22) depending on the inclusion or exclusion of *distance to prior deforestation*. This might be caused by multicollinearity despite a correlation coefficient of only 0.39. (VIF values are 2.95 for *fertile soils* and 2.18 for *distance to prior deforestation*). We suppose that there is nevertheless a stronger correlation of the two variables in certain parts of the study area. If we divide the study area into four parts and solely investigate the northwestern quarter, where the most deforestation was concentrated between 2001 and 2005, we find that the correlation coefficient between *distance to prior deforestation* and *fertile soils* is 0.56, which apparently represents a critical statistical association (VIF values change to 1.66 for *fertile soils* and 3.76 for *distance to prior deforestation*). A further division of the study area would likely lead to even higher correlations.

Validation of probability maps

Probability maps indicate the risk of future deforestation and can be used for model validation. We evaluate the accuracy of the different models in predicting the observed state of the dependent variable, and find high AUC values between 0.92 and 0.96 (see supplemental material). We further validate the prediction accuracy against independent data (see e.g., Mertens and Lambin 2000). Therefore, two options of computing probability maps based on data before 2001 are validated against observed deforestation between 2001 and 2005. A first probability map is computed using average values[4] of the coefficients of the three models between 1976 and 2001, thereby representing long-term deforestation dynamics. We find an AUC value of 0.952 when evaluating its accuracy in predicting deforestation between 2001 and 2005. We also validated this map by consecutively selecting those cells with the highest deforestation probabilities, until reaching the observed number of cells deforested from 2001 to 2005. In 37.9% of the selected cells, deforestation really occurred between 2001 and 2005.

A second probability map was computed using coefficients of the 1992-2001 model, representing the latest deforestation dynamics before 2001. This map yields an AUC value of 0.954 if validated against deforestation between 2001 and 2005; 38.5% of the cells predicted as being deforested by selecting highest probabilities were really deforested between 2001 and 2005. The AUC values indicate an excellent predictive accuracy of both probability maps, while the percentage of correctly predicted cells also yields adequate predictive power given the very small percentage of cells that were deforested between 2001 and 2005.

2.3.4 Deforestation probability after 2005 and future deforestation scenarios

Probability maps represent an important ingredient for future predictions of deforestation, e.g., within the CLUE-S model (Verburg et al., 2006). We produce a map indicating the probability of expansion of mechanized agriculture after 2005 (Figure 2.5). We base this map on recent dynamics reflected in the coefficients of the 2001-2005 model rather than applying the averages of coefficients across all time steps. This decision is supported by results of the validation presented in Section 2.3.3, but our main argument is that plausible explanations could be found for changes of deforestation dynamics

---

[4] Averages were weighted according to the number of cells deforested in each period.

over time (see Section 2.3.2). We therefore assume that the most recent dynamics will best characterize future deforestation risks. We further exclude the variable *fertile soils* because of the interactions with *distance to prior deforestation* (see Section 2.3.2). We include the latter variable because of its predictive strength and its temporal explicitness. We use the most recent available states of *distance to prior deforestation* (distance to 2001-2005) and *transportation costs* (based on the road network in 2005) to calculate the predicted probabilities.

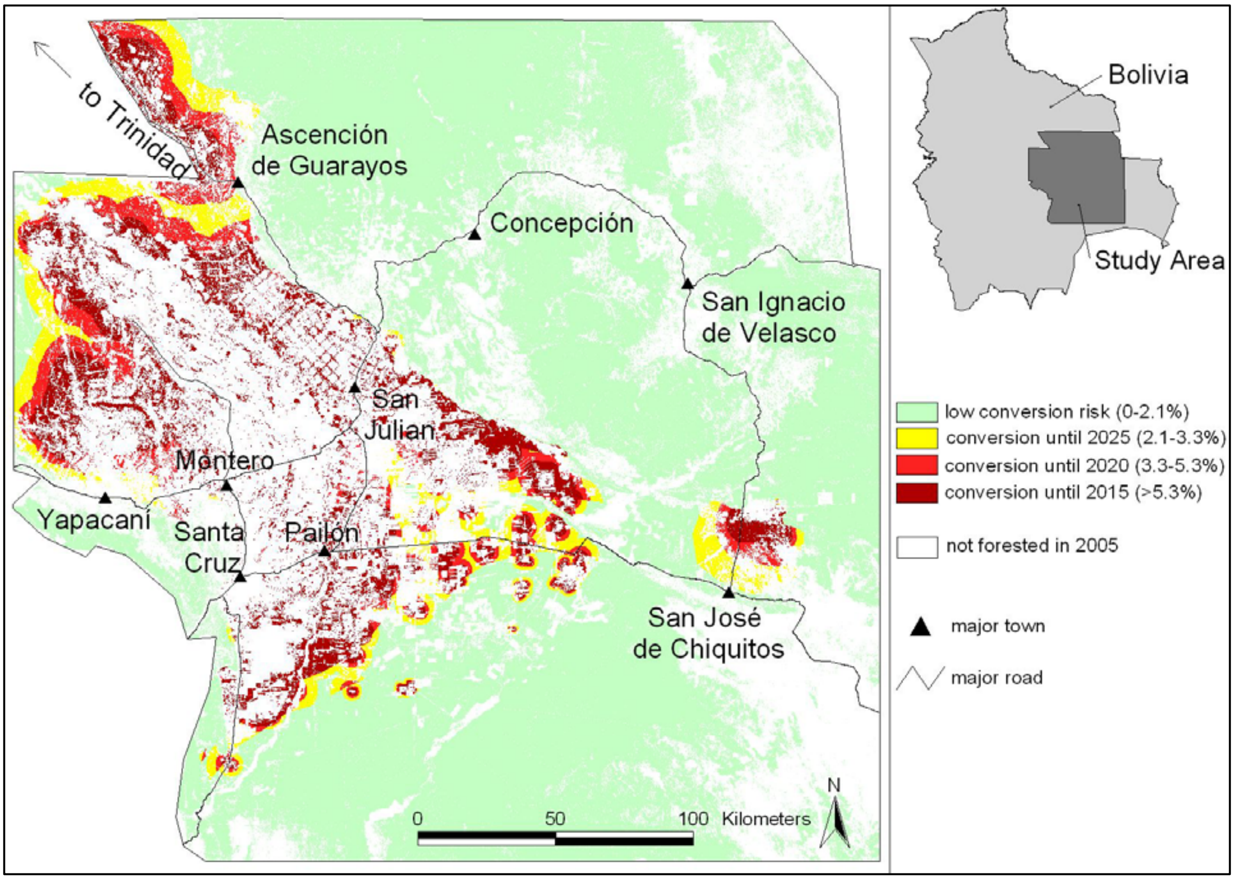


Figure 2.5 Year of probable conversion to mechanized agriculture and modelled conversion probability. Source: Authors.

The deforestation scenarios in Figure 2.5 show the forest patches that are under the most imminent threat of conversion to mechanized agriculture. This map indicates both the absolute probabilities and the likely conversion to mechanized agriculture in 2015, 2020 and 2025, respectively. The scenarios are based on the assumption that deforestation will continue at the same rate as was observed between 2001 and 2005[5]. Areas in the northwestern part of the study area are clearly identified as being most threatened by the expansion of mechanized agriculture. The probability of deforestation is especially high north of Ascención de Guarayos, along the highway to Trinidad, which was paved during the first years of the last period (2001-2005. Further, the remaining forests of the alluvial plain southeast of San Julian are part of the areas that are most threatened by mechanized agriculture. Our analysis

---

[5] The rate was 0.7%/a, which is very similar to the annual deforestation rate from 1992-2001 (see Table 2.1).

indicates a very low probability of deforestation due to mechanized agriculture on the *precambrian soils* in the east of the study area. In Brazil, such soils are intensively used for soybean cultivation using advanced fertilizing technology (Kaimowitz and Smith 2001). In Bolivia, this is currently not profitable due to higher costs of transportation and fertilizer, but also because areas with higher rainfall and better soils are still available. It is, however, possible that crop price increases, further infrastructural improvements, or advances in fertilization technology will render such areas attractive for mechanized agriculture in the near future. Increasing soybean prices will likely promote the expansion of mechanized agriculture into areas with higher deforestation probability. As a consequence, a new soybean boom may lead to an earlier conversion of forested areas.

2.4 Conclusions

Our analysis reveals that the spatial dynamics of deforestation due to mechanized agriculture remained relatively stable between 1976 and 2005. The unsuitable soils of the Brazilian shield strongly prevented the expansion of mechanized agriculture during this period. The effect of high soil fertility east of the Río Grande is mostly positive, but less stable over time. Factors that reduce natural suitability, such as excessive rainfall, drought risk and steep slopes, consistently reduce the probability of an expansion of mechanized agriculture. Better physical accessibility to forested areas, measured in terms of transportation costs to markets and distance to areas deforested in the previous period, trigger the conversion of forests. Land tenure is probably another important factor that shapes deforestation, but this could not be evaluated because the consolidation of land rights is still an ongoing process in the study area (INRA 2009).

An investigation of temporal dynamics shows that the expansion of mechanized agriculture between 2001 and 2005 became more tolerant to *excessive rainfall* and less dependent on *fertile soils* in the most recent surveyed period (2001-2005). This corresponds to the increased expansion of mechanized agriculture into humid and less fertile Amazonian rainforests in the northwestern part of the study area, a process similar to the recent penetration of soybean cultivation into the Amazon in Brazil (Kirby et al. 2006). In the study area, one reason for this development is that since 2001, few forested areas remain on the excellent soils east of the Rio Grande, which constituted the main area of expansion until then. Moreover, farmers apparently perceive droughts as a greater risk than excessive rainfall.

Our approach for generating maps of predicted deforestation risk can inform the selection of priority areas for measures to mitigate deforestation, e.g., in the context of REDD. The high probability of deforestation goes along with a high suitability for mechanized agriculture. The choice for policy-makers is to safeguard these places from deforestation despite their high opportunity costs, or to allow full conversion amidst the associated environmental costs, and focus conservation efforts on areas with lower agricultural suitability. The identification of future deforestation hotspots is therefore an important ingredient for improving the effectiveness and efficiency of land use planning. We find that the northwestern part of the study area is most threatened by the expansion of mechanized agriculture, especially north of Ascención de Guarayos along the highway to Trinidad. In order to reduce deforestation there, the existing departmental land use plan that assigns non-agricultural use to this area (Prefectura de Santa Cruz – Consorcio IP/CES/KWC 1996) would need to be adapted and enforced. At the same time, efforts could be undertaken to improve agricultural production in areas near Santa Cruz that have good market access, but where soils are already degraded from intensive cultivation. Since the shift to the Morales government in 2006, Bolivian politics regarding land tenure strongly favor smallholders. This is cause for insecurity among agribusinesses, but a significant effect on deforestation reduction rates could not be demonstrated thus far (Redo et al. 2011).

Spatially explicit logit models are useful tools for analyzing deforestation dynamics. Logit coefficients provide information about the direction and the importance of the effects of hypothesized drivers. Dynamics of deforestation over time can be analyzed by comparing the development of standardized logit coefficients for subsequent models. Accounting for historical information on deforestation patterns reduces the risk of conducting snapshot analyses and provides a more solid basis for the interpretation of the results. We urge a careful assessment of the biases that may distort the results of single time steps. Interactions between independent variables can cause concern even if correlation coefficients and VIFs stay below the critical limits indicated in the literature, which in our case was caused by the local correlation of variables in parts of the study area.

Finally, logistic regression allows us to calculate predicted probabilities of deforestation, which in turn can provide critical input for spatial planning and policy interventions, e.g., by identifying likely hotspots of future deforestation. Also in the case of probability maps, it is important to base them on a thorough analysis of model outcomes, investigating temporal dynamics of patterns and processes, and verifying these findings on the ground.

Chapter 3

Proximate causes of deforestation in the Bolivian lowlands – an analysis of spatial dynamics

Co-authors: Daniel Müller, Florian Schierhorn, Gerhard Gerold, Pablo Pacheco

Abstract

Forests in lowland Bolivia suffer from severe deforestation caused by different types of agents and land use activities. We identify three major proximate causes of deforestation. The largest share of deforestation is attributable to the expansion of mechanized agriculture, followed by cattle ranching and small-scale agriculture. We utilize a spatially explicit multinomial logit model to analyze the determinants of each of these proximate causes of deforestation between 1992 and 2004. We substantiate the quantitative insights with a qualitative analysis of historical processes that have shaped land use patterns in the Bolivian lowlands to date. Our results suggest that the expansion of mechanized agriculture occurs mainly in response to good access to export markets, fertile soil and intermediate rainfall conditions. Increases in small-scale agriculture are mainly associated with a humid climate, fertile soil and proximity to local markets. Forest conversion into pastures for cattle ranching occurs mostly irrespective of environmental determinants and can mainly be explained by access to local markets. Land use restrictions, such as protected areas, seem to prevent the expansion of mechanized agriculture but have little impact on the expansion of small-scale agriculture and cattle ranching. The analysis of future deforestation trends reveals possible hotspots of future expansion for each proximate cause and specifically highlights the possible opening of new frontiers for deforestation due to mechanized agriculture. Whereas the quantitative analysis effectively elucidates the spatial patterns of recent agricultural expansion, the interpretation of long-term historic drivers reveals that the timing and quantity of forest conversion are often triggered by political interventions and historical legacies.

3 Proximate causes of deforestation in the Bolivian lowlands - an analysis of spatial dynamics

3.1 *Introduction*

Reducing tropical deforestation is of global importance for the mitigation of climate change and for the conservation of biodiversity (IPCC 2007). Bolivia is among the ten countries with the highest absolute forest loss over the last decade (FAO 2010). However, the country still harbors critical regions of intact and highly diverse tropical lowland rainforests totaling approximately 400,000 km^2 (based on Killeen et al. 2007). Deforestation is the result of different land use activities by various classes of agents (Killeen et al. 2008). For a better understanding of the patterns and processes of deforestation, we have analyzed the factors that determine the expansion of three forest-depleting land use types that are the main proximate causes of deforestation in Bolivia: mechanized agriculture, small-scale agriculture and cattle ranching. These categories can explain a very large portion of the deforestation occurring in the Bolivian lowlands and can differentiate between the key groups of land use agents. Similar categories have also been adopted in other studies in the Brazilian Amazon (e.g., Kirby et al. 2006). Herein, we conduct a multinomial spatial regression analysis of forest conversion in the Bolivian lowlands between 1992 and 2004 using the three proximate causes and stable forest as response categories. The model outcome allows us to quantify the effects of the hypothesized determinants of forest conversion by interpreting the significance, sign and strength of the logit coefficients (Chomitz and Gray 1996; Müller and Zeller 2002; Munroe et al. 2004). Moreover, the regression results help in the development of spatial scenarios of future deforestation (e.g., Verburg et al. 2006).

Improved knowledge of future land use trends can be valuable for informed policy decision-making and management interventions, such as those under the REDD mechanism (Reducing Emission from Deforestation and Degradation, Miles and Kapos 2008). Regression analysis, however, provides information about only the statistical associations between independent and dependent variables and does not explain the underlying causal interactions among the different variables included in the analysis. To broaden our understanding of contemporary land use changes and the regression results, we also assessed the historical land use processes taking place in five different zones identified in lowland Bolivia, such as government programs previously aimed to develop agriculture in specific parts of the lowlands.

The overall objective of this study is to achieve a better understanding of the processes and conditions explaining land use/cover change in lowland Bolivia based on a quantitative regression analysis of recent changes in land use and a qualitative understanding of historical changes in land use trends. We use these insights to project impending deforestation patterns that in turn augment the knowledge base that can be used to develop strategies and policy instruments to reduce pressure on forested lands.

3.2 *Methods and Data*

3.2.1 Study area and historical land use

The study area includes all forests in the Bolivian lowlands. The Bolivian lowlands are defined as all land in Bolivia below 500 meters above sea level covering 670,000 km^2 between the Andes in the West and neighboring countries in all other directions. This area currently includes approximately

400,000 km^2 of forests, corresponding to about 90% of the original lowland forest cover. The annual deforestation rate was approximately 0.5% between 1992 and 2004 (Killeen et al. 2007), which is comparable to the deforestation rate in the Brazilian Amazon in that period (FAO 2010). Areas where no natural forest occurs or where forests were cleared prior to 1992 were excluded from the analysis (i.e., the Beni savannahs in the north, the wetlands of the Pantanal in the southeast and the Cerrado formations of the Chiquitania in the east).

For a qualitative analysis of the historical processes that shape land use patterns in the Bolivian lowlands to date, we roughly divide the Bolivian lowland forests into five zones (Figure 3.1); similar, but more detailed divisions have been proposed by Ibisch et al. (2003); Montes de Oca (2004), Killeen et al. (2008); Navarro and Maldonado (2002) and Pacheco (1998).

The northern part of the study area (referred to as the "Amazonian North") is covered by Amazonian moist rainforests and has a very low population density. Land estates for rubber extraction were established 100-150 years ago during the rubber boom (Gamarra Téllez 2004), which attracted a population that originated largely from other zones of the Bolivian lowlands. Recently, there has been a growing proportion of internal migrants from the highlands (Stoian and Henkemans 2000). After the final collapse of the rubber economy in the mid-1980s, the major current uses of the forest are Brazil nut extraction and selective logging (Stoian and Henkemans 2000). Deforestation is predominantly caused by cattle ranching on formerly forested pastures (Pacheco et al. 2009).

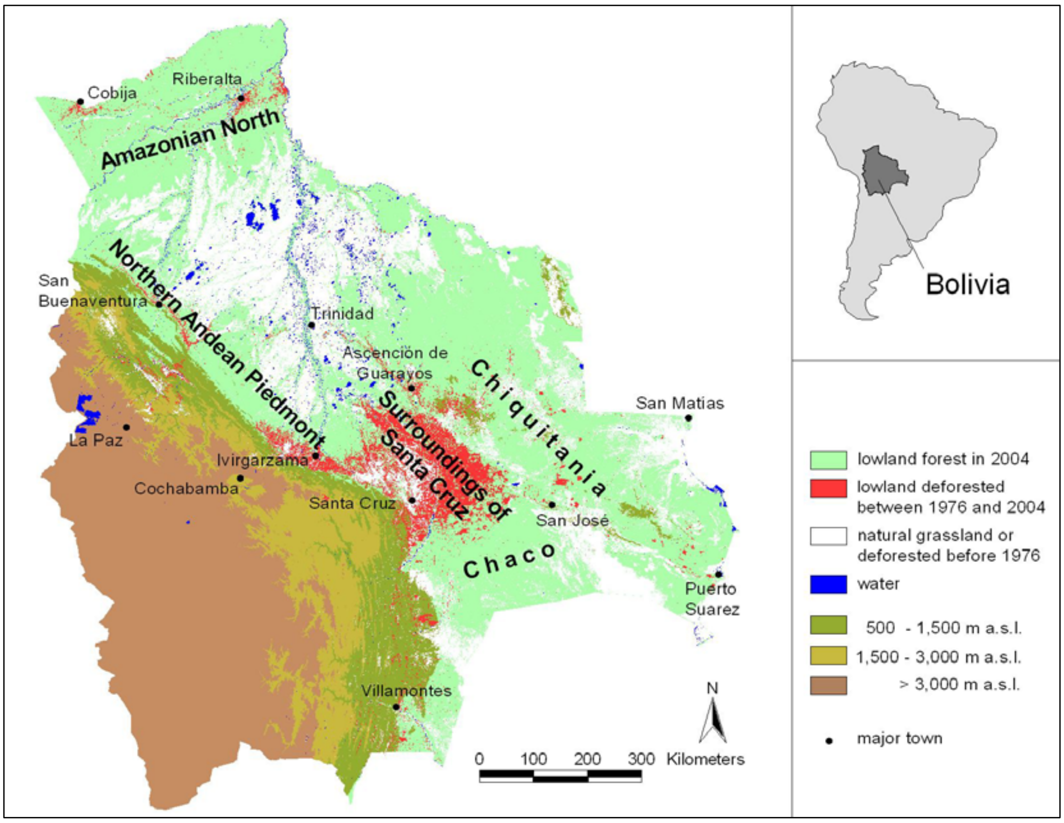


Figure 3.1 The Bolivian lowlands. Source: Adapted from Killeen et al. (2007) and USGS (2004).

The northwest region of the study area (termed "northern Andean piedmont") comprises very humid Amazonian rainforest. Most people living in this area are national settlers who have arrived within the past 30 years from western Bolivia and cultivate rice and perennial crops, e.g., banana, with few external production inputs. Migration was largely planned and supported by the government in the 1960s and 1970s (Eastwood and Pollard 1985; Thiele 1995). Thereafter, most migration occurred spontaneously and was mainly driven by poverty, e.g., after the collapse of tin mining in 1985 (Pacheco 2006a). In the Chapare zone (east of Cochabamba, around Ivirgarzama, Figure 3.1), coca is also an important crop. Several large indigenous territories (*Tierras Comunitarias de Origen,* TCO) are located in this region and belong to different lowland indigenous peoples.

The area around the city of Santa Cruz de la Sierra ("surroundings of Santa Cruz") is heterogeneous in terms of vegetation, land use and population. It is located in the transitional zone between the Amazonian rainforests in the north, the Chiquitano semi-deciduous forests in the east and the Chaco dry forest in the south (Navarro and Maldonado 2002). The alluvial soils east of the Río Grande are very fertile (Gerold 2004). Traditionally, sugar cane was the main crop and was planted near the city of Santa Cruz (Pacheco 2006a). Since the 1980s, industrial soybean production has become the most important land use (Hecht 2005); its development has been facilitated by preferential tariffs in the Andean markets, export incentives in the context of structural adjustment (Pacheco 2006a) and a development program funded by multilateral donors (Baudoin et al. 1995; Gerold 2007). Additional land uses include cattle ranching and manual agriculture (Pacheco 1998). Most of the lowland population is concentrated in this area, particularly in and around the city of Santa Cruz, which is the largest and fastest-growing town in Bolivia. It has a heterogeneous population composed of people originating from the lowlands and western Bolivia as well as immigrants from other countries (Sandoval et al. 2003).

The eastern region of the study area is called "Chiquitania" and is characterized by semi-deciduous forests growing in the poor soils of the Precambrian shield. Today's settlements were predominantly founded by Jesuits some 300 years ago (Tonelli Justiniano 2004). The most common traditional and current use of land is cattle ranching, both in natural grasslands and in pastures established on former forest land (Killeen et al. 2008). In addition, the timber industry is an important economic sector. The population mainly consists in descendants of lowland indigenous peoples.

The southern region of the study area ("Chaco") is virtually uninhabited, with the exception of the Andean foothills in the west. The predominating vegetation is Chaco dry forest. A large portion of this zone lies within the "Kaa-Iya del Gran Chaco" National Park. Only in the western parts is there enough rainfall to allow cattle ranching and limited agriculture (Killeen et al. 2008). A large proportion of the population consists of the descendents of lowland indigenous people.

3.2.2 Three proximate causes of deforestation

We define three major proximate causes of deforestation, following the concept of Geist and Lambin (2002). We base our definition of the proximate causes on the prevalent land use practices in the study area, which are closely related to specific social groups.

Mechanized agriculture refers to the intensive production of annual cash crops, mainly soybean, sugar cane and rice. Soybean is often double-cropped and alternated with sunflower or wheat cultivation in the dry season (CAO 2008). Mechanized agriculture is typically based on large production units, heavy machinery and large capital investments. Typical agents are large-scale corporations from

Bolivia or Brazil, medium-scale national landholders, and foreign, mainly Mennonite or Japanese, producers. To some extent, mechanized agriculture is also practiced by national settlers, especially around San Julian (south of Ascención de Guarayos), though this group is mostly associated with small-scale agriculture. Most production involves oil and cake processing in the country and is exported mainly to the Andean market. Mechanized agriculture is concentrated to the east and north of the city of Santa Cruz. In the 1990s, mechanized agriculture expanded mainly into the floodplain east of the Río Grande; however, the recent expansion is concentrated in the area north of Santa Cruz (Killeen et al. 2007; see also Chapter Two).

Small-scale agriculture comprises several forms of labor-intensive production of mainly rice, maize and perennial crops, such as banana. The corresponding agents often have the combined objectives of production for subsistence and of generating cash income. Only a very small share of the products of small-scale farming is exported. Also some cattle breeding integrated in multiple purpose small-scale farming is included in this category. Typically, about two hectares per family are cultivated annually in a shifting cultivation system. The small-scale producers are mostly national settlers that have migrated from the highlands (see Killeen et al. 2008). They are mostly found in the humid areas of the northern Andean piedmont and to the north of the city of Santa Cruz. In the latter region, these producers have increasingly adopted mechanized production systems; where this has occurred, the corresponding systems are included in the category “mechanized agriculture”. The population of lowland indigenous people is small and makes a minor contribution to agricultural production and deforestation (Pacheco 2006b).

Cattle ranching leads to the replacement of forests by pasture that is predominantly used for breeding and fattening cattle for beef production in Bolivia (CAO 2008). In this article, only the expansion of cattle ranching at the expense of forested areas is considered and cattle ranching on natural grasslands was excluded from the analysis. Both systems are estimated to sustain comparable numbers of cattle (CAO 2008). Nearly all produced beef is sold on the national market. In 2008, merely a single company exported beef (CADEX 2008) because Bolivia is not officially free from foot and mouth disease. The size of production units ranges from a few hectares to several thousand hectares. However, a census of cattle conducted by the National Veterinary Service (*Servicio Nacional de Sanidad Agropecuaria e Inocuidad Alimenticia,* SENASAG) has shown that in the lowlands, over 50% of cattle belong to farms with 1,000 animals or more. On average, the levels of production technology and efficiency are low (Merry et al. 2002). Cattle ranching is widespread in the Bolivian lowlands, but its importance for deforestation is especially high in the Chiquitania and in the Amazonian north. Most cattle ranchers are Bolivians, but Brazilian capital plays an important role, especially in areas near the border with Brazil (see Killeen et al. 2008).

3.2.3 Mapping the proximate causes of deforestation

In order to map the expansion of the proximate causes of deforestation, we used a stepwise procedure to assign the three proximate causes of land use change to the areas that were deforested between 1992 and 2004 (Figure 3.2). This period is assumed to be long enough to exhibit reliable trends; moreover, suitable data are available. Deforested areas as well as areas of stable forest were identified based on the report by Killeen et al. (2007) that distinguished forest and non-forest in the lowlands over five different points in time, including 1992 and 2004. We excluded the classes “Cerrado” and “deforestation in Cerrado” defined by Killeen et al. (2007) because these vegetation types have no closed canopy cover, which makes estimation of deforestation difficult. They used unsupervised classifications of Landsat satellite data, corrected the results manually, and validated the maps with aerial videography. For the region in the department of Santa Cruz, we assigned all areas deforested between 1992 and 2004 to one of the three defined proximate causes of deforestation using an existing land use map (Museo Noel Kempff and Prefectura de Santa Cruz 2008), which distinguishes seven classes of forest-replacing agricultural land use in 2005. This map has similar characteristics to the map of Killeen et al. (2007) and was prepared by the same institution the Museo Noel Kempff in Santa Cruz (full name *Museo de Historia Natural Noel Kempff Mercado*). It was based on a classification of 20 Landsat images and was thoroughly refined in cooperation with the most important associations of agricultural producers (Museo Noel Kempff and Prefectura de Santa Cruz 2008). We reclassified this map according to the three proximate causes of deforestation. Outside the department of Santa Cruz, several sources were used to allocate deforested areas to one of the three proximate causes. We first undertook a preliminary classification of the deforested areas according to the land use traditions described in Section 3.2.1 and agricultural statistics from the CAO (2008). Deforested areas in the northern Andean piedmont were preliminary classified as small-scale agriculture; deforested areas in other zones (outside Santa Cruz) were assigned to cattle ranching. Agricultural statistics from the CAO (2008) suggest that virtually no mechanized agriculture exists or existed outside the department of Santa Cruz and that crop production is very low in the Amazonian north. This incipient classification was refined using unpublished spatial data obtained from the National Institute for Agrarian Reform (*Instituto de Reforma Agraria,* INRA) and derived from the sanitation process occurring in lowland Bolivia (see Pacheco 2006b), which distinguishes between landholdings dedicated to crop production or cattle ranching.

Step	Information source
Delineation of areas deforested between 1992 and 2004	Remote sensing by Killeen et al. (2007)
Assignment of deforested areas within the department of Santa Cruz to the three proximate causes of deforestation	Map of land use in 2005 in Santa Cruz (Museo Noel Kempff and Prefectura de Santa Cruz 2008)
Preliminary assignment of deforested areas in the remaining study area to the three proximate causes of deforestation	Prevailing traditional land use (as described in the section on the study area) and agricultural statistics from CAO (2008)
Refinement of results	National Agrarian Reform Institute INRA (Pacheco 2006b); livestock survey (Animal Health Service SENASAG); visual evaluation of CBERS satellite imagery in Northern Amazon and Northern Andean Piedmont
Quantitative accuracy assessment	CBERS satellite imagery

Figure 3.2 Procedure to map the proximate causes of deforestation. Source: Authors.

Results were further improved by incorporating data from an unpublished survey of the SENASAG that indicated the cattle herd size for every landholding in Bolivia. Finally, we conducted a visual evaluation of critical areas (Northern Andean piedmont and Amazonian north) using China-Brazil Earth Resource Satellite (CBERS) satellite images (INPE 2010). The panchromatic channel of the high-resolution camera (HRC) of the CBERS has a resolution of 2.5 m, which allows for visual distinction between pasture and agriculture by a qualitative analysis of criteria such as shape, uniformity and reflectance of clearings. Deforestation patterns from small-scale agriculture typically consist of many small rectangular patches with different degrees of vegetation removal. In contrast, clearings for pastures are generally larger and more uniform, and they often leave a few scattered trees behind (see Supplemental Material for examples).

A quantitative validation of the final map was conducted for the area within the department of Santa Cruz, where this map is based on Museo Noel Kempff and Prefectura de Santa Cruz (2008). The validation utilizes 18 CBERS HRC scenes that are spread over the entire lowland area of the department of Santa Cruz. For each proximate cause of deforestation identified on the final map, 150 pixels were randomly chosen within the area covered by the 18 satellite images. Proximate causes of deforestation were identified in the 450 selected pixels based on a visual interpretation of the satellite images, and the results were then compared with the final map. A coincidence of 88% was found (weighted average of the user's accuracy); the allocation disagreement was 6.5% and the quantity disagreement 5.5% (see Pontius and Millones 2011, details in the Supplementary Material in Appendix B). Small errors may have been caused by the minute size of some clearings in small-scale farming or by changing land use within the analyzed period (1992-2004); e.g., patches of small-scale agriculture may have been missed if they became secondary forest or were converted to cattle ranching before 2004.

The resulting map (Figure 3.3) approximates land use changes in the Bolivian lowlands by incorporating the best data and information currently available. Table 3.1 summarizes the share of deforestation between 1992 and 2004 due to each of the three proximate causes. The expansion of mechanized agriculture made the largest contribution (54%), followed by cattle ranching (27%) and small-scale agriculture (19%). Killeen et al. (2008) found a much higher share of deforestation due to small-scale agriculture because they assigned deforestation in northeastern Bolivia to lowland indigenous communities. Based on the different sources mentioned and our knowledge of the area, we mostly attribute deforestation in this area to cattle ranchers.

Table 3.1 The contributions of the three proximate causes to deforestation between 1992 and 2004. Source: Authors.

Land Use	Deforested area (km^2)[a]	Percent of total deforestation (%)
Agribusiness	10,110	53.7
Small scale agriculture	3,560	18.9
Cattle ranching	5,170	27.4
Total deforested	**18,840**	**100.0**

[a]Forest persistence 1992-2004: 399,060 km^2

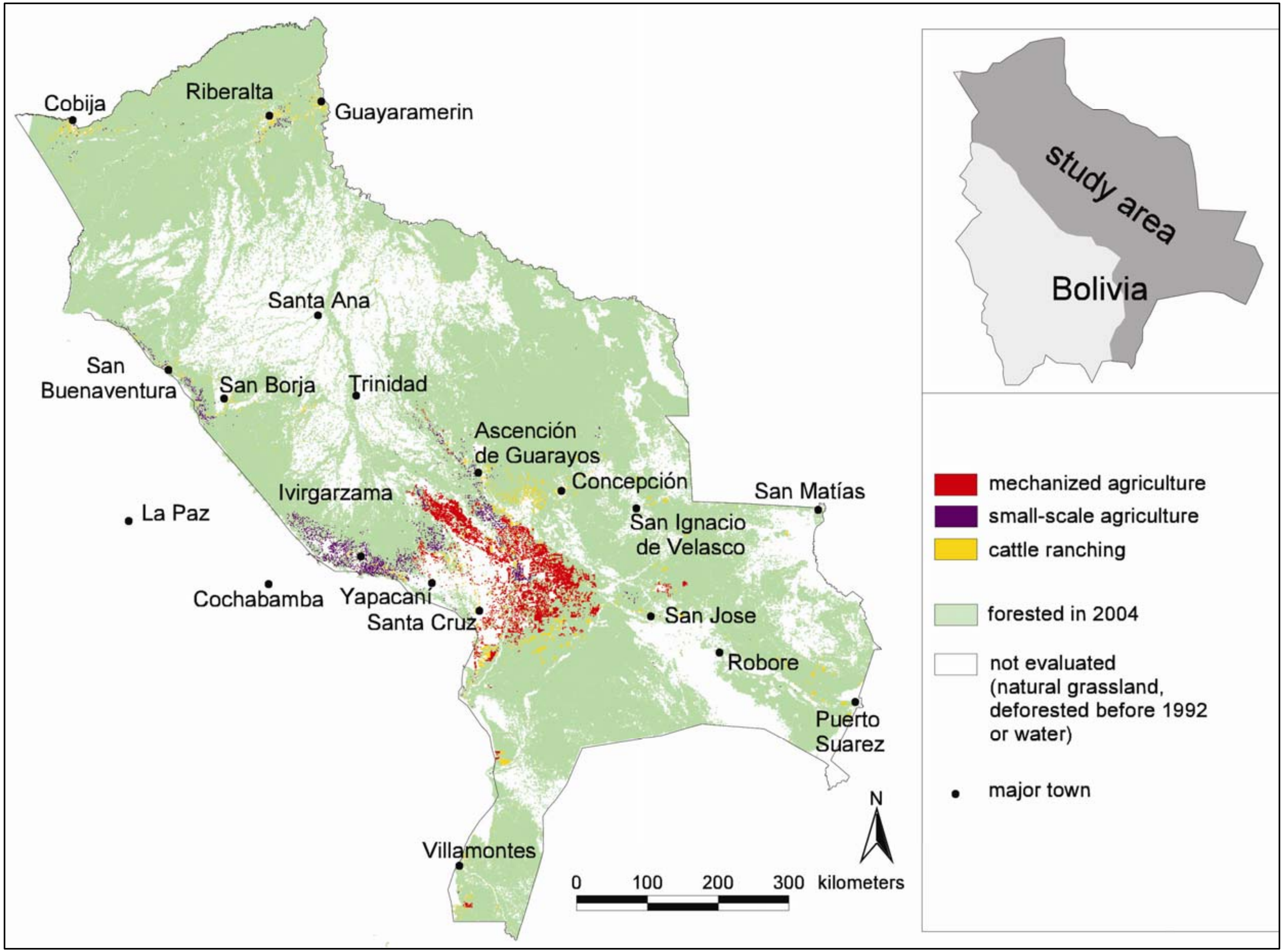


Figure 3.3 Proximate causes of deforestation and forest persistence from 1992 to 2004. Source: Authors, based on sources indicated in Figure 3.2.

3.2.4 Multinomial logistic regression

We have formulated a spatially explicit multinomial logistic regression model (MNL, e.g., Chomitz and Gray 1996; Hosmer and Lemeshow 2000; Menard 2002; Long and Freese 2006). Multinomial logistic regression is most suitable here because the dependent variable is categorical and consists of four unordered outcome categories: forest conversion due to mechanized agriculture, small-scale agriculture and cattle ranching as well as stable forest. The four outcome categories were regressed against a set of independent variables that include geophysical, socioeconomic and political factors. The coefficients are presented with stable forest as the base outcome or comparison category. For each of the three proximate causes, the resulting regression coefficients indicate the direction and strength of each independent variable's influence on forest conversion and allow us to rank the importance of each factor (Munroe and Müller 2007). The significance of coefficients is measured by z-statistics (Long and Freese 2006). We present the results as standardized logit coefficients and as odds ratios. Standardized logit coefficients can be used to compare the relative effects of the different independent variables and are calculated by multiplying the logit coefficient of an unstandardized independent variable by its standard deviation (Long and Freese 2006; Müller et al. 2011).

The spatial resolution of the regression analysis is 500 m. We also tested a coarser resolution of 1 km to check for possible biases but did not encounter meaningful differences in the results. To correct for potential spatial autocorrelation in the dependent variable, we computed spatially lagged models that included cells from non-neighboring grids and estimated the regressions using samples from every second and every third grid cell in both the East-West and North-South directions (Besag 1974).

Again, no substantial difference in the results was found between the two spatial samples. Correlation coefficients between independent variables never surpassed 0.8 which is mentioned as a critical threshold by Menard (2002). Only two pairs of variables showed correlations over 0.5, i.e., drought risk and fertile soils (0.74) as well as fertile soils and poor soils (0.52). Multinomial logit models can suffer from a violation of the independence of irrelevant alternatives (IIA) that may occur if an additional land use outcome affects the relative probabilities of the other alternatives. Statistical tests for IIA such as the Small-Hsiao and the Hausman test yield inconclusive results (Hilbe 2009; Long and Freese 2006). However, we argue that the choice of the three outcomes is unaffected by the potential presence of other outcomes and that they "can plausibly be assumed to be distinct and weighed independently in the eyes of each decision maker" (McFadden 1973, cited in Long and Freese 2006). Indeed, the inclusion of a hypothetical fifth land use option is unlikely to influence the weighting of the three proximate causes in the eyes of the local agents. The goodness of fit of calibration of the model was assessed by calculating the area under the curve (AUC) of the receiver operating characteristic (ROC) (Pontius and Schneider 2001; Pontius and Pacheco 2004). The AUC was derived on the basis of continuous fitted probabilities that were calculated at varying cut-off values. An AUC of 0.5 indicates an accuracy equal to that of a random model, and a value of one indicates a perfect fit. Based on the coefficients obtained from the model, we also derived maps of the propensity of future deforestation by applying the modeled equations to the values of the independent variables for all cells in the study area.

3.2.5 Independent variables

The independent variables encompass geophysical factors, transportation costs, and land policies (Table 3.2). We selected these variables based on reviews of tropical deforestation studies (e.g., Geist and Lambin 2002; Kaimowitz and Angelsen 1998; Kirby et al. 2006; Mertens et al. 2004) and our field expertise in the study area. To reduce potential endogeneity biases, i.e., biases caused when the causality between dependent and independent variables may go both ways, we defined all variables according to their state at the beginning of the change period in 1992. When it was not possible to obtain exact data from 1992, we used the most suitable information available, e.g., the most recent map of forest concessions in 1997.

Geophysical variables

Rainfall

The rainfall variables (Figure 3.4) were based on a map of the mean annual precipitation presented in Soria-Auza et al. (2010). The map was generated using a modeling approach that combines long-term rainfall data from weather stations with topography. We transformed the rainfall data and created two variables to better capture climatic conditions that limit agricultural production (see Section 2.2.3). The variable *excessive rainfall* indicates the amount of annual rainfall that surpasses 1,700 mm in steps of 100 mm; i.e., an area with 1,800 mm rainfall receives the value of one, an area with 2,000 mm of rainfall receives a value of three. Areas with precipitation below 1,700 mm receive a zero value. *Drought risk* is proxied by the amount of rainfall below 1,100 mm in steps of 100 mm; i.e., an area with 800 mm rainfall receives a value of three. Areas with precipitation above 1,100 mm are labeled zero.

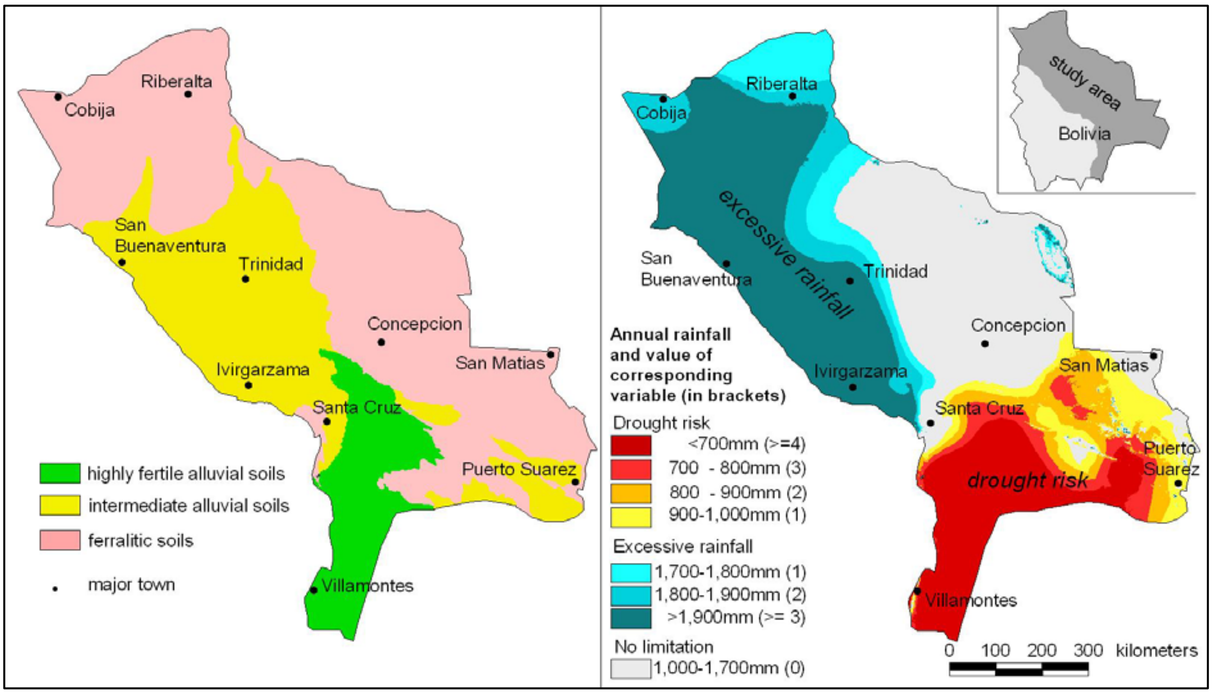


Figure 3.4 Drought risk, excessive rainfall and soil fertility. Source: Authors; rainfall data from Soria-Auza et al. (2010).

Soil fertility

Soil fertility is represented by two dummy variables that were derived based on three generalized soil categories (Figure 3.4). First, we defined the binary variable *ferralitic soils* and allocated a value of "one" to soils of the Precambrian Shield in the Chiquitania and the poor soils of the Amazonian north. In these areas, mainly Ferralsols, Plinthosols and Acrisols (Gerold 2001; Gerold 2004) have been formed by ferralitization and clay lixiviation, resulting in low nutrient availability and low organic matter content. We delimited this zone based on the geological map of Bolivia (Servicio Geológico de Bolivia 1978) and the vegetation map of Navarro and Ferreira (2007). Second, we created the binary variable *fertile soils* where a value of "one" refers to a zone of alluvial soils from the area between the Rio Grande and the Brazilian Shield to the south of Bolivia, were Fluvisols with high nutrient availability and organic matter content are found (Gerold 2001). The limits of this zone were chosen based on expert knowledge (Gerold 2001; Gerold 2004; see Section 2.2.3). Areas where both dummy variables are zero refer to alluvial soils with intermediate fertility that are influenced largely by white water streams; these areas were delimited based on the authors' judgment supported by the vegetation map of Navarro and Ferreira (2007).

Slope

We used the Shuttle Radar Topography Mission (SRTM, USGS 2004) digital elevation model to calculate values of the *slope* variable in each grid cell in degrees. The elevation values of the SRTM model account for the height of vegetation. Therefore, the slope values at the forest edge appear overly high in flat areas because of the sharp distinction between low and high vegetation cover. To avoid this bias, we merged all slope values from 0-5° into a single class (labeled "5°") and grouped higher values in steps of 1° ranging from 6° to 46° (see Section 2.2.3).

Access to markets

We calculated transportation costs as a measure of physical access to markets (see Figure 3.5). To avoid problems with road endogeneity (Müller and Zeller 2002), we included only major roads that connect major settlements (see Müller et al. 2011). To calculate transportation costs we used a road network of the 1990s that differentiates between paved and dirt roads (Figure 3.5, based on unpublished data obtained from the Bolivian road infrastructure authority *Servicio Nacional de Caminos*). Underlying transportation costs are applied in US$/(t km) as 0.05 for paved roads, 0.1 for gravel and dirt roads and 0.5 for land without roads (Müller et al. 2011). The road network serves to estimate the average transportation costs for transporting agricultural products from the farm gate to local and exportation markets. The variable *access to local markets* is defined by the transportation costs in US$ per ton to the nearest settlement with more than 5,000 inhabitants. The variable *access to export markets* is defined by the transportation costs in US$ per ton to the main ports for exportation of agricultural products, i.e., the "Hydrovia" via the Paraguay River to the Atlantic and the road to the Pacific across the Bolivian highlands. To calculate the propensity of future deforestation, we modified the road network by changing the status of selected gravel and dirt roads into "paved roads" according to the observed road construction in the last years or road construction plans for the near future (Figure 3.5). We also included the transportation costs via the bi-oceanic highway in the Amazonian north as an additional layer to capture future accessibility to export markets.

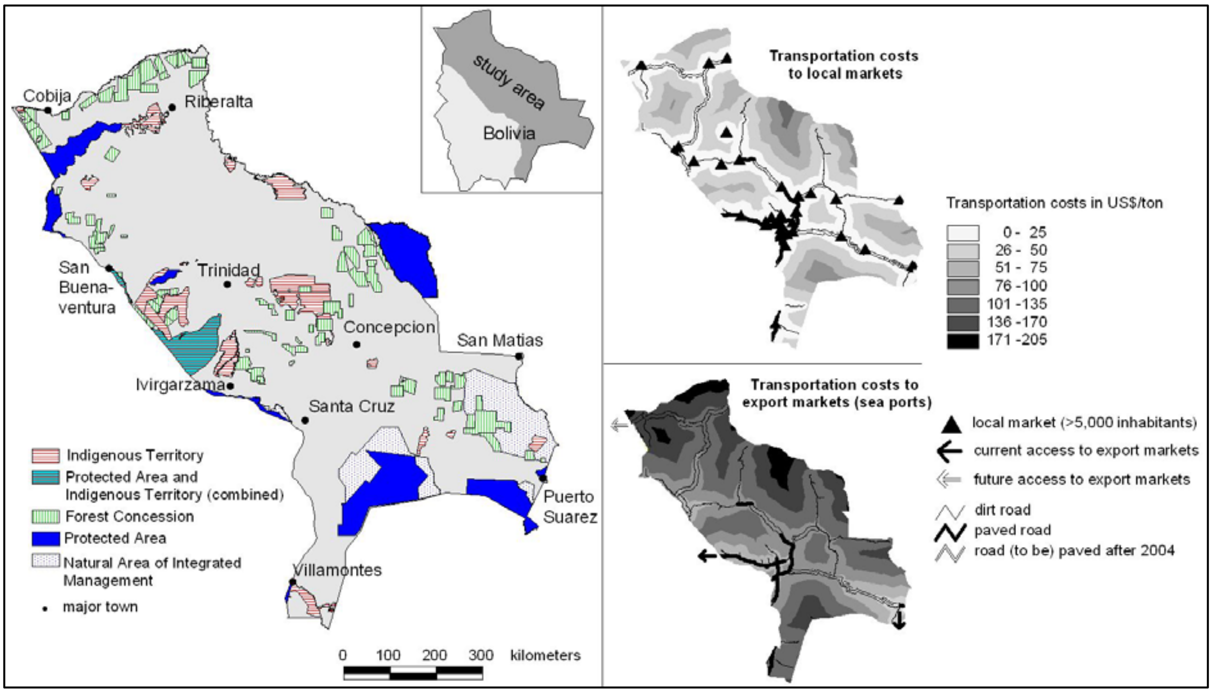


Figure 3.5 Independent variables on market access and land policies. Sources: SERNAP, INRA and Authors.

Variables on land policies

All variables related to land policies are shown in Figure 3.5. The variable *national parks* includes all zoned areas that are administrated by the national authority for protected areas (*Servicio Nacional de Areas Protegidas,* SERNAP,) and are attributed to the category of strict protection (national parks, reserves of flora and fauna and core zones of biosphere reserves). The variable *areas of integrated management* represents protected areas administrated by SERNAP but with a less strict protection status (*Áreas Naturales de Manejo Integrado,* ANMI). Data on both national parks and areas of integrated management were obtained directly from SERNAP and represent the state of the early 1990s. We define the variable *forest concessions* as the areas where private agents obtained the right to exploit timber for a 40-year period according to the rules of the Bolivian forestry law (No. 1700). The map of forest concessions was obtained from the former forestry state agency (*Superintendencia Forestal*) and characterizes forest concessions in 1997. The variable *indigenous territories* refers to the TCOs, which are rural communal properties granted to indigenous communities. These data characterize the situation in the early 1990s and were obtained from the INRA.

Table 3.2 Descriptive statistics of independent variables. Number of observations: 1,668,104. Source: Authors.

Variable	Unit	Mean	Standard deviation	Minimum	Maximum	Year of information
Excessive Rainfall	100 mm	1.22	3.44	0	43	
Drought Risk	100 mm	0.86	1.72	0	7	
Fertile soils	Binary	0.15	0.36	0	1	
Poor soils	Binary	0.61	0.49	0	1	
Slope	Degrees	5.09	0.87	5	46	
Transportation costs to local markets	US$/t	35.89	22.11	0	118.1	Road network of the mid-1990s
Transportation costs to exportation markets (sea ports)	US$/t	118.05	32.37	30.2	203.8	Road network of the mid-1990s
National parks	Binary	0.12	0.32	0	1	Early 1990s
Areas of integrated management	Binary	0.07	0.25	0	1	Early 1990s
Forest concessions	Binary	0.11	0.32	0	1	1997
Indigenous territories	Binary	0.09	0.28	0	1	Early 1990s

Potentially important variables that could not be included

There are additional factors that potentially influence deforestation patterns in Bolivia, but suitable data are not available. Examples are flood risk, soil drainage and land tenure (Müller et al. 2011). Land consolidation is still in process in Bolivia (INRA 2010). In populated and already deforested areas, it is generally more advanced than in sparsely populated and forested areas. However, the inclusion of inconsistent data on land tenure may bias the results; such data were thus excluded. We also refrained from using the variable "distance to prior deforestation", which often has high explanatory power in deforestation models (e.g., Kirby et al. 2006). However, besides its intrinsic meaning, this variable confounds other independent variables that triggered deforestation patterns in a former time step. Hence, issues with multicollinearity arise when including the distance to prior deforestation, and we therefore excluded this variable from the analysis (see Mertens et al. 2004; Müller et al. 2011).

3.2.6 Propensity of future deforestation

We derived maps of future deforestation propensity by applying the modeled equations to the independent variable's values for all forested cells in 2004 within the study area. For the variables representing access to markets, we used the updated road network (see *Access to markets)*. Maps of deforestation propensity were used to allocate deforestation during 2004-2030, assuming that, for each of the three proximate causes of deforestation, the same quantity of square kilometers will be deforested per year as during the 1992-2004 period. In other words, the relative contribution of each proximate cause and the deforestation rate are assumed to remain constant (as in Table 3.1). Thus, the fitted probabilities derived from the regression are interpreted as purely relative measures of local propensity, whereas the quantity of expected forest conversion is derived by an independent procedure (see Pontius and Batchu 2003).

In the first step, the cells with the highest deforestation propensities were selected for each proximate cause until 2.17 times the number of cells deforested between 1992 and 2004 had been selected, because the 26 years from 2004 to 2030 correspond to 2.17 times the 12 years from 1992 to 2004. This procedure caused some cells to be selected for forest conversion more than once for different proximate causes. In such cases, we chose the category with the higher propensity of deforestation. For the non-selected category, additional cells were selected by reducing the corresponding propensity threshold. This procedure was repeated until the expected number of converted cells for each land use category was reached. The resulting map visualizes the future propensity for deforestation due to each proximate cause. This allocation strategy resembles the land use allocation procedure applied for example in the CLUE-S model (Verburg and Veldkamp 2004).

3.3 Results

3.3.1 Dynamics of land use change

The results of the MNL regressions characterize the dynamics of expansion of the three proximate causes of deforestation compared to stable forest (Table 3.3). For nine of eleven independent variables, the standardized coefficient is highest for mechanized agriculture, which indicates that this expansion pathway is best explained by the set of covariates. This is supported by the AUC, which is highest for the mechanized agriculture model (AUC=0.97, see also supplemental material). Mechanized agriculture mainly expanded in areas with good access to export markets and favorable environmental conditions. Fertile soil increased the likelihood of the expansion of mechanized agriculture by 15-fold (odds ratio = 14.77), whereas on poor soil, mechanized agriculture was approximately 50 times less probable to drive deforestation (odds ratio = 0.021). A 100-mm increase in annual rainfall in humid areas decreased the probability of the expansion of mechanized agriculture onto formerly forested areas by 50%, and a 100-mm reduction in rainfall had a comparable effect in drought-prone areas. A one-degree increase in slope reduced the probability of mechanized agriculture expansion by 32%. The compliance of mechanized agriculture with land use restrictions appeared to be high, and little expansion was observed in protected areas, areas of integrated management, forest concessions or indigenous territories. There was virtually no overlap between industrial agriculture and protected areas, which explains the extremely high value of the corresponding coefficient. This can also be interpreted as an indication that protected areas are mainly located in regions where the agricultural potential is low.

The expansion of small-scale agriculture was promoted predominantly by local market access, fertile soil and humid climate conditions, and it was prevented by high drought risk. Compliance with land use restrictions was considerably lower for small-scale agriculture than for the other types of land use. Pixels inside a protected area were only 9% less likely to be converted to small-scale agriculture, and thus parks were not very effective in halting this expansion pathway. Similarly, forest concessions and indigenous territories had marginal effects on this proximate cause of deforestation. The AUC was 0.96 (see also supplemental material) for small-scale agriculture, indicating an excellent calibrated fit of the model.

Table 3.3 Standardized logit coefficients and odds ratios (in brackets). Source: Authors.

	Unit	Mechanized agriculture	Small scale agriculture	Cattle ranching
Excessive Rainfall	100 mm	-2.56[b] (0.48)	*0.24* *(1.07)*	-0.06 (0.98)
Drought Risk	100 mm	-1.55 (0.40)	-2.82 (0.19)	-0.31 (0.84)
Fertile soils	dummy (1/0)	2.69 (14.77)	2.24 (9.40)	1.40 (4.06)
Poor soils	dummy (1/0)	-3.85 (0.021)	-1.91 (0.15)	*0.40* *(1.48)*
Slope	degrees	-0.34 (0.68)	-0.19 (0.81)	-0.15 (0.85)
Transportation costs to local markets	US$/t	-0.35 (0.98)	-1.41 (0.94)	-1.83 (0.92)
Transportation costs to exportation markets	US$/t	-0.99 (0.97)	-0.87 (0.97)	-0.14 (1.00)
National parks	dummy (1/0)	-51.21 (0.00)	-0.10 (0.91)	-1.17 (0.31)
Areas of integrated management	dummy (1/0)	-7.55 (0.001)	-1.61 (0.20)	-2.06 (0.13)
Forest concessions	dummy (1/0)	-1.63 (0.20)	-0.71 (0.49)	-0.78 (0.46)
Indigenous territories	dummy (1/0)	-7.09 (0.001)	-0.77 (0.46)	-0.87 (0.42)

[b] Standardized logit coefficients and odds ratios (in brackets) from the MNL model using stable forest as the base category. Coefficients of the dummy variables were not standardized. Observations without forest cover in 1992 were excluded. All coefficients are significant at the 99% level. N = 1,668,104.

The expansion of cattle ranching was relatively less influenced by environmental conditions. The average of the absolute values of coefficients was much lower and the AUC was 0.84 (see also Appendix B). Although fertile soil increased the probability of cattle ranching by four-fold, poor soils also doubled its probability. This latter result is likely due to low competition with the other two proximate causes on poor soils. Access to local markets was an important driver of the expansion of cattle ranching, and an increase in transportation costs by one dollar per ton decreased the likelihood of cattle expansion by 8%. In fact, cattle ranching expanded in most accessible locations across the study area. Compliance with land use restrictions was only slightly higher than in the case of small-scale agriculture.

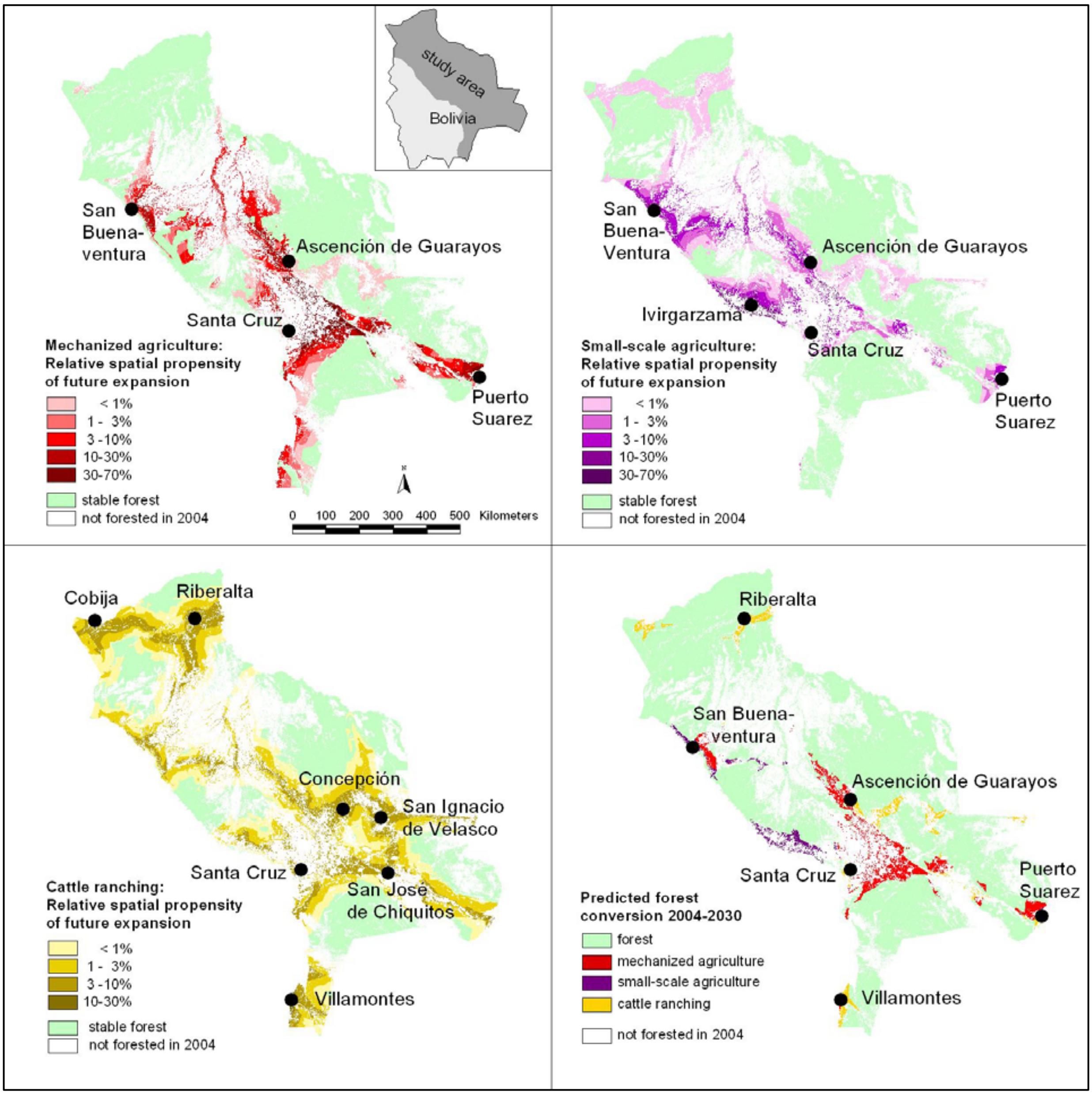


Figure 3.6 Propensities of agricultural expansion from 2004 to 2030. Source: Authors.

3.3.2 Propensity of future deforestation

An evaluation of the propensity maps (Figure 3.6) reveals that the expansion of mechanized agriculture is likely to be concentrated in areas where conditions are particularly suitable, mostly near the current areas of mechanized agriculture and particularly north of Ascención de Guarayos and near the Brazilian border (Puerto Suarez). The area near San Buenaventura in the northern Andean piedmont also shows some potential for expansion. Small-scale agriculture may experience the most expansion near the northern Andean piedmont but expansion is also predicted to some extent in areas identified as threatened by mechanized agriculture. The potential expansion of cattle ranching is more evenly distributed and threatens virtually all of the accessible forest areas in the lowlands, but there is particularly a high propensity of expansion in the Amazonian north, the Chiquitania, and the southern Andean foothills near Villamontes. This is consistent with the observation that the expansion of cattle ranching is relatively indifferent to environmental conditions. The map of projected deforestation clearly identifies areas around Cobija, Riberalta, Concepción, San Ignacio de Velasco, San José de Chiquitos and Villamontes as the most threatened by conversion to cattle ranching.

In the lower right of Figure 3.6, these findings are combined to depict the projected land use in 2030. The resulting map predicts an expansion of each of the three proximate causes near areas where the same land uses are currently practiced (compare with Figure 3.3); i.e., mechanized agriculture near Santa Cruz, small-scale agriculture at the northern Andean piedmont, and cattle ranching near local market centers in the Chiquitania and Amazonian north. In addition, an expansion of mechanized agriculture into new areas near Puerto Suarez and San Buenaventura is likely. We do not show a map of propensity for the category stable forest because we are mainly interested in the propensities of conversion.

3.4 Discussion and substantiation of the regression results

The multinomial logit model allowed us to evaluate spatial determinants of deforestation between 1992 and 2004. These findings are useful as they permit valuable insights into the land use transitions in the recent past (Table 3.3) and facilitate awareness of potential future pathways (Figure 3.6). We first discuss the plausibility of the model's results and then connect these results with the context of historical land use changes in lowland Bolivia to analyze potential drivers and legacies that cannot be captured by the model. It is not surprising that the predicted expansion of each type of land use is concentrated near areas already under the same land use. This suggests an increasing spatial concentration of land use dynamics in the study area and indicates that land use determinants are spatially clustered. The result is noteworthy, however, because the distance to prior deforestation was not included as a covariate in the model. In the case of mechanized agriculture, the model predicts new potential hotspots of forest conversion near Puerto Suarez and near San Buenaventura (Figure 3.6). In the area surrounding Puerto Suarez, fertile alluvial soils and beneficial access to export markets via the Paraguay River foster the expansion of mechanized agriculture. In addition, experimental soybean plantations have been initiated in this area by international corporations (CIAT Santa Cruz, *Centro de Investigación Agrícola Tropical*, personal communication). In the area surrounding San Buenaventura, an agro-industrial complex for the production and processing of sugar cane has long been planned, and these plans have been revived under the current government (Malky and Ledezma 2010). Soils are of intermediate quality, but access to La Paz is fairly good. Thus, the predicted expansion of mechanized agriculture into these two new hotspots indeed captures probable future dynamics. The predicted land use in 2030 is based not only on the regression results, which reveal spatial patterns, but also on the assumption that deforestation will continue at the same rate observed in the past. This is one of many possible scenarios because an alteration of macroeconomic or political drivers can considerably alter the demand for agricultural products. For example, a future expansion of mechanized agriculture will depend on macroeconomic conditions, such as those linked to prices of agricultural commodities, exchange rates, or the success of Bolivia in securing markets for exportation (see Morton et al. 2006; Nepstad et al. 2006; Pacheco 2006a).

As follows, we intend to enrich the discussion of the regression results by analyzing spatial dynamics of land use change in a historical context to identify additional drivers and land use legacies for the different zones of the study area that may shape historical and future land use patterns (see Liu et al.

2007). The development of the *Amazonian north* was originally triggered by the rubber boom some 150-100 years ago. Cattle ranching was first adopted as a supplementary land use activity that provided animal products to the rubber tappers that settled in the rubber land estates (Gamarra Téllez 2004). However, over time, cattle ranching has taken over the more accessible forest areas that were first opened by the logging industry and later converted to pastures. As a consequence, access to local markets seems to be the most valid spatial determinant shaping the spatial patterns of cattle ranching in this area to date. This is plausible and validates the finding of the regression model that indicates relative indifference towards environmental conditions. In addition, the inability of other agricultural activities to prosper in the Amazonian north, probably also due to the economic dominance of Brazil nut extraction, is in line with the model's finding that cattle ranching is currently the only viable farming activity on the poor ferralitic soils of Bolivia. Land use patterns in the *northern Andean piedmont* were originally shaped by government-planned settlements of poor rural internal migrants ("colonos") who originated from western Bolivia and practiced small-scale agriculture. An important factor for the successful establishment of smallholders in this area may have been the persistence of linkages between these settlers and their areas of origin because many "colonos" tend to maintain strong connections to their places of origin in the dry valleys and highlands. The regression model therefore tends to overestimate the importance of climatic conditions as a determinant of small-scale agriculture because it does not capture the persistence of cultural associations. In turn, settlers of foreign origin, mainly the Mennonites and Japanese, are important agents in mechanized agriculture in the *surroundings of Santa Cruz*. Government policies between the 1950s and the 1970s assigned land to these settlers, along with national producers, in areas near Santa Cruz with the objective of enhancing the production of sugar cane and cotton for the national market as part of a broader plan aimed at import substitution of these agricultural goods for the domestic market (Pacheco 2006a). These programs strongly shaped patterns of mechanized agriculture but - since the high agricultural potential of the area was known - they also promoted land occupation within the spatial potential identified by the multinomial logit model. The same is valid for the program to support agricultural development by multilateral donors during the early 1990s in the expansion zone in eastern Santa Cruz (Baudoin et al. 1995; Hecht 2005; Gerold 2007). In the *Chiquitania*, where cattle ranching is the predominant economic activity, land use patterns were originally shaped by the locations of Jesuit missions (Tonelli Justiniano 2004). As in the Amazonian north, the prevalence of cattle ranching is likely due to the poor quality of soils, which limits other agricultural activities. This is also in line with the regression results.

The discussion reveals that the regression model and the maps of propensity of future deforestation deliver plausible results but merely reflect a portion of the dynamics determining land use change. An inspection of historical land use reveals underlying drivers and historical legacies that cannot be emulated by regression analysis. However, such legacies not only affect historical trajectories but can also have a bearing on future developments and therefore can cause large deviations from predicted land use changes. For instance, it is possible that the strong political support by the current government for smallholders originating from western Bolivia and the government's interest in securing political influence in the Amazonian north might lead to a stronger expansion of small-scale agriculture in this zone than that projected by our model.

3.5 Conclusions

We have explored the spatial dynamics of the expansion of the three main proximate causes of deforestation in the Bolivian lowlands. Mechanized agriculture caused the largest share of deforestation, followed by cattle ranching and small-scale agriculture. For the period between 1992 and 2004, we estimated a spatially explicit multinomial logistic regression using these three proximate causes of deforestation as outcome categories. The set of predictor variables captures the natural suitability of a location, physical accessibility conditions and land policies that can all be assumed to shape the expansion of agriculture into previously forested areas. The regression results were used to predict the likely future of deforestation throughout the Bolivian lowlands. To corroborate the regression results, we also conducted a qualitative analysis of historical drivers and legacies of land use that have shaped long-term land use patterns in the Bolivian lowlands to date. Placing the regression into a broader historical context augmented the discussion of regression outcomes and facilitated a more profound assessment of the future deforestation risks.

The model suggests that the expansion of mechanized agriculture will occur in areas with good access to international markets and favorable environmental conditions, whereas land use restrictions efficiently prevent the expansion of mechanized agriculture. Potential future deforestation due to mechanized agriculture expansion will likely occur to the North and the South of its current extension, but newly emerging frontier areas near Puerto Suarez and San Buenaventura may also open up. The expansion of small-scale agriculture is predicted to be concentrated in areas with a humid climate, good soil and local market access. The compliance with land use restrictions is low in this category, and designation of protected areas has little effect on curbing deforestation arising from small-scale agriculture. In the future, small-scale agriculture will likely continue to expand in humid areas at the northern Andean piedmont. Forest conversion for cattle ranching is largely independent of environmental factors and is instead driven by access to local markets. Land use restrictions are also relatively ineffective in delaying the expansion of cattle ranching. The future of cattle ranching is likely to affect various parts of the Bolivian lowlands without dominant spatial clusters.

Our results can aid in the development of policies aimed to reduce deforestation, e.g., in the context of REDD. An important part of such policies may be a national land use plan that admits expansion into some suitable areas while restricting expansion in other areas. This may avoid the development of new deforestation hotspots, for example due to the expansion of mechanized agriculture. The regulation of small-scale agriculture, which has caused much less deforestation in the past, may be even more demanding because compliance to land use restrictions is low and monitoring costs are likely to be high because of the large number of agents. The mitigation of deforestation caused by small-scale agriculture may be important in the Amazonian north, where small-scale farming will probably expand despite the low natural suitability. For a reduction of the expansion of cattle ranching, which threatens forests in many different parts of the Bolivian lowlands, the enforcement of existing legislation seems most adequate and might avoid large illegal clearings (Superintendencia Forestal 2006).

The presented regression analysis helps distinguish the specific dynamics of forest conversion due to different proximate causes. Moreover, the model allows calculations of the propensity of agricultural expansion, which in turn facilitates the prediction of future deforestation. However, the interpretation of regression models can lead to erroneous conclusions due to a dearth of knowledge of the historical framework. In particular, the timing and quantity of forest conversion are often affected by political interventions and historical legacies that are difficult to capture in regression models. A strength of these models is their ability to elucidate the spatial patterns of recent changes and statistically infer their determinants. However, supplementing the models with explanatory frameworks based on long-term historic drivers and legacies can render the inferences more convincing and generate more valuable insights for policy and management.

Chapter 4

Policy options to reduce deforestation based on a systematic analysis of drivers and agents in lowland Bolivia

Co-authors: Till Pistorius, Sophia Rohde, Gerhard Gerold, Pablo Pacheco

Abstract

The reduction of tropical deforestation is of crucial importance for mitigating climate change and curbing the loss of biodiversity. In light of the current international efforts to reduce deforestation associated to REDD, effective and efficient country-specific policy options need to be identified to make progress on the ground. Taking lowland Bolivia as an example, we propose a systematic approach to identify and discuss such policy options; this systematic approach can be applied to other tropical contexts with ongoing conversion of forests to agricultural uses. We begin with the distinction of three land use categories associated with the main proximate causes of deforestation in lowland Bolivia, viz. mechanized agriculture, small-scale agriculture and cattle ranching, each of them linked to typical agents. Based on a systematic analysis of spatial and socioeconomic criteria, we then estimate the potential expansion and likely costs of deforestation reduction in order to formulate suitable policy options for each of the three proximate causes of deforestation. Although mechanized agriculture caused more than half of deforestation in lowland Bolivia, we argue that cattle ranching activities, which contributed to 29% of deforestation between 1992 and 2004, should be targeted as a priority since its expansion threatens forests in many different locations and improvements could be achieved at relatively low costs. In this light, enforcing land use legislation, accompanied by strengthening institutions on national and local levels, constitute tasks of utmost importance.

4 Policy options to reduce deforestation based on a systematic analysis of drivers and agents in lowland Bolivia

4.1 Introduction

The present destruction of tropical forests accounts for up to 20% of total anthropogenic carbon emissions (IPCC 2007) and leads to dramatic losses of biodiversity and vital ecosystem services. Tropical forests constitute a key resource for a successful global strategy: not only to mitigate, but also to adapt to the consequences of climate change (FAO 2010). The reduction of deforestation is considered to be one of the most cost-efficient activities (Stern 2007; Eliasch, 2008), with additional potential to generate synergies between environmental and development objectives (Pistorius 2009). There is an ongoing debate among the Parties to the UNFCCC to negotiate a mechanism that could reduce greenhouse gas emissions from deforestation and forest degradation (Reducing Emissions from Deforestation and Degradation, REDD). By including a broad range of forest-related activities such as conservation, sustainable forest management and enhancement of forest carbon stocks, the planned REDD mechanism was expanded into REDD+.

As a general guide, Stern (2008) proposed to assess the effectiveness, efficiency and equity of policies aiming to reduce deforestation. We argue that in order to do so, there is a need for in-depth and country-specific knowledge about relevant land use trends and their outcomes in concrete locations (Angelsen et al. 2009; Miles and Kapos 2008). Processes and patterns of deforestation are related to specific underlying causes, proximate causes, and agents that tend to vary across regions and are associated with diverse ecological settings and national political and economic circumstances (Geist and Lambin 2002). This implies a need for systematic analyses of regional conditions driving deforestation and the opportunity costs of agents involved, in order to inform decision-makers on suitable policy options that minimize the trade-offs between forest conservation and development.

This paper pursues two objectives. First, based on an analysis of drivers, agents, patterns, and trends of land use change, we develop a systematic approach that allows us to identify and specify policy options for effective and efficient deforestation reduction for the three main proximate causes of deforestation. We develop this approach for lowland Bolivia, but it is intended to serve as a blueprint which is also applicable in other tropical forest countries. Second, we intend to provide specific input on the ongoing policy debate in Bolivia regarding effective ways to halt expanding deforestation – within or beyond REDD[6]. Forest degradation is not considered here because suitable data for mapping are not yet available, let alone a robust quantification (Souza and Roberts 2005).

Bolivia demonstrates an illustrative case since its tropical forests are highly threatened by the expansion of a variety of different agricultural and ranching land uses associated with diverse agents (Killeen et al. 2008), and suitable spatial data for the analysis are available. We focus on the Bolivian lowlands defined as areas below 500 meters above sea level. We refrain from delving into the important discussion of equity issues, since that would require an additional analysis on access to land, resources, and distribution of benefits from forest conversion and conservation, which is beyond the scope of this paper.

---

[6] Currently it is not clear if and how Bolivia will continue to participate in REDD, also see Section 2.

4.2 Political and legal context shaping deforestation in Bolivia

Today, tropical rain forests cover around 40 million ha of the Bolivian lowlands, corresponding to 90% of its original extent (Killeen et al. 2007). Deforestation rates exceed 0.5% and tend to increase over time. From 1992 to 2004, about 150,000 ha of forest were cleared per year (Killeen et al. 2007). As mentioned earlier, there is no reliable data on forest degradation, although some reports indicate that the most valuable timber species have already been exhausted in lowland Bolivia (Superintendencia Forestal 2003). In this region, significant pressures on forests persist in spite of the land and forest tenure reforms implemented in Bolivia during the mid-1990s that, among other aims, were supposed to reduce deforestation through clarifying and securing property rights (Hecht 2005; Pacheco 2006a).

In 1996, the Bolivian government issued a revised Land Law (No. 1715) and a Forest Law (No. 1700) with the intention of promoting sustainable land and forest management and preventing deforestation in lands unsuitable for agriculture. The Land Law introduced a process of land regularization (*saneamiento*) aimed at granting land titles based on the verification of the social and economic function of the land (*Función Económica Social*, FES). In addition, land use plans (*Planes de Uso de Suelo*, PLUS) were introduced at both departmental and municipal levels. In turn, the Forest Law and its corresponding legislation, along with specific regulations for undertaking sustainable forest management, introduced land use plans at the property level (*Plan de Ordenamiento Predial*, POP) aimed at defining suitable areas for agricultural production based on the agro-ecological conditions of the land. Any landholding with a size larger than 50 ha requires an approved POP in order to obtain permits for clear cutting (see Pacheco 2005 for details).

The mentioned reforms have had relatively poor outcomes in practice due to both design shortcomings and implementation failures (Pacheco et. al. 2010) that contributed to the persistence of insecure land tenure and weak enforcement capacities. For example, from 2002 to 2006, more than 80% of deforestation took place without fulfilling legal requirements (Resnikowsky 2007). In addition, POPs have often been used to justify inappropriate forest clearing instead of regulating agricultural expansion, an issue that has been highly controversial in Bolivia. Currently, the Bolivian government is attempting again to change the forestry legislation and related norms, yet much of the problems linked to deforestation are not due to the lack of norms but to lack of their enforcement (Pacheco et al. 2010). A new authority has been formed to control and enforce land use related legislation (ABT, Autoridad de Fiscalización y Control Social de Bosques y Tierras).

In spite of the shortcomings mentioned above, land tenure regularization has achieved some outcomes, mainly in the titling of indigenous territories. Yet as of 2009, approximately 60% of the land in Bolvia was still in the process of sanitation (INRA 2010), which likely encourages deforestation since forest clearing is still regarded as a way to justify land ownership. The land titling process is influenced by competing claims between different agents, for example, between smallholder colonists and large-scale landholders, or smallholders attempting to encroach community lands demanded by indigenous people (*Tierra Communitaria de Origen*, TCO, see fugure 3.5). Furthermore, Bolivia has made important progress in establishing forest protected areas. These areas cover approximately 17% of the Bolivian lowlands, while some of them are subject to considerable conflicts (Zea O'Phelan et al. 2002).

In the context of international negotiations on climate change, Bolivia was one of the countries supported by the UN-REDD program. In March 2010, the UN-REDD board approved $ 4.7 M for the development of a national REDD strategy (UN-REDD 2011b). Yet, at the "World People's Summit on Climate Change" (April 2010), the Bolivian government was opposed to carbon markets and REDD programs, a position which was defended in the climate change negotiations during COP 16 in Cancun, Mexico. Thereby the Bolivian Government puts into question the Bolivian REDD program supported under UN-REDD as well as some ongoing and planned REDD pilot projects in the country. But the discussion of REDD implementation in Bolivia is outside the scope of this paper.

4.3 Methods

We suggest a systematic approach in order to identify the most suitable measures for effective and efficient deforestation reduction (Figure 4.1). Since different agents are involved in driving land-use change, measures to reduce deforestation must take into account the diversity of these agents' strategies and the resulting land-use outcomes. In this light, we link spatial patterns of deforestation with relevant agents in order to identify specific policy options for the main proximate causes of deforestation.

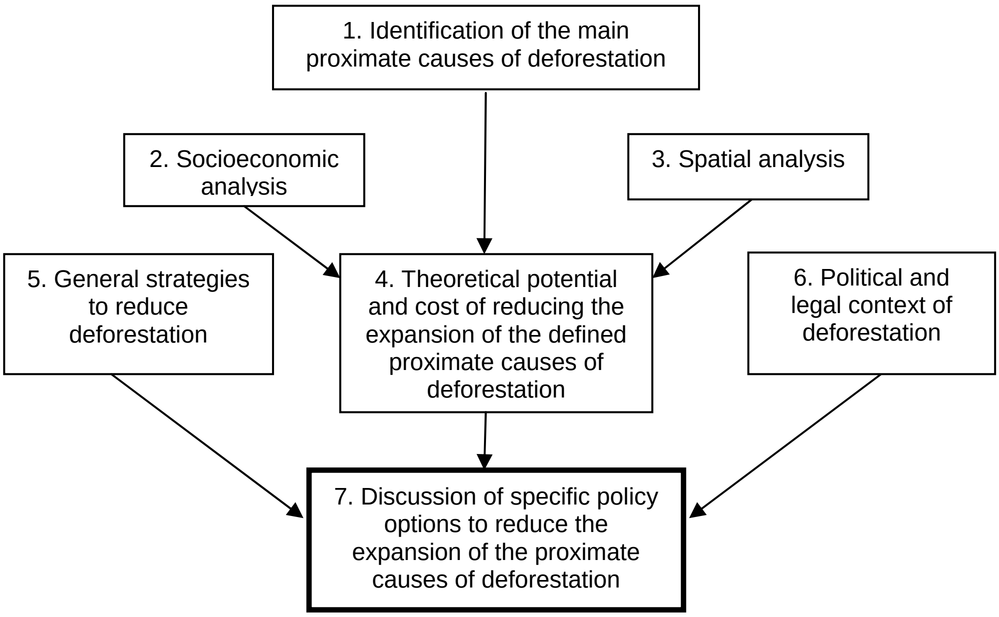


Figure 4.1 Schematic approach for assessing and prioritizing measures aiming at reducing deforestation. Source: Authors.

The different seven steps of the procedure shown in Figure 4.1 are carried out as follows:

Step 1: For the identification of the main proximate causes of deforestation, we modify the categories of Geist and Lambin (2002) and define three categories based on prevalent land use practices that are also characterized by typical agents and their motivations: mechanized agriculture, small-scale agriculture and cattle ranching. These categories currently apply to most contexts of tropical deforestation in Latin America (Kirby et al. 2006; Pacheco et al. 2011). These generalized land use categories are by far the most important proximate causes for forest conversion in Bolivia (Müller et al. in press). Other activities, such as logging or mining, are regarded as much less relevant due to their low impact on forest conversion for the research area (see Killeen et al. 2008). Where mixed systems exist, these are assigned to one of the three proximate causes, for example, traditional small-scale agricultural systems which also include a few cattle are included under small-scale agriculture. In the Brazilian Amazon, pasture is often converted into soybean plantations (Nepstad et al. 2006); in this case, it would be difficult to attribute deforestation to a single agent. But in Bolivia, the conversion of pasture to plantations is currently not common.

Step 2: The socioeconomic analysis of the three proximate causes of deforestation describes and helps to understand the processes behind the expansion of the defined land uses. By reviewing literature and agricultural statistics (CAO 2008; INE 2008), we analyze agents, locations, main products and production systems as well as relevant agricultural and beef markets, with a special focus on assessing the socioeconomic drivers and motivations of agents to invest into the different land uses (Pacheco 1998; Pacheco and Mertens 2004; Pacheco 2006a,b). This analysis is completed with findings from previous fieldwork conducted by the authors during many years in lowland Bolivia.

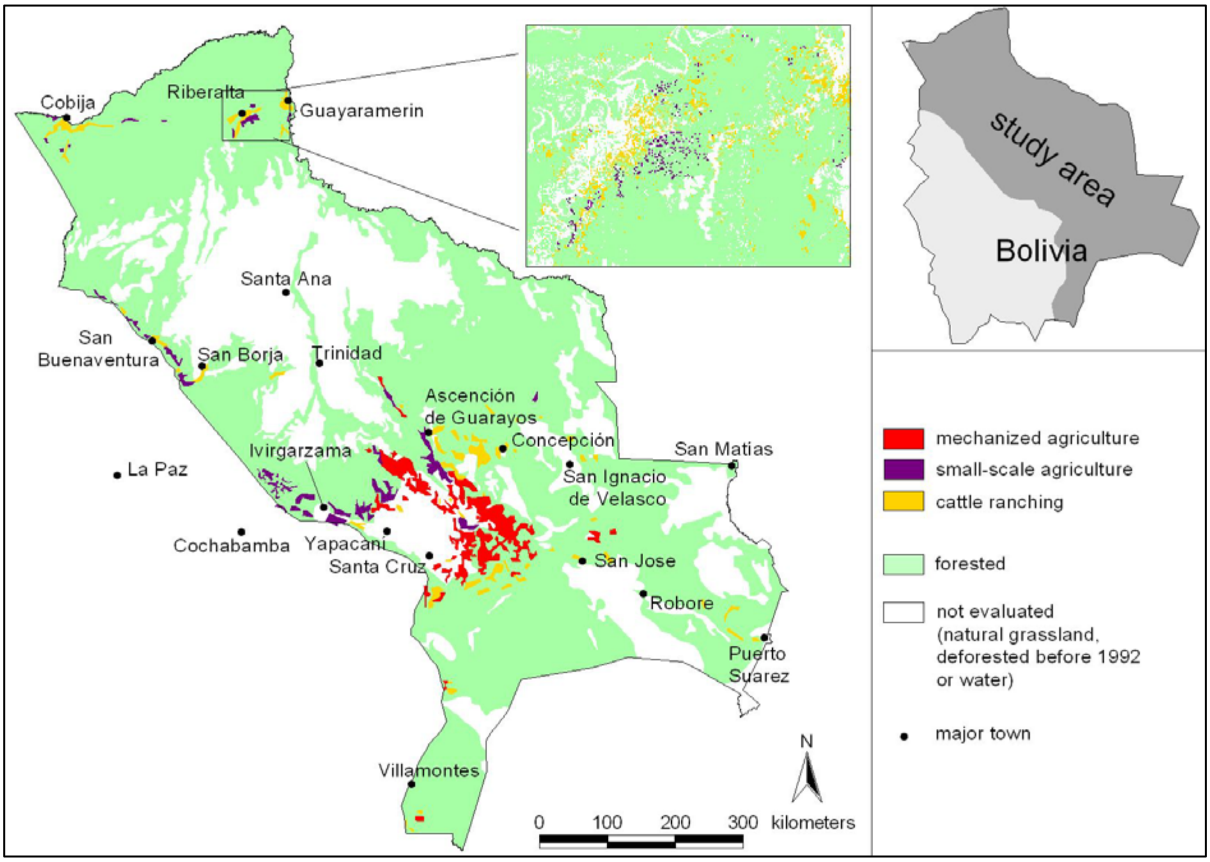


Figure 4.2 Land use change 1992-2004 in the Bolivian lowlands. (Based on Figure 3.3).

Step 3: The spatial analysis heavily draws on Chapter 3. This analysis consists of the following: 1) mapping and localizing the expansion of the three proximate causes of deforestation; 2) quantifying their impact in the past, and 3) estimating the dynamics of expansion by evaluating spatial drivers with a logistic regression model.

The map of land use change from 1992 to 2004 (Figure 4.2) has a pixel resolution of 500 m. Existing classifications (Killeen et al. 2007; Museo Noel Kempff and Prefectura de Santa Cruz 2008) were adapted to three proximate causes of deforestation (i.e., mechanized agriculture, small-scale agriculture, and cattle ranching). This information was further improved with data from land registers from the state land agency (*Instituto Nacional de Reforma Agraria* INRA) (Pacheco 2006b) and a visual interpretation of the panchromatic channel of the CBERS satellite with a pixel resolution of 2.5 m. The resulting map identifies the quantity and location of forest loss resulting from the three proximate causes. We estimate the total area covered by each of the land use types in 2004, based on a combination of agricultural statistics (CAO 2008; Pacheco 2006b; Museo Noel Kempff and Prefectura de Santa Cruz 2008).

For the assessment of spatial drivers, we refer to the results of a spatially explicit, multinomial logit model of forest conversion caused by each of the three proximate causes of deforestation (see Chapter Three), similar to the study of Chomitz and Gray (1996). Independent variables of the model are excessive rainfall, drought risk, fertile soils, poor soils, transportation costs to domestic and export markets, protected areas including areas of integrated management (*Área Natural de Manejo Integrado*, ANMI), forest concessions, and TCOs. Main outputs of the model are standardized logit coefficients which indicate both direction and strength of the effects of each independent variable on forest conversion and allow for evaluating the relative influence of each independent variable (see Chapter Two).

Step 4: We also assess the theoretical potential and cost of deforestation reduction. In theory, when the potential of deforestation is high, there is also a high potential of deforestation avoidance. We analyze different potentials of land use expansion for each of the three proximate causes of deforestation. First, the empirical potential of expansion is assessed by quantifying forest conversion in the past as an indicator for future expansion potential, based on the map of land use change (Figure 4.2). Second, a spatially explicit potential of expansion is analyzed by using maps of deforestation propensity based on a multinomial logit regression (see Müller et al., in press). Third, the market potential of land use expansion is estimated using economic statistics (e.g., CADEX 2008; CAO 2008)[7]. The theoretical cost of reducing deforestation for each of the three proximate causes is estimated by calculating the approximate opportunity costs of forest conservation and by appraising the possibilities of increasing the spatial efficiency of production. The calculation of opportunity costs is based on agricultural statistics for the department of Santa Cruz (CAO 2008) which are likely to be representative for the entire Bolivian lowlands[8]. Opportunity costs are expressed as net present values (NPVs) per hectare, derived from the cost of the initial establishment of fields or pastures, annual production cost and annual revenues from selling crops or beef. Average values from the last 10 years were applied. NPVs are calculated over a period of 30 years, using an 8% discount rate as an average value applied in comparable studies (e.g., Davies 1996; Merry et al. 2002). Accordingly, NPVs per hectare were also approximated for selective logging (based on Superintendencia Forestal 2003) and, in a rough estimate, for Brazil nut extraction (based on Bojanic 2001). Possibilities of increasing the spatial production efficiency were estimated by analyzing information on yields and production systems, based on a review of literature and agricultural statistics (CAO 2008).

Step 5: We then apply a definition of four non-exclusive general strategies to reduce deforestation**,** as a basis for the subsequent identification of policy options to reduce deforestation: 1) restricting the expansion of land use activities with likely impacts on forest conversion; 2) increasing the spatial

---

[7] Due to the high uncertainties no projections of agricultural markets were made.

[8] Detailed agricultural statistics are only available from CAO (2008) for the department of Santa Cruz which comprises the largest share of deforestation in Bolivia and includes large extensions of all three proximate causes.

efficiency of existing land uses; 3) replacing existing land uses by alternative land uses with lower impact on forests, and 4) using degraded or/and non-forested lands for agricultural land use expansion as a way to reduce the pressure on remaining primary forests.

Step 6: We account for the current *legal and political context* of land use change in Bolivia as described in Section 4.2.

Step 7: finally, based on the integration of all foregoing steps, we identify and discuss concrete *policy options to reduce deforestation*. For this discussion, we refer to a variety of sources of which UNFCCC (2006) and Angelsen (2009) are particularly important since they include general lists of possible measures.

4.4 Results

4.4.1 Socioeconomic analysis

This section describes the main socioeconomic aspects of the three main land use trends taking place in lowland Bolivia, specifically mechanized agriculture, small-scale agriculture, and cattle ranching. Table 4.1 below summarizes the most important characteristics of these three proximate causes of deforestation.

Mechanized agriculture is characterized by capital intensive, mechanized production of commodity crops in medium and large-sized plantations and constitutes one of the main causes of deforestation in lowland Bolivia (Killeen et al. 2008; Pacheco 2006a; Pacheco and Mertens 2004). It plays an important role in the national economy, contributing to about 12% of Bolivian exports (CAO 2008) and creating an estimated 150,000 jobs, both directly and indirectly (oil seed farmers association ANAPO, personal communication). This sector’s activities are mostly located on the fertile alluvial soils to the north and east of Santa Cruz de la Sierra (Figure 4.2). Main production concentrates on soybeans, often in rotation with sunflower and wheat, as well as sugarcane and rice (CAO 2008). Soybean production began to expand in the late 1980s and is currently by far the most important crop, mainly targeting export markets. Soybean producers include, among others, Mennonites and Brazilians. Also some colonists in the north of Santa Cruz are increasingly producing soybeans by adopting mechanized agriculture. Sugarcane production is concentrated in the north of Santa Cruz, mainly to supply the national market (CADEX 2008). Around 75% of the production takes place on landholdings larger than 50 ha (OTAI 2008). Finally, rice is mainly produced in the more humid areas in the northern part of Santa Cruz, almost exclusively for the national market (CADEX 2008). Subsidies for diesel fuel contribute to an increase in the profitability of mechanized agriculture in Bolivia.

Small-scale agriculture is conducted using traditional (manual) cultivation methods in small units dedicated to the production of crops and livestock. In the lowlands of Bolivia an estimated 400,000 people depend on small-scale agriculture (Pacheco 2005; discounting farmers in the Yungas above 500 meters above sea level). Small-scale landholders typically depend on local markets, and often pursue both subsistence and cash income objectives. In Bolivia, small-scale agriculture comprises several forms of relatively low intensive production under diversified systems including annual crops (e.g., rice, maize, manioc) and some perennials including banana, cacao, coffee, and coca, in some cases combined with livestock activities. Only a small portion of producers, often those producing perennial crops, are linked to external markets mainly as a result of government policies seeking to substitute coca plantations (Barrientos 2005). Most smallholders are colonists originating from the Bolivian highlands. While the first settlers often benefited from governmental programs between the 1960s and early 1980s, a larger portion settled spontaneously given the availability of land – allocated by the state – and expansion of road infrastructure (Pacheco 1998). During the 1980s, after the collapse of the state's tin mining industry, many former miners migrated to the Chapare region which in part stimulated the growth of coca production. Since then, immigration flows of smallholders placed additional pressure in the forestlands at the northern Andean piedmont (Figure 4.2).

Table 4.1 Basic facts on the main proximate causes of deforestation in the Bolivian lowlands. Source: Authors.

	Mechanized agriculture	Small-scale agriculture	Cattle ranching
Main agents	Foreign and national corporations (including Brazilians and Mennonites)	Smallholders mostly originating from the highlands (often known as colonists), few lowland-indigenous groups	Medium- and large-scale landholders, with some involvement of Brazilian capital
Location	North and east of the city of Santa Cruz	Northern Andean piedmont and northern Santa Cruz	Distributed in most lowland areas, mainly Chiquitania and Amazonian north
Main products	Soybean, sugarcane, sunflower, rice	Rice, maize, banana, some beef and dairy	Beef, some dairy products
Production systems	Highly mechanized and capital-intensive large-scale production units	Traditional systems of manual and shifting cultivation	Different systems, mainly extensive and low productive range fattening, property sizes range from small to large
Markets	Predominantly Andean countries (mainly Colombia and Venezuela) and national markets	Subsistence, local and national markets, very little connection to export markets	Local and national markets, very little connection to export markets

Cattle ranching mainly serves the increasing domestic demand for beef and leads to the replacement of forests by pastures. Though cattle in Bolivia are also raised on natural vegetation, e.g., in the Beni savannahs, this paper refers only to non-natural pastures, carrying an estimated 50% of the Bolivian cattle herd (own estimate based on CAO 2008). Mostly, semi-intensive range fattening on medium- and large-scale units is practiced, mainly around Santa Cruz, in the Amazonian north and in the Chiquitania (Figure 4.2). The largest share of deforestation for cattle is caused by large-scale ranches (see Chapter Three). Most large cattle ranchers are traditionally wealthy families which have access to extensive land areas, though some Brazilian capital also plays an important role, especially in areas near the border (see Killeen et al. 2008).

For most agents, cattle are the preferred and most accessible asset to invest in, but cultural aspects (e.g., social status) can also constitute an important factor. Export plays only a marginal role, for example in 2008, only one company exported beef (CADEX 2008). One reason for this is that the country has not been declared as free from the mouth and food disease, another reason is the low competitiveness of the Bolivian beef production due to low production efficiency (Merry et al. 2002).

4.4.2 Spatial analysis

Mechanized agriculture is concentrated in the surroundings of Santa Cruz; small-scale agriculture is mainly found in the northern Andean piedmont and cattle ranching virtually everywhere, mostly concentrated in the Amazonian north and the Chiquitania (Figure 4.2). Between 1992 and 2004, mechanized agriculture had the largest share of deforestation, followed by cattle ranching and small-scale agriculture[9] (Table 4.2). It is also worth noting that the contribution of small-scale agriculture to greenhouse gas emissions from land use change is probably much lower than the contribution of 19% to deforestation as indicated in Table 4.2, since less biomass is removed from converted areas in comparison to mechanized agriculture and cattle ranching (Müller 2011).

Table 4.2 Three proximate causes of deforestation– estimated total extension and contribution to deforestation. Source: Authors and Chapter Three, based on Killeen et al. (2007).

	Total area occupied (rough estimates)	Area deforested 1992 - 2004	% of deforested area
Mechanized agriculture	900,000 ha under cultivation 200,000 ha as fallow	1 million ha	54
Small-scale agriculture	120,000 ha under cultivation 250,000 ha as fallow / early regeneration[a]	350,000 ha	19
Cattle ranching on artificial pastures	1 million ha	500,000 ha	27
Total	2.47 million ha	1.85 million ha	100

[a] We estimated the area under fallow and young secondary forests as twice as large as the area currently under cultivation, based on CAO (2008) and practices of shifting cultivation.

When evaluating the total area occupied by each of the three proximate causes of deforestation (i.e., not only the area deforested between 1992 and 2004), it is found that mechanized agriculture and cattle ranching have similar extents. Most areas that were deforested before 1992 are currently being used for cattle ranching.

An analysis of logit coefficients of the multinomial logit model (Chapter Three) reveals that spatial patterns of the expansion of mechanized agriculture can mainly be explained by access to export markets and favorable environmental conditions such as fertile soil, intermediate rainfall and gentle slopes. The adherence to land use restrictions is relatively high and there is virtually no overlap with protected areas. Small-scale agriculture mainly responds to access to local markets, humid climatic conditions and favorable soil. The adherence to land use restrictions is low, and deforestation within restricted areas is common. Cattle ranching is characterized by indifference to environmental

---

[9] Killeen et al. (2008) find a much higher share of deforestation due to small-scale agriculture (about 30% between 1992 and 2004), mainly because they allocate deforestation in north eastern Bolivia to lowland indigenous communities, whereas we attribute it to cattle ranchers.

conditions, its expansion is mainly driven by the proximity to local markets. The compliance to land use restrictions is only slightly higher than in the case of small-scale agriculture.

4.4.3 Theoretical potential and cost of deforestation reduction

As mentioned in Section 3, we define the theoretical potential of deforestation reduction as equivalent to the potential of expansion of each of the proximate causes. The empirical potential of future expansion, solely based on expansion in the past, is highest for mechanized agriculture, followed by cattle ranching and small-scale agriculture (see Table 4.2).

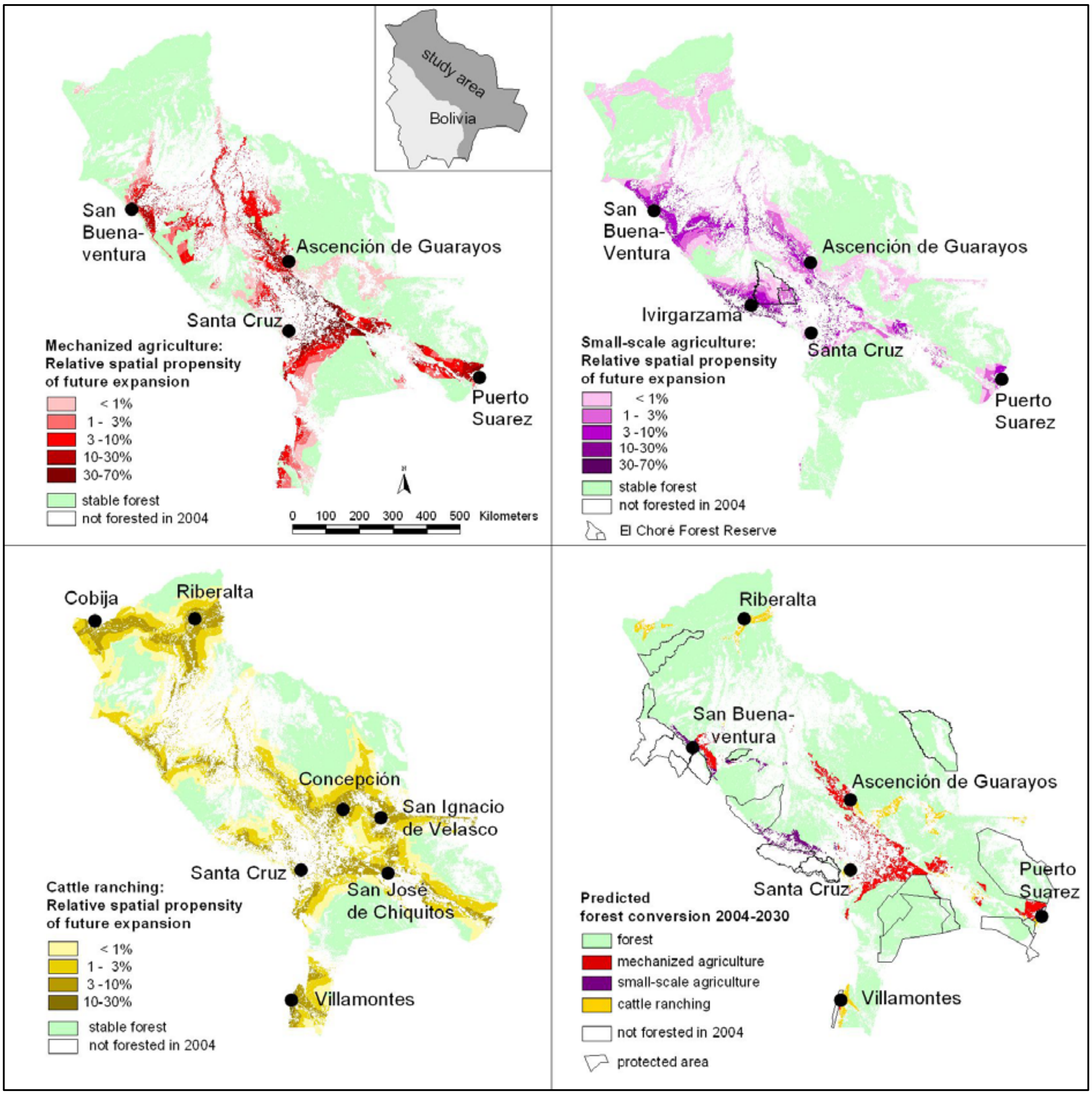


Figure 4.3 Spatial potential of the expansion of the three proximate causes of deforestation. Source: Slightly modified from Figure 3.6.

The maps of the spatially explicit expansion potential (Figure 4.3) show that mechanized agriculture will most likely expand to areas adjacent to its current extension, especially to the north along the highway from Santa Cruz to Trinidad (see also Chapter Two). Further expansion seems possible to the area near Puerto Suarez or near San Buenaventura. In the latter area, the government plans to establish a sugar mill (Malky and Ledezma 2010). Small-scale agriculture is likely to expand further at the northern foothills of the Andes while cattle ranching might expand at any accessible place in the low lands, thus depending mainly on road expansion.

The market potential of mechanized agriculture for further expansion is assumed to be high since products are mainly oriented to export markets (e.g., 70% of soybean production) and global demand tends to grow. Yet, in Bolivia there is a high dependence on preferential markets (i.e., Andean Community of Nations, CAN) which may also have influence on future expansion. For small-scale agriculture, the market potential seems to be moderate because products are mostly produced for subsistence and national markets; as the demographic development shows significant population increases in most relevant areas, subsistence-driven, small-scale agriculture is likely to expand accordingly (INE 2009). Cattle ranching currently covers the national demand, limiting the market potential for further expansion. However, if Bolivia will be declared officially free from the mouth and food disease, this situation might change.

When opportunity costs are scrutinized (Table 4.3), mechanized agriculture is by far the most profitable agricultural land use, and small-scale agriculture seems to be slightly more profitable than cattle ranching[10]. The complementary evaluation of selective logging shows values comparable to cattle ranching. For the extraction of Brazil nuts – which was not evaluated in detail – we estimate a value around 10 US$/ha (based on Bojanic 2001). We estimate that removal of subsidies for diesel would increase production costs for mechanized agriculture by approximately 25% and halve the NPVs. Particularly the implementation of new plantations could become less profitable without subsidies to diesel, because the removal of the original vegetation requires more heavy machinery.

Table 4.3 Average calculated NPVs for different land uses in the department of Santa Cruz (30 years, 8% discount rate). Source: Authors' evaluation of data from CAO (2008) and Superintendencia Forestal (2003).

	Details	Average calculated NPVs
Mechanized agriculture	Soybean (summer) + sunflower (winter)	2,244 US$/ha
	Soybean (summer + winter)	1,956 US$/ha
	Rice (mechanized cultivation)	1,372 US$/ha
	Sugarcane	1,176 US$/ha
Small-scale agriculture	Rice + Maize (manual)	541 US$/ha
Cattle ranching on artificial pastures	Cattle (surroundings of Santa Cruz)	270 US$/ha
	Cattle (Chiquitania)	43 US$/ha
Selective logging	Different regions in the department of Santa Cruz	182-388 US$/ha

---

[10] In the case of small-scale agriculture, perennial products were not evaluated due to the lack of adequate data. Barrientos (2005) finds however that gains and losses of banana production of most farmers in the Chapare region are almost the same over the years, resulting in an NPV of close to zero.

Possibilities of increasing the spatial production efficiency seem to be quite different for the three proximate causes. For mechanized agriculture, the productivity expressed in yield per hectare is fairly high in Bolivia, although soybean yields in Brazil are higher than in Bolivia (2.6 TM/ha in comparison to 2.0 TM/ha from 2000-2006, CONAB, 2009; CAO, 2008). This is mainly due to the use of fertilizers, which are sparsely applied in Bolivia because of the high cost (association of oil seed farmers ANAPO, personal communication). The current production efficiency of small-scale agriculture is low; e.g., rice yields are typically around 2 TM/ha, clearly below the yields achieved by industrial agriculture (3-3.5 TM/ha, CAO, 2008). However, improvements would require a fundamental change in the production system; efforts to increase the returns from small-scale agriculture have had little success in the past (Eyzaguirre 2005). For cattle ranching, no accurate numbers on stocking densities were available, but an evaluation of different unofficial sources shows that animal units per hectare range from 0.5 to 2 on forest-replacing pastures. A comparison of the number of cattle and the total grazing area in the Amazonian north (department of Pando) shows that the average stocking density is only around 0.5 animals per hectare. This already implies a high potential to improve spatial efficiency, especially since it was shown in Brazil that stocking densities of two animals per hectare can be achieved through adequate management (Walker et al. 2009).

4.5 Discussion of policy options to reduce deforestation

Before we discuss specific policy options, we assess which one of the three proximate causes of deforestation offers the best opportunities for effective and efficient deforestation reduction (see also Table 4.4). Mechanized agriculture constitutes a large threat to forests, but it is concentrated on suitable areas where high opportunity costs limit the possibilities of containing its expansion, making it difficult to achieve efficient deforestation reduction without negative economic impacts. Small-scale agriculture threatens forests in a minor degree. Though its current spatial efficiency is low, it seems difficult to increase, mainly due to coordination difficulties because of the large number of farmers involved. Therefore, for small-scale agriculture, deforestation reduction is probably efficient in theory, but less effective in practice.

Table 4.4 Summary of theoretical potential and cost of deforestation reduction. Source: Authors.

	Mechanized agriculture	Small-scale agriculture	Cattle ranching
Empirical potential of expansion based on expansion in the past	high	low	moderate
Spatially explicit potential of expansion based on landscape factors	limited to certain suitable areas	limited	possible in most parts of the lowlands
Market-based potential of expansion	high	low to moderate	low to moderate
Opportunity costs of forest maintenance	high	low	low
Potential of increasing the spatial efficiency of production	low	moderate	high

The pressure of cattle ranching on forests is moderate in comparison to mechanized agriculture, but it threatens all accessible forests. The theoretical costs of reducing the expansion of cattle ranching are comparably low, especially if measures can be taken to successfully increase the spatial efficiency without decreasing profitability. It is likely that a reduction of the observed current expansion of cattle ranching should be easier to achieve when compared with the other land use categories. Consequently, targeting cattle ranching could allow for the most effective and efficient deforestation reduction - but deforestation due to the other proximate causes should be targeted simultaneously.

4.5.1 Policy options with applicability to all proximate causes of deforestation

Change or enforcement of land use policies

As mentioned earlier, a significant portion of deforestation in Bolivia has taken place without complying with the legal requirements. Clarifying access and property rights to land and forests, and strengthening the capacity of the national agency in charge of forest control (*Autoridad de Fiscalización y Control Social de Bosques y Tierras*, ABT) should be among the priorities for deforestation reduction, along with developing a more efficient system of land use change monitoring, which could also involve greater collaboration and capacity building at the departmental and municipal level, accompanied by a more active role of local social organizations. Furthermore, the actions of the ABT need to be backed up by increasing the effectiveness of the judiciary system regarding the pursuance of environmental crimes[11], which also includes the need of higher legal fees for deforestation – currently just 15 US$ per hectare (Instructivo para demontes IOP – 007/2001) - as well as higher penalties for illegal deforestation. Another issue remaining to be solved is related to the monitoring of FES (as stipulated in the new National State Constitution), which could indirectly promote increased deforestation, but could also be used as an instrument to properly regulate land-use planning.

Establishing new forest protected areas will probably be difficult in Bolivia, due to the existing conflicts and the current portion of land already under protection (Zea O'Phelan et al. 2002). The compliance of small-scale farmers to such restrictions is low, as shown in the results of the spatial analysis. At the same time, existing protected areas are mostly located where the agricultural potential is low (see Figure 4.3, also Müller 2011).

Particularly for smallholders, the consolidation of land tenure is considered important for deforestation reduction (e.g., McGrath et al. 2010). A positive example may be the fact that properties of 500 ha per family are granted to communities in the northern Bolivian Amazon that live from the extraction of Brazil nuts (Duchelle et al. 2002). Large indigenous territories (TCOs) are located within primary forests with comparably low deforestation pressure; they might be important to guarantee the long term conservation of these forests, provided that pressure from other agents, including small-scale farmers, can be controlled. In the current conflict on the planned highway through the national park and TCO Isiboro Sécure (Territorio Indígena y Parque Nacional Isiboro Sécure, TIPNIS), the protests of the lowland indigenous peoples owning the TCO were able to stop the project (BBC News, 2011). This example also shows the importance of questioning large infrastructure projects under the aspect of possible impacts on deforestation.

---

[11] Recently, such measures have been initiated but it is still to early to evaluate their impact.

Positive economic incentives for reducing deforestation

When discussing general possibilities of reducing deforestation, it is a common approach to consider payments to local agents in order to offset their opportunity costs from forest-competing land uses (e.g., Silva Chavez 2005). Such local schemes of payments for environmental services (PES) require certain institutional preconditions to be in place (Boerner et al. 2010b), many of which are currently missing in Bolivia (Pokorny et al., in press). Particularly in frontier landscapes, land rights are disputed and governance is weak (compare Wunder 2006, for the case of Brazil). If land owners under a PES scheme (especially large-scale landholders) received a compensation for simply holding land, that would bear potential for social conflicts since it contradicts the usufruct philosophy of land tenure that requires to justify land ownership by "making use" of it (Skutsch et al. 2007). Moreover, it seems highly unlikely that payments could be recovered from land owners if it turns out that they have not complied with PES agreements on the long term.

For a sustainable reduction of deforestation, unsustainable production systems would need to be changed towards more environmentally friendly practices (McGrath et al. 2010) and positive incentives should support more sustainable production. In the state of Acre in the Brazilian Amazon, for example, this concept is reflected in the guidelines for PES schemes which define "incentives for environmental services" with the purpose of increasing sustainable production in forests, on degraded land and within existing production units; there is also a planned program for certification of sustainable smallholder farms (Acre Government 2010). Certification allows for providing incentives through premium prices for products and thereby supporting sustainable production. In this sense, Trines et al. (2006) suggest to combine ecological certification, such as the Forest Stewardship Council (FSC), with additional economic incentives derived from the carbon value of reduced deforestation. Such incentives could also be used to support sustainable agriculture and cattle production (see concept of "Alianza da Terra" in Brazil[12] or Nepstad et al. 2006).

4.5.2 Specific measures for each of the proximate causes of deforestation

In the following, potential policy options are discussed for each of the three proximate causes of deforestation, following the framework of the four pre-defined strategies of deforestation reduction introduced in Section 3. We also discuss specific policy options for areas particularly threatened by each of the proximate causes. A summary is provided in Table 4.5.

Mechanized agriculture

When discussing possible restrictions of mechanized agriculture development, it must be recognized that it is a highly profitable activity and contributes significantly to the Bolivian economy. However, if current subsidies for diesel and environmental externalities (e.g., losses of carbon stock) are taken into account, further expansion into forested areas is probably not justified from a national economic point of view. As this does not necessarily hold true from the point of view of the deforesting agents, regulatory instruments, such as restrictions in selected areas or increasing the fee for legal deforestation, appear to be an option[8]. The compliance with environmental legislation might also be controlled through banks that provide financing, a measure which has been implemented in Brazil

---

[12] Alianca da Terra is a Brazilian NGO promoting economic incentives for cattle produced under forest friendly conditions (http://www.aliancadaterra.org.br).

(May et al. 2011). Another measure would be to support an increase of the spatial efficiency by using more fertilizers – which so far are hardly used in Bolivia – as well as improved soil management. Investments aiming at increasing yields on existing plantations would become more attractive if subsidies for diesel were removed and/or fees for deforestation increased, which would raise the costs of establishing new fields. A switch to alternative land uses does not seem to be an option since most alternatives would probably be less profitable than mechanized agriculture.

Table 4.5 Summary of priority measures to reduce deforestation in the Bolivian lowlands. Source: Authors.

	Mechanized agriculture	Small Scale Agriculture	Cattle Ranching
Suitable policy options for deforestation reduction	- Restriction to selected suitable areas - Enforcement of land use legislation (higher fees) - Reassessment of projects to create new agro-industrial zones - Recovery of degraded soils near Santa Cruz - Cut of subsidies for diesel	- Enforcement of existing land use restrictions - Incentives for a change towards sustainable production - Foster non-agricultural employment	- Enforcement of land use legislation - Improve spatial efficiency
Priority areas	North of Santa Cruz, San Buenaventura, Puerto Suarez	Reserva Forestal El Choré, north of La Paz, possibly Amazonian north	Chiquitania, Amazonian north

Furthermore, there may be a possibility of recovering degraded lands near the city of Santa Cruz that were intensively used for cotton and sugarcane production in the past decades and are now being used for extensive cattle production systems. The proximity of such areas to road and energy networks could justify investments required to recover their productivity. Positive incentives could possibly stimulate such activities, especially if coupled with technical support. Since mechanized agriculture mainly serves the global market, incentives would ideally be provided through premium prices within the framework of an international certification scheme for products cultivated on degraded land or long-established plantations. There is also an increasing mechanized production of rice within wet savannahs, for example around Trinidad, which may be able to lower the pressure on forests, but environmental impacts would need to be assessed in detail.

Policy options applicable to the areas highly threatened by mechanized agriculture include possible limitations of the expansion of mechanized agriculture in parts of these areas. One approach is to adapt existing land use plans to reality and to begin to enforce them. For example, according to the departmental Land Use Plan of Santa Cruz (Prefectura de Santa Cruz – Consorcio IP/CES/KWC 1996), the area north of Santa Cruz, where mechanized agriculture is currently expanding to, is not suitable for such land use activities due to flood risk. But the obvious profitability of established mechanized agriculture in many parts of this zone inspires doubts about the accuracy of the assessment of land suitability. A more accurate delineation of suitability for agriculture could be combined with support for mechanized agriculture in highly suitable areas and restrictions elsewhere[13]. In order to prevent the conversion of areas identified as possible new hotspots of agricultural expansion (Puerto Suarez and San Buenaventura), it might be possible to restrict mechanized agriculture by increasing fees for deforestation or denying access to subsidized diesel and financing by banks.

Small-scale agriculture

Since the rural population in the lowlands largely depends on small-scale agriculture to support their livelihoods, a simple restriction of this kind of agricultural expansion seems to be unrealistic. This is even harder to achieve due to persistent pressures of migrants from the Bolivian highlands and landless people to occupy lands. Nonetheless, there is a need to better regulate land tenure in already occupied lands and to redirect new settlements to public lands suitable for agriculture or to expropriated, non-productive landholdings. Furthermore, enforcement of existing legislation is necessary in order to avoid the encroachment of smallholders into forestlands already devoted to conservation, under restricted land uses, or belonging to lowland indigenous peoples (TCOs). Community-based and socially-controlled zoning of individual farms appears to be an option to control deforestation by fostering more sustainable land use. Typical properties of colonists include 50 ha; zoning of these farms has been proposed by smallholder leaders and might work if the concept is appropriated by farmers and implemented and controlled at the level of communities[14]. Indirect measures, such as policies aiming at expanding urban-based employment, could also decrease population pressure along the agricultural frontiers, though immigrants settling in these areas often lack the necessary skills to be absorbed in more specialized sectors.

There is a significant potential for increasing the spatial efficiency of small-scale agriculture, although changing the traditional production systems is a challenge, particularly considering the lack of access to financial capital and markets. There are several NGO initiatives attempting to enhance the productivity of annual crops, for example the irrigation of rice fields with the potential of duplicating current yields (Eyzaguirre 2005). Any support for the intensification of agriculture should be combined with efforts to promote the conservation of remaining forestlands in order to protect the provision of local environmental services. A switch to alternative land uses is a promising option if perennial crops are adopted (i.e., banana, cocoa, or copoazú), but these crops also face more complex marketing systems and are generally more difficult to store. Alternative agricultural crops have been promoted extensively to replace the space-efficient coca plantations, but do not always show the expected success. The potential of community forestry to reduce agricultural pressures on forests is probably low, but forestry-based activities can generate additional income and replace a part of the traditional agriculture. The same is true for the sustainable use of non-timber forest products (NTFPs) or ecotourism as an alternative source of income for settlers not originating from low land forests (Eyzaguirre 2005). Recovery of degraded land is not a priority since the traditional system applied by small-scale farmers leaves large areas of secondary forest and little degraded land.

Two forest landscapes with a particularly high threat of expansion of small-scale agriculture include areas north of the La Paz department (around San Buenaventura) and the Forest Reserve “El Choré” in

---

[13] In Brazil, the soybean moratorium in the Amazon declared in 2006 apparently led to a reduction of deforestation (Butler 2009)

[14] In the area of Yapacaní, the campesino leader Cimar Victoria suggested a zonification defining cultivation areas of annual products, perennial products and forest. This concept is not being officially employed but seems to encounter good acceptance amongst smallholders of the zone.

north of Santa Cruz (see Figure 4.3). In the first case, the promotion of agroforestry systems (with cacao cultivation) could probably help stabilize the forest frontier (Malky and Espinoza 2010). Important lessons can be learned from the cacao cooperative “El Ceibo” in northern La Paz (Robertson and Wunder 2005). The case of “El Choré” is relatively complex since it formally constitutes a forest reserve. Approximately 200,000 ha from the original 1,000,000 ha reserve were abrogated in 2000, due to the factual occupation by smallholders originating from the Bolivian highlands (Pinto 2006). At present, smallholder encroachment in the remaining reserve leads to exponentially increasing deforestation (Müller 2009). Though the current situation of infrastructure does not allow for profitable agriculture, there are probably expectations of a future legalization of the occupied lands; a better enforcement of the current legislation would be needed in combination with support for more efficient production outside the reserve (e.g., by paddy rice) (Müller 2009). The aforementioned community-based policies on zoning of individual 50 ha farms could be a framework for implementing such measures.

Cattle ranching

Restriction of the expansion of cattle ranching within forests seems feasible through better enforcement of land use legislation, since much of the current deforestation takes place illegally on unsuitable forest lands; particularly large illegal clearings should be avoidable by consequent application of existing laws. A portion of clearings may also be avoided by clarifying the need of landholders to justify their land ownership by showing a FES. There is potential for increasing the spatial efficiency on existing pastures, for example, by increasing the stocking densities and promoting the introduction of better practices of pasture management, i.e., through a wider adoption of rotational pasture techniques as generally practiced in the Brazilian Amazon (da Veiga et al. 2004) or improving cattle herd management by enhancing artificial insemination.

However, a support of increased production efficiency needs to be combined with efforts to improve legal enforcement and higher fees for deforestation, in order to minimize the risk of an increased profitability leading to higher expansion of cattle ranching (see Kaimowitz and Angelsen 2008). Furthermore, most beef production currently supplies a relatively stable domestic demand and seems unlikely to expand to export markets. Alternative land uses such as selective logging can theoretically compete with cattle ranching in terms of profitability, as shown in the analysis of opportunity costs. This should be the case especially in the Amazonian north, where timber volumes of single trees are large. Currently, there is uncertainty about the development of the legal framework for forestry in Bolivia; however, it will be important to provide favorable conditions for sustainable forestry in the future in order to maintain competitiveness against cattle ranching in forest areas. Over time it will also be important to support more integrated systems of production, that embrace silvicultural and forestry activities alike, as a way for ranchers to diversify their sources of income. The recovery of degraded land in order to raise cattle does not seem to offer a large potential of reducing the expansion of cattle ranching. Particularly around Santa Cruz, cattle are already replacing soybeans and sugarcane on many degraded soils. Nevertheless, improving cattle production on degraded pastures and particularly on natural grasslands is an important measure to improve efficiency.

A highly threatened area is the Amazonian north, where cattle ranching is by far the most common cause of deforestation (see also Pacheco et al. 2009). More than 50% of cattle are owned by some 20 families (own evaluation based on data of the animal health service, SENASAG). In the past, large illegal clearings occurred, but were not pursued due to the weak controlling institutions. Recently, because of greater enforcement, cattle ranchers have had to pay accumulated penalties retroactively for illegal clearings since 1996, when the forest law was renewed, but it is uncertain if and how enforcement will be maintained in the future. Since few agents are responsible for a high percentage of clearings, legal enforcement has a large potential and should be highly effective. The currently low stocking density (approx. 0.5 animals per hectare in the Amazonian north) could theoretically be multiplied by increasing production efficiency. The situation in the region of Chiquitania is comparable.

4.6 Conclusions

Based on a systematic approach of assessing driving factors, agents and processes of deforestation, and associated policy options, we argue that there is significant potential for reducing deforestation in lowland Bolivia without causing significant negative impacts on economic welfare. Cattle ranching offers the best opportunities for effective and efficient deforestation reduction. The enforcement of existing legislation could particularly prevent large illegal clearings caused by a relatively small number of cattle ranchers. Currently, the overall efficiency of cattle production is low in Bolivia. Therefore, the promotion of increased spatial efficiency, for example through extended grazing rotation and genetic improvement, could help keep beef production at stable levels. Action is mainly required in Amazonian north (departments of Pando and north of Beni) and in the region of Chiquitania.

The high profitability of mechanized agriculture, which is responsible for approximately half of deforestation in Bolivia, makes it difficult to reduce its expansion. Yet, increasing legal fees for deforestation and abolishing diesel subsidies could reduce the profitability of new plantations significantly. In addition, important gains in deforestation reduction could be achieved through improving existing land use plans, and supporting agricultural commodities' production in selected suitable zones, but restricting it in the most environmentally vulnerable areas. The possible expansion of agro-industrial production into new zones with intact forest cover, particularly in San Buena Ventura and near Puerto Suarez, could be put on hold and re-assessed under the inclusion of environmental costs. Furthermore, technical support and incentives could be provided to improve production on degraded soils near Santa Cruz.

Tackling the expansion of small-scale agriculture would mainly require improved governance. In the mid-term, such measures should aim at creating sustainable and more land-efficient forms of production, for example, by supporting perennial crops or promoting paddy rice. Policies aiming at increased off-farm employment might also lower the pressure on forests. We find that the potential of reducing deforestation due to small-scale agriculture is relatively low, mainly due to the high number of farmers involved who are difficult to reach by legal measures. Furthermore, small-scale agriculture contributes much less to total deforestation than mechanized agriculture and cattle ranching.

Our analysis shows that measures to reduce deforestation should primarily target those land uses and agents responsible for the largest share of deforestation. On the global level, there may be a lack of strategies to tackle deforestation caused by cash crop cultivation and large-scale cattle ranching. Existing pilot projects under REDD focus rather on smallholders and indigenous people (see, e.g., an evaluation of pilot REDD projects, Wertz-Kanounnikoff and Kongphan-apirak 2009), although a few initiatives are being implemented in the Brazilian Amazon to reduce the expansion of large-scale plantations and ranching, combined with greater policy enforcement (May et al. 2011).

The Bolivian example suggests that if resources are available for deforestation reduction, within or beyond REDD, these resources should be used primarily to strengthen institutions that control, monitor and enforce existing legislation on land use (see also Boerner et al. 2010a). In combination with such legal enforcement and an increase of legal fees for deforestation, the promotion of higher production efficiency also has considerable potential to reduce deforestation. Economic incentives for local agents will probably be most effective if combined with a stimulus and technical support to promote the transition towards more spatially efficient and sustainable land-use practices.

Last but not least, tropical deforestation must also be tackled within the global economic context: Not only in Bolivia, but also other countries with heavy tropical deforestation such as Brazil and Indonesia, the export of agricultural commodities is a major driver of forests conversion (Grieg-Gran 2008). Therefore, successful deforestation reduction depends strongly on joint efforts on the international level of producers and consumers of products coming from forest clear-cuts.

Chapter 5

Synthesis

Confluence of the Rivers Madera and Orthon (Picture: Juan Carlos Montero)

5 Synthesis

This chapter gives an overview over the main conclusions of the three analyses described in Chapters Two, Three and Four.

The main objective of Chapter Two is the exploration of the logistic regression as a modeling technique in different respects. The expansion of mechanized agriculture around the city of Santa Cruz is particularly suitable for this purpose because mechanized agriculture responds relatively well to different spatial determinants. This allows the formulation of meaningful models, which is then also confirmed in Chapter Three.[15] The models render very plausible results and show high accuracies of calibration. A special focus is put on the identification of possible biases, such as the effects of missing or redundant, i.e., intercorrelated independent variables. Such potential biases are explored in depth with the example of the variable "distance to prior deforestation". This variable tends to show a high explanatory power as an independent variable in many deforestation models, but is found to be particularly sensitive to correlation biases since it is implicitly correlated with all other independent variables. As a consequence, distance to prior deforestation was excluded as an independent variable in the model of the entire lowlands in Chapter Three.

An important application of deforestation models is the projection of future deforestation. This implies a need to deal with the dimension of time. Any extrapolation of present dynamics into the future assumes that these dynamics will continue to be valid. Still in Chapter Two, the stability of deforestation dynamics in time is tested by applying similar models to the expansion of mechanized agriculture in four subsequent time steps between 1976 and 2005. A method is developed to investigate spatiotemporal deforestation dynamics by plotting standardized regression coefficients against time, which allows for empirical and quantitative analyses of the changing impacts of independent variables. It is found that the standardized regression coefficients remain relatively constant, indicating that deforestation dynamics are generally stable in time. In addition, a comparison between projected and observed deforestation is conducted which shows a high coincidence. But a more detailed exploration of temporal dynamics reveals that regression coefficients indicate a decreasing influence of humidity as a limiting factor, reflecting the increasing tendency of mechanized agriculture to penetrate into more humid forests in northern Santa Cruz. Hence, there is at least a slight change in deforestation dynamics, implying that scenarios can be built either on recent or on long-term dynamics: a choice that needs to be taken based on a discussion of the situation on the ground as opposed to calculations. This finding shows that an evaluation of temporal dynamics can be important.

The interpretation of the model outputs in Chapter Two leads to findings that are interesting and plausible, but probably not really surprising, since the recent expansion of mechanized agriculture into humid forests in northern Santa Cruz can also be observed on satellite images. Deforestation models should not be expected to uncover completely unexpected relationships; rather, they constitute a tool for systematic analyses of deforestation dynamics. An interpretation of the modeled deforestation dynamics of mechanized agriculture becomes particularly interesting in a comparison with other land uses – as conducted in Chapter Three.

---

[15] A diploma thesis (Schierhorn 2008) in the context of this study modeled the expansion of cattle ranching in the Chiquitania region; it was found that, apart from accessibility, the independent variables showed only little influence on the location of forest conversion to pasture.

After confidence is gained on the suitability of logistic regression, this modeling approach is applied to explore the whole picture of deforestation in the Bolivian lowlands in Chapter Three. In a multinomial logistic regression model, the expansion of the main forest-depleting land uses between 1992 and 2004 is analyzed. In a previous step, these proximate causes of deforestation have to be mapped, which reveals that mechanized agriculture is responsible for 54% of deforestation between 1992 and 2004, followed by cattle ranching with 27 % and small-scale agriculture with 19%. These results are different from the findings of Killeen et al. (2007) who assign a much higher share of deforestation to smallholders. (The tendency to focus on smallholder deforestation is further discussed in the outlook in Chapter Six). The results suggest that the expansion of mechanized agriculture occurs mainly in response to good access to export markets, fertile soil and intermediate rainfall conditions – just as seen in Chapter Two. Increases in small-scale agriculture are mainly associated with a humid climate, fertile soil and proximity to local markets. Forest conversion into pastures for cattle ranching occurs mostly irrespective of environmental determinants and can mainly be explained by access to local markets. Land use restrictions, such as protected areas, seem to prevent the expansion of mechanized agriculture but have little impact on the expansion of small-scale agriculture and cattle ranching. An analysis of future deforestation trends reveals possible hotspots of future expansion for each proximate cause; it specifically highlights the possible opening of new frontiers for deforestation due to mechanized agriculture in the areas of Puerto Suarez and San Buenaventura. These results are not completely unexpected, but they constitute important ingredients for the systematic development of strategies to mitigate deforestation in Chapter Four. Still in Chapter Three, a qualitative analysis of historical processes is conducted to complement the quantitative insights of the regression model. Therefore, land use traditions in five different parts of the Bolivian lowlands are explored and compared with the modelled dynamics. It is found that the modeling of spatial propensities of deforestation leads to very plausible results, while the timing and quantity of deforestation is highly dependent on historical events that are difficult to model. One such example is the collapse of tin mining in 1985, which caused increases in small-scale agriculture driven by the migration of ex-miners from the highlands. It can be concluded that model outputs, together with a qualitative analysis, can generate a detailed picture of deforestation dynamics that represents a useful basis for practical applications, such as the development of strategies to reduce deforestation.

The development of such strategies is undertaken in Chapter Four, which concentrates on practical ways to achieve effective and efficient deforestation reduction. Concrete policy options are derived specifically for the three proximate causes of deforestation, thus assuming that different deforestation dynamics also require different possible solutions. The results of spatial deforestation modeling represent important inputs for Chapter Four, but a much broader analysis is needed to derive policy options. Therefore, a systematic approach is developed that takes into account many different aspects of deforestation. This systematic approach itself constitutes an important result of the entire study and is also intended to be applicable to other countries where tropical deforestation occurs.

The suggested systematic approach includes the evaluation of the potential and probable costs of reducing the expansion of the three proximate causes. Apart from the spatial potential, which is based on the model outputs of Chapter Three, an economic potential is also assessed based on markets for agricultural products, e.g., taking into account that mechanized agriculture is different from the other proximate causes since its products are mainly exported. As an input for the assessment of possible costs of deforestation reduction, opportunity costs of forest conservation are calculated for different forms of agriculture and cattle ranching. It is found that mechanized agriculture is by far the most profitable land use form on a per-hectare basis, while lower values are obtained for small-scale agriculture and even lower values for cattle ranching. Possible policy options are discussed in the framework of four possible strategies to reduce the expansion of a land use activity: inhibiting its expansion, increasing its spatial efficiency, replacing it by alternative land uses or recovering degraded areas for its expansion. The current legal and political framework in Bolivia is also taken into account.

A discussion of possible solutions applicable to all land uses shows that legal enforcement, accompanied by strengthening institutions on both a national and local level, should be a priority, while positive incentives such as a direct compensation for reduced deforestation seem to be less promising. In terms of concrete policy options for the three proximate causes, it is found that cattle ranching should be targeted as a priority since its expansion threatens forests in many different locations, and improvements could be achieved at relatively low costs. It should be aimed at giving an advantage to more efficient production on existing farms over the expansion into forested areas. In this context, a higher legal fee for deforestation has the potential to mitigate forest conversion due to mechanized agriculture and large cattle farms, while a removal of subsidies for agro-diesel may specifically reduce the expansion of mechanized agriculture. Such measures could be complemented with a support for higher production efficiency, such as better access to fertilizer and techniques to increase cattle stocking densities. The expansion of small-scale agriculture seems to be difficult to control due to the large number of agents; measures should focus on mitigating the encroachment into areas with land use restrictions such as the El Choré Forest Reserve, fostering more sustainable and space-efficient agricultural practices, as well as off-farm employment. For all suggested measures, priority areas are also identified. There are probably no entirely new ideas among the identified policy options, but Chapter Four presents perhaps the first systematic evaluation of possible strategies to mitigate deforestation based on a broad variety of input data, including the outcomes of deforestation models. It is hoped that the results can be useful for planning concrete activities particularly under REDD.

The context of a possible implementation of such concrete activities, as well as further possibilities of deforestation modeling, are discussed in the Outlook in Chapter Six.

Chapter 6

Outlook

Rio Yata (Picture: Juan Carlos Montero)

6 Outlook

In this chapter, the needs and possibilities of further research are identified and discussed. In the field of deforestation modeling, additional analyses are introduced as examples for potential further research. In the field of policy options to reduce reforestation, a focus is put on the international discussion of the REDD mechanism, which constitutes the major effort of the international community to reduce tropical deforestation. An attempt is made to analyze why so little research on concrete policy options to reduce deforestation on the ground exists. Based on this discussion, some recommendations are derived.

6.1 Outlook on deforestation modeling

The decision for a transparent and simple modeling approach was found to be helpful in this study, particularly when discussing model outcomes in the context of historical land use processes. Nevertheless, this decision may also imply that further possible applications of deforestation modeling have not been fully exploited. Such applications include the generation of more elaborated scenarios, as well as the inclusion of non-spatial data into quantitative modeling.

In terms of deforestation scenarios, more sophisticated rules for the allocation of quantified deforestation onto maps of deforestation propensity are available in existing modeling frameworks, e.g., by accounting for neighborhood interaction. There are also possibilities of running dynamic simulations where model outputs are used as model inputs in a subsequent time step[16]. Several existing modeling frameworks, such as LandSHIFT (Schaldach et al. 2011), Dinamica EGO (Soares-Filho et al. 2009) and CLUE-S or Dyna-CLUE (Verburg and Veldkamp 2004; Verburg and Overmars 2009) offer such possibilities.

There are still only limited possibilities of integrating non-spatial data into spatial deforestation models (Heistermann et al. 2006). LandSHIFT is probably the most advanced model in this regard. It combines macro-level modeling of a total demand of land for housing, agriculture or grazing with spatially-explicit micro-level analyses. Dynamic simulations of land use patterns are possible and include feedback-modeling, e.g., by evaluating changing yields. Also possible impacts of climate change can be simulated. In a practical application, Lapola et al. (2011) modeled the probable consequences of Brazil's biofuel policies on land use change and carbon emissions. Dinamica EGO is a modeling platform allowing for highly dynamic simulations under the consideration of neighborhood functions. CLUE-S has its strength in applying advanced rules of allocating quantified deforestation to maps of deforestation propensity; Dyna-CLUE is a similar dynamic model that includes a possibility of modeling the re-growth of vegetation.

Particularly the integration of economic feedback loops, i.e., effects of changing agricultural production on demand and prices of agricultural goods, still remains a very challenging task and would require a coupling with economic equilibrium models such as FASOM (Adams et al. 2005). The complexity of such coupled models would possibly put serious constraints on their applicability as analytical tools.

Further research could explore in detail the possibilities offered by applying integrated models to the Bolivian data. An interesting option would be to test some of the policy options suggested in Chapter

---

[16] The findings of Chapter Two on changing temporal deforestation dynamics however suggest a cautionary approach to such dynamic simulations.

Four by building scenarios or running simulations. While options like the enforcement of existing legislation or the improvement of land use plans may be difficult to simulate (since their success depends on the adherence of agents which is hard to predict), interesting results might be achieved when testing policy options that influence the profitability of different land uses, such as higher fees for deforestation, a cut of diesel subsidies or an increased cattle stocking density. Microeconomic data such as production costs are still difficult to include in existing modeling approaches, but the simulation of stocking densities is an integrated part of LandSHIFT. A simple simulation of policy options that influence the profitability of land uses may also be possible by the approach of mapping opportunity cost described in Section 6.1.2.

By evaluating different scenarios, the application of more complex models may contribute to the prioritization of pre-selected policy options for deforestation reduction; another application of concrete scenarios is that they may be helpful to convince decision makers. The importance of producing tangible simulations became evident in the case of the National Park and Indigenous Territory Isiboro Sécure (TIPNIS). In the context of the conflict around the planned road through the TIPNIS, a deforestation scenario included in Müller (in press) was often quoted in the Bolivian and international press (BBC News 2011). All articles cited just a single result of the report, stating that 64% of the area's forest cover could be lost due to the road until 2030[17].

Such simple scenarios can also be generated with logistic regression; the scenario on the TIPNIS is described in the following section. In this case, as well as in a study on the El Choré forest reserve (Müller 2009), the demand modeling was based on a trend analysis assuming a sigmoid growth of deforestation (see next section).

For the generation of maps of the propensity of deforestation, also alternative approaches were tested in the context of this thesis. While only short experiments were conducted with the neural networking software LTM (Pijanowski et al. 2006) and LCM (Clark Labs 2009), detailed analyses were undertaken with the machine learning-based software MAXENT (Phillips et al. 2006) in a diploma thesis that was prepared by Moritz Maneke and supervised within the context of this doctoral thesis (Maneke 2010). It was found that MAXENT is suitable for deforestation modeling, although it was originally designed for the extrapolation of species' distributional ranges by analyzing presence-only data (Maneke 2010). It was also found that MAXENT has advantages over LTM and LCM in terms of user-friendliness and possibilities of evaluating the influences of independent variables. In terms of transparency, however, logistic regression still offers much better possibilities.

As a closing remark to this section it shall be noted that more complex modeling would have been possible within the framework of this study, but it was felt that transparency should be weighted higher than complexity – which may also be simply a question of personal predisposition.

6.1.1 Deforestation scenarios based on logistic regression – example of TIPNIS

Even without a dynamic component, rough scenarios can be generated with the help of logit models (as also shown in the Chapters Two and Three). The logistic regression delivers an equation for calculating propensities of deforestation, consisting in regression coefficients of the different independent variables and a constant. This equation can be applied to different sets of values of the

---

[17] However, press releases never stated that, according to the study, 48% may be lost without the road anyway.

independent variables, which includes the possibility of changing their values, e.g., of updating transportation costs to markets in consequence of newly built infrastructure.

In this section, an example of a simulation of deforestation in the national park and indigenous territory Isiboro Sécure (TIPNIS) is given. This analysis is part of Müller (in press). As mentioned in the previous section, the Bolivian governments planned to build a road right through the TIPNIS, which caused massive protests of lowland indigenous peoples, until the government finally had to stop the project (BBC News 2011).

The analysis is based on the logistic regression of the observed deforestation between 1986 and 2007 against a set of independent explanatory variables. The availability of accurate data of possible independent variables was very limited; therefore, only a rough simulation was possible. Finally, only slope, market access, distance to settlements and distance to rivers were evaluated as independent variables. In the scenario including the planned road, market access improves greatly in the northern part of the TIPNIS. The propensities of deforestation in the TIPNIS with or without the planned road are shown in Section 6.1.

The quantification of areas that are expected to be deforested requires an external analysis of the "demand for deforestation" (see Sections 1.3 and 6.1). But if such an externally generated demand was assumed to remain stable in both scenarios, both with and without the road, it would not be possible to measure an impact of the road on the quantity of deforestation – only the shape of the area expected to be deforested would change. This assumption is not sensible in the case of the TIPNIS. Deforestation is not caused by agricultural production serving a fixed demand, but by smallholder encroachment. It is therefore assumed that deforestation would expand to all grid cells that surpass a certain probability threshold and that the number of cells above this threshold would increase with road construction.

In a first step, the expected quantity of deforestation in the scenario without the road is modeled by a sigmoid trend analysis which is described in the next paragraph. Thereby, the probability threshold can be determined.

In a second step, the increased quantity of deforestation due to the road is calculated by selecting all cells above this probability threshold. In Figure 6.1, it becomes evident that this will lead to a higher quantity of deforested cells.

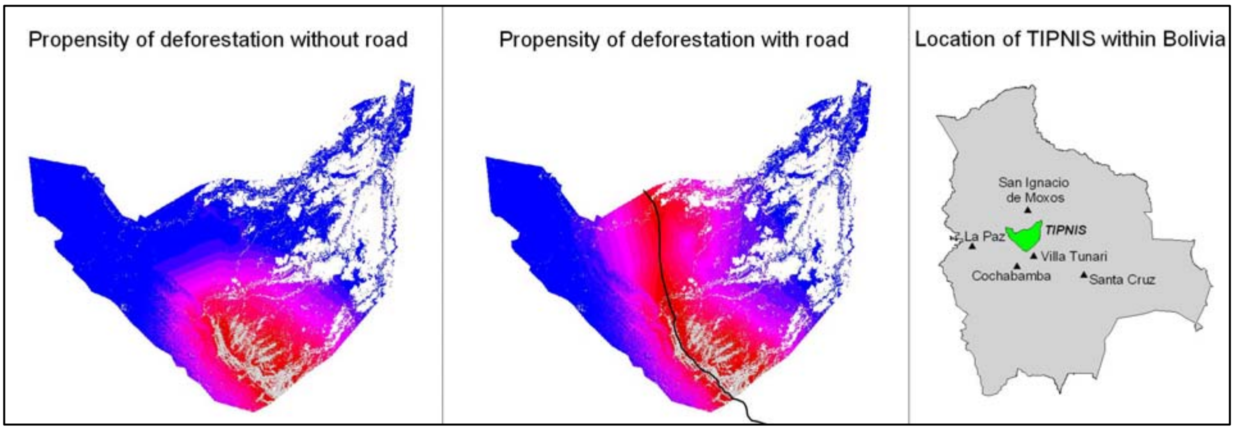


Figure 6.1 Modeled impact of a planned road through the TIPNIS area. Propensities of deforestation increase from blue to red; already deforested areas are represented in gray; natural savannahs in white. Source: Author.

The sigmoid trend analysis that was applied to derive the quantity of expected deforestation is best described in Müller (2009), where it was applied to simulate the deforestation in the El Choré forest reserve in Bolivia. It is based on the assumption that the deforestation of a limited area follows the shape of a sigmoid curve (Figure 6.2). In the beginning of the deforestation process, when forests still cover the major part of an area, deforestation will probably advance at an exponential growth rate. As the quantity of remaining forested land declines, deforestation rates will also decline, first leading to a linear growth of deforested areas and finally fading out due to the simple reason that only few forested areas will be left. Logistic regression was applied to fit deforestation data of different past observations to a sigmoid curve, which was then used to predict the quantities of expected deforestation in the future.

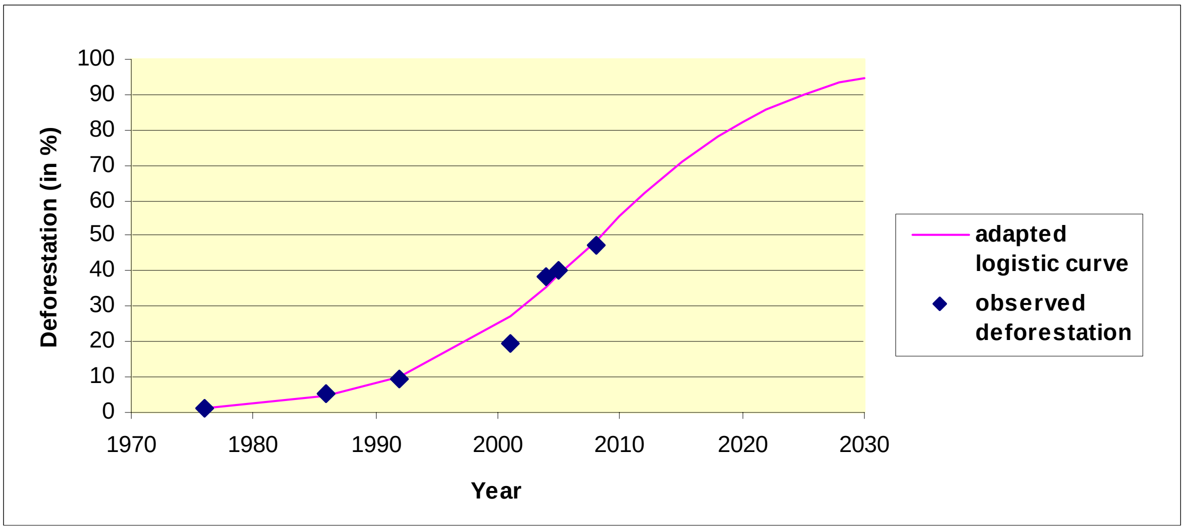


Figure 6.2 Example of a sigmoid growth curve of deforestation (from the reverted part of the El Choré forest reserve). Source: Author.

By combining the sigmoid trend analysis with the two different modeled maps of deforestation propensity in the TIPNIS, the progress of deforestation with and without the planned road can be simulated (Figure 6.3).[18]

The approach is still simple in comparison to integrated, dynamic models. But since the complexity of deforestation processes puts severe limitations to the projection of future developments, a simple and transparent approach may also have advantages over a complex methodology, particularly in the case of limited availability of data.

---

[18] It can be seen that even without road construction, deforestation is projected to progress quickly. Deforestation is currently surpassing a “red line,” which limits the area officially accessible for colonos in the south. Observed deforestation data show that this red line is not being respected, but it may still have an impact on deforestation. Due to the recent surpassing of this line, its effect could not be modelled.

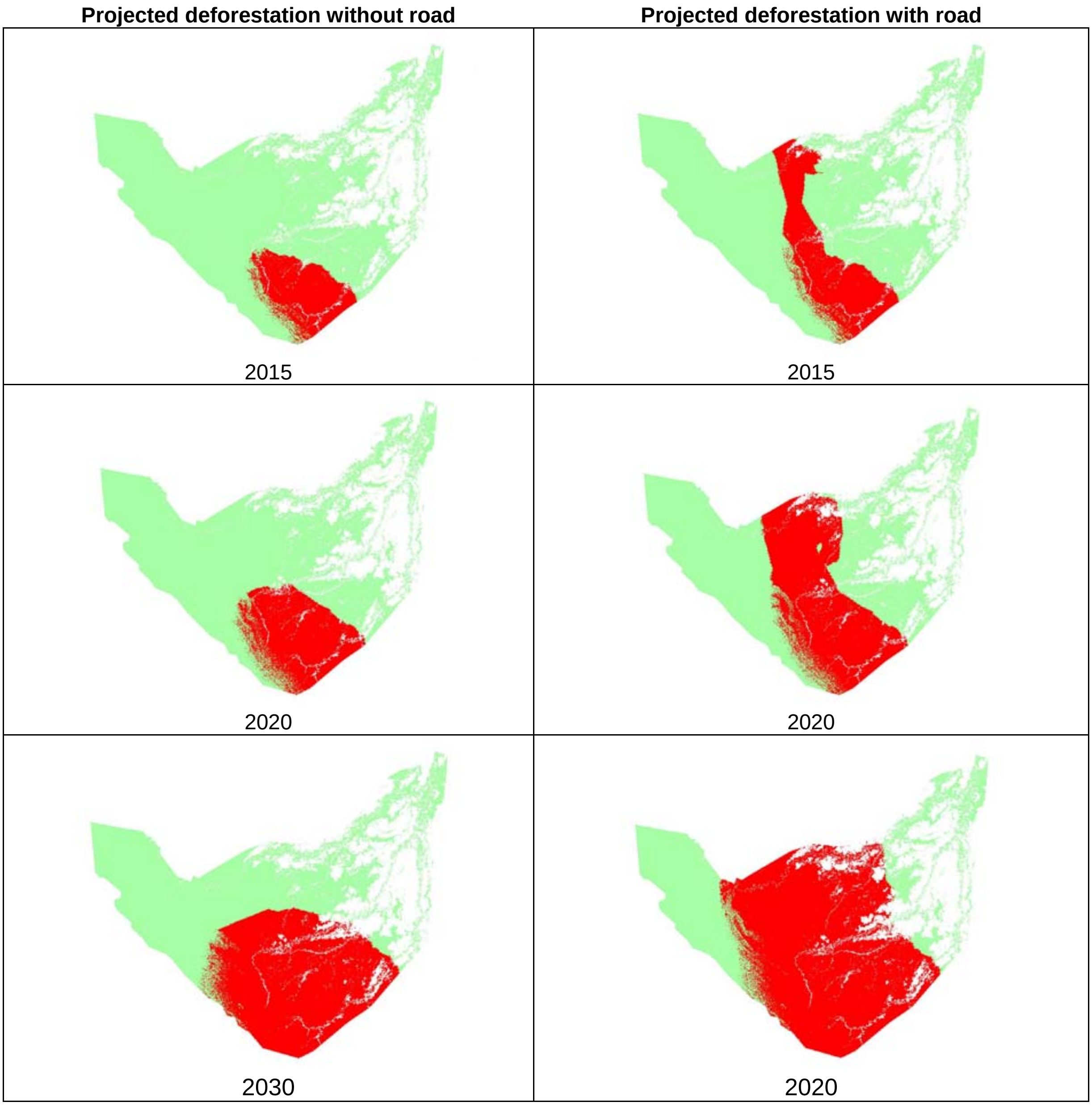


Figure 6.3 Scenarios of deforestation in TIPNIS with and without road construction.

6.1.2 Mapping opportunity costs - example of mechanized agriculture around Santa Cruz

Since spatial deforestation models are generally based on the assumption that agents seek to maximize the land rent, it seems worthwhile trying to build a map that represents the potential land rent based on a direct evaluation of economic factors, such as the costs and revenues of agricultural production. Such a map could allow to build scenarios and draw important conclusions regarding deforestation tendencies. In Section 4.4.3, opportunity costs of forest conservation are calculated for different land use options. The same approach can be used to generate a map of opportunity costs or potential profitabilities of agricultural land uses, provided that information on the spatial variability of the input data is available. Such a map would be similar to a map of deforestation propensities generated with the help of regression models, but it would be derived from very different input data. This would allow a comparison between the results of a deductive (empirical) and an inductive modeling approach (Overmars et al. 2007).[19]

In this section, an example of opportunity cost mapping is shown partially based on Müller et al. (in press), in which an attempt of mapping opportunity costs was undertaken for the activity of mechanized agriculture in the department of Santa Cruz. A comparable analysis was conducted by Vera-Diaz et al. (2007) for soybean cultivation in the Brazilian Amazon. The analysis is based on agro-statistical data of CAO (2008). The three most important combinations of crops are evaluated: soybeans in the summer in combination with sunflowers in the winter (suitable for drier areas), double-cropped soybeans (suitable for areas with intermediate rainfall), and dry rice cultivated only in the summer season (suitable for humid areas). Details are found in Table 6.1.

The input data used to determine the profitability of land use in Chapter Four are production costs, yields, and producer prices. The main spatial factors that influence profitability are probably soil fertility, rainfall and access to markets – the same factors that were also found to have significant effects in the logistic regressions. We assume that lower soil fertility will be compensated by increased fertilizer use. Poor soils will thereby increase the production costs without changing the yields. Unfavorable rainfall conditions, however, cannot be compensated and will directly impact yields. While lack of rainfall obviously decreases yields, the same effect is found for excessive amounts of rainfall. Excessive rainfall also leads to higher expenses for pest control. Finally, also the transportation costs to markets have an important impact on production costs.

A rough quantification of these assumed impacts was undertaken based on an evaluation of agro-statistical data of CAO (2008). The study area was divided into 12 zones characterized by different averages of rainfall and soil fertility, based on Figures 2.3 and 2.4. Average yields of different crops depending on rainfall data were evaluated by assigning rainfall values from nearby weather stations to different areas analyzed in CAO (2008). Average expenses for fertilizer and pesticides were estimated based on cost examples provided in CAO (2008). Since only a small sample of cost data was available, the estimate of expenses is very rough. Producer prices for agricultural products were estimated based on average values over the last 10 years. Transportation costs to export markets were assumed as in Figure 3.5. Based on these data, net present values (NPVs) were calculated as described in 4.3, with a time horizon of 30 years, assuming a discount rate of 8%. The crop combination with the highest NPV was then selected and represented in a map (Figure 6.4).

The explanatory power of the map of opportunity costs as a determinant for the expansion of mechanized agriculture can be assessed by logistic regression. In a logit model with opportunity costs as single independent variable, an AUC value of 0.92 was achieved, indicating a high explanatory power of opportunity costs for the patterns of mechanized agriculture. An interpretation of the odds ratio revealed that an opportunity cost increase in 100 US$ increased the risk of forest conversion to mechanized agriculture by 16%.

In order to compare the outputs of opportunity cost mapping with logistic regression, the results of the logit model described in Chapter Three are also indicated in Figure 6.4. A comparison shows a rather similar distribution of high values. The logit model assigns relatively higher values to the area of Puerto Suarez, which has very good access to export markets. The influence of market access seems to be weighted higher in the logit model.

---

[19] However, the inductive approach would still be empirical in the sense that empirical data from the study area can be used.

Table 6.1 Estimated data for opportunity cost mapping. Source: based on CAO (2008).

	Annual rainfall	Yield			Fertilizer cost in US$			Pesticide cost in US$		
		Fertile soil	Intermediate soil	Poor soil	Fert. soil	Interm. soil	Poor soil	Fert. soil	Interm. soil	Poor soil
Soybean summer	800-1100 mm	1.7	1.7	1.7	0	40	200	50	50	50
	1100-1400 mm	2	2	2	0	40	200	60	60	60
	1400-1800 mm	2.1	2.1	2.1	0	40	200	80	80	80
	>1800 mm	1.7	1.7	1.7	0	40	200	120	120	120
Soybean winter	800-1100 mm	1	1	1	0	40	200	50	50	50
	1100-1400 mm	1.5	1.5	1.5	0	40	200	60	60	60
	1400-1800 mm	1.8	1.8	1.8	0	40	200	80	80	80
	>1800 mm	1.7	1.7	1.7	0	40	200	120	120	120
Sunflower winter	800-1100 mm	0.9	0.9	0.9	0	25	150	20	20	20
	1100-1400 mm	1.3	1.3	1.3	0	25	150	30	30	30
	1400-1800 mm	1.2	1.2	1.2	0	25	150	40	40	40
	>1800 mm									
Rice summer	800-1100 mm				0	50				
	1100-1400 mm	2.5	2.5	2.5	0	50		25	25	25
	1400-1800 mm	3	3	3	0	50		30	30	30
	>1800 mm	2.8	2.8	2.8				40	40	40

Figure 6.5 compares two possible scenarios, a boom scenario, where all prices are assumed to increase by 50%, and a crisis scenario, where prices decrease by 50%. It can be seen that in the crisis scenario, mechanized agriculture is hardly viable anywhere.

In an additional analysis, the observed expansion of mechanized agriculture between 1992 and 2004 was compared to the mapped opportunity costs as well as the land use plan of Santa Cruz (Prefectura de Santa Cruz – Consorcio IP/CES/KWC 1996).[20] In order to evaluate whether mechanized farmers obeyed the land use plan or simply sought the highest return on investment, the map of opportunity costs was modified to a binary form; all cells with opportunity costs >1,400 US$ were assigned the value “1”, the rest “0”. The threshold of 1,400 US$ was chosen since it leads to the same quantity of cells being classified as “1” as contained in the zone of mechanized agriculture in the land use plan. It was found that 47% of the deforested cells were in cells with values over 1,400 US$, while in the evaluation of the land use plan, 57 % of the deforested cells were inside the category “mechanized

---

[20] This plan was intended to guide the development of agriculture and forestry in the department of Santa Cruz; it was legally binding, although not aligned with land use plans on the municipal level.

agriculture”. Though the land use plan performs slightly better than the binary map of opportunity costs, 57% seems to be a very poor success rate for a land use policy; it suggests that without the land use plan, mechanized agriculture would probably have expanded in the same way – searching suitable areas that allow for a good return on investment (Figure 6.6).

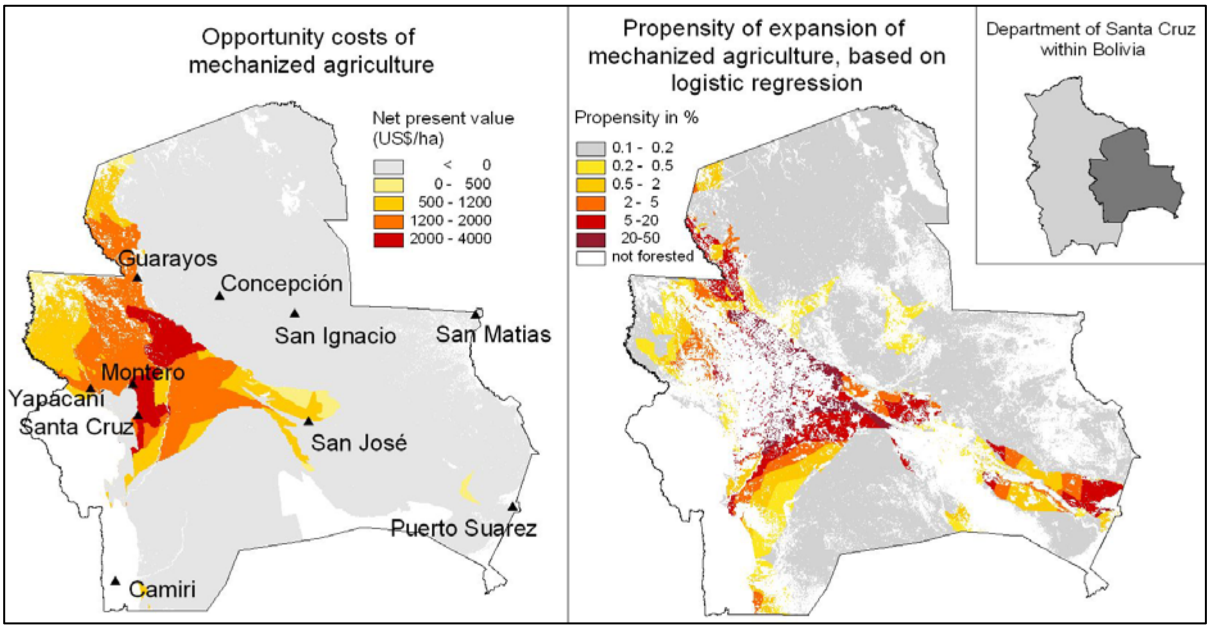


Figure 6.4 Comparison of mapped opportunity costs of mechanized agriculture with deforestation propensities based on logistic regression. Source: Author, based on CAO (2008).

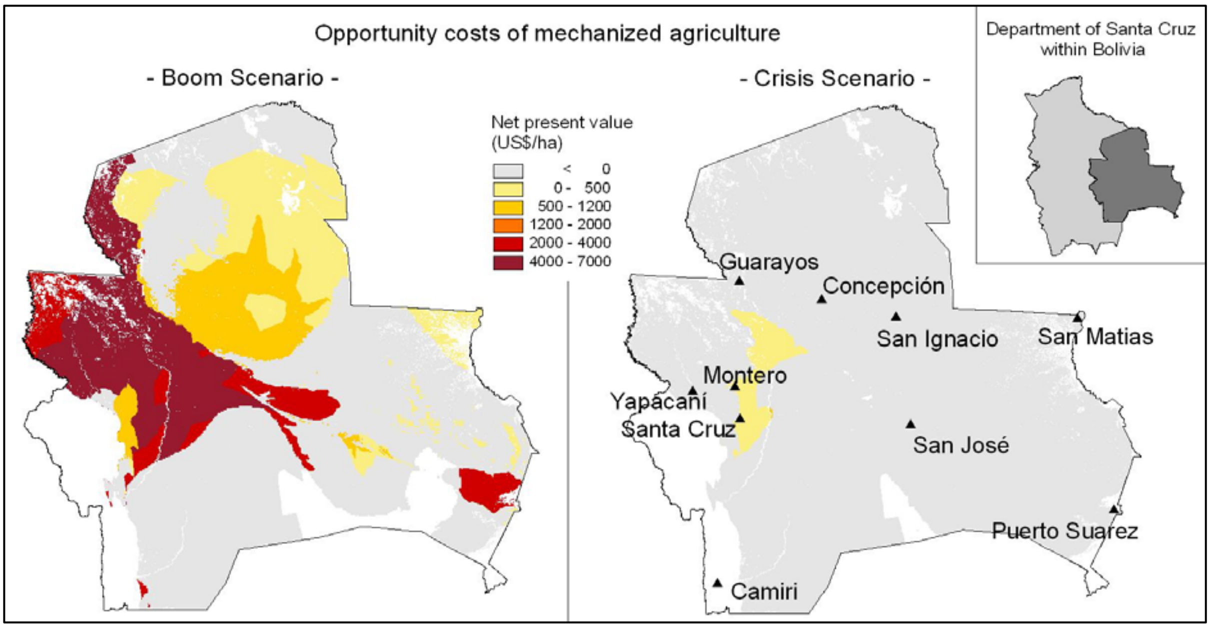


Figure 6.5 Opportunity costs of mechanized agriculture in a boom scenario and a scenario of economic depression. Source: Author, based on CAO (2008).

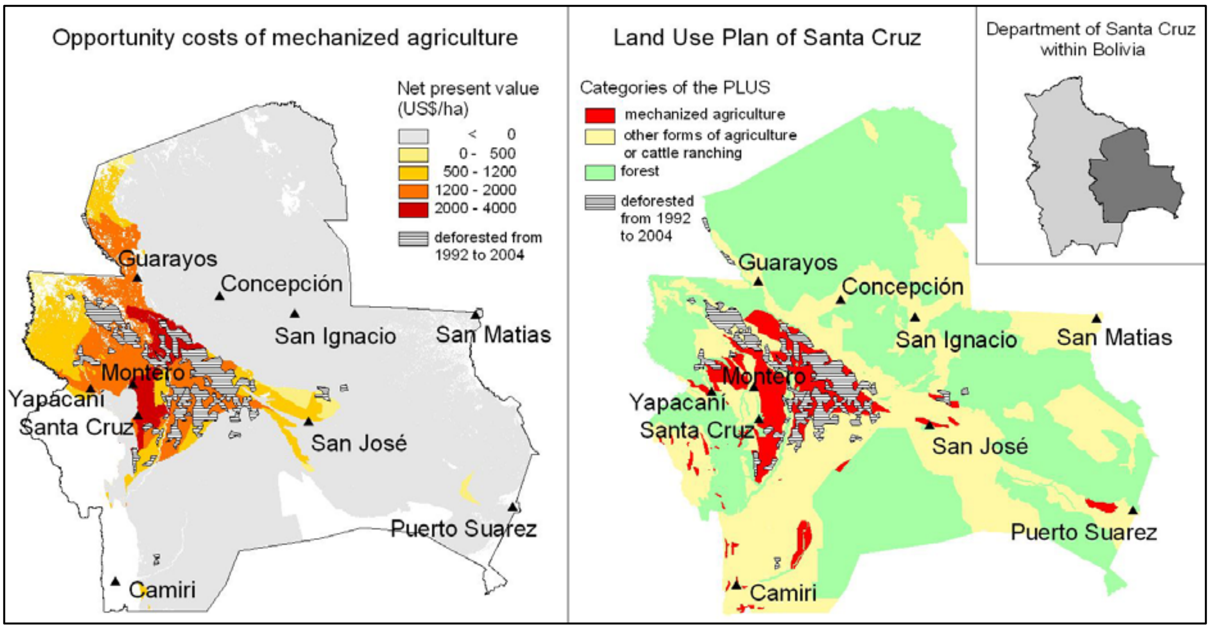


Figure 6.6 Observed expansion of mechanized agriculture compared to opportunity costs and the land use plan of Santa Cruz. Sources: Author, Prefectura de Santa Cruz – Consorcio IP/CES/KWC (1996).

The mapping of opportunity costs can be a powerful tool for spatial analyses of land use change and the generation of scenarios. The mapped value, i.e., the opportunity costs per hectare, is directly calculated by microeconomic data and is more meaningful than the relative propensities generated by logistic regression. The issue with opportunity cost mapping is that accurate, spatially explicit microeconomic data are generally not available: the examples presented in this section are based on rough estimates. This issue could possibly be overcome by using external data on yield responses to changing geophysical conditions, as in the LandSHIFT model (Schaldach et al. 2011). But a comparison with Brazil shows that the practices of soybean cultivation are quite different, e.g., much higher amounts of fertilizer are used there (Kaimowitz and Smith 2001). The use of external data may thus be more suitable for studies on a continental to global level.

By offering the possibility of analyzing agricultural costs, the mapping of opportunity costs may enable to evaluate some of the suggested policy options to reduce deforestation, as mentioned in Section 6.1.1. Taking measures such as removing diesel subsidies might change the pattern of land uses by making certain forms of agriculture more profitable than others. One example is the mechanized cultivation of dry rice, which may become more attractive in comparison to double-cropped soybean in some areas since a single cultivation cycle per year would imply less use of heavy machinery. A cut of diesel subsidies would also increase transportation costs and thus give an advantage to areas with better market access. A higher cattle stocking density would significantly increase the profitability of cattle ranching and increase its competitiveness over small-scale agriculture and mechanized agriculture in marginal areas. However, for the generation of scenarios, the demand for beef would also have to be taken into account. In the current situation of a rather isolated national market, this would limit the possibilities of a further extension of cattle ranching. Such effects could only be modeled by coupling with macroeconomic models such as FASOM (Adams et al. 2005), which would probably lead to very high complexity. Further developments of the technique of opportunity cost mapping could also aim at simple dynamic modeling, e.g., including effects of degrading soils due to intensive cultivation (Krüger 2005) which should have an effect on yields and/or fertilizer costs. But still the limited availability of data remains an issue.

Opportunity cost mapping should be understood as an analytic tool in the first place. The approach could be categorized as an agent-based modeling approach (Matthews et al. 2007; Parker et al. 2002).

6.2 Outlook on policy options to reduce deforestation in the context of REDD

Despite the global effort to reduce deforestation in the context of REDD, there have been very few attempts to define policy options for deforestation reduction in a systematic way (see Chapter 1.1). There are different possible explanations for the small number of relevant studies:

a) Traditional approaches of biodiversity conservation, such as protected areas, still play an important role in the discussion of possibilities to reduce tropical deforestation and may often be seen as priorities without further analysis.

b) There is a tradition of focusing on smallholders as agents causing deforestation, which may distract attention from the main proximate causes of deforestation.

c) REDD is being designed in the tradition of the Kyoto Protocol, with a strong focus on market-based solutions, such as emissions trading, where, in theory, the most efficient mitigation measures are identified automatically by market mechanisms.

d) In a possible UN-based international REDD mechanism, the decisions on concrete measures of deforestation mitigation will probably be left to the governments of the participating tropical countries. This may be seen as a reason not to prioritize investigation on this matter.

In this section, these potential explanations are discussed to derive tentative conclusions and recommendations for the setting of priorities in the design of the REDD mechanism, as well as for the prioritization of policy options to reduce deforestation in general.

a) The significance of traditional approaches of biodiversity conservation

An evaluation of REDD pilot projects shows that the vast majority of these initiatives support traditional conservation activities, such as the creation or improved management of protected areas[21]. REDD often seems to be seen as an alternative source of funding for existing conservation activities. In the field of conservation biology, there is still a strong focus on protecting biodiversity within protected areas. The concept of protected areas has been widened and improved, e.g., by regarding local people as an integrated part of protected areas (Borgerhoff Mulder and Copolillo 2004) or by defining priority areas for conservation that include sustainable forms of land use, such as Biosphere Reserves or large conservation corridors (e.g., UNCESCO 2006, Lombard et al. 2010). But often, the focus on conservation within prioritized areas leaves those areas apart that are facing the most urgent threats of deforestation. The attempt to achieve an ideal representation of biodiversity in conservation

---

[21] An analysis of 44 existing REDD demonstration activities worldwide (Wertz-Kanounnikoff and Kongphan-apirak 2009) shows that most of them focus on protected areas; many have mixed objectives, but none of them explicitly addresses deforestation caused by agribusiness or cattle ranching. Of the 17 REDD projects in Latin America evaluated by The Nature Conservancy (2009), only four of them do not explicitly focus on protected areas.

areas (Myers et al. 2000; Rodriguez et al. 2004) automatically leads to a prioritization of rather undisturbed areas. But naturally, deforestation happens where the agricultural pressure is high – a concentration of conservation efforts in areas with low deforestation pressure will thus not be sufficient for a significant reduction of deforestation rates.

In order to increase efforts on deforestation reduction, a paradigm shift in conservation biology may be important – giving a higher priority to functional entire landscapes that include deforestation hotspots (see e.g., Kareiva and Marvier 2003; Higgins et al. 2004; Ibisch et al. 2006). Particularly REDD should be seen as a source of funding for new approaches rather than supporting traditional conservation activities.

b) Focus on smallholders

The evaluation of existing REDD pilot projects mentioned in the previous section also reveals a nearly exclusive focus on smallholders (Wertz-Kanounnikoff and Kongphan-apirak 2009; The Nature Conservancy 2009). Again, this can probably be explained by the prevalence of traditional approaches of biodiversity conservation since conservationists mostly have to deal with smallholders in areas with low deforestation pressure, not agribusiness or large cattle ranchers.

The same focus on smallholders seems to be prevalent in the negotiations on REDD under the UNFCCC (personal observation). In the early days of REDD (which was called "avoided deforestation" then), one of the most prominent champions of REDD, Papua New Guinea's Ambassador for Environment and Climate Change, often explained that in Papua New Guinea, poverty was a major driver of deforestation and that REDD would finally offer a possibility of compensating poor people for not cutting down trees, without making any reference to other drivers of deforestation. Simultaneously, the draft R-PIN (Readiness Plan Idea Note) of Papua New Guinea (Government of Papua New Guinea 2008) contains a short analysis of deforestation drivers, stating that 45.6% of deforestation was caused by subsistence agriculture. But a footnote mentions that "it is not clear if the oil palm and large agriculture land clearing is included under the subsistence agriculture component." It is hard to believe that a detection of agro-industrial clearings should have been more difficult than the detection of subsistence agriculture clearings, which are much harder to distinguish by remote sensing than the former (see Figure B1 in Appendix B); and it is known that palm oil plantations are responsible for large forest clearings in Papua New Guinea (e.g., Reuters 2010). A document which is frequently used for the preparation of national REDD programs is the so-called McKinsey cost curve (McKinsey&Company 2010), an estimation of the total potential and the marginal costs of avoiding greenhouse gas emissions from different sources. Again, subsistence agriculture is identified to have a higher potential (at much lower costs) than the avoidance of the expansion of agribusiness or cattle ranching. The sources for this study are not publicly available. There is, however, very clear evidence that subsistence agriculture plays a minor role in global deforestation compared to agribusiness and cattle ranching (Boucher 2010; Butler and Laurance 2008; Rudel 2005). In the Brazilian Amazon, cattle ranching is by far the most important driver of deforestation (Butler 2011).

In Bolivia, in spite of the unclear governmental position on REDD (see Section 4.2), REDD is generally regarded as a potential source of immense benefit for smallholders which is supposed to be distributed through compensation schemes, while there is little discussion on the impact of soybean farmers and cattle ranchers (personal observation).

A detailed analysis of the issue is beyond the scope of this study, but there seems to be a clear tendency in the negotiations on the design of REDD to focus on smallholders as main potential beneficiaries of REDD – and implicitly also as main responsible agents. There is also a huge and justifiable discussion on possible negative effects of REDD on smallholder rights (Boerner et al. 2010a), but again, this discussion seems to distract the attention from those agents responsible for the largest portion of deforestation, i.e., agribusiness, large-scale cattle and clear-cut logging in South East Asia. Only recently, the discussion seems to have shifted slightly more to those agents (see e.g., the examples from Brazil in Section 4.5.1, Boucher 2010, Rudel 2005). Still, much higher efforts are needed to develop suitable strategies to mitigate deforestation caused by them and to directly address corporate agents (Butler and Laurance 2008).

c) Focus on market-based solutions

REDD is being designed in the tradition of the Kyoto protocol, where a strong preference is given to market-based solutions to reach the targets for greenhouse gas reduction (Cohen 2002; McKibbin and Wilcoxen 2002). The main instruments for the implementation of the Kyoto protocol are based on emissions trading[22]. In the theory of emissions trading, it is the market itself that identifies the most cost-efficient measures to reduce greenhouse gas emissions (Tietenberg 2006)[23]. In this case, there would be little need to actively prioritize policy options. However, a look at the existing carbon market, particularly at the Clean Development Mechanism (CDM), inspires serious doubts about the applicability of this theory in practice. Under the CDM, carbon credits are issued to projects that reduce greenhouse gases in non-industrialized countries ("Non-Annex 1 countries"). There are currently more than 3,500 registered CDM projects with over 750 million carbon credits issued (nearly equaling the annual emissions of Germany) (Fenhann 2011). However, half of these credits have been issued to just 10 projects that reduce very powerful greenhouse gases from the production of refrigerants (HFC gases) and fertilizers (N_2O gas). Around two billions of US$[24] were thus paid for the carbon credits generated by these 10 projects, a multiple of the real mitigation costs. Moreover, CDM created perverse incentives, not only against a ban of such production techniques, but even to increase the production of those gases (Wara 2009). In the case of renewable energy projects under the CDM, it is often questionable if such projects are really additional, i.e., if they would not have happened anyway even without CDM funding. Additionality of renewable energy projects is generally difficult to prove, since carbon credits only increase the return on investment in renewable power production in 1 or 2% (e.g., Singh 2010). On the other hand, transaction costs of all CDM projects for paying auditors, consultants and the corresponding UNFCCC bureaucracy easily amount to 500 millions of US$[25]. It becomes evident that CDM ends up being a rather expensive and inefficient solution for greenhouse gas reduction.

---

[22] Emission allowances are traded between countries and within the European Emissions Trading Scheme; the two flexible mechanisms, i.e., the Clean Development Mechanism (CDM) and Joint Implementations (JI), are also integrated into these schemes by generating tradable carbon credits (Freestone and Streck 2010).

[23] Under a cap-and-trade scheme, tradable pollution permits are issued by a central authority; by limiting the total sum of these pollution permits, a pollution cap is defined. The participating polluters start trading the permits; those who are able to implement cheap measures of pollution reduction will sell permits to such participants with higher marginal costs of pollution reduction. Thereby, those measures with the lowest marginal costs should automatically be implemented.

[24] Assuming average prices of 8 US$ (Intercontinental Exchange 2011)

[25] Assuming average costs of 50-100,000 US$ per project

In the case of emissions from deforestation, market-based instruments are particularly hard to apply due to much higher levels of uncertainty and the complexity of the underlying processes (see Müller 2011). Nevertheless, market-based instruments play a very important role in the design of the REDD mechanism. In investigations around REDD, it is a common approach to take the expected costs of deforestation reductions as a point of departure (e.g., Grieg-Gran 2008). These costs are generally derived from opportunity costs of forest conservation. This way, hypothetical prices per ton of CO_2 can be defined that would be required to achieve certain levels of deforestation reduction. Many similar studies exist that define so-called “break-even prices,” i.e., price levels at which carbon credits would exceed opportunity costs of avoided deforestation in certain circumstances. Examples can be found in Nepstad (2007), Parker et al. (2008), Silva Chavez (2005), Vera-Diaz (2005). For Bolivia, Silva Chavez (2005) calculates a break even price between 4.43 and 9.50 US$ based on a comparison of forest-carbon with revenues from soybean cultivation. It is generally concluded in the mentioned studies that moderate carbon prices could significantly reduce deforestation (see also Müller 2011).

Table 6.2 Theoretical relation between CO_2 prices and deforestation reduction under REDD in 2020. Source: Adapted from Boucher (2008).

Carbon price in US$/($tCO_2$)	Deforestation reduction in %
2	10
5	25
10	50
20	70
50	95
70	99

Table 6.2 shows a typical calculation of hypothetical deforestation reduction on the global level as a function of carbon prices. But such calculations assume the existence of a mechanism that transfers carbon funding to agents on the ground whereupon these agents give up forest-depleting activities. Without such a mechanism, the calculated numbers are rather meaningless. And indeed, there are many different issues which make the successful implementation of such a mechanism highly unrealistic, such as baseline setting and additionality, leakage, risk of fraud, lack of governance and unclear tenure rights, among others (see chapter 4.5.1 and Müller 2011 for details). There are some pilot experiences with payments for environmental services in tropical countries but with questionable success (Pokorny et al. in press, Müller 2011).

In the light of all those issues, it may be more reasonable to take a more direct route towards the target. In the example of renewable energy projects under the CDM, funds might be used more efficiently to help directly subsidize feed-in tariffs in Non-Annex 1 countries instead of trading carbon credits based on expensive and doubtful analyses of project additionality. A first step for achieving a reduction of tropical deforestation reduction could probably be the identification of measures that need to be taken, based on a thorough analysis of the drivers of deforestation. International negotiations could then directly focus on the implementation of the most promising measures in a joint effort of the international community. Market-based solutions may be adequate to tackle deforestation caused by existing markets, e.g., for agricultural commodities, but there is still a lack of evidence that the creation of new environmental markets is helpful to reduce deforestation.

d) National governments decide on policy options

There is a relatively broad consensus that REDD should be based on national baselines (Dutschke and Pistorius 2008), i.e., deforestation should be measured on the national level and all measures to reduce deforestation would be controlled by national governments. The alternative would be a project-based approach such as the CDM, which would present a variety of issues such as control of additionality and leakage (see Müller 2011)[26]. Within the negotiations on REDD under the UNFCCC, the approach of national baselines is often seen as an argument against detailed assessments of policy options to reduce deforestation under the UNFCCC since this would be a matter of national politics. Issues of national sovereignty are also important in this context. On the other hand, improved knowledge of practical measures to reduce deforestation should only be helpful for the governments of tropical countries.

Encouraging examples of direct governmental action can be found in Brazil, e.g., the moratorium on soybean cultivation in the Amazon or the requirement of keeping 80% of Amazonian properties forested[27] (Boerner and Wunder 2008). An evaluation of such targeted action to mitigate deforestation would be another priority in order to identify the most suitable policy options (e.g., Fearnside 2003).

6.3 Summary of recommendations for further research

Spatial deforestation modeling is primarily applied as an analytical tool in this study, with the purpose of deriving practical solutions for deforestation reduction. Logistic regression is found to be a suitable modeling approach due to its transparency, allowing for quantitative analyses of hypothesized drivers as well as detailed plausibility checks of the model outcomes. Temporal deforestation dynamics are also explored with logistic regression and simple scenarios of future deforestation are generated. In this Outlook Chapter, such simple scenarios are explored by assuming a sigmoid growth of deforestation. It is found that deforestation modeling serves its purpose in this study.

There are, however, additional features of modeling that could be tested in further research, mainly in terms of generating more elaborated scenarios and use of non-spatial data. Such features include the application of neighborhood interaction in the procedure of allocating quantified deforestation onto maps of deforestation propensity, and also the generation of dynamic models, i.e., simulations where model outputs are used as inputs in a subsequent time step. Several existing modeling frameworks, such as LandSHIFT, Dinamica EGO, or CLUE-S allow for such analyses. There are still only limited possibilities of integrating non-spatial data into spatial deforestation models (Heistermann et al. 2006). LandSHIFT allows for coupling demographic data and data on agricultural production with spatial models. But particularly the integration of economic feedback loops, i.e., effects of changing agricultural production on demand and prices of agricultural goods, still remains a very challenging task and would require a coupling with economic equilibrium models such as FASOM. Further research is needed in this area, but it must be kept in mind that there will always be a trade-off between the complexity and the transparency of models. More sophisticated models will not necessarily have a better applicability for practical purposes. It is shown in the Outlook Chapter how economic data can be used for spatial modeling by mapping opportunity costs of forest conservation.

---

[26] However, there is a huge market of REDD projects under the so-called voluntary, non-Kyoto carbon market (Peters-Stanley et al. 2011).

[27] Though currently, the Brazilian Forest Code is about to change (Toleffson 2011)

This offers the possibility of translating changing macroeconomic data, such as prices for agricultural goods, into spatial scenarios. Further research may explore the possibilities of simulating the effect of possible measures to reduce deforestation by mapping opportunity costs. An important constraint is, however, the availability of spatially explicit data on yields and production costs.

There is still little research on suitable policy options to reduce deforestation on the ground. In order to enhance the development of such policy options, it seems necessary to overcome the prevalence of traditional approaches to biodiversity conservation which tend to concentrate on defined conservation areas with low deforestation pressure. Similarly, an unjustified focus on smallholders may often draw the attention of policy makers and scientist away from developing strategies to mitigate large forest clearings driven by agents such as agribusiness or large cattle ranchers. Existing experiences with market-based solutions for the reduction of greenhouse gases inspire doubts on the suitability of such approaches to reduce deforestation under the framework of REDD. Further research should therefore concentrate on direct ways of supporting the governments of tropical countries in implementing measures that seem to be promising for the reduction of deforestation. The identification of such measures could be based systematic evaluations similar to the systematic approach presented in this study. Further refinement of this approach and its replication in other countries is certainly another topic of future research. Evaluations of programs and projects implemented with the objective of reducing deforestation are important in this context. On the international level, it may be particularly important to target existing markets that drive deforestation, i.e., global markets for beef, soybean, palm oil and tropical timber stemming from clear-cuts.

References

Adams D, Alig R, McCarl BA, Murray BC (2005): FASOMGHG - Conceptual Structure, and Specification: Documentation. Electronic version at: http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf (Accessed: November 2011).

Acre Governemnt (2010): Payments for environmental services – carbon project. Acre Government, Rio Branco, Brazil. http://www.katoombagroup.org/rapidresponse/Acre%20PES%20Carbon%20Project%20exp%20version%2006nov09.pdf (accessed in February 2011).

Agarwal C, Green GM, Grove JM, Evans T, Schweik CM (2002): A review and assessment of land-use change models: dynamics of space, time, and human choice. Gen. Tech. Rep. NE-297. Newton Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station, 61 pp.

Angelsen A (2007): Forest cover change in space and time: combining the von Thünen and forest transition theories. World Bank Research Working Paper 4117, World Bank,Washington DC.

Angelsen A (2009): Policy options to reduce deforestation. In: Angelsen, A., Brockhaus, M., Kanninen, M., Sills, E., Sunderlin, W.D., Wertz-Kanounnikoff, S. (eds.): Realising REDD+: National strategy and policy options. Center for International Forestry Research (CIFOR), Bogor, Indonesia. http://www.cifor.cgiar.org/Knowledge/Publications/Detail?pid=2871 (accessed in January 2010).

Angelsen A, Brown S, Loisel C, Peskett L, Streck C, Zarin D (2009): Reducing Emissions from Deforestation and Forest Degradation (REDD): An Options Assessment Report. Meridian Institute. 116 pp.

Araujo N, Müller R, Nowicki C, Ibisch PL (2010, eds.): Prioridades de Conservación de la Biodiversidad de Bolivia. SERNAP, FAN, TROPICO, CEP, NORDECO, GEF II, CI, TNC, WCS, Universidad de Eberswalde. Editorial FAN, Santa Cruz, Bolivia.

Barrientos J (2005): Vermarktung der den Kokaanbau ersetzenden Alternativen Produkte der Tropen von Cochabamba (Bolivien). PhD thesis, Institut für Agrarpolitik, Marktforschung und Wirtschaftssoziologie, Bonn University, Germany. http://hss.ulb.uni-bonn.de/2005/0509/0509.pdf (accessed in September 2011).

Baudoin M, Gerold G, Hecht S, Quintanilla O, Roca C (1995): Evaluación del Proyecto Tierras Bajas del Este: Proyecto de Manejo de Recursos Naturales y de Producción Agropecuaria. World Bank; Kreditanstalt fur Wiederaufbau, CORDECRUZ. World Bank, Washington DC.

BBC News (2011): Bolivia's Evo Morales scraps Amazon road project. BBC News Latin America & Caribbean, 21 October 2011. http://www.bbc.co.uk/news/world-latin-america-15409447 (accessed in October 2011).

Besag JE (1974): Spatial interaction and the statistical analysis of lattice systems. Journal of the Royal Statistical Society Series B 36: 192-236.

Bojanic AH (2001): Balance is beautiful: Assessing sustainable development in the rain forest of the Bolivian Amazon. PROMAB scientific series 4, Riberalta, Bolivia

Bond I, Grieg-Gran M, Wertz-Kanounnikoff S, Hazlewood P, Wunder S, Angelsen A (2009): Incentives to sustain forest ecosystem services: A review and lessons for REDD. Natural Resource Issues No. 16. International Institute for Environment and Development, London, UK, with CIFOR, Bogor, Indonesia, and World Resources Institute, Washington D.C., USA.

Boerner J and Wunder S (2008): Paying for avoided deforestation in the Brazilian Amazon: from cost assessment to scheme design. International Forestry Review 10(3): 496-511.

Boerner J, Wunder S, Wertz-Kanounnikoff S, Hyman G, Barona E, Guevara E, Nascimento N (2010a): Cost-effective REDD++ policy design in the Brazilian Amazon: How to combine incentives and control without harming the poor? Conference paper prepared for the ISEE Conference 2010, Oldenburg, Germany.

Boerner J, Wunder S, Wertz-Kanounnikoff S, Tito M, Pereira L, Nascimento N (2010b): Direct conservation payments in the Brazilian Amazon: Scope and equity implications. Ecological Economics, 69(6): 1272-1282.

Borgerhoff Mulder M, Coppolillo P (2004): Conservation and People: An invitation to debates in the natural and social sciences. Princeton University Press, Pricenton. 347 pp.

Boucher D (2008): Estimating the Cost and Potential of Reducing Emissions from Deforestation. Tropical Forest and Climate Initiative, Union of Concerned Scientists. www.ucsusa.org/REDD.html (accessed in November 2011).

Boucher D (2010): Deforestation today – it's just business. Tropical Forest and Climate Initiative, Union of Concerned Scientists. www.ucsusa.org/REDD.html (accessed in November 2011).

Brown S, Hall M, Andrasko K, Ruiz F, Marzolli W, Guerrero G, Masera O, Dushku A, Dejong B, Cornell J (2007): Baselines for land-use change in the tropics: application to avoided deforestation projects. Mitig Adapt Strat Glob Change 12: 1001–1026.

Butler R (2009): Rainforest soy moratorium shows success in the Brazilian Amazon. Online news article. http://news.mongabay.com/2009/0415-amazon_soy.html (accessed in February 2011).

Butler R, Laurance W (2008): New strategies for conserving tropical forests. Trends in Ecology & Evolution 23(9): 469-472.

Butler R (2011): Deforestation in the Amazon. Mongabay.com http://www.mongabay.com/brazil.html (accessed in November 2011).

CADEX (Cámara de Exportadores de Santa Cruz) (2008): Statistical information on Bolivia exports available on request. CADEX, Santa Cruz, Bolivia.

CAF (Corporación Andina de Fomento) (2004): Análisis del Sector Transporte de Bolivia. Informes Sectoriales de Infraestructura, 6, Corporación Andina de Fomento, Caracas. http://www.caf.com/attach/17/default/Infor_Bolivia.pdf (accessed November 2009).

CAO (Cámara Agropecuaria del Oriente) (2008): Números de nuestra tierra. Statistical agricultural information available on CD-ROM at the Cámara Agropecuaria del Oriente, Santa Cruz de la Sierra, Bolivia.

Chatterjee S, Hadi AS, Price B (2000): Regression Analysis by Example. John Wiley & Sons, New York.

Chomitz K, Gray D (1996): Roads, land use and deforestation: A spatial model applied to Belize. Word Bank Economic Review 10(3): 487-512.

Clark Labs (2009): The Land Change Modeler for Ecological Sustainability. Clark University, Worcester, Massachusetts, USA. http://www.clarklabs.org/applications/upload/Land-Change-Modeler-IDRISI-Focus-Paper.pdf (accessed in November 2011).

Clark Labs (2010): Modeling REDD Baselines using IDRISI's Land Change Modeler. Clark University Worcester, Massachusetts, USA http://www.clarklabs.org/applications/upload/IDRISI_Focus_Paper_REDD.pdf (accessed in November 2011).

Cohen B (2002): The Kyoto instruments: are they adequate for achieving the stabilisation of carbon dioxide concentrations? International Journal of Environment and Pollution 17(3): 275-278.

CONAB (Companhia Nacional de Abastecimiento) (2010): Statistical agricultural data available at http://www.conab.gov.br/ (accessed in December 2010).

Conrad O, Krüger JP, Bock M, Gerold G, Böhner J (2006): Soil degradation risk assessment integrating terrain analysis and soil spatial prediction methods. Geoöko 27 (3-4): 165-174, University of Göttingen.

da Veiga JB, Tourrand JF, Piketty MG, Poccard-Chapuis R, Alves AM, Thales MC (2004): Expansão e Trajetórias da Pecuária na Amazônia. Editora UNB, Brasilia, 2004, 161 pp.

Davies P (1996): Valuing Soils in the Tropical Lowlands of Eastern Bolivia. In: Abelson P. (Ed.), Project Appraisal and Valuation of the Environment, General Principles and Six Case Studies in Developing Countries. Macmillan Press, London.

Duchelle AE, Cronkleton P, Kainer K, Guanacoma G, Gezan S (2011): Resource theft in tropical forest communities: implications for non-timber management, livelihoods, and conservation. Ecology and Society 16(1): 4.

Eastman JR (2005): Transition Potential Modeling for Land-Cover Change. In Maguire D, Batty M and Goodchild M (eds.): GIS Spatial Analysis and Modeling. ESRI press.

Eastwood D, Pollard H (1985): The Development of Colonization in Lowland Bolivia: Objectives and Evaluation. Boletín de Estudios Latinoamericanos y del Caribe 38: 61-83.

Eliasch J (2008): Climate Change: Financing Global Forests. MPG press, Bodmin, UK.

Eyzaguirre JL (2005): Composición de los ingresos familiares de campesinos indígenas. Un estudio en seis regiones de Bolivia. CIPCA, Centro de Investigación y Promoción del Campesinado. La Paz.

FAO (Food and Agriculture Organization of the United Nations) (2010): Global Forest Resources Assessment 2010. Food and Agriculture Organization of the United Nations, Rome www.fao.org/forestry/fra/fra2010/en/ Accessed November 2009.

FCPF (2011): The Forest Carbon Partnership Facility – 2011 Annual Report. Carbon Finance Unit. The World Bank, Washington, USA. http://www.forestcarbonpartnership.org/fcp/sites/forestcarbonpartnership.org/files/Documents/PDF/Oct2011/FCPF_Carbon_AR_FINAL_10_3.pdf (accessed in November 2011).

Fearnside P (2003): "Deforestation control in Mato Grosso: A new model for slowing the loss of Brazil's Amazon Forest. Ambio, 32 (5): 343-345.

Fenhann J (2011): UNEP Risoe CDM/JI Pipeline Analysis and Database, November 2011. UNEP Risoe Centre, Denmark. http://cdmpipeline.org/ (accessed in November 2011).

Freestone D and Streck C (2010): Legal aspects of carbon Trading: Kyoto, Copenhagen and beyond. Oxford University Press, 01.01.2010 – 657.

Gamarra Téllez M (2004): Amazonía Norte de Bolivia - Economía Gomera. Colección Colegio. Nacional de Historiadores de Bolivia, producciones CIMA editores. La Paz, Bolivia.

Geist H, Lambin E (2002): Proximate Causes and Underlying Driving Forces of Tropical Deforestation. Bioscience 52: 143–150.

Gerold G (2001): The pedo-ecological consequences of different land use-systems in the Lowlands of Bolivia (Dep. of Santa Cruz). In: García-Torres L, Benites J, Martinez-Vilela A (eds.): Conservation Agriculture, A Worldwide Challenge, vol 2, ECAF-Madrid.

Gerold G (2004): Soil: The foundation of biodiversity. In: Ibisch PL, Mérida G (eds.): Biodiversity: the richness of Bolivia. Fundación Amigos de la Naturalzea, Santa Cruz, Bolivia.

Gerold G (2007): Agrarkolonisation – Entwicklungschancen durch Globalisierung oder Raubbau natürlicher Ressourcen. Kieler Geographische Schriften 117: 23-52.

Grieg-Gran M (2008): The Cost of Avoiding Deforestation - Update of the Report prepared for the Stern Review of the Economics of Climate Change. International Institute for Environment and Development. London.

Hecht S (2005): Soybeans, Development and Conservation on the Amazon Frontier. Development and Change 36(2): 375–404.

Heisterman M, Müller C, Ronneberger K (2006): Land in sight? Achievements, deficits and potentials of continental to global scale land-use modeling. Agric Ecosyst Environ 114: 141–158.

Higgins J, Ricketts T, Parrish J, Dinerstein E, Powell G, Palminteri S, Hoekstra J, Morrison J, Tomasek A, Adams J (2004): Beyond Noah: saving species is not enough. Conservation Biology 18: 1672-1673.

Hilbe JM (2009): Logistic Regression Models. Chapman & Hall/CRC, Boca Raton.

Hosmer D, Lemeshow S (2000): Applied Logistic Regression (2nd Edition). John Wiley & Sons Inc., New York.

Ibisch PL, Beck SG, Gerkmann B, Carretero A (2003): Ecorregiones y ecosistemas. In: Ibisch PL, Mérida L (eds.): Biodiversidad: La riqueza de Bolivia. Editorial FAN, Santa Cruz de la Sierra, Bolivia.

Ibisch PL, Araujo N, Nowicki C (2007, eds.): Visión de Conservación de la Biodiversidad del Corredor Amboró - Madidi. FAN/WWF/TNC/CI. Editorial FAN, Santa Cruz de la Sierra - Bolivia. 379 pp.

Ibisch PL, Nowicki C, Araujo N, Müller R, Reichle S (2006): Bolivia: targeting ecological processes and functionality, not the “living dead”. In: Dudley N, Parrish J (eds.): Closing the gap creating ecologically representative protected area systems: a guide to conducting the gap assessments of protected area systems for the Convention on Biological Diversity. Secretariat of the Convention on Biological Diversity, Montreal, Technical Series no. 24: 83-84.

INPE (Instituto Nacional de Pesquisas Espaciais) (2010): Collection of CBERS satellite images. http://www.inpe.br/index.php. (accessed in December 2010).

INRA (Instituto Nacional de Reforma Agraria) (2010): Notas de Prensa. http://www.inra.gob.bo (accessed in February 2011).

Intercontinental Exchange (2011): ECX product suite – Emissions. https://www.theice.com/productguide/ProductGroupHierarchy.shtml?groupDetail=&group.groupId=19 (accessed November 2011).

IPCC (Intergovernmental Panel on Climate Change) (2007): Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.ipcc.ch/ipccreports/ar4-wg1.htm (accessed in February 2010).

Kaimowitz D, Angelsen A (1998): Economic Models of Tropical Deforestation: A Review. Center for International Forestry Research. Bogor, Indonesia.

Kaimowitz D, Angelsen A (2008): Will livestock intensification help save Latin America's tropical forest? Journal of Sustainable Forestry 27(1-2): 6-24.

Kaimowitz D, Byron, N, Sunderlin W (1998): Public policies to reduce inappropriate deforestation. In E. Lutz, ed. Agriculture and the environment: perspectives on sustainable rural development, p.303-322. Washington, DC, USA, World Bank.

Kaimowitz D, Smith J (2001): Soybean technology and the loss of natural vegetation in Brazil and Bolivia. In: Angelsen, A., Kaimowitz, D. (eds): Agricultural Technologies and Tropical Deforestation. CAB International, Wallingford, UK.

Kaimowitz D, Mendez P, Puntodewo A, Vanclay JK (2002): Spatial regression analysis of deforestation in Santa Cruz, Bolivia. In: Wood, C.H., Porro, R. (eds): Deforestation and land use in the Amazon. University Press of Florida, Gainesville, pp 41-65.

Kareiva P, Marvier M (2003): Conserving biodiversity coldspots: recent calls to direct conservation funding to the world's biodiversity hotspots may be bad investment advice. American Scientist 91(4): 344-351.

Kemp A (2006): Niederschlagsvariabilität und Ertragsrisiko im Tiefland von Santa Cruz (Bolivien). EcoRegio 18, University of Göttingen.

Killeen T, Calderon V, Soria L, Quezada B, Steininger M, Harper G, Solórzano L, Tucker C (2007): Thirty Years of Land-Cover Change in Bolivia. AMBIO: A Journal of the Human Environment 36(7): 600-606.

Killeen T, Guerra A, Calzada M, Correa L, Calderon V, Soria L, Quezada B, Steininger M (2008): Total Historical Land-Use Change in Eastern Bolivia: Who, Where, When, and How Much? Ecology and Society 13(1), 36. http://www.ecologyandsociety.org/vol13/iss1/art36/ (accessed in January 2011).

Kirby KR, Laurance WF, Albernaz AK, Schroth G, Fearnside, PM, Bergen S, Venticinque EM, da Costa C (2006): The future of deforestation in the Brazilian Amazon. Futures 38(4): 432-453.

Krüger JP (2005): Waldkonversion und Bodendegradation im tropischen Tiefland von Ostbolivien. GIS-gestützte Analyse zur Regionalisierung der Bodendegradation im Department Santa Cruz. EcoRegio 17, University of Göttingen.

Lambin EF (1997): Modelling and monitoring land-cover change processes in tropical regions. Progress in Physical Geography 21: 375-93.

Lambin EF, Geist H (2006, eds.): Land-use and Land-cover Change: Local Processes, Global Impacts. The Synthesis Report of the Land Use and Cover (LUCC) Project of IHDP and IGBP. Springer, Berlin.

Lapola D, Schaldach R, Alcamo J, Bondeau A, Koch J, Kölking C, Priess J (2010): Indirect land-use changes can overcome carbon savings by biofuels in Brazil. Proceedings of the National Academy of Sciences of the United States of America 107 (8): 3388-3393Long JS, Freese J (2006) Regression Models for Categorical Dependent Variables Using Stata. Stata Press, College Station, TX.

Liu J, Dietz T, Carpenter SR, Alberti M, Folke C, Moran E, Pell AN, Deadman P, Kratz T, Lubchenco J, Ostrom E, Ouyang Z, Provencher W, Redman CL, Schneider SH, Taylor WW (2007): Complexity of Coupled Human and Natural Systems. Science 317: 1513-1516.

Lombard A, Cowling R, Vlok J, Fabricius C (2010): Designing Conservation Corridors in Production Landscapes: Assessment Methods, Implementation Issues, and Lessons Learned. Ecology and Society 15(3): 7.

Malky A, Espioza S (2010): Factibilidad económica y proyeccion de negocio para la producción de cacao en el norte de La Paz.Conservation Strategy Fund, Serie Técnica 19, La Paz, Bolivia.

Malky A, Ledezma J (2010): Factibilidad económica y financiera de la producción de caña de azúcar y derivados en el norte del departamento de La Paz. Conservation Strategy Fund, Serie Técnica 18, La Paz, Bolivia.

Maneke M (2010): Analyse und Bewertung von MAXENT im Vergleich mit logistischer Regressionsmodellierung von Entwaldungsprozessen in Ostbolivien. Unveröffentlichte Diplomarbeit. Geographisches Institut, Universität Göttingen.

Manson SM (2005): Agent-based modeling and genetic programming for modeling land change in the Southern Yucata´n Peninsular region of Mexico. Agric Ecosyst Environ 111: 47–62.

Maplecroft (2011): Climate Change and Environmental Risk Atlas 2012. Maplecrot, London, UK. http://maplecroft.com/about/news/deforestation.html (accessed in November 2011).

Matthews R, Gilbert N, Roach A, Polhill J, Gotts N (2007): Agent-based land-use models: a review of applications. Landscape Ecol 22:1447–1459.

May PH, Millikan B, Gebara M (2010): The context of REDD+ in Brazil: Drivers, agents and institutions. Occasional paper 55. Center for International Forestry Research (CIFOR), Bogor, Indonesia.

McConnell, WJ, Sweeney SP, Mulley B (2003): Physical and social access to land: spatio-temporal patterns of agricultural expansion in Madagascar. Agriculture, Ecosystems & Environment 101, 171-184.

McGrath DG, Nepstad D, Stickler C (2010): Smallholder, Rural Development and REDD in the Brazilian Amazon. The Woods Hole Research Center, IPAM - Amazon Environmental Research Center (IPAM), Brazil. http://www.ipam.org.br/biblioteca/livro/Smallholders-Rural-Development-and-REDD-in-the-Brazilian-Amazon-/367 (accessed in January 2011).

McKibbin W, Wilcoxen P (2001): The Role of Economics in Climate Change Policy The Journal of Economic Perspectives, Vol. 16(2): 107-129.

McKinsey & Company (2010): Impact of the financial crisis on carbon economics – Version 2.1 of the cost abatement curve. McKinsey & Company. http://www.mckinsey.com/Client_Service/Sustainability/Latest_thinking/Costcurves (accessed in November 2011).

Menard S (2002): Applied logistic regression analysis (2nd edition). Thousand Oaks, CA.

Merry FD, Hildebrand, PE, Pattie P, Carter DR (2002) An analysis of land conversion from sustainable forestry to pasture. A case study in the Bolivian Lowlands. Land Use Policy, 19(3): 207–219.

Mertens B, Lambin EF (2000): Land-Cover-Change Trajectories in Southern Cameroon. Annals of the Association of American Geographers, 90(3): 467–494.

Mertens B, Kaimowitz D, Puntodewo A, Vanclay J, Mendez P (2004): Modeling Deforestation at Distinct Geographic Scales and Time Periods in Santa Cruz, Bolivia. International Regional Science Review 27 (3): 271-296.

Miles L, Kapos V (2008): Reducing Greenhouse Gas Emissions from Deforestation and Forest Degradation: Global Land-Use Implications. Science 320: 1454-1455.

Millennium Ecosystem Assessment (2005): Ecosystems and Human Well-being: Biodiversity Synthesis. World Resources Institute, Washington, DC.

Montes de Oca I (2004): Enciclopedia Geográfica de Bolivia. Editora Atenea. La Paz, Bolivia.

Morton DC, DeFries RS, Shimabukuro YE, Anderson LO, Arai E, del Bon Espirito-Santo F, Freitas R, Morisette J (2006): Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. Proceedings of the National Academy of Sciences 103(39): 14637 – 14641.

Müller D, Zeller M (2002): Land-use dynamics in the Central Highlands of Vietnam: A spatial model combining village survey data with satellite imagery interpretation. Agricultural Economics 27 (3): 333-354.

Müller R (2009): Reserva Forestal El Chore: Analisis de deforestacion y estrategias para reducirla. Naturalia, Fundación Natura Bolivia, Santa Cruz de la Sierra, Bolivia.

Müller R (2011): Possibilities to reduce tropical deforestation by carbon funding - general reflections and examples from Bolivia. In: Hansjürgens, B., Antes, R., Schrunz, M. (eds.): Permit Trading in Different Applications. Routledge, London.

Müller R (in press): Proyección de la deforestación en el TIPNIS. In Vargas M (ed.): Compensación por servicios ambientales de carbono. Una alternativa para reducir la deforestación en el TIPNIS. PIEB. La Paz, Bolivia.

Müller R, Nowicki, C, Barthlott W, Ibisch P (2003): Biodiversity and endemism mapping as a tool for regional conservation planning – case study of the Pleurothallidinae (Orchidaceae) of the Andean rainforests in Bolivia. Biodiversity and Conservation 12: 2005-2024.

Müller R, Schierhorn F, Rohde S, Gerold G (in press): Landnutzungsänderungen und Entwaldung im bolivianischen Tiefland – Analyse von Einflussfaktoren, räumliche Modellierung und Entwicklung von Szenarien. In: Coy M a Neuburger M (eds): Global Change: Herausforderungen für Lateinamerika. Proceedings of the Annual Conference of the Society of German Geographers, Geographical Institute, Innsbruck University.

Munroe DK, Müller D (2007): Issues in spatially explicit statistical land-use/cover change (LUCC) models: Examples from western Honduras and the Central Highlands of Vietnam. Land Use Policy (24): 521-530.

Munroe DK, Southworth J, Tucker CM (2004): Modeling Spatially and Temporally Complex Land Cover Change: The Case of Western Honduras. Professional Geographer 56(4): 544-559.

Museo Noel Kempff, Prefectura de Santa Cruz (2008): Cobertura y Uso Actual de la Tierra. Land use map of the Santa Cruz department. Santa Cruz, Bolivia. www.museonoelkempff.org/sitio/descargar_archivo.php?id=3134 (accessed in June 2011).

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca G, Kent J (2000): Biodiversity hotspots for conservation priorities. Nature 403, 853-858.

Nagendra H, Southworth J, Tucker C, (2003): Accessibility as a determinant of landscape transformation in western Honduras: linking pattern and process. Landscape Ecology 18: 141–58.

NASA (2009) The NASA LCLUC Program – An interdisciplinary approach to study land-cover and land-use change. NASA and Univserity of Maryland.

http://lcluc.umd.edu/products/BROCHURE/2009_NASA_LCLUC_brochure.pdf (accessed in April 2010).

Navarro G, Ferreira W (2007): Mapa de Vegetación de Bolivia a escala 1:250.000. On CD-ROM. The Nature Conservancy (TNC), RUMBOL. Cochabamba, Bolivia.

Navarro G, Maldonado M (2002): Geografía ecológica de Bolivia. Vegetación y ambientes acuáticos. Fundación Simón I. Patiño. Cochabamba, Bolivia.

Nepstad DC, Stickler CM, Almeida OT (2006): Globalization of the Amazon soy and beef industries: opportunities for conservation. Conserv. Biol. 20: 1595–1603.

Nepstad DC, Stickler, CM, Soares- Filho B, Merry F (2008): Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. Phil. Trans. R. Soc. B 363: 1737-1746.

OTAI (Organización de Técnicos de la Agroindustria) (2008): Principales datos de la agro-industria azucarera: Zafra 2008. Santa Cruz, Bolivia.

Overmars KP, Verburg PH, Veldkamp T (2007): Comparison of a deductive and an inductive approach to specify land suitability in a spatially explicit land use model. Land use policy 24: 584–599.

Pacheco P (1998): Estilos de desarrollo, deforestación y degradación de los bosques en las tierras bajas de Bolivia. CEDLA, TIERRA, CIFOR. La Paz, Bolivia.

Pacheco P (2005): Descentralización forestal en Bolivia: Implicaciones en el gobierno de los recursos forestales y el bienestar de los grupos marginados. Santa Cruz, Bolivia: CIFOR, IDRC.

Pacheco P (2006a): Agricultural expansion and deforestation in Lowland Bolivia: the import substitution versus the structural adjustment model. Land Use Policy 23: 205-225.

Pacheco P (2006b): Acceso y uso de la tierra y bosques en Bolivia: sus implicaciones para el desarrollo y la conservación. La Paz, Bolivia: UDAPE.

Pacheco P, Mertens B (2004): Land use change and agriculture development in Santa Cruz. Bois et Forêt des Tropiques 280(2): 29-40.

Pacheco P, Ormachea E, Cronkleton P, Albornoz M, Paye L (2009): Trayectorias y tendencias de la economía forestal extractiva en el norte amazónico de Bolivia. CIFOR/CEDLA/RRI. La Paz, Bolivia.

Pacheco P, de Jong W, Johnson J (2010): The evolution of the timber sector in lowland Bolivia: Examining the influence of three disparate policy approaches. Forest Policy and Economics 12(4): 271-276.

Pacheco P, Aguilar-Støen M, Börner J, Etter A, Putzel L, Vera-Diaz M (2011): Landscape transformation in tropical Latin America: Assessing trends and policy implications for REDD+. Forests 2(1): 1-29.

Papua New Guinea Government (2008): READINESS PLAN IDEA NOTE (R-PIN). Department of Environment and Conservation, Papua New Guinea. http://forestcarbonpartnership.org/fcp/sites/forestcarbonpartnership.org/files/Documents/PDF/PNG_R-PIN_07-31-08.pdf (accessed in August 2010).

Parker DC, Manson SM, Janssen MA, Hoffmann MJ, Deadman P (2002): Multiagent systems for the simulation of land-use and land-cover change: a review. Annals of the Association of American Geographers 93 (2): 314-337.

Pedroni L, Dutschke M, Streck C, Porrúra ME (2009): Creating incentives for avoiding further deforestation: The nested approach. Climate Policy 9, 207-220.

Perz S, Skole D (2003): The Social Determinants of Secondary Forests in the Brazilian Amazon. Social Science Research 32, 25-60.

Peters-Stanley M, Hamilton K, Marcello T, Sjardin M (2011): State of the Voluntary Carbon Markets 2011. Ecosystem Marketplace, New York, and Bloomberg New Energy Finance, Washington.

http://www.forest-trends.org/publication_details.php?publicationID=2828.

Phillips SJ, Anderson RP, Schapire RE (2006): Maximum entropy modeling of species geographic distributions. Ecological Modelling 190: 231–25.

Physorg (2010): Germany, Norway give $1.5B to fight deforestation. http://www.physorg.com/news194102799.html (accessed in November 2011).

Pijanowski BC, Alexandridis KT, Mueller D (2006): Modelling urbanization patterns in two diverse regions of the world. Journal of Land Use Science 1: 83–10.

Pinto J (2006): Evolución del paisaje de conservación de la reserva forestal el Choré. Kempffiana 2006 2(1): 45-56.

Pistorius T (2009): “Co-benefits” on the paper vs. multiple benefits on the ground – Implications and tools for REDD pilot projects with a high value of biodiversity. ETFRN newsletter 50: 11-19.

Pokorny B, Johnson J, Medina G, Hoch L (in press): Market-based conservation of the Amazonian forests: Revisiting win–win expectations. In press at Geoforum. doi:10.1016/j.geoforum.2010.08.002

Pontius RG, Batchu K (2003): Using the relative operating characteristic to quantify certainty in prediction of location of land cover change in India. Transactions in GIS 7(4): 467-484.

Pontius RG, Malanson J (2005): Comparison of the accuracy of land change models: cellular automata markov versus geomod. Int J Geogr Inf Sci 19: 243–265.

Pontius RG, Millones M (2011): Death to Kappa: birth of quantity disagreement and allocation disagreement for accuracy assessment. International Journal of Remote Sensing 32 (15): 4407-4429.

Pontius RG, Pacheco P (2004): Calibration and validation of a model of forest disturbance in the Western Ghats, India 1920 - 1990. GeoJournal 61(4): 325-334.

Pontius RG, Schneider L (2001): Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA. Agriculture, Ecosystems and Environment 85: 239–248.

Prefectura de Santa Cruz – Consorcio IP/CES/KWC (1996): Memoria del Plus, Plan de Uso de Suelo del Departamento de Santa Cruz, Bolivia. Santa Cruz, Bolivia.

Redo D, Millington A, Hindery D (2011): Deforestation dynamics and policy changes in Bolivia’s post-neoliberal era. Land Use Policy 28: 227-241.

Resnikowski H (2007): La detección de la reducción de bosques en Bolivia y las proyecciones futuras de la Superintendencia Forestal en Bolivia. Ecología en Bolivia, 42(1): 1-3.

Reuters (2010): New Britain Palm to buy PNG plantations; shares rise. News article from February 25th 2010. http://www.reuters.com/article/2010/02/24/newbritainpalmoil-idUSSGE61M0IZ20100224?type=marketsNews (accessed in November 2011).

Ricardo D (2002): The Principles of Political Economy and Taxation. Janus Publishing, London. (Original publication from 1817).

Robertson N, Wunder S (2005): Fresh Tracks in the Forest - Assessing Incipient Payments for Environmental Services Initiatives in Bolivia. CIFOR, Jakarta, Indonesia.

Rodrigues A, Akçakaya R, Andelman S, Bakarr M, Boitani L, Brooks T, Chanson J, Fishpool L, da Fonseca G, Gaston K, Hoffmann M, Marquet P, Pilgrim J, Pressey R, Schipper J, Sechrest W, Stuart S, Underhill L, Waller R, Watts M, Yan X (2004): Global Gap Analysis: Priority Regions for Expanding the Global Protected-Area Network. BioScience 54 (12): 1092-1100.

Rosegrant MW, Ringler C, Msangi S, Sulser TB. , Zhu T, Cline SA (2008): International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute, Washington, D.C.

Rudel T (2005): Changing agents of deforestation: From state-initiated to enterprise driven processes, 1970–2000. Land Use Policy (24): 35-41.

Sampaio G, Nobre C, Heil Costa M, Satyamurty P, Soares-Filho B, Cardoso M (2007): Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. Geophysical Research Letters 34.

Sandoval CD, Sandoval AV, del Río MA, Sandoval F, Mertens C, Parada C (2003): Santa Cruz – Economía y poder. Fundación PIEB. La Paz, Bolivia.

Santilli M, Mouthino P, Schwartzman S, Nepstad D, Curran L, Nobre C (2005): Tropical deforestation and the Kyoto protocol. Climatic Change 71: 267-276.

Schierhorn F (2008): Landnutzungsänderung im tropischen Tiefland im Department Santa Cruz (Bolivien) - GIS-gestützte und statistische Modellierung der Waldkonversion. Unveröffentlichte Diplomarbeit. Geographisches Institut, Universität Göttingen.

Servicio Geológico de Bolivia (1978): Mapa Geológico de Bolivia, 1:1,000000. Servicio Geológico de Bolivia. La Paz, Bolivia.

SEPCAM (Servicio Prefectural de Caminos) (2008): Red prefectural de caminos en el departamento de Santa Cruz, Bolivia. http://www.sepcamsc.gob.bo (accessed in August 2008).

Silva Chavez G (2005): Reducing Emissions from Tropical Deforestation by Applying Compensated Reduction to Bolivia. In: Moutinho P., Schwartzman, S. (eds): Tropical Deforestation and Climate Change. Amazon Institute for Environmental Research, Belém, Para, Brazil and Washington, DC, USA.

Singh G (2010): Understanding Carbon Credits. Adithya Books. New Delhi, India, 266 pp.

Skutsch M, Bird N, Trines E, Dutschke M, Frumhoff P, de Jong B, van Laake P, Masera O, Murdiyarso D (2007): Clearing the way for reducing emissions from tropical deforestation. Environmental Science and Policy 10(4): 322-334.

Soares-Filho BS, Nepstad DC, Curran LM, Cerqueira GC, Garcia RA, Ramos CA, Voll E, McDonald A, Lefebvre P, Schlesinger P (2006): Modelling conservation in the Amazon basin. Nature 440: 520–523.

Soares-Filho B, Rodrigues H, Costa W (2009): Modeling environmental dynamics with Dinamica Ego. Centro de Sensoriamento Remoto/Universidade Federal de Minas Gerais. Belo Horizonte, Brazil. http://www.csr.ufmg.br/dinamica/tutorial/Dinamica_EGO_guidebook.pdf (accessed in November 2011).

Sohl TL, Sayler KL, Drummond MA, Loveland TR (2007): The FORE-SCE model: a practical approach for projecting land cover change using scenario-based modeling. Journal of Land Use Science 2: 103–126.

Soria-Auza RW, Kessler M, Bach K, Barajas-Barbosa PM, Lehnert M, Herzog S, Böhner J (2010): Impact of the quality of climate models for modelling species occurrences in countries with poor climatic documentation: a case study from Bolivia. Ecological Modelling 221: 1221-1229.

Souza C, Roberts D (2005): Mapping forest degradation in the Amazon region with Ikonos images. Int. J. Remote Sensing 26: 425–429.

Stoian D, Henkemans AB (2000): Between Extractivism and Peasant Agriculture: Differentiation of Rural Settlements in the Bolivian Amazon. International Tree Crops Journal 10 (4): 299-319.

Superintendencia Forestal (2003): Potencial de los bosques naturales de Bolivia para la producción forestal permanente. Santa Cruz, Bolivia. http://www.cfb.org.bo/cfbinicio/BoliviaForestal/PotencialForestal.htm accessed in April 2009).

Superintendencia Forestal (2006): Avance de la deforestación en Bolivia. Tasa anual de deforestación en los años 2004 y 2005. Superintendencia Forestal, Santa Cruz de la Sierra, Bolivia.

Stern N (2007) The economics of climate change. American Economic Review 98(2): 1-37.

Thiele G (1995): La dinámica del asentamiento campesino en la frontera agrícola en Santa Cruz. Revista Ruralter (13/14): 109-146.

Tietenberg T (2006): Emissions trading: principles and practice, 2nd edition. Resources for the Future, Washington, USA, 233 pp.

TNC (2009): Casebook of REDD projects in Latin America. The Nature Conservancy & IDESAM, Manaus, Brazil.

Toleffson J (2011): Brazil revisits forest code Changes to legislation could undermine authorities' power to halt deforestation. Nature 476: 259-260.

Tonelli Justiniano O (2004): Reseña histórica social y económica de la Chiquitania. Editorial El País. Santa Cruz, Bolivia.

Trines E, Höhne N, Jung M, Skutsch M, Petsonk A, Silva-Chavez G, Smith P, Nabuurs G, Verweij P, Schlamadinger B (2006): Integrating Agriculture, Forestry and Other Land Use in Future Climate Regimes. Report 500102002 under the “Climate Change Scientific Assessment and Policy Analysis” Research Fund. Netherlands. http://www.pbl.nl/en/publications/2006/integrating_agriculture_forestry_and_other_land_use_climate_regimes (accessed in February 2011).

UNESCO (1996): Biosphere Reserves: The Seville Strategy and the Statutory Framework of the World Network. UNCESCO, Paris.

UNFCCC (2006): Background Paper for the workshop on reduced emissions from deforestation in developing countries. Part 2: policy approaches and positive incentives. Working paper 1(b). http://unfccc.int/files/meetings/ad_hoc_working_groups/lca/application/pdf/mitigation1biiinp18081009.pdf (accessed in January 2011).

UN-REDD (2011a): National programs. http://www.un-redd.org/AboutUNREDDProgramme/NationalProgrammes/tabid/584/Default.aspx (accessed in November 2011).

UN-REDD (2011b): Bolivia, DRC and Zambia Secure Critical Funding for their REDD+ Readiness. UN REDD newsletter. http://www.un-redd.org/Newsletter7_PB4_Countries_Reactions/tabid/3924/Default.aspx (accessed in February 2011).

USGS (U.S. Geological Survey) (2004): 3 Arc Second SRTM Elevation model, Unfilled Unfinished 2.0. Global Land Cover Facility, University of Maryland, Maryland. http://www.landcover.org/data/srtm/. (accessed in November 2009).

van der Werf GR, Morton, DC, DeFries, RS, Olivier, JG, Kasibhatla, PS, Jackson, RB, Collatz GJ, Randerson JT (2009): CO_2 emissions from forest loss. Nature Geosciences 2: 737-738

Venter O, Laurance WF, Iwamura T, Wilson, KA, Fuller, RA, Possingham HP (2009): Harnessing Carbon Payments to Protect Biodiversity. Science 326: 1368.

Vera-Diaz M, Kaufmann R, Nepstad D and Schlesinger P (2007): An interdisciplinary model of soybean yield in the Amazon Basin: The climatic, edaphic, and economic determinants. Ecological Economics: 420–431.

Vera Diaz MC, Reid J, Soares Filho B, Kaufman R, Fleck L (2007): Efectos de los proyectos de energía y transporte en la expansión del cultivo de soya en la cuenca del río de madeira. Serie Técnica 7, Conservation Strategy Fund, La Paz, Bolivia.

Verburg PH, Kok K, Pontius RG, Veldkamp A (2006): Modeling land-use and landcover change. In: Lambin EF, Geist HJ (eds.): Land-use and land-cover change: local processes and global impacts, Springer, Berlin, pp. 117-135.

Verburg PH, Overmars KP (2009): Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landscape Ecology 24 (9): 1167-1181.

Verburg P, Schot P, Dijst M, Veldkamp A (2004): Land use change modeling: current practice and research priorities. GeoJournal 61: 309-324.

Verburg PH, Veldkamp A (2004): Projecting land use transitions at forest fringes in the Philippines at two spatial scales. Landscape Ecology 19 (1): 77-98.

von Thünen J (1990): Der Isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie. Scientia Verlag, Aalen. (Original publication from 1826).

Walker R, Browder J, Arima E, Simmons C, Pereira R, Caldas M, Shirota R, Zen S (2009): Ranching and the new global range: Amazonia in the 21st century. Geoforum 2009, 40: 732-745.

Wara M (2009): Measuring the Clean Development Mechanism’s performance and potential. In Schneider S, Rosencranz A , Mastrandrea MD (eds.): Climate change science and policy. Island Press, Washington DC, USA. 522 pp.

Wertz-Kanounnikoff S, Kongphan-apirak M (2009): Emerging REDD+: A preliminary survey of demonstration and readiness activities. CIFOR Working Paper 46, CIFOR.

http://www.cifor.cgiar.org/Knowledge/Publications/Detail?pid=2869 (accessed in January 2010).

Wunder S (2006): Are direct payments for environmental services spelling doom for sustainable forest management in the tropics? Ecology and Society 11(2): 23.

WWF (1998): Guidance for Ecoregion-based Conservation: Principles, Essential Elements, and General Approach. World Wildlife Fund, Washington, USA.

Zea O´Phelan M, Guachalla Argandoña J, Molina F (2002): Medición de la efectividad del manejo del Sistema Nacional de Áreas Protegidas. Servicio Nacional de Áreas Protegidas, La Paz, Bolivia.

Appendix

Appendix A - Supplementary material for Chapter Two

Table A.1 Description and basic statistics of independent variables used in Chapter Two.

Variable	Unit	Number of observations	Mean	Standard Deviation	Minimum	Maximum
Excessive rainfall	100 mm	2968407	0.33	1.66	0.00	41.00
Drought risk	100 mm	2968407	1.28	1.78	0.00	6.00
Fertile soils	Dummy (1/0)	2968407	0.31	0.46	0.00	1.00
Precambrian soils	Dummy (1/0)	2968407	0.49	0.50	0.00	1.00
Slope	degrees	2968407	5.09	0.94	5.00	48.00
Transportation costs 1976	US$/t-km	2968407	48.25	23.66	0.45	104.06
Transportation costs 1986	US$/t-km	2968407	40.50	20.06	0.45	101.68
Transportation costs 1992	US$/t-km	2968407	37.61	19.59	0.45	101.28
Transportation costs 2001	US$/t-km	2968407	35.87	19.18	0.47	101.36
Transportation costs 2005	US$/t-km	2968407	34.74	19.03	0.47	101.36
Dist. to deforest. before 1976	ln(distance in 100 km)	2966253	11.18	1.26	5.30	12.66
Dist. to deforest. 1976-1986	ln(distance in 100 km)	2942472	10.66	1.21	5.30	12.45
Dist. to deforest. 1986-1992	ln(distance in 100 km)	2925875	10.64	1.39	5.30	12.45
Dist. to deforest. 1992-2001	ln(distance in 100 km)	2828678	10.30	1.59	5.30	12.44
Dist. to deforest. 2001-2005	ln(distance in 100 km)	2933807	10.37	1.37	5.30	12.45

Table A.2 Coefficients and z-statistics for all models calculated in Chapter Two.

Table A.2 a) Model results including distance to prior deforestation

		Logit coefficient	Standardized logit coefficient	Odds Ratio	z-statistic
Model 1976-86 AUC: 0.958 Pseudo R2: 0.417	Excessive rainfall	-0.359	-0.59	0.699	-38.6
	Drought risk	-0.556	-0.99	0.573	-57.6
	Fertile soils	0.265	0.27	1.304	17.1
	Precambrian soils	-2.723	-2.72	0.066	-49.4
	Slope	-0.324	-0.30	0.723	-3.5
	Transportation costs	-0.046	-1.09	0.955	-54.6
	Distance to prior deforestation	-0.599	-0.75	0.549	-113.8
	Constant	4.951			10.6
Model 1986-92 AUC: 0.956 Pseudo R2: 0.424	Excessive rainfall	-0.527	-0.88	0.590	-44.3
	Drought risk	-0.389	-0.69	0.678	-83.0
	Fertile soils	0.832	0.83	2.299	79.8
	Precambrian soils	-2.092	-2.09	0.123	-58.3
	Slope	-0.758	-0.72	0.469	-5.8
	Transportation costs	-0.084	-1.68	0.920	-127.9
	Distance to prior deforestation	-0.615	-0.73	0.540	-157.5
	Constant	8.050			12.4
Model 1992-2001 AUC: 0.950 Pseudo R2: 0.457	Excessive rainfall	-0.393	-0.66	0.675	-69.8
	Drought risk	-0.341	-0.61	0.711	-114.3
	Fertile soils	0.508	0.51	1.662	64.1
	Precambrian soils	-3.101	-3.10	0.045	-130.2
	Slope	-0.779	-0.74	0.459	-8.4
	Transportation costs	-0.030	-0.58	0.971	-78.4
	Distance to prior deforestation	-0.690	-0.91	0.502	-242.8
	Constant	9.288			20.1
Model 2001-05 AUC: 0.963 Pseudo R2: 0.479	Excessive rainfall	-0.253	-0.44	0.776	-41.7
	Drought risk	-0.497	-0.91	0.608	-90.9
	Fertile soils	-1.021	-1.02	0.360	-89.3
	Precambrian soils	-2.232	-2.23	0.107	-92.8
	Slope	-0.384	-0.38	0.681	-8.7
	Transportation costs	-0.037	-0.69	0.964	-70.7
	Distance to prior deforestation	-0.934	-1.35	0.393	-267.2
	Constant	9.013			40.4
Model 2001-05 without Fertile soils AUC 0.962 Pseudo R2: 0.468	Excessive rainfall	-0.140	-0.24	0.869	-27.1
	Drought risk	-0.710	-1.31	0.491	-143.3
	Precambrian soils	-2.044	-2.04	0.129	-84.6
	Slope	-0.364	-0.36	0.695	-8.7
	Transportation costs	-0.029	-0.55	0.971	-55.7
	Distance to prior deforestation	-0.851	-1.23	0.427	-253.0
	Constant	7.743			36.5
Model 1976-2005 AUC: 0.962 Pseudo R2: 0.542	Excessive rainfall	-0.753	-1.25	0.471	-166.5
	Drought risk	-0.765	-1.36	0.465	-291.1
	Fertile soils	1.399	1.40	4.052	200.3
	Precambrian soils	-3.319	-3.32	0.036	-219.3
	Slope	-0.596	-0.56	0.551	-15.7
	Transportation costs	-0.049	-1.17	0.952	-181.8
	Distance to prior deforestation	-0.449	-0.56	0.639	-151.5
	Constant	8.262			43.1
- all values are significant at the 99% level -					

Table A.2 b) Model results without distance to prior deforestation

		Logit coefficient	Standardized logit coefficient	Odd Ratio	z-Statistic
Model 1976-86 AUC 0.955 Pseudo R2: 0.390	Excessive rainfall	-0.517	-0.86	0.596	-54.0
	Drought risk	-0.861	-1.53	0.423	-90.9
	Fertile soils	-0.413	-0.41	0.662	-30.8
	Precambrian soils	-3.695	-3.70	0.025	-69.0
	Slope	-0.434	-0.41	0.648	-4.4
	Transportation costs	-0.107	-2.54	0.898	-154.1
	Constant	1.800			3.6
Model 1986-92 AUC: 0.947 Pseudo R2: 0.388	Excessive rainfall	-0.746	-1.24	0.474	-62.7
	Drought risk	-0.576	-1.03	0.562	-118.7
	Fertile soils	0.827	0.83	2.287	81.4
	Precambrian soils	-2.876	-2.88	0.056	-81.3
	Slope	-0.922	-0.87	0.398	-6.8
	Transportation costs	-0.123	-2.47	0.884	-211.3
	Constant	4.322			6.4
Model 1992-2001 AUC: 0.935 Pseudo R2: 0.409	Excessive rainfall	-0.643	-1.08	0.526	-104.8
	Drought risk	-0.546	-0.98	0.580	-198.0
	Fertile soils	1.044	1.04	2.842	141.4
	Precambrian soils	-3.715	-3.72	0.024	-158.4
	Slope	-1.029	-0.98	0.357	-10.4
	Transportation costs	-0.084	-1.63	0.919	-259.9
	Constant	5.373			10.8
Model 2001-05 AUC: 0.932 Pseudo R2: 0.362	Excessive rainfall	-0.515	-0.89	0.597	-97.3
	Drought risk	-0.636	-1.17	0.530	-150.2
	Fertile soils	0.062	0.06	1.064	6.5
	Precambrian soils	-3.835	-3.84	0.022	-168.1
	Slope	-0.337	-0.33	0.714	-8.3
	Transportation costs	-0.088	-1.65	0.916	-206.2
	Constant	1.989			9.8
Model 1976-2005 AUC: 0.952 Pseudo R2: 0.531	Excessive rainfall	-0.797	-1.32	0.451	-185.8
	Drought risk	-0.918	-1.63	0.399	-354.5
	Fertile soils	1.150	1.15	3.159	179.5
	Precambrian soils	-3.712	-3.71	0.024	-250.9
	Slope	-0.699	-0.65	0.497	-17.7
	Transportation costs	-0.081	-1.91	0.922	-384.2
	Constant	5.394			27.3
- all values are significant at the 99% level -					

Appendix B - Supplementary material for Chapter Three

Validation of the map of the proximate causes of deforestation (Figure 3.3)

A quantitative validation of the final map was conducted for the area within the Department of Santa Cruz, where this map is based on Museo Noel Kempff and Prefectura de Santa Cruz (2008). The validation uses 18 scenes from the High Resolution Camera of the China-Brazil Earth Resource Satellite (CBERS HRC) with a spatial resolution of 2.5 meters distributed over the entire lowland area of the Department of Santa Cruz. For each proximate cause of deforestation identified on the final map, 150 pixels were randomly chosen within the area covered by the 18 satellite images. Proximate causes of deforestation were identified in the 450 selected pixels based on a visual interpretation of the satellite images, and the results were then compared with the final map. A coincidence of 88% was found (weighted average of the user's accuracy); the allocation disagreement was 6.5% and the quantity disagreement 5.5% (see Pontius and Millones 2011).

Deforestation patterns from small-scale agriculture typically consist of several small rectangular patches containing different degrees of vegetation removal, whereas clearings for pastures are generally larger, more uniform and often contain a few scattered remaining trees as well as drinking ponds. Mechanized agriculture is characterized by generally large, geometrically shaped clearings. These clearings often contain windbreaks and furrows and have highly varying reflectivities due to particular agricultural phases (e.g., sewing or harvesting).

Table B.1 Validation of the map of land use change in Chapter Three: confusion matrix of the sample, unadjusted for stratified sampling design (following Pontius and Millones 2011).

Map of proximate causes of deforestation

		Mechanized agriculture	Small-scale agriculture	Cattle ranching	Total	**Producer's accuracy**	**Producer's accuracy adjusted for class sizes**
CBERS interpretation	Mechanized agriculture	129	3	9	141	**91%**	**96%**
	Small-scale agriculture	3	139	8	150	**93%**	**87%**
	Cattle ranching	18	8	133	159	**84%**	**77%**
	Total	150	150	150	450		
	User's accuracy	**86%**	**93%**	**89%**			

Table B.2 Accuracy assessment for the land use map in Chapter Three (following Pontius and Millones 2011).

Results adjusted for class sizes	
Weighted average of user’s accuracy (proportion agreement)	**88.0%**
Allocation disagreement	**6.5%**
Quantity disagreement	**5.5%**

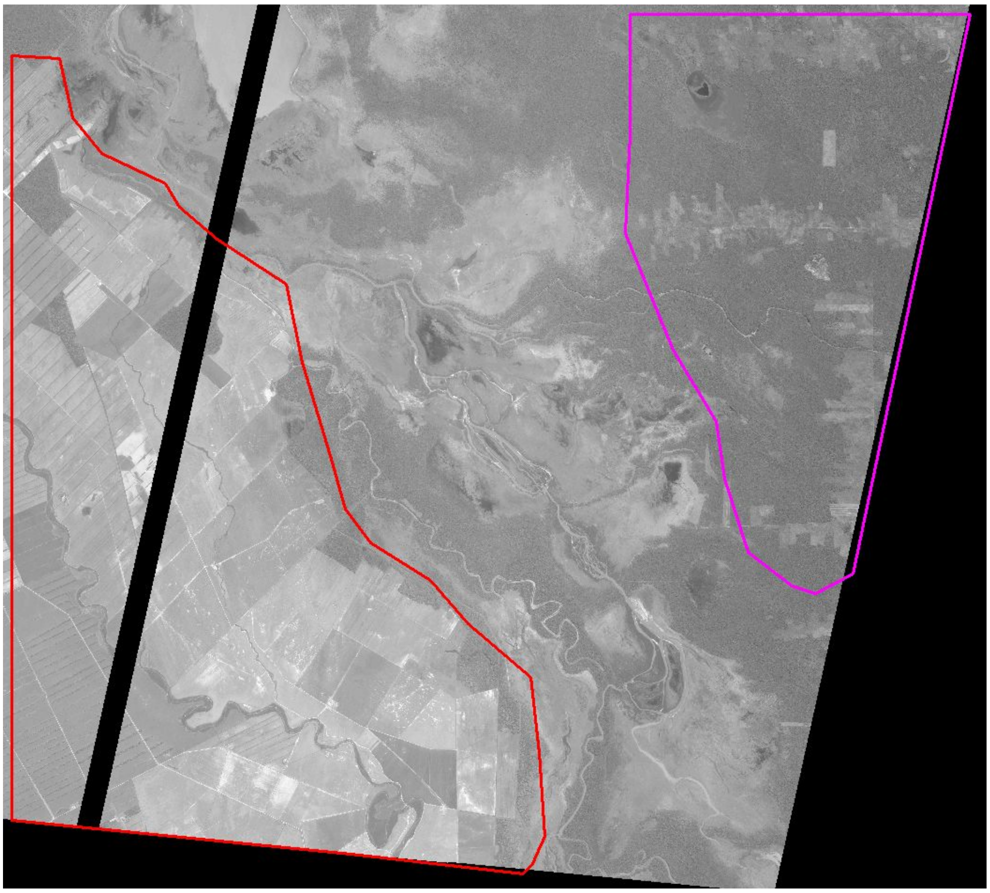
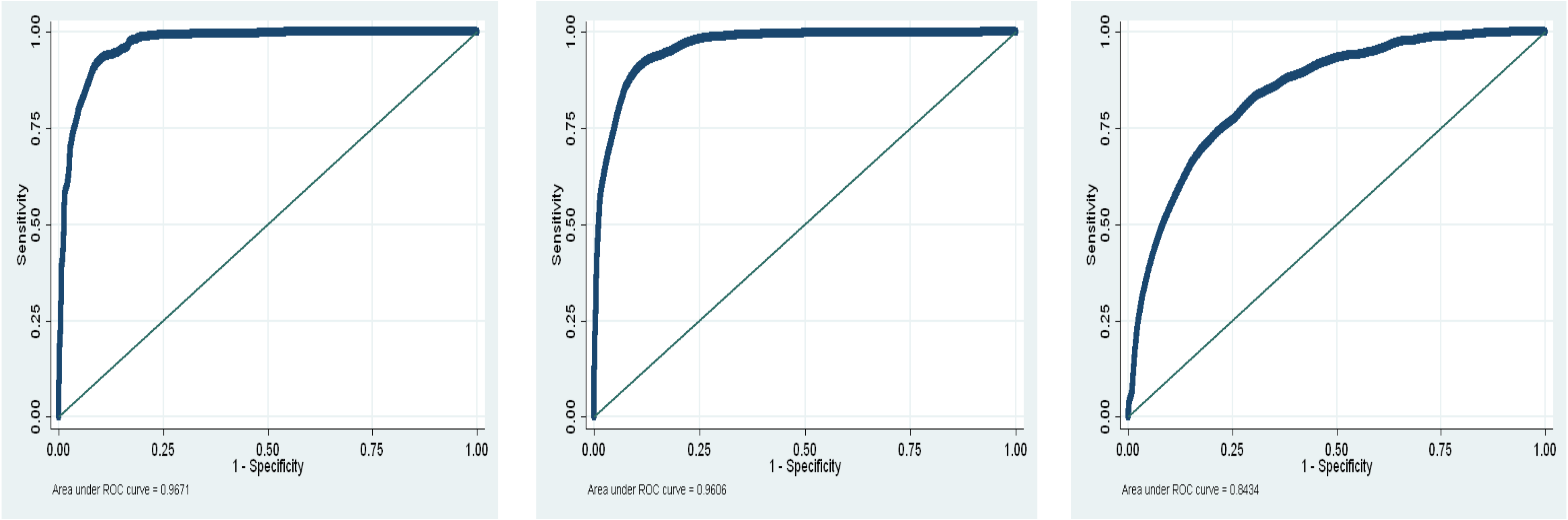


Figure B.1 a) Examples of the identification of proximate causes of deforestation from CBERS HRC images (mechanized agriculture in red, small-scale agriculture in purple and cattle ranching in yellow). Example from the north of Santa Cruz

Figure B.1 b) and c) Example from the South of Santa Cruz and the East of Riberalta

Figure B.2 Visual representations of the AUC values to evaluate the goodness of fit of calibration for the three proximate causes of deforestation, for the model in Chapter Three.



a) Mechanized agriculture

8 b) Small-scale agriculture

8 c) Cattle ranching

Curriculum Vitae

Personal data

Robert Christian Müller

Date of birth: 25.04.1974

Place of birth: Heidelberg, Germany

Nationality: German

Education

2007 – 2011	PhD studies at Göttingen University, Department of Landscape Ecology
1998 - 2001	Studies of Biology at Bonn University (major subjects: Botany, Zoology, Soil Science, Ecology). Diploma thesis in cooperation with the Fundación Amigos de la Naturaleza (FAN), Santa Cruz, Bolivia, titled: “Extrapolation von Diversität und Endemismus der Pleurothallidinae (Orchidaceae) im Biokorridor Amboró-Madidi sowie Empfehlungen für die Naturschutzplanung“.
1995-1997	Studies of Biology at Vienna University.
1993	Abitur at Kurfürst Friedrich Gymnasium Heidelberg.

Work Experience

2006 – present	Carbon project development for atmosfair gGmbH, Bremen Overseas Development Agency (BORDA), Women in Europe for a Common Future (WECF) and others. Focus on pro-poor energy projects in Latin America and Asia.
2007 – 2010	Coordination of the DFG funded research project “Landnutzung, Entwaldung und Naturschutz in Bolivien – Analyse und modellgestützte Prognose zukünftiger Entwicklungen“ at Göttingen University, Department of Landscape Ecology.
2001 – 2005	Consultant and project coordinator for biodiversity conservation, reforestation and sustainable agriculture in Bolivia, for Trópico - Asociación Boliviana para la Conservación, Fundación Amigos de la Naturaleza and Fundación Natura Bolivia.