UNDERSTANDING AND MAPPING
LAND-USE AND LAND-COVER CHANGE ALONG
BOLIVIA’S CORREDOR BIOCEÁNICO

A Dissertation

by

DANIEL J. REDO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2010

Major Subject: Geography

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Approved by:

Chair of Committee,	Andrew Millington
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ABSTRACT

Understanding and Mapping Land-Use and Land-Cover Change
along Bolivia's Corredor Bioceánico. (May 2010)
Daniel J. Redo, B.S.; M.S., The University of Southern Mississippi
Chair of Advisory Committee: Dr. Andrew Millington

The Corredor Bioceánico is a major transportation project connecting the agricultural heartlands of South America to the Atlantic and Pacific coasts. The final link is in southeastern Bolivia – an underdeveloped area that is home to two indigenous groups and globally-significant woodlands and wetlands. Infrastructure developments – comprising a major highway upgrade, revitalized railway services and increased flows along gas pipelines to Brazil – pose major threats to livelihoods and the region's ecological integrity. There are two broad objectives: (i) to map and quantify the spatial patterns of land change using a time-series of coarse and medium resolution satellite imagery; and (ii) to understand the socio-economic and political drivers of change by linking household surveys and interviews with farmers; environmental, climatic, and political data; and classified satellite imagery.

Overall, large-scale deforestation has occurred along the Corredor Bioceánico for mechanized commercial production of oil-seed crops such as soybeans and sunflower. The significance of these findings is that agriculture-driven deforestation is pushing into sensitive areas threatening world-renowned ecosystems such as the Chaco, Chiquitano and Pantanal as well as noteworthy national parks. Though quantity remains relatively small compared to other parts of South America, rates of forest loss match or exceed those of more publicized regions such as Rondônia or Mato Grosso, Brazil. Moreover, rates of forest loss are accelerating linearly with time due to policies implemented by incumbent president Evo Morales. Results also show that in the first years of cultivation, pasture is the dominant land-use, but it quickly gives way to intensively cropped farmland. The main findings in terms of percentage area cleared according to forest type is that farmers appear to be favoring transitional forest types on deep and poorly drained soils of alluvial plains. Semi-structured interviews with farmers and representatives of key institutions illustrate that price determined by the global market is not proportionally the most dominant motive driving LULCC in the lowlands of Santa Cruz, Bolivia – an area seen as a quintessential neoliberal frontier.

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I would also like to thank my family, whom I love dearly and who have always encouraged me in my endeavors. I would never made it this far without their support and patience. Finally, I thank my wife Katherine, who accompanied me on my first expedition to Latin America many years ago. For me to have adventures is lucky enough, but to share them with a beautiful, intelligent and wonderful woman like her is all a man could ever ask for. You have also been willing to endure the difficulties of student life today for a more promising tomorrow. To all of you, words cannot express my gratitude – my accomplishments would not have been possible without your support. I hope that I have made all of you proud.

NOMENCLATURE

ANAPO	*Asociación de Productores de Oleaginosas y Trigo* (Association of Oilseed and Wheat Producers)
AVHRR	Advanced Very High Resolution Radiometer
CAF	*Corporación Andina de Fomento* (Andean Development Corporation)
CAO	*Cámara Agropecuaria del Oriente* (Agricultural Chamber of the East)
CBERS	Chinese-Brazil Earth Resources Satellite
DN	Digital Number
ETM+	Enhanced Thematic Mapper
GLCF	Global Land Cover Facility
HRCCD	High-Resolution Charge Coupled Device
IADB	Inter-American Development Bank
IMA	Integrated Management Area
INPE	Brazilian National Space Research Institute
IRS	Indian Remote Sensing Satellite
KINP	Kaa-Iya del Gran Chaco National Park
LULC	Land-Use and Land-Cover
LULCC	Land-Use and Land-Cover Change
MAS	*Movimiento al Socialismo* (Movement Towards Socialism)
MERCOSUR	*Mercado Común del Sur* (Common Market of the South)
MODIS	Moderate Resolution Imaging Spectroradiometer

MSS	Multispectral Scanner
MVC	Maximum Value Composite
NDVI	Normalized Difference Vegetation Index
NGO	Non-Governmental Organization
NP	National Park
LP DAAC	Land Processes Distributed Active Archive Center
RMSE	Root Mean Square Error
SEA	Strategic Environmental Studies
SEF	Socio-Economic Function
SPOT	*Satellite Pour l'Observation de la Terre* (Earth Observation Satellite)
TM	Thematic Mapper
USGS	United States Geological Survey
WB	World Bank
WWF	World Wildlife Fund

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1. INTRODUCTION

Just wait until we learn how to farm here; then we will really show people how to produce (Mennonite farmer interviewed by J.W. Lanning, 1971)

There seems every reason to believe that growth of the region [Santa Cruz], for at least the next few decades, may well be at a rate seldom excelled in the Western Hemisphere (O.E. Leonard, 1948)

1.1 CONTEXT AND STATEMENT OF THE PROBLEM

Infrastructure development and improvement projects are under way across the South American continent. These consist of investments in the construction of highways, rail lines, and oil and natural gas pipelines to tap into the rich and relatively untouched natural resources of the Amazon Basin. Investments of hundreds of millions dollars by organizations such as the Inter-American Development Bank (IADB) and World Bank (WB) have one long-term goal – to accelerate economic development through accessibility and mobility and chink away at Latin America's multi-trillion dollar infrastructural deficit (Killeen 2007a; Becqué et al. 2007; Keeling 2002; Pató 2000). One such project is the Corredor Bioceánico[1] (Figure 1; Figure 2) in southeastern Bolivia where the eventual aim is to strengthen Bolivia's weak transportation

This dissertation follows the style of the *Annals of Association of American Geographers.*

[1] In this dissertation, the Corredor Bioceánico has been subdivided according to a 50-km buffer to the north and south as well as three natural subdivisions within the corridor: Tierras Bajas (Sp. Low Lands), Brazilian Shield, and Pantanal (Po. Swamp). The 50-km swath width is based on the fact that (1) the oldest colonization in the Tierras Bajas, close to Santa Cruz has extended ~50 km from the main highway in a period of ~50 years, and (2) similar studies in the Brazilian Amazon indicate that the influence that can be attributed to a road decreases to zero after a distance of 50 km (Fearnside 2007; Carvalho et al. 2002; Laurance et al. 2001a, b; Nepstad et al. 2001). The latter subdivisions are based on distinct differences in topography, soils, precipitation, available soil moisture, vegetation and land use.

network by relieving the isolation of the still remote eastern Santa Cruz Department[2] and linking it to national and international markets. With 571 km of raised, paved road beds and new bridges, it is hoped producers in the region will be competitive in these markets.

Unlike other 'corridors' in the Amazon Basin, particularly well-recognized road corridors in Brazil (see Fearnside 2002; 2006; 2007), the Corredor Bioceánico consists of a two-lane highway, a railroad, and two natural gas pipelines. All three bisect territories of indigenous peoples; relatively undisturbed, biologically-important ecoregions; and several noteworthy national parks (Figure 2). Aided by foreign direct investment in the form of substantial loans, the Bolivian government is currently upgrading the highway, upgrading track and revitalizing railway services, and increasing natural gas flow along the Bolivia-Brazil and Cuiabá pipelines. When finished in 2011 (Medalla 2009), the new highway will complete the only paved, all-weather route in central South America connecting Pacific ports in Chile with Atlantic ports in Brazil (Vargas Ríos and Hamerschlag 2001). The highway and railway will connect the continent's agricultural heartlands of Santa Cruz and neighboring Mato Grosso do Sul, Brazil (IADB 2004) more directly to international markets through Brazilian and Chilean ports, as well as reduce the time and cost of getting exports to the ports of Arica and Santos. Soybeans, sunflower, and wheat grown in Santa Cruz will reach the main outlet for goods – the Hidrovía Parana-Paraguay – much faster (Figure 2). Therefore, shipping costs to the main export destinations for Bolivian soybeans – Venezuela and

[2] Bolivia is divided into nine departments (analogous to U.S. states) and each department is subdivided into provinces (analogous to U.S. counties). The Department of Santa Cruz, at 370,621 km^2, is the largest of Bolivia's departments and occupies 33% of the total national territory. It is roughly the same size as the United Kingdom or slightly larger than the state of New Mexico.

Colombia – will be significantly reduced (Dros 2004). It will integrate, both economically and commercially, the countries of *Mercado Común del Sur* or Common Market of the South (MERCOSUR).

Nationally, the upgraded corridor will overcome the transportation inadequacies that have isolated eastern Santa Cruz and inhibited effective economic and social development (Minchin 1881; Romecin 1929; Crist 1946; Heath 1959; Heath et al. 1969; Fifer 1967; Tigner 1982; Fifer 1982). It will finally help put to an end to the department's seclusion from Brazil and inability to move agricultural products to market, a problem emphatically emphasized by nearly every writer on Bolivia as symptoms and causes of the nation's long track record of woeful economic underdevelopment. Inadequate accessibility and mobility are seen as symptoms of why Bolivia lags behind wealthier countries in terms of social and economic development (Keeling 2008). For example, in 2007, Bolivia ranked 118 globally in infrastructure ranking, with only Paraguay ranking lower in South America (WEF 2008).

Research from South America has shown that road building projects have traded economic benefits (e.g., integration, cheaper access to markets) for a multitude of negative social and environmental outcomes (e.g. Fearnside 2002, 2006, 2007; Locklin and Haack 2003; Alves 2002; Nepstad et al 2001; Nelson and Hellerstein 1997). As the cost of transporting goods decreases and once remote lands become accessible for agricultural production, migrants relocate in search of better opportunities. Well-established settlements experience an increase in the area cleared as exemplified in the Brazilian Amazon (Fearnside 2005). If, as seems likely, this occurs along the Corredor

Bioceánico, indigenous peoples and well-established settlers will become vulnerable to socio-economic and political marginalization (Killeen 2007a). There is some evidence for this already as land speculation in unclaimed forests, and forest reserves is occurring along eastern Bolivia's Corredor Bioceánico (Damien Rumiz and Oscar Castillo, personal communications, 04 August 2007). This dissertation shows that the agricultural frontier has extended well beyond the agricultural 'expansion zone' outlined by Davies (1993) and Steininger et al. (2001a, b) into regions once thought impervious to large-scale, mechanized agriculture (Hecht 2005; Pacheco 2006). Settlers are already transforming the formerly remote, relatively undisturbed Chaco and Chiquitano forests and savannas – two tropical dry forest and savanna ecosystems of high ecological significance (Killeen 2007a) – which are poorly documented regarding land change (Geist and Lambin 2002; Lepers et al. 2005). In the 1920s and 30s, the pioneer fringe was still at the gates of the city of Santa Cruz[3]. In the 1960s the fringe pushed east of the Rio Grande. Today, the Tierras Bajas (between the Río Grande and Río Quimome) is almost entirely cultivated and new pioneer fringes are emerging in the uninhabited forests of Chiquitanía and Pantanal. Both are on the brink of a significant conversion to agriculture due to the availability of cheap, abundant land, groundwater, and underground aquifers for irrigation. By 2012, it is anticipated that Bolivia will double oilseed production and export to consolidate existing markets and access new market opportunities (ANAPO, 2008b). The only way this target can be met realistically is

[3] Unless otherwise specified, Santa Cruz as used in this dissertation means the city of Santa Cruz. Because Santa Cruz is also the name of the department of which the city is the capital, I use the prefix "Department" when referring to the regional level of government.

through forest-to-farmland conversion along the Corredor Bioceánico. Economic development based on agriculture in the region will likely be reinforced by the exploitation of natural gas deposits and the upgraded transport and agricultural infrastructures.

1.2 RESEARCH OBJECTIVES/QUESTIONS

The overall goal of this research is to map, quantify, and understand the drivers of land-use and land-cover change (LULCC) along eastern Bolivia's Corredor Bioceánico. There are two primary objectives, each with two sets of questions:

<u>Objective 1</u>: Map and quantify the spatial patterns of LULCC from 1975 to 2008 along eastern Bolivia's portion of the Corredor Bioceánico using a time-series of medium resolution Landsat (MSS, TM, and ETM+) and CBERS-2 and 2B data, and coarse resolution MODIS NDVI data. Specific questions answered in this objective are:

(i) Can the land change record be extended at low cost without the loss of information using CBERS-2 and 2B imagery?; and

(ii) What types of forest are being converted to pasture or a particular cropping regime, where and why; and what types of land-use modification changes have occurred?

<u>Objective 2</u>: Understand the socio-economic and political drivers of change and develop a conceptual model of drivers by linking social science to image processing techniques.

Specific questions in this objective are more easily answerable to hypothesis testing:

(i) The effects of institutions and organizations, changes in government policies, physical and climatic influences, and individual land-use decisions, rather than economic factors as argued by Hecht et al., are the most important drivers of land change.

(ii) The rise to power of Evo Morales' government and their land-use policies has introduced signals in the land-use change record. More specifically, the rates of forest clearance for agriculture changed since December 2005 and the loci of agriculture-driven deforestation have changed.

1.3 RESEARCH SIGNIFICANCE AND INTELLECTUAL MERIT

This research is significant because it partially addresses questions relevant to national and international programs. The objectives emanate, in part, from the U.S. Global Change Research Program (USGCRP) (which are incorporated in NASA's LULCC goals) and the Global Land Project: (i) Where and what type are LULC conversions occurring, and to what extent and over what time scales?; and (ii) What are the major human causes and consequences of LULCC in different geographical historical contexts (Loveland et al. 2003)?

Specifically in the region, it addresses three critical knowledge gaps: (i) less is known about the spatial pattern of LULCC in the central and eastern Corredor Bioceánico compared to the western Tierras Bajas; (ii) spatial patterns of change in previous studies are generalized due to broad-scale coverage of either the entire

Department or the entire eastern lowlands of Bolivia; and (iii) underlying drivers and proximate causes of LUC have only been vaguely specified in the dry forests and savannas of South America.

This study is undertaken in a hotspot for undertaking research in human-environment relations – Latin America (Vadjunec et al. 2002), and more specifically, southeastern Bolivia. It advances the field of land change science through the integration of remotely sensed data sources and social science thereby advancing the agenda set out by Lambin et al. (2003) and Lambin et al. (2006): using well-established social science methods to supply socio-economic parameters for interpreting land-use change (i.e. linking social science to satellite data). The research integrates and applies several sources of remotely sensed data (Landsat, CBERS and MODIS) and establishes hybrid protocols for expanded level of detail for both natural vegetation and agricultural classes. Overall, I advance the basic scientific knowledge of LULCC in southern hemisphere semi-arid wooded ecosystems previously identified as being some of the most poorly known and understood tropical and subtropical areas at the end of the IHDP/IGBP LUCC program (Lepers et al. 2005).

1.4 BROADER IMPACTS OF RESEARCH

The broad impacts of this research are twofold and are organized into the two National Science Foundation categories: (i) benefits to society; and (ii) results disseminated broadly and collaboration with agencies.

1.4.1 Benefits to Society

Currently, some of the largest stretches of intact dry forest left in the world (Chaco and Chiquitano), and the largest Neotropical wetland – the Pantanal – are threatened by development of the Corredor Bioceánico in southeastern Bolivia. They contain high levels of biodiversity (Killeen 2007a) and represent an unquantified but potentially important carbon sink (Sánchez-Azofeifa et al. 2003). Parts of these dry forests and wetlands are protected (e.g. Kaa-Iya del Gran Chaco, Pantanal de San Matías, and Otuquis National Parks and Integrated Management Areas), but all can be considered vulnerable to encroachment and degradation from current and future settlement generated by economic development along the Corredor Bioceánico.

1.4.2 Results Disseminated Broadly and Collaboration with Agencies

This doctoral dissertation has resulted in four peer-reviewed journal articles and dissemination of information through presentations at six professional and academic conferences and workshops. Local collaboration with key informants of departmental government offices, local producer organizations, and individual producers formed a significant part of this research. Results of field work (see Sections 5-8) in the form of abbreviated summaries have been made available (in Spanish) to all participants as well as the Departmental government.

1.5 DISSERTATION ORGANIZATION/OVERVIEW

In addition to the introductory section, this dissertation is organized into nine sections. Each of the four research sections (5-8) corresponds to one of the specific questions outlined in section 1.2. Moreover, this dissertation includes a detailed description of the study area, a literature review and methodology section. Due to the nature of this research and the journal article format of the research sections, similar background, study area, and data description information is contained in many of the sections. Thus, there is overlap between Sections 5 and 8. The research sections collectively represent a single body of work, but the dissertation is formatted so that each research section also represents a ‘stand alone’ publication.

Section 2 is divided into two distinct sections. The first looks at the history of LULCC and is sub-divided into global initiatives, regional change in South America, and local change in the tropical dry forests of Bolivia. It highlights the previous studies that have reported on LULCC in parts or all of the area covered in this dissertation and how I attempt to contribute to this literature. The second half assesses how researchers have attempted to understand the drivers of LULCC and outlines gaps and how I propose to fill them.

Section 3 describes the infrastructure, physical and cultural elements of the Corredor Bioceánico. Aspects covered include: the three infrastructure components which comprise the Corredor Bioceánico (highway, railroad, pipelines, and urban areas); physical environment (climate, soils, topography, land use); types of commercial agriculture; types of forests and woodlands; and inhabitants. Each aspect is described according to three natural subdivisions of the study area: Tierras Bajas, Brazilian Shield, and Pantanal.

Section 4 covers the methods used to achieve each of the two main objectives. Two major sections will cover the remote sensing and GIS data sources and methods used for research sections 5 and 6, and the semi-structured interview and survey protocols used to gather information for the research papers for Section 6 and 7.

Section 5 uses a combination of Landsat series data (MSS, TM and ETM+) to map LULCC from 1975 to 2001. It extends the land change record to 2008 using CBERS-2 and -2B data on a multi-scene level. I also establish a methodology to correct for systematic distortion without the loss of information.

Section 6 explores the use of MODIS and CBERS imagery data to map and quantify seasonal forest to cropland conversion pathways in the seasonal tropics of southeastern Bolivia. Training data to predict class membership was based on NDVI statistics derived from field observations and semi-structured interviews. Through this method, I was able to move beyond simple classification of LULC classes commonly classified in the remote sensing and land change literature, providing the fundamental foundation to ultimately linking pattern to process.

Section 7 is designed to understand the socio-economic and political drivers of LULCC through semi-structured interviews and the use of surveys. It shows that some studies have overlooked (or ignored) the effects of institutions and organizations, government policies, physical and climatic influences, and other processes important in an individual’s decision-making process. In addition, it shows that the global increase in commodity price was, and is not the only factor causing LULCC among both high-input, high-output agriculture systems and peasant production.

Section 8 compares the effects of neoliberal and post-neoliberal land-use policies on forest cover to determine if rates of agriculturally-driven forest clearance have changed since Morales' 2005 election. Satellite image analysis, supported by semi-structured interviews with farmers and representatives of key institutions, shows that deforestation for commercial agriculture in Santa Cruz continues and increased in certain "hotspots." Rates have continued to increase under the administration's new Agrarian Reform and pro-environmental regulations.

Section 9 summarizes the main research findings and considers to what extent I met my research objectives and answered the questions I posed in the introductory section. I also reflect on the implications for the wider LULCC community.

2. STATE OF KNOWLEDGE

2.1 MAPPING LAND-USE AND LAND-COVER CHANGE

A generic theme of land change science is to determine the quantity of LULC, the spatial distribution, and how much of it is in a state of expansion, decline, or resistant to change (Rindfuss et al. 2004). In addition, it is also important to determine the causes of change, the types of change, and location of change. Finally, there are reasons behind mapping LULCC.

Between 1990 and 2005, the FAO's Global Forest Resources Assessment Report (2005) stated that over 125 million hectares of tropical forest had been cleared world-wide – a combined area roughly the size of Peru or twice that of Texas. Just over half was lost in Latin America alone. Sobering statistics such as these are behind the pressing need to accurately document contemporary rates and extent of tropical deforestation at small, intermediate and large scales to support sustainable resource development, environmental protection goals, and better understand the impact humans have on the environment (Sánchez-Azofeifa et al. 2003).

Despite long-standing calls for these data, very few countries outside of the developed world have reliable estimates on the rates of LULCC (Grainger 2008). For most developing countries, annual or decadal estimates of forest cover are reported to international organizations like the FAO by national governments. This leads to different types of data being reported owing to the type of methodology used, definitions of land-cover and land-use, and variability of scale and spatial extent (Kuemmerle et al.

2009; Grainger 2008). Thus, the reliability of deforestation estimates is often questionable due to a lack of consistency and comparable data. This has led to global approaches for mapping LULC.

2.1.1 Global Initiatives

Major initiatives have been implemented to map LULCC at the global scale using historical data and medium to coarse-resolution, multi-temporal datasets. The international BIOME 300 project, for example, used agricultural statistics, land surveys, tax records, and census data to map the history of permanent cropland change for the last three centuries (Ramankutty and Foley 1999; Klein Goldewijk 2001). Global land-cover datasets, at 1-8 km resolution, have been developed: e.g. AVHRR data sets developed by the International Geosphere-Biosphere Programme (IGBP) (Loveland et al. 2000) and the Global Land-cover facility at the University of Maryland (Hansen et al. 2000; Tucker 2004; DeFries et al. 1998); the MODIS-Terra dataset developed by Friedl et al. (2002); the AVHRR long-term record released in 2007 (Pedelty et al. 2007); and the SPOT-4 continental dataset (Global Land-Cover [GLC] 2000 Project) for South America (Eva et al. 2004), Africa (Mayaux et al. 2004), and southeast Asia (Stibig et al. 2004). The main objective of many of these efforts has been to classify LULC into broad categories to detect long-term trends in Earth system dynamics, but also for dissemination to support and promote international coordination and achieve global comparisons and applications (www.igbp.net/).

Other efforts have focused specifically on tropical forests, e.g. Hansen et al. (2008a), DeFries et al. (2002) and the TREES (Tropical Ecosystem Environment Observations by Satellite) project (Achard 2002; Mayaux et al. 1999). One of the most significant gaps in global approaches is that change in tropical and sub-tropical dry forest and woodland ecosystems (especially in South America) have been largely ignored (Ramankutty et al. 2006: 28-29) because of their apparent low rates of biological activity and sparse biota (Schimel 2010: 418). Lepers et al. (2005) recognized this in their synthesis of land change for the period 1981-2000 at the end of the International Geosphere-Biosphere Programme/International Human Dimensions Programme LUCC project in stating that changes in the tropical and subtropical forests of South America (and the entire southern hemisphere) were poorly understood. Since then, there has been only one major global product which has attempted to fill the gap. Miles et al. (2006) produced a global distribution map of tropical dry forests and woodlands using the MODIS Vegetation Continuous Fields (VCF) product at 500 m resolution.

2.1.2 Regional Studies of LULCC in South America

Many LULCC assessments have been conducted in South America in the last two decades, particularly since 1999. Tucker and Townshend (2000) undertook the monumental effort to estimate deforestation in lowland Bolivia, Peru, and Colombia using 130 Landsat MSS and TM scenes coupled with a computer simulation program. Other than this, most efforts have focused on changes in smaller regions, and the overwhelming majority have been directed toward the humid tropics (e.g. Bradley and

Millington 2008; Hansen et al. 2008a, b; Etter and McAlpine 2008; Brown et al. 2007; Etter et al. 2006; Messina et al. 2006; Van Giles et al. 2006; Altstatt 2006; Morton et al. 2005; Bradley 2005; Viña et al. 2004; Millington et al. 2003; Cardille and Foley 2003; Locklin and Haack 2003; Alves 2003, 2002; Hagen et al. 2002; Walker et al. 2000; Sydenstricker-Neto et al. 2000; McCracken et al. 1999; Viña and Cavelier 1999; Moran et al. 1994; Brondizio et al. 1994; Skole and Tucker 1993; Stone et al. 1991; Malingreau and Tucker 1988; Nelson and Holben 1986; Tucker et al. 1984b), indicating a bias toward the humid Amazon Basin (Fuller 2006).

Remarkably few studies have addressed changes in the seasonal drylands of South America. This is in stark contrast to those conducted in African semi-arid grasslands and woodlands (e.g., Ringrose et al. 2002; Rasmussen et al. 2001; Bassett and Zuéli 2000; Mertens and Lambin 1997, 2000; Nyerges and Green 2000; Abbot and Homewood 1999; Ringrose et al. 1996; Matheson and Ringrose 1994b; Gilruth and Hutchinson 1990). A few authors have considered such biomes in Central America and Mexico (e.g. Redo et al. 2009; Nagendra et al. 2004; Southworth et al. 2004; Turner II et al. 2001), but the number of studies in this region is few, as it is in Australia (e.g. Pickup et al. 1993; Matheson and Ringrose 1994a). The low number of studies in some dryland ecosystems is surprising given that they are considered one of the most endangered biomes on the planet (Janzen 1988) and cover approximately 45% of Earth's land surface (Schimel 2010). They also constitute 22% of total forest extent in South America (Murphy and Lugo 1986). Yet, these sensitive areas have been used more than tropical moist forests and evergreen forests (Bullock et al. 1995) and have experienced the greatest decrease in percentage cover over the last 20 years (DeFries et al. 2005). They have been designated as “throw away” forest (Hecht 2005: 397).

Only a handful of authors (e.g., Gasparri and Grau 2009; Brannstrom et al. 2008; Jepson et al. 2008; Grau et al. 2008; Jepson 2006, 2005; Grau et al. 2005a, b; Zak et al. 2004a, b; Batistella et al. 2002) have mapped and quantified LULCC in South American dry forests and savannas. A common theme of the results from these papers is that they are characterized by some of the highest contemporary deforestation rates. This is particularly so for the Brazilian Cerrado and Argentine Chaco. Zak (2004a: 596) found that between 1969 and 1999, annual deforestation rates were approximately 2.2% during the 30-year time period – a figure that is comparable or higher than deforestation in most humid forest studies. Brannstrom et al. (2008) and Jepson (2005) reported even higher annual estimates at 2.6% for western Bahia (1986-2002) and 5.39% in eastern Mato Grosso (1986-1999).

At the beginning of the 21st century, Loveland et al. (2000) used 1 km AVHRR data to estimate that nearly one-quarter (22%) of the South American continent is under some form of agriculture. Over a decade ago, pasture expansion was thought to be the main contributor of dry forest loss in South America (Maass 1995). In the Cerrado and Caatinga of Brazil; Chaco and Chiquitano dry forests of Argentina and Bolivia, vast areas of these once extensive biomes have been cleared for pasture (Bucher 1983; Zak et al. 2004a, b; Sampaio 1995; Pacheco 2006 and Hecht 2005). Though most early clearance was for pastureland, today, crops such as corn, sorghum, sunflower and soybean can now be found in great abundance. During the 1950s and 1960s, the vast and relatively unpopulated dry forests were opened for immigration. Roads were paved and new land settlement schemes precipitated hundreds of thousands of square kilometers being distributed to nationals and foreigners. Agricultural production increased and was further augmented as exports diversified under import-substitution industrialization policies aimed at subsidizing credit, government price control, and investment in infrastructure. In countries such as Bolivia, several financial measures were enacted in the 1980s and 1990s to halt the downward spiral of the economy: currency devaluations; road construction; export tax rebates; reduction of import taxes; and suppression of price controls. The policy most relevant to land-use policy and deforestation was the accrual of foreign exchange through increased cash crop production.

2.1.3 The Tropical Dry Forests of Bolivia

In Bolivia, dry forests located in the 'expansion zone' of the Tierras Bajas (see Section 3) have seen the most, if not all the attention due to their longer settlement history and historically high clearance rates (Table 1). Davies (1993) was the first to assess LULCC in the department of Santa Cruz in a 15,659 km^2 swath of the Tierras Bajas between 1975 and 1991. She found that 10% of the woodlands and forest had been lost to agricultural production. In 2000, Tucker and Townshend (2000) found that deforestation for the entire Bolivian lowlands (784,759 km^2) for 1992-1994 was 28,208 km^2, but noted caution due to the nature of the sampling they carried out. In the most widely cited estimates for the Bolivian lowlands, Steininger et al. (2001a) reported high deforestation totals in their assessment of lowland forest in areas of precipitation greater than 1,000 mm – 24,700 km^2 of 700,000 km^2 of eastern Bolivia's dry woodlands, wet forest, and savannas had been lost to the agricultural expansion of soybeans and other crops from 1975 to 1998. Steininger et al. (2001b) also conducted a land-cover change assessment between 1976 and 1998 for a 19,533 km^2 area between the Rio Grande and Quimome – the entire Tierras Bajas defined in this dissertation and including areas bordering the Chapare region. They found that 9,400 km^2 of the 19, 533 km^2 had been cleared due to cattle ranching and agricultural cultivation spurred by road and railway expansion. Most of this was in the dry forests of Santa Cruz. Mertens et al. (2004) assessed forest loss for the entire Santa Cruz Department and seven user-defined seven colonization zones between 1989 and 1994. They found that only 5,117 km^2 had been deforested in this comparatively short time period. Krüger (2006) has recently evaluated deforestation for the Tierras Bajas extending the timeline to 2001. Over a 17-year period from 1984 to 2001, he found that 13,000 km^2 of 18,000 km^2 or 72% of total forest had been lost to agricultural production. Killeen et al. (2007b, 2008) extended the time-series of Steininger et al. (2001a) for the lowland forests of eastern and northern Bolivia and found that the amount of deforestation up to 2004 had increased to 45,411 km^2 in addition to 9,042 km^2 of scrub and savanna. Seventy-five percent of all change that occurred from 1975 to 2004 occurred in the Department of Santa Cruz.

These studies either focus on all the lowland forests in Bolivia or only the Tierras Bajas (Table 1). Overlooked or more likely unforeseen in the earlier, more detailed studies were the drier parts of eastern Santa Cruz Department along the Corredor

Bioceánico. New pressures such as clearance for agriculture and ranching are occurring in new expansion zones in the eastern Chaco, eastern Chiquitano and Pantanal ecoregions. Research Objective 1 addresses these knowledge gaps by building on the land-change mapping carried out in Santa Cruz. I expanded the area covered by Davies (1993), Steininger et al. (2001b), and Krüger (2006) by mapping the entire 'corridor' between Santa Cruz and Puerto Suarez, and, extended the time frame backwards to 1975 and forwards to 2007. I included three intermediate time periods (1986-89, 1992-94, and 2000-01).

2.2 MAPPING LAND-USE AND LAND-COVER CLASSES

Environmental and social disciplines as well as institutions now require a diverse array of detailed LULC maps to support scientific and policy needs. Detailed and accurate LULC maps, which identify crop types as well remaining forest types and those cleared, are needed in order to better indentify environmental concerns. The previous sections in this section illustrate the great advances that have been made over the last couple of decades in mapping land change at a variety of scales. However, with the exception of a handful of studies, there have been relatively few advances in providing detailed and accurate regional and local-scale (at least in Bolivia) mapping of forest and crop types. This section identifies those studies which have attempted forest and crop classification and identifies the needs of future endeavors.

Since the mid-1980s, vegetation phenology derived from AVHRR has been successfully used to map land cover at regional, continental and global scales (e.g.

Tucker et al. 1985; Justice et al. 1985; Malingreau 1986; Millington and Townshend 1988; Achard and Blasco 1990; Reed et al. 1994; Achard and Estreguil 1995; Moulin et al. 1997; DeFries et al. 1998; Hansen et al. 2000; Loveland et al. 2000). In the case of forest and woodlands, the overarching aims of these studies have generally been to map spatial distributions and assess productivity, resulting in land-cover classes being related to known biomes and ecosystems, or categorized into classes defined in terms of biomass or plant productivity. Generally, land-use change has not been a major focus (if at all) in these studies and areas which are forest or other types of natural vegetation are often mapped under generalized categories like vegetation-agriculture mosaics (but see Millington et al. 1992; Reed et al. 1994). Besides the major focus on achieving natural vegetation mapping objectives, a more pragmatic reason for not using a detailed land-use classification with these data has been sensor limitations, e.g., pasture establishment and cultivated areas often occurs below AVHRR's finest spatial resolution of 1.1 km^2.

Since 2000, the potential for land-cover classification using coarse spatial resolution data has improved with the availability of 250 m^2 and 500 m^2 resolution MODIS data and the standard data products made available by the MODIS Land Science Team. The downside in terms of LULCC analysis is the relatively short data archive (back to February, 2000) compared to AVHRR, which limits land change studies to less than one decade with the sole use of MODIS data. Though MODIS imagery is a significant spatial and radiometric improvement over AVHRR, the minimum 250 m resolution still restricts its use for agricultural land-use mapping to regions of large-scale agriculture such as western Brazil (Wessels et al. 2004; Lobell and Asner 2004; Brown et al. 2007; Galford et al. 2008), the United States (Jakubauskas et al. 2002; Lunetta et al. 2006; Wardlow 2005, 2006, 2007) and Southeast Asia (Sakamoto et al. 2005, 2009; Xiao et al. 2005, 2006). These studies show that (1) the methodology behind mapping LULC has been greatly improved over the last few years; (2) one particular curve-fitting algorithm or metric to derive thresholds is not a panacea, but that a mix of procedures should be adapted to regional and local conditions; and (3) LULC change has not yet been attempted using a phenological-based approach.

Seven studies that have previously reported on LULCC in parts or all of the area I cover in this dissertation (Table 1). Yet, we still do not know about the spatial pattern of LULCC in the central and eastern parts of the study area because the focus of the most detailed studies has been on the western Tierras Bajas (Davies, 1993; Steininger et al., 2001a, b). In addition, the last years in these studies, 1991 and 1998 respectively, were at times when the greatest rates of forest loss in much of the Tierras Bajas had not been attained. In the papers where the entire corridor is covered (Mertens et al. 2004; Killeen et al. 2007b, 2008; Tucker and Townshend 2000), spatial patterns of change are generalized due to broad-scale coverage of either the entire department or the entire eastern lowlands of Bolivia. In terms of LULC classes, only two have gone beyond forest and non-forest classification: Davies (1993) used a threefold forest classification which included regrowth, and Killeen et al. (2007b, 2008) identified forest, shrubland, and grassland classes. Only Davies (1993) sub-divided non-forest land-use into agriculture and pasture. In this section I update these studies and provide an expanded level of detail for agricultural classes. I use Navarro and Ferreira's (2007) digital map of land-cover from the mid-1990s, capturing a time point in the decade when clearance for agriculture attained the highest rates (see Sections 5-6). Moreover, I consider the entire corridor which serves to illustrate that to the east new pressures on forests from clearance for cultivation and ranching are occurring is well beyond the traditional agricultural zones and into areas once thought to be impervious to large-scale agriculture (Pacheco 2006).

2.3 DRIVERS OF LAND-USE AND LAND-COVER CHANGE

Over the last decade, significant effort has been geared toward better understanding the underlying drivers and proximate causes of LULCC (Millington 2006; Geist et al. 2006; Rindfuss 2004; Lambin et al. 2006; 2003; 2001) – one of the major goals of the IHDP-LUCC program (Turner et al. 1995). A large number of case studies have been published, many of which focus on deforestation. Angelsen and Kaimowitz (1999), Geist and Lambin (2001, 2002) and Lambin et al. (2001, 2003) provide comprehensive syntheses of approximately 150 case studies each from Amazônia, central Africa, and Southeast Asia. Geist and Lambin (2004) used 132 case studies to look for patterns in the driving forces of land change in dryland environments. Some individual, localized studies concentrate on the role institutions play in explaining deforestation (e.g., Gibson et al. 2000; Sanderson 1994; Tucker and Ostrom 2005), while others focus on economic development and technological change (e.g., Jepson 2006; Walker 2004; Angelsen et al. 2001), household characteristics (Walker 2003; McCracken et al. 1999) or demographics (e.g., Perz 2001). All case studies rebuke a single causation theory of land change and illustrate that the drivers of deforestation cannot be solely attributed to population growth or shifting cultivation, but are instead immersed in a complex web of several underlying and proximate causes which Geist and Lambin (2004: 817) call “recurrent core variables” at the underlying level such as weak government, corruption, competing territorial claims, accumulation of international capital, institutions, market opportunities, policy reforms, demographic change, infrastructure development, technological advances, and in some cases climatic factors. They argue that globalization links drivers and patterns of land change, and that it appears to underpin change in South America (see for example, Hecht 2005).

Much research in South America has focused on drivers of humid tropical deforestation (e.g., Lambin et al. 2001, 2003), but the pattern and processes of conversion in tropical dry forests are poorly understood (Lepers et al. 2005). This is particularly so in Bolivia when compared to Argentina and Brazil. What is known is that commercial agriculture – which is mostly attributed to Mennonite farmers, foreign firms, and Brazilian and North America landowners – has expanded significantly during the past two decades, converting large areas of dry woodland and savanna into croplands which are well integrated into global markets (Hecht 2005; Dros 2004; Steininger et al. 2001a; Davies 1993; Zak et al. 2004a, b; Grau et al. 2005a, b; Fearnside 2001; field observations, 2007). Agricultural expansion in the drylands of South America has been attributed to market-oriented, structural adjustment policies (e.g. presence of trans-national agri-food corporations, technologies for agricultural intensification, land privatization policies, and currency devaluations) (Jepson 2006; Pacheco 2006; Hecht

2005; Kaimowitz et al. 1999). In Mato Grosso, for example, Jepson (2006) found that cooperative firms had mitigated the risks of insecure land tenure and poor infrastructure by offering farmers greater access to markets and credit as well as introducing technological advancements. In the Tierras Bajas of Bolivia, agricultural expansion from the 1960s to the 1980s was attributed to road building, subsidized credit targeting, agricultural price supports, greater allocation of land, and support from formal rural settlements (Pacheco and Mertens 2004). From the 1980s to the 1990s, neoliberal policies were put into place. Devaluation of the national currency, fiscal incentives to promote exports, and efforts to open up regional markets for non-traditional exports through bilateral and multilateral trade agreements, all contributed to the explosive growth of the agricultural sector during the 1990s and well into the 21st century (Pacheco 2006). Thus it is markedly similar and yet still different to that of other, more well-known agricultural frontiers such as those in humid tropical forests where fiscal or tax incentives and population growth drive change (Lambin et al. 2003).

Largely ignored in the recent research on tropical dry forest conversion has been ranching (but see Hecht 1985), and the roles pedological and topographic constraints may play in farming choices. Land cleared for grazing is an important agent of land transformation in the Corridor Bioceánico in southeast Bolivia, but appears to be constrained by soil properties. So far, cropland expansion has taken place on the alfisols and inceptisols in the west, and ranching is expanding on less fertile ferralsols to the east. Topographic differences may also affect agricultural expansion; for example, in the east the undulating topography of the eastern Corredor Bioceánico have reportedly inhibited mechanized agriculture at present. This is not the case. Mennonites have cleared vast tracks of level forest north of the Santa Cruz-Puerto Suárez highway for agricultural production as is shown in Section 5. Other factors overlooked in the recent literature on dry forest conversion in South America are the effects of infrastructure investments (e.g. the roads and railroads associated with the Corredor Bioceánico), logging, and the activities of small-scale cultivators such as the indigenous Chiquitano; even though they have been identified as threats to biodiversity in the region (e.g. FVSA 2005). A comprehensive analysis of drivers of dry forest conversion has yet to the undertaken for a dry forest region in South America. This dissertation research addresses this deficiency in Objective 2.

Studies which look at the drivers of the unprecedented deforestation which occurred after 1985 attribute neoliberalism. David Kaimowitz attributed deforestation solely to "soybean production for export, stimulated in part by improvements in road and railroad infrastructure" (Kaimowitz 1997: 540) and "structural adjustment, [which] contributed to large-scale forest clearing for soybean production for export" (Kaimowitz et al. 1999: 505). Hecht (2005: 375) argued "that the new context of globalization, structural adjustment, regional integration and rapid technological change contributed to accelerated forest cutting during the 1990s." Pacheco (2006: 222) contended that "the single most important factor that stimulated the large expansion of the soybean production [and subsequent, large-scale deforestation] was the preferential access of Bolivian producers to the Andean pact market." He further purported that "the implementation of the structural adjustment program based on fiscal and government policies stimulated the expansion of the agricultural frontier at rates of growth never before experienced in Bolivia [with] much of the frontier expansion [relying] on soybean production" (223). While not denying structural adjustment policies were instrumental in causing deforestation, they are not the only factors. These studies have overlooked individual farmers. They have ignored the fact that people make decisions based not only on needs but also on limitations and desires. They have also overlooked meso-scale institutions/organizations, which play an important role in determining or removing limitations.

3. STUDY AREA

This section describes the structural, physical, and cultural components which comprise the Corredor Bioceánico: infrastructure (highway, railroad, pipelines, and urban areas); physical environment (climate, soils, topography, land use); types of commercial agriculture; types of forests and woodlands; and peoples.

3.1 STRUCTURAL ELEMENTS

The Corredor Bioceánico in southeastern Bolivia comprises a highway, railway, and two pipelines which run roughly in parallel 571 km from the departmental capital, Santa Cruz de la Sierra, to the border towns of Puerto Suárez and Puerto Quijarro (Figure 3).

3.1.1 Urban Areas

Santa Cruz de la Sierra (here after referred to as Santa Cruz) is the departmental capital and one largest cities located on the Corredor Bioceánico (Figure 3). Historically, Santa Cruz was the first permanent European settlement in the Bolivian lowlands[4]. Originally founded in 1561 where present day San José de Chiquitos lies, the city was eventually moved to a location near the Rio Grande (present-day Cotoca) in 1601 due to invasion by aboriginals and renamed San Lorenzo el Real. San Lorenzo was abandoned due to floods and moved to its present location on the east bank of the

[4] The name Santa Cruz de la Sierra is taken from the Spanish village in Extremadura where Ñuflo de Chávez, the founder of the first town site, was born.

Rio Piraí in 1608. Later renamed Santa Cruz de la Sierra after the original settlement in the Brazilian Shield, the city remained a small, isolated town on the edge of true wilderness for nearly four centuries. Mule trains supplying the highlands with cattle products, fruits, and vegetables provided the only economic lease, and even this was short-lived as trade between La Paz and Peru intensified in the late 19th century provided cheaper produce. Isolation, a trickle of immigration, a small, but hostile aboriginal population, the drain of labor during the mining and Amazonian rubber boom, and the Chaco War all played a part in keeping growth further in check (Hiraoka 1974). By the 1920s, population was estimated at only 25,000 to 30,000 (Mather 1922; Weeks 1946; Heath 1959).

Stagnant growth persisted throughout the 1930s and 1940s until the nationalist revolution of 1952 was fought to release population pressure from the highlands by fragmenting the vast landholding of the lowlands. In 1950, 4.5% of landowners controlled 90% of private land (Censo Agropecuario 1950, cited in Heath 1959). The result of the agrarian revolution was more than simply land tenure reformation; the vast lowlands had been opened for immigration. In addition to reform, isolation was coming to end as the Santa Cruz-Cochabamba highway was completed in 1955 linking highland and lowland Bolivia. The Santa Cruz-Puerto Suárez highway was finished a few years later linking Bolivia to Brazil. Promotion pamphlets were printed and widely distributed to colonists seeking opportunity and adventure on the fertile frontier (Figure 4; Figure 5). But even by 1961, Santa Cruz was still a backwater as “one-storey buildings with covered and raised boardwalks still flank unpaved streets which become torrents in times of heavy rain" (Crossley 1961: 231). Hitching posts dominated most street corners and cattle wandered the streets freely (Heath 1959). But with the seemingly unending influx of immigrants, capital, and available land, coupled with road and rail access, the city was growing and would never be the same.

Since 1960, thousands of Bolivian nationals from the overcrowded, impoverished highlands as well as lowlanders and foreign immigrants (Mennonites, Japanese, Brazilian, and North Americans) have moved to the region to cultivate crops such as cotton and sugarcane or work in the commercial and industrial sectors. Other roads were built, an international airport was constructed, communication systems were laid, and with the introduction of soybeans and sunflowers in the 1950s and 1960s, industrial agriculture flourished north and east of the city turning Santa Cruz into one of the largest cash-crop producing regions in South America. Money from the cocaine trade in the Chapare has also flowed into the city further stimulating growth. As a result, in the short span of only four decades, Santa Cruz has evolved from a relatively neglected city into the largest and most dynamic city in the country. It is today the most populous city in Bolivia with over 1.5 million people – up from 1.1 million in 2001, 700,000 in 1992, and 254,000 in 1976 (INE 2006, 2001, 1992; Rojas 2004). Much of this explosive growth has caused Santa Cruz to become the economic, industrial, transportation and cosmopolitan heart of Bolivia taking in one-third of the nation's GDP.

More recently, Cruceños have been responsible for the largely symbolic movement toward declaring autonomy (Rojas 2004) where each department has control over taxes, production, and certain internal laws. Santa Cruz has overwhelmingly voted to keep two-thirds of departmental tax revenues. By 2008, the three other richest departments in Bolivia – Beni, Pando and Tarija – have also followed suit in spite of President Evo Morales' wishes to keep power within Bolivia centralized. The national government, however, has declared the referendum illegal. Nevertheless, Santa Cruz continues to be the center of opposition to 'traditional Bolivia,' accentuating the political, economic, and cultural differences between the Altiplano and wealthier lowlands.

North of Santa Cruz sit the important textile and sugar manufacturing centers of Warnes and Montero with 42,000 and 80,000 persons, respectively (INE 2001). East of the Rio Grande in the Tierras Bajas are small, but well established settlements such as Pailón, Tres Cruces, Pozo del Tigre, El Tinto, and Quimome (Figure 6) which serve as trading posts and transportation midway points for the summer soy and winter sunflower/sorghum crops along the Corredor Bioceánico. With the exception of Pailón (28,000), all communities in the Tierras Bajas on the Corredor Bioceánico have a population less than a few hundred.

Midway along the corridor in the Brazilian Shield lies the settlement of San José de Chiquitos with a population of ~17,000 (INE 2001). It continues to be the largest city in the region and serves as a crossroads for transport west to Santa Cruz and east to Roboré, south to Kaa-Iya del Gran Chaco National Park and Paraguay, and north to San Rafael de Velasco and other towns along the Jesuit mission circuit. The second largest city in the region is Roboré – a military outpost and market city of ~15,000 (INE 2001) – at the base of the Serranía Santiago. It is connected by paved road to San José de

Chiquitos and since 2008, to other cities further east. Other smaller towns in the Brazilian Shield which lie on the main highway include: Piococa, Taperas, and Chochis with its famous inselberg spire or 'tower' (Figure 7), Limoncito, Aguas Calíentes, and Naranjos. All have populations in the hundreds.

Towards the Pantanal are Santa Ana de Chiquitos and El Carmen, two of the largest towns between Roboré and the Brazilian border, (Figure 3). Anchoring the eastern end of the Corredor Bioceánico in the Bolivian Pantanal are Puerto Suárez and Puerto Quijarro, separated by only 12 km with a combined population of approximately 33,000 inhabitants (INE 2001). The former was founded in 1875 by Don Miguel Suarez Arana along the southern rim of Lago Cáceres as a port for exterior commerce and eastern outpost (Figure 8) while the latter is a modern boom-town situated on the Rio Paraguay.

3.1.2 The Bolivian-Brazil Railroad

Up to the 1950s, a traveler had two methods of transport along the present-day Corredor Bioceánico: (1) a mule train which roughly followed today's route or (2) a combination of intermittent and dangerous[5] river transport and oxcart (Weeks 1946). Clearly, a safer and quicker method of travel was needed, a fact not lost on the central and departmental governments.

[5] According to Weeks (1946: 551), in 1944 'unescorted freight trucks were waylaid within sight of the city of Santa Cruz; and two years earlier [1942] a boy had been killed near his home northeast of Montero, by a hardwood javelin hurled from the jungle."

In the late 1930s, reconnaissance work on building a railway had begun. By 1938, a survey was carried out by the Brazilian-Bolivian Joint Railroad Commission using aerial photography (Rudolph 1944). With Brazilian funding, work along the eastern sections began in 1939, and 16 years later, the rail-heads reached the east bank of the Rio Grande, 60 km from Santa Cruz near Pailón. The rail was finally bringing once rare manufactured goods from Brazil at a fraction of pre-rail costs. Goods were also traveling in the other direction, but many illegally. Contraband freight (rice, sugar cane, and maize), estimated at 95% of all goods in 1956, were shipped from Santa Cruz to Brazil commanding prices three times above average in Bolivia (Crossley 1961).

In 1958, the Río Grande was bridged and tracks finally reached Santa Cruz. However, even by 1960, no permanent bridge had spanned the Rio Grande (Heath 1959) and by 1964, the Bolivian government refused sole responsibility to maintain the track (Heath 1959). A crisis ensued, rail service halted, and the track and rail equipment began to deteriorate. But in the late 1990s, soybeans and tourism created renewed interest in the railway, and Canadian companies provided the funding to revitalize services (Oscar Castillo and Damian Rumiz, personal communications, August 2007). In 1999, the railway carried 600-1,000 passengers per day (Aguirre 2000) and an unknown (or unrecorded) tonnage of freight.

3.1.3 The Santa Cruz – Puerto Suárez Highway

Despite the completion of the railway in 1958, the adjacent automobile highway remained unpaved (Figure 9). For decades the dream of upgrading and paving the highway had to be ignored, at least initially, due to high cost and hard lessons learned from the construction of the railroad[6]. But with the explosive growth of agriculture east of the Rio Grande in the 1980s and 1990s, plans for the construction of a modern, paved highway had to push forward to meet the growing demand for quicker, cheaper transport of goods.

Since the early 1990s the Bolivian government has actively promoted the paving of the Santa Cruz – Puerto Suárez highway (Vargas Ríos and Hamerschlag 2001). In 1997, it officially solicited a loan of 135 million USD from the Inter-American Development Bank (IADB). The next year the IDB initiated the first of many environmental impact studies along the length of the corridor followed by Strategic Environmental Studies (SEA) from a number of NGOs. In one of the more positive scenarios, it was estimated that five million hectares would be deforested in the eight years following construction. A few of the environmental and social recommendations included: (i) strengthen and expand protected areas while creating three new ones in the Serranía Chiquitanía, Tucavaca Valley, and Lake Concepción; (ii) create a regional fund to attract resources for conservation activities, (iii) initiate a process of land titling, and (iv) establish a development plan for indigenous and peasant communities (Vargas Ríos and Hamerschlag 2001). Few of these recommendations were ever enacted. The protected areas were scaled-down, conservation activities are limited, land titling has

[6] The flagrant disregard for the highway was most evident over the Rio Grande. Even in 2008, an automobile bridge had not been built across the river. Vehicles passed single-file, in turn roughly every thirty minutes, over a decrepit and ageing one-lane railroad bridge (Figure 10). With funding from Japan, construction of an automobile bridge over the river began in earnest in 2006. The new bridge was expected to open in November 2009 (El Deber 2008a), but was not passable on my last visit in May 2009.

been a contentious and muddled process, and development plans have been largely piecemeal.

Over the next few years, plans for paving the highway stalled due to the pullout of World Bank as well as corruption and the subsequent 'rebuilding' of the Bolivian National Road Service Agency. Nevertheless, millions of hectares of woodland were cleared between 2001 and 2006 (see Section 5). By 2006, funding was sorted out and building contracts awarded, and construction finally began. Different financial institutions have funded different sections of the highway totaling 312 million USD (BICECA 2006). Moving from west to east, sections, lender organizations, and monetary value include (Figure 11):

> **Section (1):** Inter-American Development Bank (IADB) pledged 66.3 million USD for the Paraíso/Pailón – El Tinto section (125 km);
>
> **Section (2):** the European Union funded the El Tinto – Quimome section (38 km) with 20.6 million USD;
>
> **Sections (3 and 4):** the *Corporación Andina de Fomento* (CAF) or Andean Development Corporation funded 18.5 and 28.7 million USD for the Quimome – San José de Chiquitos (43 km) and the San José de Chiquitos – Taperas sections (48 km), respectively; and
>
> **Sections (5, 6, and 7):** the IADB and CAF pledged 53.1, 76.9, and 47.9 million USD for the Taperas – Roboré (90 km)[7], Roboré – El Carmen (139 km) and El Carmen – Puerto Suárez (47.9 km) sections, respectively.

Crews responsible for construction are underwritten by five different Bolivian, Italian, and Brazilian consortiums: APOLO-IASA (Section 1); ASTALDI SpA (Sections 2 and

[7] The San José de Chiquitos – Taperas and Taperas – Roboré sections are the only ones completely paved with asphalt. Originally, this was not planned. It was advertised to be paved and was sponsored by World Bank and funded by the Corporación Andina de Fomento (Oscar Castillo and Damian Rumiz, personal communications, August 2007).

3); ARG-COPESFigure ICA (Sections 4 and 5); ARG-CAMARGO-CORREA (Section 6); and ODEBRECHT – IASA (Section 7) (El Deber 2008b).

As of June 2008, the Roboré – El Carmen and El Carmen – Puerto Suárez sections are very near completion (Figure 12). Only bridges over the various branches of the Rio Tucavaca were incomplete. Two years later, it was possible to drive continuously on asphalt from San José de Chiquitos to Puerto Suárez, a distance of 325 km. While great progress has been made in the east, little development is underway in the agriculturally-dominated Tierras Bajas. The 125 km Pailón – El Tinto section has one to two kilometers of paved road and only a handful of drainage infrastructure installed under the roadbed. Completion of the El Tinto – Quimome and Quimome – San José de Chiquitos sections through the region's hillocks and wetlands will require formidable effort (Figure 13). Although work is well underway, the undulating terrain and annually flooded wetlands will add years to the timetable. The Quimome – San José de Chiquitos section has had half of its infrastructure (drainage pipes) installed and appeared ready to be paved in mid-2009.

3.1.4 The Bolivia-Brazil and Cuiabá Gas Pipelines

Running parallel to the highway and railway is the longest pipeline in South America, the 3,056 km Bolivia-Brazil pipeline (GasBol) (Figure 3). Constructed underground between 1997 and 1999, it bisects northern Kaa-Iya del Gran Chaco and Otuquis National Parks (NP) and Integrated Management Areas (IMA). It carries gas from the Yacimientos Petrolíferos Fiscales Bolivianos (YFPB) Rio Grande natural gas plant 40 km southeast of Santa Cruz to Porto Alegre, Brazil, through 250-350 km of Bolivian territory (Winer 2003; Beltran 2000). The 556 km Rio San Miguel – Cuiabá splits off from the Bolivia-Brazil pipeline and runs northeast from San José de Chiquitos to the border town of San Matías in Mato Grosso. It then crosses the western edge of Pantanal de San Matías IMA through 390 km of Bolivian territory (Figure 14).

The Bolivia-Brazil pipeline was funded by the following consortium of financers in descending order of loan and equity amounts: sponsor equity [Pertrobras, British Gas, El Paso Energy, Broken Hill Proprietary, Enron, and Shell] (821 M), Banco Nacional de Desenvolvimento Economico e Social (333 M), World Bank (310 M), Petrobras (280 M), the Inter-American Development Bank (240 M), Export Import Bank of Japan (104 M), Andean Development Corporation (80 M), and European Investment Bank (60 M) (Pató 2000). Half of Bolivian ownership is in the hands of Transredes and another third with Enron and Shell (Mares 2006). The Rio San Miguel – Cuiabá pipeline, on the other hand, was built by ENRON and Shell with financing from the Overseas Private Investment Corporation (OPIC) and the Kreditanstalt fur Wiederaufbau (KfW). Today, both lines are owned by Gas TransBoliviano and the Brazilian Gas Transport Company.

Hindery (2003; 2004) has studied the Rio San Miguel – Cuiabá section (Figure 15) and noted spills, leaks, land ownership changes, degradation of basic infrastructure, and social issues. Pató (2000) has pinpointed problems associated with the Bolivia-Brazil line which include increased crime and violence as well as loss of land by indigenous groups.

3.2 PHYSICAL ENVIRONMENT

3.2.1 Climate

Climate along the Corredor Bioceánico is considered subtropical and strongly seasonal with a warm, wet season from November to March/April, and marked east-west and north-south precipitation and temperature gradients (Figure 16). Northwest of the city of Santa Cruz, rainfall is higher and temperatures markedly lower compared to the southern Santa Cruz region only 50-75 km southeast of the elbow of the Andes. At the cities of Montero and Warnes, mean annual temperatures range between 21-26 °C and mean annual rainfall between 1,100 and 1,500 mm (PLUS 1995; Tigner 1982). The highest precipitation totals are found nearest mountain ranges and the adjoining plains. Between the Rio Grande and San José de Chiquitos in the Tierras Bajas, temperature varies little, but rainfall decreases from 900 mm in the north to 400 mm in the south (Rafiqpoor et al. 2004; PLUS 1995). In the western Brazilian Shield (e.g., around San José de Chiquitos), mean annual temperatures are quite similar to the Tierras Bajas. Mean annual precipitation increases to 1,400 mm on the Rio Tucavaca. In the Pantanal study region, annual rainfall totals average between 1,100 and 1,200 mm along the border with Brazil.

During the dry season, high winds and accompanying dust storms are commonplace in the Tierras Bajas. The strong winds, known locally as *nortes*, are found year-round and are intensified by south winds – *surazos* – associated with cold fronts between October and February. High winds and associated soil losses have given rise to thousands of tree windbreaks of varying widths (5 m – 30 m) and lengths (0.25 km – 10 km) in the Tierras Bajas and northern Brazilian Shield (Figure 17).

3.2.2 Soils, Topography, and Land Use

Soils and land-use also show east-west trends. Covering much of the Tierras Bajas and the most gently sloping parts of the Brazilian Shield study region are haplic ferralsols (PLUS 1996) (Figure 18). These are slightly acidic, fine-textured, light yellowish-brown soils developed by the accretion of iron and aluminum oxides. They have characteristically low fertility, but additions of lime and fertilizer have turned areas with these soils into very productive crop-producing regions in Bolivia, and in the Cerrado of Brazil. These soils are classified as high (Class II) to moderate (Class IV) in terms of land-use potential according to the PLUS (*Plan de Uso de Suelos* or Land-Use Plan), which takes into account soil fertility, depth, texture, slope, salinity and chemical toxicity (Figure 19). Created by the Santa Cruz Natural Resources Protection Project and funded by the World Bank Eastern Lowlands Project in the mid-1990s, the PLUS was designed to plan development in Santa Cruz Department and is still closely followed by government agencies and producer's associations. According to the PLUS, the vast majority of the Tierras Bajas is classified as Class III – high-moderate potential – due mainly to the presence of deep alluvium (Figure 19). The alluvium consists mainly of unconsolidated gravels, sands, silts and clays from the Pleistocene epoch and more recent origin, occasionally reaching thicknesses of 2000 or more meters (Hiraoka 1974). According to this same plan, only Class II, III, and IV soils can support annual crops.

Therefore, by law the entire Department can only devote to 12% or 44,474 km^2 of available land to agricultural production.

Most of the Tierras Bajas lies on the Chaco plain below 1,000 m in elevation (Figure 20). The Chacoan landscape is considered flat, though it is interspersed with mesas about 200-400 m in height (Taber et al. 1997; SERNAP 2000). It is in this level plain where most of the agricultural development in the region has occurred. Large farms, rivaling those of the American Midwest in size, are planted to crops which, in order of importance are soybeans, sunflower, rice, maize, sugar cane, sorghum, and wheat (ANAPO 2007; Hecht 2005). These crops are under mechanized production on the alluvial plain known as the Tierras Bajas, which is limited physically by Andean foothills to the west, the Brazilian Shield to the east, and the seasonally flooded *Banados del Izozog* (Izozog Swamp) to the south. Generally, two crops are sown per year – soy, wheat, or maize in the wet, summer months and soy, sunflower, rice, sugar cane or sorghum in the drier winter months. Due to inherently unstable soil structure and general lack of soil conservation, at least 50-75% of the sites sampled by Barber (1995) were classified as moderately to highly compact.

Areas of the Brazilian Shield adjacent to the cities of Quimome, San José de Chiquitos, and Taperas as well as areas to the south are made up of Chromic Luvisols (Figure 18). These are relatively well-drained, acidic, dusky red colored soils resulting from the weathering of igneous rocks (ITC 1973). They have a weakly developed profile and are often found in upland, mixed woodland/savanna regions. Near the cities of Roboré and Aguas Calíentes, Dystric Cambisols dominate. These are rusty brown in color and form in the alluvial deposits laid down by the Rio Tucavaca. They have been generally considered good for agriculture since the 1950s (Storie 1953). Near the main highway, the Brazilian Shield study region is defined by peneplains and granite and basalt inselbergs, relicts of ancient, Precambrian landscapes (Ibisch et al. 1995; Rafiqpoor and Ibisch 2004), which are dome or bell shaped monoliths that rise several hundred (200-900) meters above the otherwise level landscape (Figure 7). The inselbergs are part of the linear mountain ranges such as the San José, Santiago, and Sunsás each of which stretch for approximately one hundred kilometers north and south of the Corredor Bioceánico.

In the Pantanal, Gleyic and Haplic Solonetz predominate (Figure 18). Solonetz generally are deep, with high organic matter content, and a nutrient-enriched surface soil making them ideal for agriculture. Like most Solonetz, those in eastern Bolivia are largely waterlogged owing to high rainfall and poor drainage due to development under conditions of poor drainage in areas such as marshes, swamps, seepage areas, or flats. Therefore, drainage will need to be implemented for large-scale agriculture to be carried out. Only along the main highway and north around the city of El Carmen in the Rincon el Tigre is land-use potential classified as a Class III (High-Moderate) or IV (Moderate-High) according to the PLUS (Figure 19). Elevation in the Pantanal study region never reaches above 250 m and is characterized by wetlands nearer the Brazilian border (Figure 20).

The leached soils of the Brazilian Shield and Solonetz of the Pantanal have, so far, limited large-scale agriculture, but there is a large presence of traditional and modern ranches such as those in Colonia La Honda and smaller ranches scattered along the Corredor Bioceánico from San José de Chiquitos to Roboré, as well as logging enterprises (Gerold 2004). Raising cattle in this region is opportunistic as Chilean markets begin to open up and the absence of foot-and-mouth disease which is prevalent in other parts of the country (Pacheco 2006). In addition to ranching, few, but nonetheless, large Mennonite settlements such as Valle Hermosa, Nuevo Mexico, and Colonia 42 are located along the mountainous spines of the Shield where the cultivation of sorghum and sunflower take precedence on soils classified as Class V (Moderate potential). Except in scale, these resemble Mennonite settlement and cultivation in the Tierras Bajas. The Pantanal is also dominated by pasture, but several mixed land uses are scattered throughout the region. East of El Carmen, sugar cane, bananas, and oranges are grown on small scales. A few kilometers west and south of Puerto Suárez on the highway to Mutún, hearts of palm are harvested on large scales.

3.2.3 Commercial Agriculture

Compared to other agricultural hotspots in South America, agricultural production in Bolivia has increased only moderately in the last 15 years. Constrained public and private sector investment and limited crop research and farm extension services have all handicapped expansion (USDA 2005), but industrial growth continues to be plagued by limited infrastructure development regardless of the millions invested by the Inter-American Development and World Banks which encouraged pricing policies, subsidies, tax breaks, trade liberalization, improvements in market structure and performance, and expansion of the capital market (Hindery 2003: 97). Despite these shortcomings, production of most commercial crops has expanded, due to high prices and the advantage of two growing seasons, which allows at least 10 major crop types to be produced (Figure 21).

Approximately 99% of commercial production along the corridor is concentrated in the Tierras Bajas in what is termed high-input, high-output agriculture[8] (Brannstrom, 2010) or industrial agriculture (Kimbrell 2002). The region is divided into two distinct, agricultural zones based on age with the Rio Grande as a convenient dividing line: (1) the older and wetter "integrated" zone and (2) younger, drier "expansion" zone. These two zones are further subdivided into sectors based on precipitation and geographic location (Figure 22).

West of the Rio Grande, in the "humid northeast" (Montero to Yapacaní), a summer soybean and winter soybean cropping system is practiced. This area also includes older areas of sugar cane and rice cultivation. In the "intermediate northeast" (Montero to the Rio Grande), "intermediate central" (area around Santa Cruz city) and "dry south" (south of Santa Cruz city, near Tres Palmas), summer soybean and winter sugar cane, rice, sunflower or wheat is cultivated. East of the Rio Grande, in the "humid north" (San Ramon and Valle Esperanza) and "intermediate north" (Cuatro Cañadas), summer soy is alternated with winter sunflower and sorghum. Near the "Pailón-El Tunás" sector and the area called "southern Pailón", summer soy is alternated with

[8] This type of system is characteristic of the following attributes: (i) takes place on large tracts of land; (ii) production is often of cash crops which are export-oriented; (iii) high use of agro-chemicals such as pesticides, herbicides, and fertilizers; (iv) soil erosion; and (v) extensive extraction of water from rivers or aquifers (Brannstrom 2010).

sunflower, sorghum and wheat (ANAPO 2002). As of yet, no such divisions have been implemented in the Brazilian Shield and Pantanal due to the historical absence of commercial agriculture. The situation, however, is rapidly changing.

Historically, commercial agriculture in the Tierras Bajas has experienced three general periods of expansion: (1) 1958-1964, rice and sugar cane: opening of Santa Cruz – Cochabamba highway and secondary roads, and state and foreign assistance from the United States; (2) 1970-1974, cotton: easy credit availability and cotton expansion followed by pest problems and market difficulties resulting in a decline of production (Thiele 1995); and (3) 1988-2008, soybeans and sunflower: increasing world soybean and sunflower demand, high prices, and resulting explosive growth of soy cultivation in the summer and sunflower in the winter (Figure 23).

3.2.4 Forest Types of the Corredor Bioceánico

Prior to human disturbance in this area, the vast majority of which has only occurred in the last 30-40 years, dry broadleaf forests dominated the Corredor Bioceánico. These fall into two continental-scale ecoregions – the Chaco forests to the south and the Chiquitano forests to the north (Dinerstein et al. 1995; WWF 2009a, b). Much of the corridor can be considered an ecotone, and some authorities even consider that the Chiquitano forests are the ecotone between the Chaco dry forests and the humid forests occupying the southwestern Amazon Basin to the north. This structure is broadly defined by pronounced latitudinal and longitudinal gradients resulting from differences in precipitation, soils, and topography.

The Chaco ecoregion in the corridor comprises habitats which range from grasslands, though savannas, to thorn forests, and transitional ecotone habitats between them (Prado 1993; Killeen 1993). This variability can be detected in terms of floristic composition, vegetation structure and physiognomy (Figure 24). Chiquitano forests (Figure 25) which generally occur north and east of the Chaco vegetation are best developed in Santa Cruz Department, though they extend into Mato Grosso. They experience a very marked winter, dry season with annual water deficits of up to 500 mm, despite having a mean annual rainfall between 900 and 1000 mm (Montes de Oca 1997). WWF (2009a) recognize four major vegetation communities whose distribution is closely related to drainage patterns. The "soto/curupaú" (*Schinopsis brasiliensis*/*Anadenanthera colubrina*) association is the most abundant and occurs in well-drained soils. It has up to five levels of strata including a 20 m canopy with up to 80% closure, emergents up to 20 m and both a shrubby and an herbaceous understory (ENTRIX, 1999). The dominant species are soto (*Schinopsis brasiliensis*), curupaú (*Anadenanthera colubrina*), momoqui (*Caesalpinia pluviosa*), morado (*Machaerium scleroxylon*), roble (*Amburana cearensis*) and cedro (*Cedrela odorata*). The "cuchi/curupaú" (*Astronium urundeuva*; *Astronium fraxinifolium*/*Anadenanthera colubrina*) association is also found on well-drained soils, but these are poorer than those of the "soto/curupaú" (*Schinopsis brasiliensis*/*Anadenanthera colubrina*). The canopy has approximately 65% closure and has a height of 10 to 15 m, emergents reach 25 m. When found on steep mountain slopes with rocky soils the dominant species is curupaú, but on sandy pediments cuchi, dominates. The "cuta/ajo-ajo" (*Phyllostylon* *rhamnoides*/*Gallesia integrifolia*) association occurs on hygrophilous soils that experience shallow flooding during the rainy season. The dominant species is "cuta" (*Phyllostylon rhamnoides*), though WWF (2009a) note that "ajo-ajo" (*Gallesia integrifolia*) is a better floristic indicator because it is highly restricted to flood-prone areas. The fourth association is the "tajibo/tusequi" (*Tabebuia impetiginosa*/*Machaerium hirtum*). These comprise small isolated forest islands that occur 0.5-1 m higher than the surrounding herbaceous savannas. Tajibo (*Tabebuia impetiginosa*) is the dominant tree species, though tusequi (*Machaerium hirtum*) is characteristic of soils that have undergone alkalinization due to inverse leaching (ENTRIX, 1999). In their classification of Bolivia vegetation, Ribera et al. (1994) classify Chiquitano forest as a "region of Precambrian semideciduous forest (Brazilian shield)."

The Chiquitano forests are deemed globally outstanding for their biological distinctiveness and are critically threatened (WWF, 2009b) because of habitat conversion, degradation and fragmentation. Bryant et al. (1997) considered them to be the largest area of healthy dry forest ecosystem left in the world, and Parker et al. (1993) labeled them one of the most biologically diverse dry forests globally. WWF (2009b) describe two large forest blocks of outstanding conservation condition, both east of San Jose de Chiquitos to the north and south of the main highway, respectively. They are partly protected by the Otuquis and San Matias protected areas and account for about one-fifth of the original ecoregion, but as we will show these blocks are being actively converted. WWF (2009b) also noted the need for the Tucavaca Valley – situated between these two blocks – to be protected to provide long term ecological viability.

Gentry (1995) measured plant species richness in this valley and recorded the second highest dry forest alpha diversity in the world.

Protection of the vast Chaco is concentrated in one protected area ‘collection’ comprising a National Park (NP) and three Integrated Management Areas (IMAs). Combined they form the highly lauded Kaa-Iya del Gran Chaco (KINP). It is South America’s largest protected area covering 3.44 million hectares or 5% of Bolivia’s national territory, an area larger than Massachusetts and Connecticut combined. With the IMAs, KINP is the size of Costa Rica. The protected area is not only important because of its size (it forms one-third of Bolivia’s total protected coverage and 3.5% of the entire Gran Chaco ecosystem); it also holds the largest area of tropical dry forest under full-protected area status anywhere in the world (Winer 2003) and is a model that puts community-based conservation into practice through being co-managed by the Bolivian government (3.44 million hectares), the Izoceño-Guarani Indian Organization, and development and conservation organizations (1.9 million hectares) (Pablo López and Zambrana-Torrelio 2006; Sunderland 2002; Taber et al. 1997). It is also contains the world’s largest known jaguar (*Panthera onca*) population with at least 1000 individuals (Maffei et al. 2004) as well as other significant populations of high profile, endemic ungulates like the Chacoan guanaco (*Lama guanicoe voglii*) and the Chacoan peccary (*Catagonus wagneri*) (Noss et al. 2004). In Kaa-Iya del Gran Chaco National Park, alone, at least fifteen interdigitated and ecologically distinct environmental units exist, each different regarding soil texture, drainage, and rainfall (Winer 2003).

3.3 PEOPLES

For the first few centuries of European occupation, only *Cambas*[9] (mestizos) and indigenous peoples lived in the region in relative isolation. But with the Bolivian revolution of 1952 and the invitation of foreign immigrants to settle into directed settlements, several ethnic groups came to the region in search of economic opportunity. The Bolivian government "anticipated that the foreign colonists, employing modern, scientific farming techniques, would provide a model for the domestic farmers to emulate" (Tigner 1982: 499). Colonists choose the Santa Cruz region for three reasons: (1) an already established commercial center – Santa Cruz; (2) the promise of infrastructure and processing plants; and (3) a seemingly inexhaustible supply of fertile land for agricultural production (Hiraoka 1974). Though several nationalities came to the region (e.g., Italians and Russians), the arrival of the Mennonites, Japanese, and Brazilians signaled a permanent landscape change. The former, however, have by all means and definitions had the most significant effect on the landscape.

3.3.1 Mennonites

Bolivia's Mennonite population traces their heritage to the original Anabaptists (meaning 'baptized again') of Catholic priest Menno Simons in Holland. Amish and Hutterites living in North America also trace their heritage back to Holland (Redekop 1971; Lanning 1971). During the past four and a half centuries, Mennonites migrated

[9] The term *camba* has several meanings. The term is believed to have originated from the Guaraní word for friend. Original usage was applied to those persons who were indebted to a large agricultural establishment (*finca*). Over time, however, the term was applied to both a peasant and aristocrat from the lowlands (Stearman 1976). Today, it is used in the same manner, but more so to distinguish the highlander from a lowlander.

repeatedly in the seemingly vain attempt to preserve their way of life, thus making them the ultimate nomads. In that time, they have accomplished extremely successful farming systems in North, Central, and South America, but especially along Bolivia's Corredor Bioceánico.

Their storied history is arduous, but fascinating, and begins in the 16th century in Holland after establishing a contrasociety (based on conflict with the outside world) which clashed with the beliefs and practices of the state church: emphasis on adult baptism, separation from the world and church in life and conduct, refusal of military service and swearing oaths. They eventually fled Holland in 1539 for Prussia after pressure to assimilate (Hostetler 1951). After two centuries in the east, they left Prussia by 1789 for the Ukraine after promise of forced military service, but nationalization and military obligations caught up to the Mennonites in Ukraine after Catherine the Great issued her Manifesto. Leaving Europe for good, many thousands fled to the Unites States and Canada, especially Manitoba, two decades after the American Civil War. Immediately after World War I, nationalization pressure was pressed upon the Old Colony once again and a contingent moved to northern Mexico in Chihuahua in 1922 and to Belize and Paraguay several years later. Others from Russia traveled directly to Mexico, Belize, Brazil, Uruguay, and Paraguay as immigration quotas in the United States and Canada became full. By the 1950s, Mennonites were flourishing in Mexico and Paraguay but population pressure and lack of adequate farmland spurred a search for a new homeland (Lanning 1971).

In 1954, the first group of Mennonites arrived in Bolivia from the Paraguayan center of Filadélfia and immediately engaged in what they knew best – farming. Their first settlements or colonies became known as Riva Palácio, Swift Current, and Tres Palmas. Only the two former colonies are still in existence, approximately 30 km southeast of Santa Cruz (the latter was 25 km northeast of Santa Cruz). In 1959, total population stood at 189 (Bender 1987). By 1986, it risen to at least 17,500 (*ibid*) and by 2005 that population had reached approximately 45,000 to 50,000 (Snader 2005). Although Tres Palmas disbanded in 1985, thousands more Mennonites came to share in the success of the first colonies, establishing new settlements in the Tierras Bajas, the Brazilian Shield, and the Pantanal. Those from the Old Colony of Mexico and Belize eventually settled under the government's directed settlement program, which meant that they were best planned and more importantly, received the most government assistance. Today, Bolivia has 54 Mennonite colonies with at least 40 contained within 50 km of either side of the Corredor Bioceánico highway. those who live south of Santa Cruz and along the Rio Parapetí transferred from Paraguay and cling more to the old ways of life. Those living in near the Rio Grande and in the Brazilian Shield are from Mexico and are less isolated than their counterparts, except for a small contingent of Paraguayan Mennonites northeast of Santa Cruz (Fretz 1960; Phil Bender and MCC staff, personal communications, 02 June 2009). However, the level of tradition or adherence to strict religious principles depends less on country of origin, but instead on individuality (Phil Bender, personal communications, 02 June 2009).

The degree of separation between a strict, conservative follower (e.g. southern Bolivian Mennonites) from the non-traditional liberals (e.g. northern Bolivian Mennonites) is a level of adherence to the two Biblical principles followed by the original Anabaptists: (1) nonconformity and (2) nonresistance (Miller 1995). Nonconformity broadly relates to the code of avoiding the outside world's cultural "norms" in terms of dress and social action. In Bolivia, women and girls generally wear the ubiquitous knee-length dresses and white or brown sun hats. Men sport blue overalls and trucker or baseball hats, resembling an American farmer from the Midwest. In terms of social action, bars, movie theaters, and similar social places are strictly forbidden. Nonresistance was best explained by Elmer Miller, a Mennonite who grew up in a traditional Pennsylvania community and worked as an anthropologist in Argentina from the 1950s to the 1980s: "One's allegiance [is] only to God, not the state" (Miller 1995: 10). This means refusal to vote in political elections, serve in military, and pledging allegiance to a flag. Basically, a traditional Mennonite must avoid any interaction in state and main-stream social affairs by "rejecting the material values and attractions of the broader society that detract from spiritual concerns and values" (Miller 1995: 103).

The rationale behind the strict adherence to these principles is that Earth is not the home of Mennonites. Everyone else belongs on Earth because Mennonites belong in heaven. Therefore, Mennonites must follow these Biblical principles and separate from the rest of the world in order to achieve salvation. Not all Mennonites adhere to these tenets. For example, the Chihuahua colony to the north of Pozo del Tigre is considered the most progressive of all the colonies and members often visit movie theaters and dine at mainstream restaurant chains in Santa Cruz. Other Mennonites do not belong to colonies and adorn "modern" dress. They do not consider this to be blasphemous. On extreme opposite end of the spectrum are the colonists of Riva Palácio who are forbidden to use rubber tires on their tractors. For others, language is what separates traditionalists from modernists.

Land tenure in the communities is entirely communal. Redekop (1971: 60) wrote extensively about tenure in the late 1960s and early 1970s, and much of it still holds true today:

> The Old Colony is a semi-communal society with church control of the land. There are common lands owned in the villages such as the cow pasture, the school grounds and teacherage, and the acreage that goes with it. The church yard and the roads between villages are all owned by the villages having been dedicated for that purpose in the original distribution of the land by church leaders. Even though families live on individual farmsteads, there is a great amount of mutual assistance and common work in the villages. The roads, schools, village cheese factories, and other institutions are maintained by common labor.

A type of theocracy dominates social life – church heads are the ultimate authorities on nearly all matters. The village council, composed of married males and land owners, handle the day-to-day decisions. Technology, except for tractors to clear land and vehicles for transporting harvests and other large items, is largely shunned by traditionalists. Nearly all Mennonites are steadfast in their refusal of participating in social and political services such as the military, sending their children to public schools, holding of public office, and cooperation with police and conservation programs. Therefore, socially and politically, Mennonite colonies are an entity contained within an entity. Economically, however, Mennonites must trade goods with the outside to continue their unique existence, and despite their closed social society they are extremely market-conscious, producing highly quality products such as cheese, which is consumed nationwide. Ecologically, traditional Mennonites appear to be clearing more forest as attested by satellite imagery (e.g., in the colonies of Riva Palácio and Swift Current). Interviews allude that knowledge (or lack or thereof) regarding soil conservation and windbreaks could be a key factor. More study, however, is clearly needed on the subject of conservation among Mennonites.

All colonies have legal title via outright purchases from public and private sources (Hiraoka 1974). With titles in hand, Mennonites have been able to acquire loans for the purchase of farm machinery such as tractors to clear woodland. It could be said that the Mennonites are a victim of their own economic success. In many ways, they are directly responsible for the paving of the highway since they were the first to open the Tierras Bajas to large-scale commercial cultivation. But with infrastructure upgrades there are always more colonists, less land available for purchase, and more pressure to conform to the outside world. Always on the mind of Mennonites leaders is the search for new land, which will allow their people the social, political, and economic freedom to pursue their way of life free of outside influence (Lanning 1971). So the question remains – will the Mennonites move once again? For the time being, they are flourishing in Bolivia and seem ready to stay indefinitely.

3.3.2 Caucasians, Mestizos and Indigenous Highlanders

For the first few centuries of European occupation, only Spaniards, *Cambas* (lowland mestizos) and indigenous peoples lived in the Santa Cruz region. A state of relative isolation dominated as travel to the highlands and deeper into the lowlands was arduous, dangerous, and extremely time consuming. For example, before the Santa Cruz – Cochabamba highway was completed in the late 1950s travel between the two cities might take four days under optimum weather and road conditions or over a month during periods of heavy rain and landslides (The New York Times, 1955). Since the Land Reform of 1952 and the paving of the Santa Cruz – Cochabamba highway and Santa Cruz – Puerto Suárez railway, thousands of indigenous Quechua and Aymara have poured down from the overpopulated and impoverished highlands in search of opportunity. Today, *Cambas*, whites, and indigenous highlanders are largely confined to major urban centers, but the former are also involved in commercial activities and subsistence farming. The conservative white elite control the region's natural gas and oil industry, banking and commerce, agriculture, and cattle ranching businesses (Guillermoprieto 2008). These are the industries which bring in the majority of Bolivia's GDP and these are the people leading the movement toward autonomy.

3.3.3 Japanese

In the 1950s, 700 families from Japan and Okinawa, mainly from the archipelago of Ryukyu, arrived in Bolivia and settled lands northeast of Santa Cruz along the western banks of the Rio Grande. Like the Mennonites, the Japanese colonies fell under the directed settlement umbrella. The first Japanese colony was a 2,500 ha plot purchased northeast of Santa Cruz on the western banks of the Rio Grande. By 1962, three colonies were flourishing within 65 km of Santa Cruz, aptly named Okinawa 1, 2, and 3. In fact, Japanese colonists were largely responsible for the cotton boom that occurred in the 1970s and Bolivia becoming self-sufficient in rice production in the 1960s (Tinger 1982). Unlike the Mennonites, the Japanese and Okinawans have intermarried with both highlanders and lowlanders alike creating a new race of Bolivians (Stearman 1976). Therefore, many are being assimilated into Bolivian society. Today, the Okinawa communities are thriving by engaging in commercial activities and cultivation of sugar cane, rice, sunflower, and soybeans (Personal Observations, 2008).

3.3.4 Brazilians and North Americans

It is unknown how many Brazilians and North Americans lie scattered from Santa Cruz to Puerto Suárez. Like the mestizos, many are confined to urban centers while others are working as foreman in the bridge-building and highway construction. An unknown number are involved in large-scale, mechanized soy farming and cattle ranching. It seems that many have come in search of opportunity. Two examples suffice to illustrate this phenomenon. In May of 2009, I interviewed two wealthy Brazilian and American ranchers. The formed originated in the Espiritu Santo region and came to Bolivia in the 1970s, at first seasonally, to work in the nascent timber industry. After several return journeys he began transporting cattle from the Brazilian plateau to the Santa Cruz market. This proved more profitable than timber and he bought

30 km^2 to raise bulls for controlled breeding. The American first came in the late 1960s in order to start a new life. His first plot of pasture proved profitable and he invested in subsequent properties. Today, he earns $600/ha and is one of the largest landowners in Bolivia with over 500 km^2 in Santa Cruz and Tarija Departments.

3.3.5 Indigenous Lowlanders

Settlements of two main ethnic groups – the Ayoreodes (or Ayoreos) and Chiquitanos – lie along the central and eastern parts of the corridor. Both groups have long-standing territorial claims to the land, particularly in the Brazilian Shield. The former group is the smaller of the two with a population of 2,000 and the least integrated into mainstream Bolivian society. Some Ayoreos are considered semi-nomadic and often migrate between southern Bolivia and northern Paraguay shadowing the edges of civilization and shunning outside contact. An unknown number (>100?) live in the heart of KINP (Taber et al. 1997). As recently as 2004, eighteen so-called "savages" abandoned this region of uninhabited forest due to hunger (El Deber, 2004). Others have been assimilated into mainstream Bolivian culture. The latter group, the Chiquitanos, is the third largest indigenous group in Bolivia next to the Quechua and Ayamara, and the largest in the Bolivian lowlands with a population of 112,216 in 2001 (INE 2001) – up from 72, 500 in 1992, a 55% increase (INE 1992). Their range extends from the Corridor Bioceánico near San José de Chiquitos in the south to deep in the Amazon Basin in the north – an area known as Chiquitanía. The people here are most known for their close association to Jesuits in the 18th century (McDaniel 2003) and many are well integrated into Bolivian society.

As the corridor develops, these ‘traditional’ communities will likely become displaced by both domestic and foreign immigrants (Mennonites, Brazilians, and North Americans in particular). Field research I have undertaken (2007, 2008) shows that these two groups are under-protected and under-represented compared to their western neighbors, the Izoceño-Guarani, a semi-nomadic people who live on Kaa-Iya’s western edge along the Rio Parapetí. For example, in interviews I conducted in 2006 with Ayoreos in Santa Teresita they noted hunting lands were already constrained by recently-developed fenced ranches. Those who have not been assimilated into Bolivian society use low-tech cultivation techniques (i.e. un-mechanized farming) to farm small, subsistence plots or graze cattle. Interviews in 2009 confirmed that immigration is a major concern. In the community of Natividad, there were 20 families living on the communal lands in 2006. Three years later this number had dwindled to 15 families as the other five had migrated to San José and Santa Cruz in search of better opportunity.

4. METHODS

4.1 MAPPING LAND-USE AND LAND-COVER CHANGE

4.1.1 Imagery Sources and Selection

I have created a six-date time series (1975-2008) of Landsat and CBERS imagery for the Corredor Bioceánico in eastern Bolivia (Santa Cruz-Puerto Suárez highway) to map past LULCC. Imagery acquired consists of Landsat 2 MSS, Landsat 4 and 5 TM, Landsat 7 ETM+, and CBERS-2 and CBERS-2B. The characteristics of Landsat sensors are well-known and will not be repeated here (see NASA at http://landsat.gsfc.nasa.gov/; Jensen 2006). CBERS, however, is less well-know (Table 2). The history, development, and salient characteristics are provided in detail in Section 5.

To cover the 2005-08 time-periods, CBERS-2 CCD imagery (15 scenes) at 20 m spatial resolution was downloaded from the Brazilian National Institute for Space Research (Figure 26; Table 3). To cover the next four time periods (2000-01, 1992-94, 1986-89, and 1975), the following Landsat imagery was downloaded and purchased from the University of Maryland's Global Land Cover Facility archive and the United States Geological Survey's (USGG) Earth Explorer: 30 meter ETM+ imagery (9 scenes), 30 meter Landsat TM (18 scenes) (Figure 27; Table 4), and 80 meter Landsat MSS (5 scenes) (Figure 28; Table 5). All scenes were radiometrically corrected to remove atmospheric attenuation in order to address atmospheric scattering (Figure 29). The Chavez Cos(t) model was used as the data necessary to perform a full correction model (e.g. optical thickness of atmosphere and spectral diffuse sky irradiance) is not available. This model removes haze and estimates the effects of absorption and Rayleigh scattering (Chavez 1996) and all input parameters are available. Empirical line calibration was used to match brightness values between scenes.

4.1.2 Steps for Removing Systematic Distortion of CBERS Imagery

Level-2[10] CBERS-2 imagery downloaded from the INPE often still retain discontinuities between the overlap of each of the three CCD array detectors due to differences in position as a result of camera instability (Jianning et al. 2005). This causes noticeable differences between the three, 9 km strips which compose a single scene, and is visually represented by residual banding and distortion between arrays (Figure 30). Figure 31 shows that the separation lines are worse in bands 1 through 3. Band 4 and the two outer 9 km strips on band 3 appear to be the result of non-uniformity between the three detector gains (high gain determined during pre-launch) and offsets (dark current caused by different residual responses for zero radiance), over-compensation by one or more detectors, and lack of on-board calibration and detection equalization capabilities (Junwu et al., 2005; Bensebaa et al. 2004), which combine to create artefacts and noise toward the strip edges.

I have devised a statistical method which is effective in minimizing spectral response variability among the three arrays without the need for calculating rigorous gain calibration whereby DN values of the middle detector array and regions of overlap are used to adjust the outer arrays. First, the image is rotated back into its original space

[10] CBERS-2 and -2B are available at three processing levels: (i) Level-0: raw data; (ii) Level-1: radiometric correction; and (iii) Level-2: radiometric and geometric calibration and correction.

(i.e. rotated to 90° verticality) and separated into like portions to create three large sub-regions (A, B and C) and four smaller sub-regions (a, b_1, b_2, and c) (Figure 32). Two methods were used to produce calibration values. First, homogenous areas were selected in each of the larger and smaller sub-regions; these were usually bare soil fields (bright or high reflectance sites) which would ideally have very similar spectral characteristics if systematic distortion was not present. Secondly, the mean values for each sub-region was calculated for the entire subset. In both cases, the middle array detector is the least corrupted among the three arrays (Jianning et al. 2005; Bensebaa et al. 2005) and is therefore designated as the control site. Once these regions are subset, histograms are computed and the mean is calculated for each band and for each subset and set to $\overline{a}$, $\overline{b_1}$, $\overline{b_2}$, and $\overline{c}$. Following Jianning et al. (2005), ΔA and ΔC are the DN values that need to be changed for array A and C and are performed by equations (1) and (2):

$$\Delta A = \overline{b_1} - \overline{a} , \tag{1}$$

$$\Delta C = \overline{b_2} - \overline{c} , \tag{2}$$

The resulting images in Figures 33 and 34 show that mean DN values calculated from homogenous sites performed best.

4.1.3 Geometric Correction and Classification

After stitching individual images together and correction of CBERS scenes, I geometrically registered the mosaics using 1:50,000 topographic maps acquired from the Bolivian Geographic Military Institute in Santa Cruz and GPS points acquired during field campaigns in 2006 and 2007 (Figure 35). Road intersections or bridge crossings were used whenever possible resulting in an average RMSE (σ) of 0.2 pixels.

A maximum likelihood supervised classification rule was employed to map three classes: natural vegetation, agriculture, and bare/open ground. Urban/infrastructure and water bodies (rivers and lakes) were classified through user-defined, digitized polygons. Field notes and ancillary data (elevation, precipitation and soil maps) were used when digitizing polygons. It was decided that forest and crop types should be grouped into two broad classes due to the nature of the data and study area (see Section 6). Post-classification change detection, where two maps are compared on a pixel-by-pixel basis using a change detection matrix, was used to extract the quantity of LULC conversion. This method was employed because it is widely used and easy to understand (Jensen 2005). In addition, this method is viable since the accuracy of the original classification maps is relatively high (See subsection 4.1.4). Ultimately, this methodology produced land-cover and land-use maps for each of the five time periods; four inter-decadal change land-cover and land-use change maps; and change statistics matrices. Results are discussed in Section 5.

4.1.4 Accuracy Assessment

Accuracy assessment was accomplished through on-site analysis: 176 locations were visited in the summers of 2006 through 2008 along the entire length of the Corredor Bioceánico and an overflight was conducted over the whole of the Tierras Bajas subset (Figure 36). At each location visited, a land-cover and land-use survey was conducted (Table 6). Site location was recorded and mapped in detail noting type of crop planted and type of vegetation. LULC height, density, and maturity were also noted along with soil colour and descriptions of landforms present. Since all four cardinal directions were recorded at each location, the number of samples that could be used to conduct an accuracy assessment quadrupled to over 700. Each location was mapped on the 2006-07 CBERS-2 and CBERS-2B mosaics and labelled polygons were used to represent the LULC assessments. During overflight, a camcorder was used to document LULC. Recordings were then visually compared to satellite images to note accuracy. Results show high overall accuracy (Table 7) for each subset with the highest accuracy achieved in the Tierras Bajas (99.92%) and the lowest in the Brazilian Shield (90.53%).

4.2 MAPPING DETAILED LAND-USE AND LAND-COVER CLASSES

My objective here is to identify, map and quantify seasonal forest to agriculture conversion pathways in the seasonal tropics of southern Bolivia between 1994 and 2008. I have established a hybrid methodology which incorporates five complementary data sources: (1) large-area, phenological data derived from MODIS (2007 and 2008, 250 m NDVI); (2) medium-resolution land-cover and land-use data from Landsat ETM+ (2001, 30 m) and CBERS-2 (2007 and 2008, 20 m); (3) a detailed forest map created by Navarro and Ferreira (2007); (4) ancillary biogeophysical information such as soil types, rainfall, elevation, and cropping calendars; and (5) interview and survey data collected between 2007 and 2009. By developing this method, I am able to progress beyond the binary forest and non-forest classification of land-cover and land-use commonly encountered in the remote sensing and land change literature, thereby providing a strong foundation for pattern to process (Nagendra et al. 2004). It is in these contexts that I seek to answer the following questions: what types of forest are being converted to pasture or a particular cropping regime, where and why; and what types of land-use modification changes have occurred?

4.2.1 Imagery Source and Selection

MOD13Q1 NDVI (16-day L3 Global 250 m) coverage for two tiles (h11v10 and h12v10) (23 scenes per tile) was acquired from the USGS Land Processes Distributed Active Archive Center (LP DAAC). The time series represents a continuous 16-day composite series only for the years 2001, 2007 and 2008 due to an incomplete data record for 2002 to 2006 as well as a lack of corresponding medium-resolution imagery. Characteristics of MODIS and the algorithm used to generate NDVI values from MODIS data can be found in Huete et al. (2002) and Xiao et al. (2006). The Enhanced Vegetation Index (EVI), which does not become saturated as easily as the NDVI when viewing rainforests and other areas with large amounts of chlorophyll, was not used since land-use (i.e., agriculture and pasture) was the area of interest. Compared to humid tropical forest, cropland does not represent high biomass and most environments in the study area do not possess significant topographical difference. The former reason also explains why other soil-adjusted indices such as SAVI, MSAVI and TSAVI were not employed in addition to the fact that most pasture along the Corredor Bioceánico is often covered with degraded or secondary natural vegetation.

Individual 16-day composites in the two adjacent tiles were mosaicked and stacked to provide coverage of the study area. I performed geometric correction using a 2007 CBERS-2[11] (20 m) classified product resulting in a RMS error of 0.21 pixels for the full set of 16-day composites (Figure 37). Resampled classification masks were created using standard, maximum likelihood unsupervised classification of the CBERS-2 imagery to remove areas that were not cropland or pasture (forest, water bodies, natural bare ground, and urban areas and infrastructure). Radiometric correction was not performed as the MOD13Q1 product is already corrected using the quality assurance **(**QA**)-**based constrained view angle**-**maximum value composite **(**CV-MVC**)** algorithm to remove atmospheric influences such as cloud, shadow and aerosols. Gao et al. (2000) and Huete et al. (2002) assessed the validity of MODIS NDVI through the measurement and comparison of top-of-canopy reflectance and found good agreement between the two.

4.2.2 Classification

Semi-structured interviews with land-owners and managers in May and June 2009 and a crop calendar confirmed the existence of two distinct growing seasons in the

[11] For more information on the characteristics of CBERS-1 and CBERS-2 visit http://www.cbers.inpe.br/?hl=en (Accessed 02 September 2009).

region: (i) a wet, summer season from mid-October to late April[12] (October 16 – April 23 in terms of MODIS 16-day composites); and (ii) a dry, winter season when irrigated crops are grown from late April to mid-August (April 23 – August 12 in terms of composite dates). Only 16-day composites which fell within these growing seasons were selected for further analysis. These dates capture the optimum periods in the life cycle of the main crops and pasture. These interviews also confirmed the types of land-use present for the study periods covered by the natural vegetation map and satellite imagery: 1994, 2001, 2007 and 2008.

I classified agricultural land uses for each time period using three separate, supervised decision trees. These have proved useful in classifying and detecting land-cover and land-use elsewhere (e.g. Friedl and Brodley 1997; Zhan et al. 2002; Wardlow 2006, 2007; Hansen et al. 2008a). Decision trees predict class membership by recursively partitioning data sets into mutually exclusive classes called parent nodes (Hansen et al. 2000). Based on 'if-then' statements, parent nodes are further subdivided into 'children' or leaf nodes using a series of splits or thresholds (Wardlow 2005; DeFries et al. 1998). For example, a parent node could be defined as cropland while children nodes could be double cropped fields or fields with bare soil. The process is complete once all pixels have been discriminated from their counterparts or, more likely, until user-defined conditions are met. The advantages of a decision tree over traditional unsupervised and supervised classification methods are several: (a) decision trees are not

[12] The summer and winter growing seasons are represented as continuous in order to account for direct or minimum tillage where the seeds are drilled into the soil almost directly after the summer harvest to reduce wind and water erosion and soil compaction.

based on assumptions of normality within training area statistics as with maximum likelihood classifiers; (b) they can reveal nonlinear and hierarchical relationships between the input variables and use these to predict class membership; and (c) it is obvious which variables contribute to the discrimination between classes (Hansen et al. 1996, 2000; DeFries et al. 1998).

Training data consisted of 74 individual plots distributed along the entire Corredor Bioceánico derived from interviews with land managers in 2009 and field-based land cover and land use assessments made in 2007 and 2008 coupled with aerial videography flown at 2,000 m.a.s.l. in July 2008. This yielded information on the type of land-use, the specific cropping regime and/or presence of pasture for all time periods covered in this study (1994-2008). Land managers identified their fields on the 2008 CBERS-2 imagery. During processing, field site data were also located on the MODIS imagery, and then divided into training (80%) and validation (20%) data sets using random sampling. Once the data set was divided, a single, centrally located pixel was selected for each field mapped to create the spectral signature instead of a kernel of pixels in an attempt to reduce the influence of mixed edge pixels (Wardlow 2006). In Figure 38, individual profiles and averages of these phenology curves for each of the three time periods are shown for pasture and each cropping regime. Pastures in Bolivia are often very productive and usually have remaining intact or degraded vegetation giving rise to relatively high NDVI values in the summer and a steady decline as the dry, winter season progresses. Croplands, on the other hand, present a more dynamic range in NDVI (Galford et al. 2008) as vegetation experiences one or two cycles per year of sowing, greening-up, flowering, maturity (maximum green leaf area), senescence, and harvest. Fields double cropped are easily distinguished by two, distinct curves corresponding to the summer and winter growing seasons. On the other hand, fields cropped only during the summer often experience longer growing seasons, but have lower NDVI values in the winter (compared to pasturelands) after harvest. Fallow fields are composed of a mixture of exposed bare and dry, crop stubble.

Identification of these distinct phenological cycles enabled me to calculate the following simple metrics for use as annual NDVI thresholds in the decision tree classifier: harmonic mean, minimum, maximum, and amplitude. According to DeFries et al. (1998), this suite of metrics had the highest accuracy compared to other available metrics when classifying land-cover and has also been used successfully by Wardlow (2005, 2007) in classification. In addition to these simple metrics, I also calculated the standard deviation of the harmonic mean (± 0.5) to account for the variable geographic differences between study regions mentioned in the previous section. Standard deviation was able to separate two or more modes which had similar NDVI values for a given date. Based on these variables, I used the decision tree structure to classify all 16-day composites which fell within the summer and winter growing seasons separately for each year (2001, 2007 and 2008) into four discrete categories: pasture, double cropped fields (cultivated in both summer and winter), single season crops (summer only), and bare soil cropland (annual fallow). An example of the decision tree used for 2007 is shown in Figure 39.

4.2.3 Accuracy Assessment

Accuracy assessment was based on the information obtained from semi-structured interviews with land-owners/ managers conducted in May and June 2009 and parcels mapped during field visits, which were not used in the classification procedure (i.e., 20% of 'sites'): 12 fields only had cropland on their farms, five only had pasture, and seven had a mix of cropland and pasture. In total these farms and ranches had approximately 28 fields under pasture or cropland. The land owners interviewed were drawn from the main groups found along the corridor: small-scale peasant farms; medium to large-scale, mechanized, owner-operator farms and/or ranches; and large-scale, mechanized, company-owned and managed farms and/or ranches. Information was gathered on crop types, cropping regimes during 2007, and the changes in regimes over time. The interviewees outlined their field boundaries on a detailed land-use map derived from 2007 CBERS-2 imagery. This resulted in high overall accuracy for each of the three time periods (between 91.64% and 92.98%) (Table 8). Kappa coefficients (κ) were slightly lower and ranged between 0.8465 and 0.8751, but still represented strong agreement that the classification products are significantly better than random class assignments. For the 2007 and 2008 classification products, relatively high commission and omission errors were generated by the poor performance of the single, cropped summer regime and bare soil fields, which I ascribe to too few fields in these two categories from the interviews (i.e., low values).

4.2.4 Mapping Natural Vegetation

Navarro and Ferreira's (2007) "Vegetation Map of Bolivia" is the most complete, up-to-date, and detailed digital map of natural vegetation for the entire country. Along the Corredor Bioceánico, 175 classes were mapped (Table 9). The authors used the GeoCover database (land-cover categorizations based on 30 m, Landsat TM imagery from 1990 to 2000) and topographic maps derived from digital elevation models for broad-scale mapping. More detailed classes relied on empirical fieldwork consisting of floristic-ecological inventories, which were georeferenced to botanical collections deposited in herbaria in Santa Cruz and La Paz. Also included are deforested areas and human-influenced clearance which occurred prior to 1994. Classes completely deforested often account for the largest amount of change between time periods (persistence); therefore, classes which represented areas completely deforested were removed from our analysis. To determine the pathways of forest to cropland transition, I first resampled the dataset to 250 m and then intersected the land-cover classes derived by Navarro and Ferreira, and the land-use classes for each time period mapped from MODIS imagery (2001, 2007 and 2008). Results of the classification are discussed in Section 6.

4.3 DRIVERS OF LAND-USE AND LAND-COVER CHANGE

The objective of this section is to determine why land-use decisions were made at particular points in time given the prevailing incentives, rules-in-use, and policies at those times. It also involved assessing the role of meso-scale organizations and institutions at work in the region. I obtained this information from a hybrid technique involving the compilation of a qualitative semi-structured interview and quantitative, landowner surveys, and archival research. These were conducted with individual producers and spokesman for international and national organizations and federations.

4.3.1 Semi-Structured Interviews and Surveys: Individual Farmers

Based on 2007-2008 fieldwork and discussions with Texas A&M faculty and stakeholders in Bolivia, I identified three types of dominant farms/land managers along the Corredor Bioceánico (Figure 40): Type 1 – medium-large, mechanized, owner-operator farms; Type 2 – large, modern livestock ranches; and Type 3 – modern, mechanized owner-operated farms which also include modern ranches. I interviewed land managers with a hybrid semi-structured/survey protocol (Tables 10; 11; 12) on all of these types of farms in locations scattered along the Corredor Bioceánico. Official approval for this fieldwork was obtained from the Texas A&M institutional review board (IRB). In this case, I received an exemption from human-subjects review (Protocol Number: 2007-0065).

The ideal sampling technique would be that performed by Brown et al. (2007) on modern, large farms and ranches in Rondônia, Brazil since at first glance, it shares many of the same characteristics as Santa Cruz. In the former, two decision-making regimes exist among producers – the mechanized farmer/modern rancher, and the land-owner (an agro-industry in the case of cropland) who lease the property (Brown et al. 2004). Ideally, an employee of the agro-industry would be interviewed and the sample selected in this manner. However, tenant-operators do not exist in Santa Cruz as a farmer owns his land whether they have a legal title or not. In other words, property is owned by 'those who work it.' To partly overcome this issue, I enlisted committee members of crop and ranching associations, whom were also producers, for interviews. Organization leaders are seen as the most knowledgeable persons in the region and subsequent respondents were selected based on the snow-ball technique. This method is flexible and based on the referrals of presidents and executive committee members (Neis et al. 1999; Ferguson and Messier 1997).

Another obstacle to overcome was to locate and interview Mennonite farmers. They are significant actors in terms of land-use, but due to their religious ideals and broad skepticism of outsiders, they are notoriously difficult to approach, much less interview. Serendipitously, I was able to locate a Mennonite dairy farmer (originally from Canada) who was formerly employed at the Santa Cruz based Mennonite Central Committee, a social and technical organization designed to help Bolivian Mennonites with a range of services (e.g. agricultural advice and loans). The Mennonite Central Committee was also able to provide me with a translator to translate responses from High German to English or Spanish. In this way, I was able to enlist respondents and while the selection of the sample may be biased, there is little choice when attempting to tackle the issue of interviewing closed societies as an outsider. In fact, I have no evidence that Mennonites in Bolivia have not been interviewed by an academic researcher since 1971 (see Lanning 1971).

Overall, I conducted interviews with a total of 33 producers distributed as follows among the three farm types: 15 – Type 1; 9 – Type 2; 9 – Type 3. I also performed 10 interviews with various state agencies and producer organizations. All interviews were transcribed. They were not recorded as few respondents were willing to go on record considering the current political climate in Bolivia. Names of the farmers, ranchers and owners remained confidential as the identities of the interviewees were not connected to the information gathered. Each respondent received a stated letter which outlined the following: (a) support from the university and advisor; (b) stated aims of the interviews; (c) benefits to the respondents; and (d) statement to protect privacy and anonymity. Confidentiality was enforced by substituting arbitrary number codes for names and classifying farm location according to a regional classification scheme. They code key (names and farm location) and the original semi-structured/survey instruments under lock and key. As a result of the changes which have occurred since Morales took office (See Sections 7 and 8), the socio-political climate of Santa Cruz is in turmoil. There is a great deal of mistrust between land-owners and representatives of the government. Posters and pamphlets litter the offices of Santa Cruz portraying Evo Morales as Joseph Stalin or Adolph Hitler. In the city's central plaza, protests draw hundreds of supporters who make speeches over loudspeakers. This often results in the formation of pro- and anti-Morales groups who participate in shouting matches or sometimes, violence. Efforts to walk the fine of neutrality and establish trust between myself and the interviewee are difficult and are discussed below.

Land managers (farmers or ranchers) were asked to recall aspects of forest clearance and what crops had been grown at the times the images used to construct the maps were acquired. In all cases, I asked questions about general household information (age, gender, birthplace, remittances, etc.) and decision-making processes behind crop choices, changes in crop type, and land conversion in the prevailing context of prices, incentives, policies, and institutions. Each land parcel received a unique identifier.

More specifically, the following information was obtained: yearly or decadal (2007, 2002, 1994, and 1974) type of crop and/or animal and variety grown, area, percentage irrigated coupled with monthly data on when soil was prepped, crop planted, irrigated, fertilizer and pesticide was applied, harvest, and fallow. Type of labor employed (percentage of household or hired help) and harvest destination (percentage destined for market, family/friends, or market) were also ascertained. Questions concerning access to (or lack of) monies and technology were asked to elicit responses on credit and equipment type, seeds, and types of contracts. A Likert scale was used to categorize responses which assessed a respondent's opinion on the following issues: the 2006 Agrarian reform (Law 3445), the 2007 prevention and control of forest fires, difficulties obtaining credit, machinery, and seeds, outside threats and opportunities regarding adjacent landowners/communities, issues associated with the highway, tertiary roads, or railway, and opinions on precipitation ad soil quality. On farm types 2 – modern ranches – livestock (cattle milk and meat, chicken meat and eggs, pigs and goats) was, of course, the main concern. I solicited data on animal type and number, area, type of forage and labor, slaughter or harvest (amount and selling price), and harvest destination (% to household, family/friends, and market).

4.3.2 Interviews with Organizations and Federations

Ten interviews with spokesman of international and domestic organizations as well as documentary and archival research of another 35 (for a total of 45) reveal their role in the region's historical and future of LULCC. This was achieved by recording general information such as mission statement (initial need, goals, and objectives), years in operation and predecessors, members (number of employees and changes over time), operational spatial distribution or coverage, and sources of funding. More specifically, I recorded specifics on work/service conducted, major concerns, and their role or advice they give (if any) on conservation (e.g., soil rotation and management, windbreaks, methods of forest clearance, agrarian reform, and control of forest fires) and how they view their future role in the region.

4.3.3 Preparing Interview Data

The first step analytic step of the data gathered was to develop a theory to explain the data through 'coding,' the process of examining the information gathered and defining the actions or events that are occurring in it or represented by it (Charmaz 2001: 341). In addition to assessing the respondent's actions and dialogue, this method also kept a nuance of objectivity by not introducing my own personal motives (Tables 13; 14; 15; 16; and 17). In these cases, pre-conceived categories were already set in place by the structure of the protocol though sub-codes were sought out through focused coding. In other situations, I used *in vivo* coding from grounded theory in order to allow key theories to emerge (Charmaz 2001). This was accomplished by taking responses directly from the discourse. Examples of this method are shown in Tables 18; 19; 20; 21; 22; 23; 24; 25. Once analysis was complete, I was able to construct two conceptual models. The first outlines the underlying drivers and proximate cause of LULCC (Figure 41); the second is a figure showing the hierarchy of organizations which affect producers (Figure 42). Results are discussed in Sections 7 and 8.

The validity of the methodology must also be assessed in terms of knowledge claims. In other words, do I doubt a claim is actually true? For justification purposes, I must identify whether the person making a claim has any personal relationship or involvement with the declaration. If the interviewee stands to gain personally or may have a bias opinion due to personal beliefs then I have reason to doubt his claim. Also my memory and personal relationship with a person making a claim can test the reliability of the claim. Since also interviews were transcribed on-site and I had no prior relationship to the respondents, the latter case is not relevant. However, the former case of a biased respondent is likely not relevant either. Each respondent received a letter before each interview which outlined the study's purpose and terms of confidentiality. This helped to establish trust and alleviate any source of anxiety the respondent might have that their narratives would be used against them. Unavoidable though is the biased opinion of some respondents. Due to the political climate in Santa Cruz, a few respondents were openly anti-Morales and this may have affected their answers to questions in the section headed “threats and opportunities” (See Tables 10, 11 and 12).

Related to knowledge claims are the satellite images used to denote the locations of properties. By possessing maps of the area, this presupposes that I have prior access to knowledge. However, the majority of all interviewees were not surprised by this so-called prior knowledge. Many already possessed satellite images of their properties given to them by the government or had bookmarked the field location in Google Earth. Most respondents were only interested in acquiring more up-to-date satellite images.

5. MAPPING LAND-USE AND LAND-COVER CHANGE ALONG BOLIVIA'S CORREDOR BIOCEÁNICO: 1975-2008[13]

5.1 INTRODUCTION

Between 1990 and 2005, the FAO's Global Forest Resources Assessment Report (2005) stated that over 125 million hectares of tropical forest had been cleared world-wide – a combined area roughly the size of Peru or twice that of Texas. Just over half was lost in Latin America alone. Sobering statistics such as these are behind the pressing need to accurately document contemporary rates and extent of tropical deforestation at all spatial scales to support sustainable resource development, environmental protection goals, and better understand the impact humans have on the environment (Sánchez-Azofeifa et al. 2003). Despite long-standing calls for these types of data, very few countries outside of North America and Europe have reliable estimates on the rates of LULCC (Grainger 2008). For most developing countries, annual or decadal estimates of forest cover are reported by international organizations, which in turn are reported by the national government of the nation in question. Also dubious are the type of methodology used, definitions of land-cover and land-use, and variability of scale and spatial extent (Kuemmerle et al. 2009; Grainger 2008). Thus, the reliability of deforestation estimates is often questionable.

[13] This section has been submitted as a paper to *International Journal of Remote Sensing*. The section numbers have been enumerated in sequence with this dissertation, the acknowledgements and abstract excluded, and the references merged in the References list for the entire dissertation.

To meet these demands and fill gaps, land change scientists have usually turned to the Landsat series (MSS, TM, and ETM+) for mapping and quantifying LULCC. This is particularly so for detailed exploration in sub-continental areas of Latin America (Boyd and Danson 2005; Rogan and Chen 2004; Foody 2003) owing to their near-global, temporal coverage of over 30 years; easily accessible archives with free data; user-community familiarity in terms of image processing and analysis; and, for inexperienced remote sensors, a lack of knowledge about alternative imagery. For these reasons, they have been the preferred choice—the workhorses—for mapping the conversion of forest to agriculture in the tropics and sub-tropics. A major drawback, however, is that Landsat satellites lack the ability to capture seasonal variations or phenological changes in vegetation due to their relatively infrequent revisit times (16-18 days), small spatial footprint (~185 km), and resulting cloud contamination, the two latter being issues common in the tropics (DeFries and Belward 2000).

The largest drawback, however, has been the recent failure of the Scan Line Corrector (SLC) of Landsat 7 ETM+ in 2003. Without the SLC, ETM+ images represent only one-quarter of the data normally acquired with a working SLC. Scenes with SLC-correction are actually an amalgam of two or more different dates where missing pixels are filled with the closest available dates. Trigg et al. (2006) show that data gaps caused by this malfunction can introduce errors of 1.47% for estimates of forest cover and 4.04% for rates of forest loss compared to pre-SLC malfunction. With the land change record partially interrupted many land change scientists have either accepted the composite imagery or turned to other sources of medium-resolution image data. Alternative sources include SPOT 3 HRV and IRS P6 (RESOURCESAT-1) LISS 3, but high costs relegate most usage to just a few scenes at small spatial scales. In this context, I seek to answer the following question: can the land change record be extended, post-SLC-correction, at low cost and without the loss of information?

This study uses a combination of Landsat series data (MSS, TM and ETM+) to map LULCC from 1975 to 2001. It extends the land change record to 2008 using CBERS-2 and -2B data on a multi-scene level. I also establish a methodology to correct for systematic distortion inherent in CBERS imagery without the loss of information present in Landsat 7 ETM+ imagery post-2003. Image analysis focuses on a 63,000 km^2 strip of land along the main highway and railroad trending east-west in southeastern Bolivia named the Corredor Bioceánico. This strip of land is one of the most important agricultural region-deforestation hotspots in Latin America (Etter et al. 2006; Perz et al. 2005), and located in one of the most poorly understood forest biomes in the world in terms of LULCC – Southern Hemisphere seasonally dry tropical forests – which have very high conservation values globally (Quesada et al. 2009; Lepers et al. 2005; Achard et al. 2002; Dinerstein et al. 1995; Janzen 1988). The Corredor Bioceánico exhibits an east-west gradient of agricultural development ranging from a well-established agricultural region in the west of the study area, adjacent to the metropolis of Santa Cruz, to an active cultivation-induced deforestation frontier in the east closer to the Bolivia-Brazil border. The area is predominantly rural, with a series of small urban-agricultural centers along the road and rail lines; apart from Santa Cruz, the two largest towns are the port cities of Quijarro and Suárez along the Brazilian border with a combined population of only 33,000 (INE 2001).

The paper is divided into two sections. First, I outline the study region and the sub-regions used to illustrate the Corredor Bioceánico's importance as a major agricultural region. I then discuss previous approaches to mapping forest loss in South America and Bolivia. In the second part of the paper the focus shifts to the methodology for mapping land change using satellite data acquired on a decadal basis from 1975 to 2008. This is underpinned by a discussion of CBERS imagery and methods to correct systematic distortion. The discussion that follows assesses the feasibility of extending the temporal resolution of land change studies through the use of CBERS data.

5.2 STUDY AREA

The Corredor Bioceánico in southeastern Bolivia is part of a larger trans-continental transportation and natural gas pipeline artery connecting the departmental capital of Santa Cruz (population ~1 million) eastward to the Brazilian Atlantic and westward to highland Bolivia and the Pacific ports in northern Chile. For the purposes of imagery analysis, I have defined a 571 km long, 100 km wide buffer, which is further divided into three sub-regions based on distinct differences in topography, soils, precipitation, available soil moisture, vegetation and land use (Figure 43). Sub-region names are largely derived from ecoregions which extend into the study areas.

The most westerly sub-region is the Tierras Bajas. Covering an area of 21,787 km^2 it comprises a relatively flat plain of alluvial soils rich in fertility. Prior to human disturbance in this area, the vast majority of which has only occurred in the last 30-40 years, dry broadleaf forests dominated the area. Modern, mechanized commercial agriculture for oilseeds and wheat has expanded significantly in this region as a result of land colonization schemes; preferential access to regional trade blocs; high soil fertility and high rainfall (compared to eastern and central parts of the corridor); close proximity to Santa Cruz; and improvements in highway and railroad links. Further east is the 'Brazilian Shield' sub-region. It is the largest of the three at 28,568 km^2 and composed mainly of quartzitic ridges and mountains of Precambrian origin (ENTRIX 1999), and floodplains located in broad valleys. The latter are emerging as zones of mechanized agriculture resembling those of the west in both crop mixes and scales of production. Adjacent to the border with Brazil is the smallest sub-region – the 'Pantanal' – covering only 12,671 km^2. It is dominated by the large floodplain created by the Río Paraguay and the terrain is generally level. Floodplains north of the highway in the Pantanal are currently the most active hotspots of deforestation along the Corredor Bioceánico, due in part to the region's relatively high rainfall and fertile soils, abundance of uncultivated forest, proximity to the Hidrovía Paraná-Paraguay as well as the paving of the main highway and revitalization of rail service.

5.3 PREVIOUS APPROACHES TO MAPPING LAND CHANGE

5.3.1 Regional Land Change in South America

Many LULC change assessments have been conducted in South America in the last two decades particularly since 1999. Tucker and Townshend (2000) estimated deforestation in lowland Bolivia, Peru, and Colombia using 130 Landsat MSS and TM scenes coupled with a computer simulation program. Other than Tucker and Townshend (2000), most efforts have focused on changes at smaller spatial scales, and the overwhelming majority have been directed toward the humid tropics in the last five years (e.g., Bradley and Millington 2008; Hansen et al. 2008b; Etter and McAlpine 2008; Brown et al. 2007; Etter et al. 2006; Messina et al. 2006; Morton et al. 2005; Viña et al. 2004), indicating a strong bias toward the humid Amazon Basin (Fuller 2006).

Few studies have addressed changes in seasonally dry forests and woodlands of South America. This overlooks the fact that tropical dry forests, particularly those in South America, are considered one of the most endangered ecosystems on the planet (Janzen 1988) and once constituted 22% of total forest extent in South America (Murphy and Lugo 1986). Yet, these sensitive ecosystems have received little attention from land change scientists even though society has converted and used them more than tropical moist forests and evergreen forests (Bullock et al. 1995). They have been designated as "throw away" forest (Hecht 2005: 397). The name seems fitting as the dry forests of South America have experienced the greatest decrease in percentage cover over the last 20 years (DeFries et al. 2005) at alarming rates. In Latin America, it is estimated that 66% of all tropical dry forests have been cleared (Quesada et al. 2009).

Five years ago, only a handful of studies had mapped and quantified LULCC in South American dry forests and savannas, but the number has been steadily increasing, particularly from the Argentine Chaco (Gasparri and Grau 2009; Izquierdo and Grau, 2009; Grau et al. 2008, 2005 a, b; Zak et al. 2008, 2004a, b; Boletta et al. 2006) and

Brazilian Cerrado (Brannstrom et al. 2008; Morton et al. 2006; Jepson 2005). A highlight of the statistical results shows some of the highest deforestation rates per area in the world – rates are as high if not higher than many tropical wet forest areas. For example, annual deforestation rates range as high as 2.5-6.2% in the Argentine Chaco and Brazilian Cerrado.

5.3.2 Land Change in Lowland Bolivia

In southeastern Bolivia, the transitional semideciduous forests located in the 'expansion zone' of the Tierras Bajas have seen the most attention due to their longer settlement history and historically high clearance rates due to oil seed production. Davies (1993) was the first to assess to land change in the department of Santa Cruz in a 15,659 km^2 swath of the Tierras Bajas between 1975 and 1991 and found that 10% of the woodlands and forest had been lost to agricultural production. For the entire Bolivian lowlands (784,789 km^2), Tucker and Townshend (2000) found that deforestation in 1992-1994 was 28,208 km^2. In the most widely cited estimates for the Bolivian lowlands, Steininger et al. (2001a) reported high deforestation totals in areas of precipitation greater than 1,000 mm as 24,700 km^2 of 700,000 km^2 of eastern Bolivia's dry woodlands, wet forest, and savannas had been lost to the agricultural expansion of soybeans and other crops from 1975 to 1998. Steininger et al. (2001b) narrowed the focus of their previous study to a 19,533 km^2 swath between the Río Grande and Río Quimome – the entire Tierras Bajas. They found that 9,400 km^2 were cleared in the 1980s and 1990s. In both studies it is unknown how much conversion can be contributed to areas around the Corredor Bioceánico as Steininger et al. (2001a) included deforestation in the Chapare, Yungas, and Beni and both Steininger et al. (2001b) and Davies (1993) included areas around the Santa Cruz-Cochabamba highway. Mertens et al. (2004) assessed forest loss for the entire Santa Cruz Department and seven user-defined seven colonization zones between 1989 and 1994. They found that only 5,117 km^2 had been deforested in this comparatively short time period. Killeen et al. (2007; 2008) extended the time-series analysis of Steininger et al. (2001a) for the lowland forests of eastern and northern Bolivia and found that the amount of deforestation up to 2004 had increased to 45,411 km^2 along with 9,042 km^2 of scrub and savannah. Seventy five percent of all change that occurred from 1975 to 2004 occurred in the Department of Santa Cruz.

Of the studies that have previously reported on LULCC in parts or all of the area I cover in this paper, we still do not know about the spatial pattern of LULCC in the central and eastern parts of the Corredor Bioceánico because the focus of the most detailed studies has been on the western Tierras Bajas (Davies, 1993; Steininger et al., 2001a, b). In addition, the last years of these studies, 1991 and 1998 respectively, were at times when the greatest rates of forest loss in much of the Tierras Bajas had not been attained. In studies where the entire corridor is covered (Mertens et al. 2004; Killeen et al. 2007, 2008; Tucker and Townshend 2000), spatial patterns of change are generalized due to broad-scale coverage of either the entire department or the entire eastern lowlands of Bolivia. In this paper, I expanded the area covered by Davies (1993) and Steininger et al. (2001b) by mapping change along the entire 'corridor' between Santa

Cruz and Puerto Suarez, and, extended the time frame backwards to 1975 and forwards to 2008. I also included four intermediate time periods (1980s, 1990s, early-2000s and mid-2000s) to give a total of six time-series intervals. I narrowed the areas cover by Tucker and Townshend (2000), Steininger et al. (2001a), Mertens et al. (2004), and Killeen et al. (2007; 2008) to highlight the most dynamic area of change in the Department of Santa Cruz and used a more detailed mapping resolution of 20-meters (CBERS-2 and -2B imagery) for the most recent time periods of 2007 and 2008. Moreover, I consider the entire corridor which serves to illustrate that to the east new pressures on forests from clearance for cultivation and ranching are occurring is well beyond the traditional agricultural zones and into areas once thought to be impervious to large-scale agriculture (Pacheco 2006; Hecht 2005).

5.4 DATA DESCRIPTION AND METHODOLOGY

I have created a six-date time series (1975-2008) of Landsat and CBERS imagery for the eastern Bolivian portion of the Corredor Bioceánico to map LULCC over a 23-year period. Imagery acquired consists of Landsat 2 MSS, Landsat 4 and 5 TM, Landsat 7 ETM+, and CBERS-2 and -2B. The characteristics of Landsat sensors are well-known (see NASA at http://landsat.gsfc.nasa.gov/; Jensen 2007). As CBERS imagery is far less well-known and utilized compared to Landsat data, a history of its development and salient characteristics are provided.

5.4.1 CBERS Sensor Characteristics

The launching of the Chinese-Brazil Earth Resources Satellites (CBERS) represents an historic venture of two developing nations – China and Brazil – in the creation of a high-technology space program. de Oliveira Lino et al. (2000) state that the transfer of Landsat to private industry in 1984, which resulted in interruptions in image acquisition coupled with the high cost of SPOT imagery, actually led to the Brazilian/Chinese alliance and the launching of CBERS.

CBERS-1 was launched in 1999 followed by CBERS-2 in 2003. By 2007, the life expectancy of CBERS-2 was nearing an end. That same year CBERS-2B was launched. It is nearly identical to its predecessors, but for a new onboard recording system and more advanced global positioning system. Both satellites are identical and contain multi-sensor payloads with different spatial resolutions and image collecting frequencies: the WFI – Wide Field Imager (provides global coverage in the red and near-infrared spectrums at 260 m spatial resolution); the IRMSS – Infrared Multispectral Scanner (middle infrared and thermal spectrums at a coarser spatial resolution of 80-120 m); and the HRCCD – High-resolution Charge Coupled Device (visible and near-infrared spectrums at finer spatial resolutions). The spectral and spatial characteristics of CBERS-2 and -2B HRCCD are similar to both Landsat 7 ETM+, SPOT 1, 2 and 3 HRV and IRS P6 (RESOURCESAT-1) LISS 3 (Table 26). The HRCCD, however, exceeds Landsat ETM+ and IRS P6 in terms of finer spatial resolution (20 m compared to 24 m and 30 m, respectively) and detects electromagnetic energy in the lower visible range of 0.45-0.52 μm (blue), which SPOT cannot. For land change scientists studying large spatial areas, an important distinction is cost. One SPOT scene currently costs 1,200-1,900 USD, while 23 m IRS RESOURCESAT-1 imagery costs 2,750 USD per scene. CEBRS-2 and 2B imagery is free of cost to all public users. Thus, imagery from SPOT and IRS is simply not cost feasible in most instances. In the case of this study, 15 CBERS scenes were needed to cover the study area; equivalent imagery from SPOT or IRS would have cost between 18,000-40,000 USD.

Imagery acquired by CBERS-1 was never made available to the remote sensing community due to problems with data reception and radiometric and geometric processing (Ponzoni et al. 2008), and CBERS-2 and -2B imagery have only been available to the public since 2004 and 2007, respectively. Outside of Brazil and China, CBERS imagery products remain underutilized, and represent an important substitute to at least reduce the imagery archive gap created by the failure of Landsat ETM+'s Scan Line Corrector (SLC) in May of 2003[14]. Without the SLC, ETM+ images represent approximately 22% of the data normally acquired with a working SLC. Recovery efforts to use the redundant Side-B electrical harness failed, and the sensor now traces a permanent zigzag pattern along the satellite ground track instead of the approximate 90 degree angle. Effects are marginal at nadir (two contiguous lines or 60 m 'no data' gap span), but scan gaps are significantly more pronounced towards the edges (14 lines or 420 m 'no data' gap span) (Trigg et al. 2006). Thus, scenes available since this time

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[14] MODIS imagery is limited by its 250-m spatial resolution to map LULCC. High-resolution imagery from ASTER, IKONOS, RESOURCESAT, QuickBird and GeoEye-1 is not considered as a viable substitute for this study due to limited coverage over Bolivia and/or cost of covering medium to large study areas.

have missing pixels replaced with pixels from the near available preceding or succeeding date.

CBERS sensors, however, are not without problems and the resulting imagery products display multiple issues which must be overcome. First, INPE only acquires CBERS data over the continent of South America and partially over Central America that is within the visibility range of the Cuiabá ground station. The Chinese acquire the imagery using three ground stations covering China and neighboring countries. Second, changes in the satellite's orbital path due to battery problems and solar activity have caused systematic errors in the form of large gaps between scenes of different dates in the same path and row. Chander (2007) found the error to be on the order of several kilometers in the along-line or track direction and a dozen kilometers in the line direction. Second, band-to-band registration of the panchromatic band (band 5) is spatially inconsistent with bands in the visible and near-infrared spectrums (bands 1-4), often displaced by 40 pixels or more. Visually, artifacts in the form of banding and distortion between arrays also pose problems. Further details regarding image artifacts and a protocol for correction is discussed later in this paper. The three, 9 km strips which compose a single scene have been displaced creating noticeable gaps. More recently in May of 2009, the attitude control systems were switched off. Therefore, scenes do not follow the original specified Worldwide Reference System (WRS) system, the 26-day revisit time has changed, and cross track swing movements have also been affected. Furthermore, in July of 2009, the CCD camera overheated and has since been switched off by the INPE (http://www.cbers.inpe.br/?hl=en&content=imprensa_inpe, Accessed 10 February 2010).

5.4.2 Image Acquisition and Pre-processing

To map LULCC along the Corredor Bioceánico and cover the 2006/07 and 2008 time-periods, CBERS-2 CCD imagery (15 scenes) at 20 m spatial resolution was downloaded from the Brazilian National Institute for Space Research. To cover the previous four time periods (2000-01, 1992-94, 1986-89, and 1975), the following Landsat imagery was downloaded and purchased from the University of Maryland's Global Land Cover Facility archive and the United States Geological Survey's (USGG) Earth Explorer: 30 m ETM+ imagery (9 scenes), 30 m Landsat TM (18 scenes), and 80 m Landsat MSS (5 scenes). Images were acquired during the dry season on days clear of atmospheric haze enabling forest cover to be relatively easily discerned from surrounding non-forest land uses, and to reduce inter-image differences between sun angle and azimuth, soil moisture and atmospheric transmission. All scenes were radiometrically corrected to remove atmospheric attenuation in order to address atmospheric scattering. The Chavez Cos(t) model was used as the data necessary to perform a full correction model (e.g. optical thickness of atmosphere and spectral diffuse sky irradiance) is not available. This model removes haze and estimates the effects of absorption and Rayleigh scattering (Chavez 1996) and all input parameters are available. Empirical line calibration was used to match brightness values between scenes and all individual scenes were mosaicked to cover the study area and all sub-regions.

5.4.3 Protocol for Removing Systematic Distortion from CBERS-2 and -2B Imagery

Level-2[15] CBERS-2 imagery downloaded from the INPE often still retain discontinuities between the overlap of each of the three CCD array detectors due to differences in position as a result of camera instability (Jianning et al. 2005). This causes noticeable differences between the three, 9 km strips which compose a single scene, and is visually represented by residual banding and distortion between arrays. Figure 44 shows that the separation lines are worse in bands 1 through 3. Band 4 and the two outer 9 km strips on band 3 appear to be the result of non-uniformity among the three detector gains (high gain determined during pre-launch) and offsets (dark current caused by different residual responses for zero radiance), over-compensation by one or more detectors, and lack of on-board calibration and detection equalization capabilities (Junwu et al., 2005; Bensebaa et al. 2004), which combine to create artifacts and noise toward the strip edges.

I have devised a statistical method which is effective in minimizing spectral response variability among the three arrays without the need for calculating rigorous gain calibration whereby DN values of the middle detector array and regions of overlap are used to adjust the outer arrays. First, the image is rotated back into its original space (i.e. rotated to 90° verticality) and separated into like portions to create three large sub-regions (A, B and C) and four smaller sub-regions (a, b_1, b_2, and c) (Figure 45). Two methods were used to produce calibration values. First, homogenous areas were selected in each of the larger and smaller sub-regions; these were usually bare soil fields (bright

[15] CBERS-2 and -2B are available at three processing levels: (i) Level-0: raw data; (ii) Level-1: radiometric correction; and (iii) Level-2: radiometric and geometric calibration and correction.

or high reflectance sites) which would ideally have very similar spectral characteristics if systematic distortion was not present. Secondly, the mean values for each sub-region was calculated for the entire subset. In both cases, the middle array detector is the least corrupted among the three arrays (Jianning et al. 2005; Bensebaa et al. 2005) and is therefore designated as the control array. Once these regions are subset, histograms are computed and the mean is calculated for each band and for each subset and set to $\overline{a}$, $\overline{b_1}$, $\overline{b_2}$, and $\overline{c}$. Following Jianning et al. (2005), ΔA and ΔC are the DN values that need to be changed for array A and C and are by equations (1) and (2):

$$\Delta A = \overline{b_1} - \overline{a} , \tag{1}$$

$$\Delta C = \overline{b_2} - \overline{c} , \tag{2}$$

Results in Figures 46 and 47 show that mean DN values calculated from homogenous sites performed best.

5.4.4 Geometric Correction and Classification

After stitching individual images together and correction of CBERS scenes, I geometrically registered the mosaics using 1:50,000 topographic maps acquired from the Bolivian Geographic Military Institute in Santa Cruz and GPS points acquired during field campaigns in the summers of 2006 and 2007. Road intersections or bridge crossings were used whenever possible resulting in an average RMSE (σ) of 0.2 pixels.

A maximum likelihood supervised classification rule was employed to map three classes: natural vegetation, agriculture, and bare/open ground. Urban/infrastructure and water bodies (rivers and lakes) were classified through user-defined, digitized polygons. Field notes and ancillary data (elevation, precipitation and soil maps) were used as supplemental aids in digitizing polygons. After analysis, it was decided that forest and crop types should be grouped into two broad classes due to the nature of the data and study area (see Redo and Millington 2010). Imagery was acquired at different times in the year and over several years. Each scene represents only one snap-shot in time. Additionally, rainfall along the corridor varies yearly. Therefore, it is simply not possible to map forest and crop types using inconsistent imagery and only one time period. Post-classification change detection, where two maps are compared on a pixel-by-pixel basis using a change detection matrix, was used to extract the quantity of LULC conversion. This method was employed because it is widely used and easy to understand (Jensen 2005). In addition, this method is viable since the accuracy of the original classification maps is relatively high (See subsection 5.4.5). Ultimately, this methodology produced land-cover and land-use maps for each of the five time periods; four inter-decadal change land-cover and land-use change maps; and change statistics matrices.

5.4.5 Accuracy Assessment

Accuracy assessment was accomplished through on-site analysis: 176 locations were visited in the summers of 2006 through 2008 along the entire length of the Corredor Bioceánico and an overflight was conducted over the whole of the Tierras Bajas. At each location visited, a land-cover and land-use survey was conducted. Site location was recorded and mapped in detail noting type of crop planted and type of vegetation. Vegetation height, density, and maturity were also noted along with soil color and descriptions of landforms present. And since all four cardinal directions were recorded at an individual location, the amount of samples used to conduct an accuracy assessment quadrupled to over 700. Each location was mapped on the 2006-07 CBERS-2 and CBERS-2B mosaics and labeled polygons were used to represent the LULC assessments. During overflight, a camcorder was used to document LULC. Recordings were then visually compared to satellite images to help calculate accuracy. Results show high overall accuracy (Table 27) for each subset with the highest accuracy achieved in the Tierras Bajas (99.92%) and the lowest in the Brazilian Shield (90.53%).

5.5 RESULTS

For the Tierras Bajas, overall results indicate that over 10,000 km^2 of natural vegetation were lost from 1975 to 2008 and was nearly entirely replaced by cropland and pasture (Table 28). In 1975, nearly all agriculture was concentrated west of the Río Grande on the outskirts of Santa Cruz. The area located east of the Río Grande was nearly one contiguous block of natural vegetation (Figure 48). Along the Santa Cruz-Puerto Suarez highway, only scattered patches of agriculture could be found and these were cultivated by early pioneers. In 1986, structural adjustment policies were introduced, soybean had been introduced as a commercial crop, and there was a veritable land rush east of the river. During this time, forest declined at an annual rate of -0.5%. In the 1990s, rising soybean and sunflower prices, easy access to credit, and favorable environmental factors such as climate, soil and terrain increased the annual rate of deforestation to 1.9%. By 2000, little forest was left to be cleared in the Tierras Bajas, and cultivation exceeded the amount of natural vegetation as rates of forest loss increased to 4.1% per year. Post-2001, the amount of land under forest dropped below 10,000 km^2 in the Tierras Bajas. Annual rates of vegetation loss decreased from 2000 to 2006, but then accelerated by 2008.

In the Brazilian Shield sub-region, agriculture increased by only 1,200 km^2 during the same time period and deforestation rates were relatively negligible to the Tierras Bajas (Table 28). In 1975, cultivation was found along the railway in small, scattered patches (Figure 48). By 1986-88, these patches had increased in size and new clearance for pastures and fields had occurred along the main highway and railway. During this time, annual deforestation rates were below 0.1%. By 1992-93, existing patches of agriculture had increased and coalesced, particularly north of San José de Chiquitos; while new patches of agriculture and pasture could be seen in the eastern Brazilian Shield near Roboré. Nearly a decade later (2000-2001), clearance for larger fields emerged raising the annual rate of deforestation to 4.1%. By 2008, deforestation for agriculture reached its height, ominously resembling early clearance for land-use in the Tierras Bajas.

The easternmost subset, the Pantanal, has also emerged as new agricultural zone with approximately 650 km^2 of forest lost to cropland and pasture from 1975 to 2008 (Table 28). Similar to the Brazilian Shield, cultivation in 1975 could only be found along the railway, particularly near the cities most influenced by Brazil and the largest cities in the Pantanal region – Puerto Suarez, Puerto Quijarro and El Carmen (Figure 48). From 1986 to 1994, clearance was concentrated along the highway and deforestation rates were also negligible. In 2001, further pasture expansion had taken place in the same locations it had been seen in 1994, but the size of some fields (some were by this time as large as 50 km^2) indicated a shift from small-scale to large-scale production. Annual deforestation rates reflect this trend growing to 0.3%. The final time periods of 2007 and 2008 show that the Pantanal is showing signs of an emerging agricultural zone of the Department of Santa Cruz. During this time, annual rates of forest loss were at their highest at 0.8% and 0.9%.

5.6 DISCUSSION

5.6.1 LULCC along the Corredor Bioceánico

The main finding from the LULC change analysis is that approximately 12,000 km^2 of forest were lost among the three sub-regions. Forest loss was greatest in the Tierras Bajas (10,000 km^2), followed by the Brazilian Shield with (1,200 km^2), and the Pantanal (650 km^2). The agricultural frontier has extended well beyond the agricultural 'expansion zone' of the Tierras Bajas into the Chiquitano and Pantanal forests, which were once thought impervious to large-scale, mechanized agriculture (Hecht 2005; Pacheco 2006). Though forest loss remains relatively small to those experienced in other parts of South America, rates of forest loss match or exceed those of more publicized or well-known regions such as Rondônia and Mato Grosso, Brazil.

The significance of these findings is that agriculture-driven deforestation is pushing into sensitive areas threatening globally-important ecosystems such as those in the Chaco, Chiquitano and Pantanal as well as noteworthy protected areas. Large areas to the south and north of the Corredor Bioceánico are protected as part of the national network of protected areas, which attempt to protect not only nature but indigenous peoples and their livelihoods. These are the Kaa-Iya del Gran Chaco, San Matías and Otuquis National Parks and Integrated Management Areas (IMA).

Protection of the Chaco is concentrated in one protected area, the highly lauded Kaa-Iya del Gran Chaco (KINP). It is South America's largest protected area covering 3.44 million hectares or 5% of Bolivia's national territory. Kaa-Iya is co-managed by the Izoceño-Guarani to ensure their livelihoods and to protect one of the last remaining vestiges of relatively undisturbed Chaco dry forest in the world, and to protect keystone species such as the jaguar (*Panthera onca*) as well as other significant populations of high profile, endemic ungulates like the Chacoan guanaco (*Lama guanicoe voglii*) and the Chacoan peccary (*Catagonus wagneri*) (Noss et al. 2004). Cultivation for agriculture and pastureland to the south of El Tinto and Quimome is beginning to put pressure on the northwestern flanks of Kaa-Iya. Further to the south, land-use is ready to cross the Río Parapetí, the western flank of Kaa-Iya and the only remaining natural barrier before entering the western and northern IMAs.

To the east lie San Matías and Otuquis National Parks and Integrated Management Areas. San Matías is Bolivia's second largest protected area at 29,185 km^2 while Otuquis is 10,095 km^2 and the nation's eighth largest. These protected areas are designed to safeguard the Pantanal, Chaco, and Chiquitano forest in order to create a corridor for flora and fauna as well as promote eco-tourism and bird observation. However, imagery analysis shows that the Corredor Bioceánico, which bisects both San Matías and Otuquis, has been filled by agricultural development. This is especially the case for the secondary roads running north from the town of El Carmen and south from Puerto Suárez. In some areas, the protected areas have been breached, particularly the San Matias IMA.

Currently, Bolivia has some 20% of its national territory under protected area status. While commendable, this study shows that three of Bolivia's largest protected areas – Kaa-Iya del Gran Chaco, San Matías and Otuquis – are under threat from mechanized crop production and pastureland. Additionally, those forests which are not under protected area status are declining rapidly. Whether inside or outside the protected areas deforestation along the Corredor Bioceánico is ongoing and severely affecting the region's water cycle, soils and biodiversity. To what degree the Bolivian government can protect the region's remaining forests is unknown and presumably bleak. By 2012, it is anticipated that Bolivia will double oilseed production and export to consolidate existing markets and access new market opportunities (ANAPO, 2008b). The only way this target can be met realistically is through forest-to-farmland conversion along the Corredor Bioceánico. In addition, economic development based on agriculture in the region will likely be reinforced by the exploitation of natural gas deposits and the upgraded transport and agricultural infrastructures.

5.6.2 Extending the Land Change Record with CBERS

The Landsat archive represents a distinct and unequalled combination of temporal, spatial, and spectral resolutions (Wulder et al. 2008), but with the failure of Landsat ETM’s SLC in 2003, missing data has plagued land change analysis (e.g., Lindquist et al. 2008; Gutman et al. 2008; Ozdogan and Woodcock 2008; Trigg et al. 2006). Missing data coupled with persistent cloud over sub-humid and humid regions, has forced land change scientists to augment or collect multiple scenes of SLC-off imagery, accept SCL-corrected imagery (i.e., a composite scene consisting of multiple dates), or turn elsewhere.

This study shows that CBERS-2 and -2B imagery can help to fill this gap. They can extend the land change record forward in time without the loss of information. As CBERS provides imagery free of charge in bandwidths in the visible and infrared ranges, and at a relatively fine spatial resolution of 20 m, it is well suited for observation of phenomena and objects where details such as small holder and industrial agriculture can be captured simultaneously. However, CBERS imagery comes with problems of its own. Available scenes are limited to the continent of South America and portions of East Asia. Artifacts caused by systematic distortion must be corrected before processing began. Regardless, these problems can be overcome through the relatively straightforward statistical correction procedure outlined in this paper.

Though the CBERS-2B CCD has recently been shutdown, the launching of CBERS-3 in 2010 and CBERS-4 shortly thereafter between 2011 and 2012, respectively, will hopefully overcome the problems experienced by its predecessors through improved radiometric and geometric performance, and continue this potentially useful data archive. The new payload module will have four redesigned cameras, which includes two new multi-spectral cameras – MUXCAM (multi-spectral camera) and PANMUX (panchromatic multi-spectral camera) with 5 m and 10 m spatial resolution, respectively, covering the green (0.52-0.59 µm), red (0.63-0.69 µm), and near-infrared (0.77-0.89 µm) spectrums. In addition to finer spatial resolution, CBERS-3 and CBERS-4 will have higher revisit times at between 3 and 5 days and equivalent swath widths of 60-120 kilometers.

5.7 CONCLUSION

This paper uses a combination of Landsat series data (MSS, TM and ETM+) to map LULCC from 1975 to 2001. Image change analysis focuses on the Corredor Bioceánico, one of the most important agricultural region-deforestation hotspots in Latin America (Etter et al. 2006; Perz et al. 2005), and located in one of the most poorly understood forest biomes in the world in terms of LULCC – Southern Hemisphere seasonally dry tropical forests – which have very high conservation values globally (Quesada et al. 2009; Lepers et al. 2005; Achard et al. 2002; Dinerstein et al. 1995; Janzen 1988). Over the 33-year study period, approximately 12,000 km^2 of forest were lost among the three sub-regions – which is an area nearly the size of Connecticut. Evidence suggests that agriculture-driven deforestation is pushing into sensitive areas threatening globally-important ecosystems such as those in the Chaco, Chiquitano and

Pantanal as well as noteworthy protected areas such as Kaa-Iya del Gran Chaco, San Matías and Otuquis National Parks and Integrated Management Areas.

This research also extends the land change record to 2008 using CBERS-2 and -2B data on a multi-scene level. I also establish a methodology to correct for systematic distortion inherent in CBERS imagery without the loss of information present in Landsat 7 ETM+ imagery post-2003. CBERS provides imagery free of charge in bandwidths in the visible and infrared ranges, and at a relatively fine spatial resolution of 20 m. Therefore, it is well suited to observation of phenomena and objects in areas where small holder and industrial agriculture can be captured simultaneously. However, CBERS imagery comes with problems of its own. Available scenes are limited to the continent of South America and the Caribbean, and portions of East Asia. Artifacts caused by systematic distortion must be corrected before processing began. These problems can be overcome through the relatively straightforward statistical correction procedure outlined in Section 5. What cannot be overcome is the loss of the CCD camera post-July 2009. CBERS-4 will not be launched until 2011 and the Landsat Data Continuity Mission is not scheduled to be launched until 2012. Clearly, land change scientists will have to turn to a limited source of other medium-resolution satellites.

6. LAND-USE MODIFICATION AND LAND-COVER TRANSITION IN THE BOLIVIAN SEASONAL TROPICS [16]

6.1 INTRODUCTION

A primary goal of remote sensing applications in land change science is to map LULC and determine how much of it is in a state of expansion, decline, or resistant to change a particular region over a defined period of time (Hansen et al. 2008a). Its importance lies in fact that many disciplines require accurate information on the outcomes of dynamic human and natural processes that shape our environment – in this case temporal and spatial changes in LULC.

To meet these demands, many scientists have turned to the Landsat series (MSS, TM, and ETM+) for mapping and quantifying LULC. This is particularly so for detailed exploration of LULCC in sub-continental areas (e.g., Rogan and Chen 2004; Boyd and Danson 2005; Redo et al. 2005; Redo et al. 2009) owing to their near-global, temporal coverage of 30+ years; easily accessible archives with much free data; user-community familiarity in terms of image processing and analysis; and, for inexperienced remote sensors, a lack of knowledge about alternative imagery. For these reasons, they have been the preferred choice – the workhorses – for mapping the conversion of forest to agriculture in the tropics and sub-tropics over relatively small areas. A major drawback, however, is that Landsat satellites lack the ability to capture seasonal variations or

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[16] This section has been submitted as a paper to *Remote Sensing of Environment* (Authors: Redo, D. and Millington, A.C.). The section numbers have been enumerated in sequence with this dissertation, the acknowledgements and abstract excluded, and the references merged in the References list for the entire dissertation.

phenological changes in vegetation due to their relatively infrequent revisit times (16-18 days), small spatial footprint (~185 km) , and resulting cloud contamination, the two latter particularly problematic in the humid and sub-humid tropics (DeFries and Belward 2000). As their papers show, past studies which have employed Landsat data for detailed classification attempt to tease out more information on the proximate causes of deforestation than is possible from what is the norm – a single ‘snapshot’ image acquired in a year. This shortcoming is particularly acute when examining highly seasonal forests or semi-arid agricultural systems, which are strongly influenced by seasonal variations in precipitation and, in the sub-tropics in particular, temperature. Related are agricultural systems which are double cropped with two different crops per season and rotated with different crops every one to two years. These issues are too important to overlook in LULCC as changes in the vegetation phenology may signal either anthropogenic or natural causes, particularly so in areas of dryland agriculture (Reed et al. 1994).

To detect phenological change, remote sensors have relied on vegetation indices, usually derived from the Advanced Very High Resolution Radiometer (AVHRR) or the Moderate Resolution Imaging Spectroradiometer (MODIS) as these sensors have the advantages of greater image acquisition frequency (<12 hours) and larger areal coverage than Landsat series data. These advantages, however, have to be balanced against a data archive of different length than Landsat (MODIS dates back to 2000, AVHRR to 1984) and coarser spatial resolution data. The latter issue is the more important of the two as much LULCC in the tropics and sub-tropics is driven by small-scale farming and forest clearance at scales below the 250 m to 1100 m resolution range of these data (Hansen et al. 2008b). In most cases, this results in an inability to distinguish small-scale land-use changes and their proximate causes or sometimes even to distinguish between human land use and natural vegetation. A further issue is that regardless of the spatial resolution used, LULC classes in many studies of land-use change in forested landscapes are conflated into a binary forest and non-forest classification scheme with the end product indicating areas of deforestation, reforestation or no change. This gives rise to pluralistic interpretations and anecdotal evidence about the changes that have occurred, or can possibly conceal them altogether (Robbins 2001). Studies which have attempted to map land-use modification using MODIS (e.g., Jakubauskas et al. 2002; Wessels et al. 2004; Lobell and Asner 2004; Xiao et al. 2005, 2006; Wardlow 2005, 2006, 2007; Lunetta et al. 2006; Brown et al. 2007; Galford et al. 2008; Sakamoto et al. 2005, 2009) or land-cover with AVHRR (e.g. Tucker et al. 1985; Justice et al. 1985; Malingreau 1986; Millington and Townshend 1988; Achard and Blasco 1990; Reed et al. 1994; Achard and Estreguil 1995; Moulin et al. 1997; DeFries et al. 1998; Hansen et al. 2000; Loveland et al. 2000) have rarely (if ever) considered land-use modification and land-cover conversion in the same study. We argue that synergistic explorations of different image data in overcoming these issues are underexplored.

Our objectives in this paper are to identify, map and quantify land-use modification and seasonal forest to agriculture conversion pathways in the seasonal tropics of southern Bolivia between 1994 and 2008. We have established a hybrid methodology which incorporates five complementary data sources: (1) large-area, phenological data derived from MODIS (2007 and 2008, 250 m NDVI); (2) medium-resolution land-cover and land-use data from Landsat ETM+ (2001, 30 m) and CBERS-2 (2007 and 2008, 20 m); (3) a detailed forest map created by Navarro and Ferreira (2007); (4) ancillary biogeophysical information such as soil types, rainfall, elevation, and cropping calendars; and (5) interview and survey data collected between 2007 and 2009. By developing this method, we are able to progress beyond the binary forest and non-forest classification of land-cover and land-use commonly encountered in the remote sensing and land change literature, thereby providing a strong foundation for pattern to process (Nagendra et al. 2004).

Analyses focuses on a 571 km long, 100 km wide buffer of southeastern Bolivia's portion of the Corredor Bioceánico, one of the most important agricultural region-deforestation hotspots in Latin America (Etter et al. 2006; Perz et al. 2005). This strip of land is located in some of the most poorly understood forest biomes in the world in terms of LULCC – southern hemisphere seasonally dry tropical forests – which have very high conservation values globally and in South America in particular (Janzen, 1988; Dinerstein et al. 1995; Lepers et al. 2005; Achard et al. 2002). The Corredor Bioceánico exhibits an east-west gradient of agricultural development ranging from a well-established agricultural region in the west of the study area, adjacent to the metropolis of Santa Cruz, to an active cultivation-induced deforestation frontier in the east closer to the Bolivia-Brazil border. The area is dominantly rural, with a series of small agricultural centers along the road and rail lines; apart from Santa Cruz, the largest town is Puerto Quijarro on the Brazilian border. Based on farm size and level of capital input (machinery, fertilizers, labor) two distinct groups of farmers/land managers can be identified: large-scale modern commercial farmers and ranchers, and small-scale traditional ranchers and farmers (mainly from the Chiquitano and Ayoreo indigenous groups). Large areas to the south and north of the Corredor Bioceánico are protected as part of the national network of protected areas, which attempt to protect not only nature but indigenous peoples and their livelihoods. These are the Kaa-Iya del Gran Chaco, San Matias and Otuquis National Parks and Integrated Management Areas. It is in these contexts that we seek to answer the following questions: what types of forest are being converted to pasture or a particular cropping regime, where and why; and what types of land-use modification changes have occurred?

The paper is divided into five sections. First, we examine the forest and cultivation along the Corredor Bioceánico. Secondly, previous approaches to mapping and quantifying LULCC are discussed. The third section outlines the mapping protocol used to process MODIS data into a meaningful LULCC product. The next section presents the results in terms of (i) quantifying land-use intensification; (ii) identifying the pathways of forest to agricultural change (extensification); and (iii) the proportions of particular forest classes cleared. Finally, we discuss the context of these changes in relation to human-environment interactions as well as the applicability of the proposed methodologies.

6.2 STUDY AREA

The analysis focuses on a 63,000 km^2 strip of land centered on the east-west trending main highway and railroad along the Corredor Bioceánico in southeastern

Bolivia (Figure 49). This is part of a trans-continental transportation and natural gas pipeline artery connecting the departmental capital of Santa Cruz (population ~1 million) eastward to the Brazilian Atlantic and westward to highland Bolivia and the Pacific in northern Chile. The area analyzed has been further divided into three sub-regions based on distinct differences in topography, soils, precipitation, available soil moisture, vegetation and land use, which all affect the length of growing season and times of peak NDVI for crops and natural vegetation.

The most westerly sub-region is the Tierras Bajas (Figure 49). Covering an area of 21,787 km^2 it comprises an almost flat landscape underlain by alluvial deposits. Modern, mechanized commercial agriculture has expanded significantly in this region since the 1970s due to agricultural development and land colonization schemes which thrived on the area's high soil fertility and high rainfall (compared to eastern and central parts of the corridor); close proximity to Santa Cruz; and, more recently, upgraded highway and railroad links to transport produce to the Hidrovía Paraná-Paraguay and Pacific ports. The main crops are soybeans, wheat, maize or sesame (in the summer growing season) and soybeans, sunflower, rice, sugar cane and sorghum in the drier, winter season. The largest of sub-region is the 'Brazilian Shield[17]' (28,568 km^2) (Figure 49). This is part of the Brazilian Shield which is a gently undulating peneplain within this region, north-west to south-east trending mainly quartzitic ridges and mountains of Precambrian origin (ENTRIX 1999). Tertiary soils derived from gneiss and granite

[17] The ecoregions known as the Brazilian Shield and Pantanal extend over three nations within central South America. Names used in this paper are largely derived from the ecoregions which extend into the study areas.

dominate, but Quaternary sediments have accumulated in the floodplains of broad valleys, and these are emerging as zones of mechanized agriculture, with similar crop mixes to that found to the west. Further east, adjacent to the border with Brazil is the smallest sub-region – the ‘Pantanal[1]’ – covering only 12,671 km^2. The area is dominated by the large floodplain created by the Río Paraguay and the terrain is generally level like the Tierras Bajas. The Pantanal is currently the most active hotspots of deforestation along the Corridor, due in part to the region’s relatively high rainfall and fertile soils, proximity to the Hidrovía Paraná-Paraguay as well as the paving of the main highway and revitalization of rail service.

Prior to human disturbance in this area, the vast majority of which has only occurred in the last 30-40 years, dry broadleaf forests dominated the area. These fall into two continental-scale ecoregions – the Chaco forests to the south and the Chiquitano forests to the north (Dinerstein et al. 1995; WWF 2009a, b). Much of the corridor can be considered an ecotone, and some authorities even consider that the Chiquitano forests are the ecotone between the Chaco dry forests and the humid forests occupying the southwestern Amazon Basin to the north. This structure is broadly defined by pronounced latitudinal and longitudinal gradients resulting from differences in precipitation, soils, and topography. Rainfall totals are highest (1,000-1,400 mm) in the northwest Tierras Bajas and the eastern Pantanal (CIFOR 1995) decreasing to 700-1,000 mm in the southern Tierras Bajas and Brazilian Shield.

The Chaco ecoregion in the corridor comprises habitats which range from grasslands, though savannas, to thorn forests, and transitional ecotone habitats between them (Prado 1993; Killeen 1993). This variability can be detected in terms of floristic composition, vegetation structure and physiognomy. Chiquitano forests which generally occur north and east of the Chaco vegetation are best developed in Santa Cruz Department, though they extend into Mato Grosso. They experience a very marked winter, dry season with annual water deficits of up to 500 mm, despite having a mean annual rainfall between 900 and 1000 mm (Montes de Oca 1997). WWF (2009a) recognize four major vegetation communities whose distribution is closely related to drainage patterns. The "soto/curupaú" (*Schinopsis brasiliensis*/*Anadenanthera colubrina*) association is the most abundant and occurs in well-drained soils. It has up to five levels of strata including a 20 m canopy with up to 80% closure, emergents up to 20 m and both a shrubby and an herbaceous understory (ENTRIX, 1999). The dominant species are soto (*Schinopsis brasiliensis*), curupaú (*Anadenanthera colubrina*), momoqui (*Caesalpinia pluviosa*), morado (*Machaerium scleroxylon*), roble (*Amburana cearensis*) and cedro (*Cedrela odorata*). The "cuchi/curupaú" (*Astronium urundeuva*; *Astronium fraxinifolium*/*Anadenanthera colubrina*) association is also found on well-drained soils, but these are poorer than those of the "soto/curupaú" (*Schinopsis brasiliensis*/*Anadenanthera colubrina*). The canopy has approximately 65% closure and has a height of 10 to 15 m, emergents reach 25 m. When found on steep mountain slopes with rocky soils the dominant species is curupaú, but on sandy pediments cuchi, dominates. The "cuta/ajo-ajo" (*Phyllostylon rhamnoides*/*Gallesia integrifolia*) association occurs on hygrophilous soils that experience shallow flooding during the rainy season. The dominant species is “cuta” (*Phyllostylon rhamnoides*), though WWF

(2009a) note that “ajo-ajo” (*Gallesia integrifolia*) is a better floristic indicator because it is highly restricted to flood-prone areas. The fourth association is the "tajibo/tusequi" (*Tabebuia impetiginosa*/*Machaerium hirtum*). These comprise small isolated forest islands that occur 0.5-1 m higher than the surrounding herbaceous savannas. Tajibo (*Tabebuia impetiginosa*) is the dominant tree species, though tusequi (*Machaerium hirtum*) is characteristic of soils that have undergone alkalinization due to inverse leaching (ENTRIX, 1999). In their classification of Bolivia vegetation, Ribera et al. (1994) classify Chiquitano forest as a "region of Precambrian semideciduous forest (Brazilian shield).”

The Chiquitano forests are deemed globally outstanding for their biological distinctiveness and are critically threatened (WWF, 2009b) because of habitat conversion, degradation and fragmentation. Bryant et al. (1997) considered them to be the largest area of healthy dry forest ecosystem left in the world, and Parker et al. (1993) labeled them one of the most biologically diverse dry forests globally. WWF (2009b) describe two large forest blocks of outstanding conservation condition, both east of San Jose de Chiquitos to the north and south of the main highway, respectively. They are partly protected by the Otuquis and San Matias protected areas and account for about one-fifth of the original ecoregion, but as we will show these blocks are being actively converted. WWF (2009b) also noted the need for the Tucavaca Valley – situated between these two blocks – to be protected to provide long term ecological viability. Gentry (1995) measured plant species richness in this valley and recorded the second highest dry forest alpha diversity in the world.

Protection of the vast Chaco is concentrated in one protected area collection comprising a National Park (NP) and three Integrated Management Areas (IMAs). Combined they form the highly lauded Kaa-Iya del Gran Chaco (KINP). It is South America's largest protected area covering 3.44 million hectares or 5% of Bolivia's national territory, an area larger than Massachusetts and Connecticut combined. With the IMAs, KINP is the size of Costa Rica. The protected area is not only important because of its size (it forms 1/3 of Bolivia's total protected coverage and 3.5% of the entire Gran Chaco ecosystem); it also holds the largest area of tropical dry forest under full-protected area status anywhere in the world (Winer 2003) and is a model that puts community-based conservation into practice through being co-managed by the Bolivian government (3.44 million hectares), the Izoceño-Guarani Indian Organization, and development and conservation organizations (1.9 million hectares) (Pablo López and Zambrana-Torrelio 2006; Sunderland 2002; Taber et al. 1997). It is also contains the world's largest known jaguar (*Panthera onca*) population with at least 1000 individuals (Maffei et al. 2004) as well as other significant populations of high profile, endemic ungulates like the Chacoan guanaco (*Lama guanicoe voglii*) and the Chacoan peccary (*Catagonus wagneri*) (Noss et al. 2004). In Kaa-Iya del Gran Chaco National Park, alone, at least fifteen interdigitated and ecologically distinct environmental units exist, each different regarding soil texture, drainage, and rainfall (Winer 2003).

6.3 PREVIOUS APPROACHES TO MAPPING LULC CLASSES

Since the mid-1980s, vegetation phenology derived from AVHRR has been successfully used to map land cover at regional, continental and global scales (e.g. Tucker et al. 1985; Justice et al. 1985; Malingreau 1986; Millington and Townshend 1988; Achard and Blasco 1990; Reed et al. 1994; Achard and Estreguil 1995; Moulin et al. 1997; DeFries et al. 1998; Hansen et al. 2000; Loveland et al. 2000). In the case of forest and woodlands, the overarching aims have generally been to map distributions and assess productivity, resulting in land-cover classes being related to known biomes and ecosystems, or categorized into classes defined in terms of biomass or plant productivity. Generally, land-use change has not been a major focus in these studies and areas which are forest or other types of natural vegetation are often mapped under generalized categories like vegetation-agriculture mosaics (but see Millington et al. 1992; Reed et al. 1994). Besides the major focus on achieving natural vegetation mapping objectives, a more pragmatic reason for not using a detailed land-use classification with these data has been sensor limitations, e.g., pasture establishment and cultivation often occurs below AVHRR's finest spatial resolution of 1.1 km^2.

Since 2000, the potential for land-cover classification using coarse spatial resolution has improved with the availability of 250 m^2 and 500 m^2 resolution MODIS data and the standard data products made available by the MODIS Land Science Team. The downside in terms of LULCC analysis is the relatively short data archive (back to February, 2000) compared to AVHRR, which limits land change studies to less than one decade with the sole use of MODIS data. Though MODIS imagery is a significant spatial and radiometric improvement over AVHRR, the minimum 250 m resolution still restricts its use for agricultural land-use mapping to regions of large-scale agriculture such as western Brazil (Wessels et al. 2004; Lobell and Asner 2004; Brown et al. 2007; Galford et al. 2008), the United States (Jakubauskas et al. 2002; Lunetta et al. 2006; Wardlow 2005, 2006, 2007) and Southeast Asia (Sakamoto et al. 2005, 2009; Xiao et al. 2005, 2006). These studies show that (1) the methodology behind mapping LULC has been greatly improved over the last few years; (2) one particular curve-fitting algorithm or metric to derive thresholds is not a panacea, but that a mix of procedures should be adapted to regional and local conditions; and (3) LULC change has not yet been attempted using these methodologies.

Seven studies that have previously reported on LULCC in parts or all of the area we cover in this paper (Table 29). Yet, we still do not know about the spatial pattern of LULCC in the central and eastern parts of the study area because the focus of the most detailed studies has been on the western Tierras Bajas (Davies, 1993; Steininger et al., 2001a, b). In addition, the last years in these studies, 1991 and 1998 respectively, were at times when the greatest rates of forest loss in much of the Tierras Bajas had not been attained. In the papers where the entire corridor is covered (Mertens et al. 2004; Killeen et al. 2007, 2008; Tucker and Townshend 2000), spatial patterns of change are generalized due to broad-scale coverage of either the entire department or the entire eastern lowlands of Bolivia. In terms of LULC classes, only two have gone beyond forest and non-forest classification: Davies (1993) used a threefold forest classification which included regrowth, and Killeen et al. (2007, 2008) identified forest, shrubland,

and grassland classes. Only Davies (1993) sub-divided non-forest land-use into agriculture and pasture. In this paper we update these studies and provide an expanded level of detail for agricultural classes. We use Navarro and Ferreira's (2007) digital map of land-cover from the mid-1990s, capturing a time point in the decade when clearance for agriculture attained the highest rates (See Section 5). Moreover, we consider the entire corridor which serves to illustrate that to the east new pressures on forests from clearance for cultivation and ranching are occurring is well beyond the traditional agricultural zones and into areas once thought to be impervious to large-scale agriculture (Pacheco 2006).

6.4 DATA DESCRIPTION AND CLASSIFICATION PROTOCOL

6.4.1 Mapping Land-Use from 250 m MODIS NDVI Data

MOD13Q1 NDVI (16-day L3 Global 250 m) coverage for two tiles (h11v10 and h12v10) for 2007 (23 scenes per tile) was acquired from the USGS Land Processes Distributed Active Archive Center (LP DAAC). The time series represents a continuous 16-day composite series only for the years 2001, 2007 and 2008 due to an incomplete data record for 2002 to 2006 as well as a lack of corresponding medium-resolution imagery. Characteristics of MODIS and the algorithm used to generate NDVI values from MODIS data can be found in Huete et al. (2002) and Xiao et al. (2006). The Enhanced Vegetation Index (EVI), which does not become saturated as easily as the NDVI when viewing rainforests and other areas with large amounts of chlorophyll, was not used since land-use (i.e., agriculture and pasture) was the area of interest. Compared to humid tropical forest, cropland does not represent high biomass and most environments in the study area do not possess significant topographical difference. The former reason also explains why other soil-adjusted indices such as SAVI, MSAVI and TSAVI were not employed in addition to the fact that most pasture along the Corredor Bioceánico is often covered with degraded or secondary natural vegetation.

Individual 16-day composites in the two adjacent tiles were mosaicked and stacked to provide coverage of the study area. We performed geometric correction using a 2007 CBERS-2[18] (20 m) classified product resulting in a RMS error of 0.21 pixels for the full set of 16-day composites. Resampled classification masks were created using standard, maximum likelihood unsupervised classification of the CBERS-2 imagery to remove areas that were not cropland or pasture (forest, water bodies, natural bare ground, and urban areas and infrastructure). Radiometric correction was not performed as the MOD13Q1 product is already corrected using the quality assurance **(**QA**)-**based constrained view angle-maximum value composite **(**CV-MVC**)** algorithm to remove atmospheric influences such as cloud, shadow and aerosols. Gao et al. (2003) and Huete et al. (2002) assessed the validity of MODIS NDVI through the measurement and comparison of top-of-canopy reflectance and found good agreement between the two.

Semi-structured interviews with land-owners and managers in May and June 2009 and a crop calendar confirmed the existence of two distinct growing seasons in the

[18] For more information on the characteristics of CBERS-1 and CBERS-2 visit http://www.cbers.inpe.br/?hl=en (Accessed 02 September 2009).

region: (i) a wet, summer season from mid-October to late April[19] (October 16 – April 23 in terms of MODIS 16-day composites); and (ii) a dry, winter season when irrigated crops are grown from late April to mid-August (April 23 – August 12 in terms of composite dates). Only 16-day composites which fell within these growing seasons were selected for further analysis. These dates capture the optimum periods in the life cycle of the main crops and pasture. These interviews also confirmed the types of land-use present for the study periods covered by the natural vegetation map and satellite imagery: 1994, 2001, 2007 and 2008.

We classified agricultural land uses for each time period using three separate, supervised decision trees. These have proved useful in classifying and detecting land-cover and land-use elsewhere (e.g. Friedl and Brodley 1997; Zhan et al. 2002; Wardlow 2006, 2007; Hansen et al. 2008a). Decision trees predict class membership by recursively partitioning data sets into mutually exclusive classes called parent nodes (Hansen et al. 2000). Based on 'if-then' statements, parent nodes are further subdivided into 'children' or leaf nodes using a series of splits or thresholds (Wardlow 2005; DeFries et al. 1998). For example, a parent node could be defined as cropland while children nodes could be double cropped fields or fields with bare soil cover. The process is complete once all pixels have been discriminated from their counterparts or, more likely, until user-defined conditions are met. The advantages of a decision tree over traditional unsupervised and supervised classification methods are several: (a)

[19] The summer and winter growing seasons are represented as continuous in order to account for direct or minimum tillage where the seeds are drilled into the soil almost directly after the summer harvest to reduce wind and water erosion and soil compaction.

decision trees are not based on assumptions of normality within training area statistics as with maximum likelihood classifiers; (b) they can reveal nonlinear and hierarchical relationships between the input variables and use these to predict class membership; and (c) it is obvious which variables contribute to the discrimination between classes (Hansen et al. 1996, 2000; DeFries et al. 1998).

Training data consisted of 74 individual plots distributed along the entire Corredor Bioceánico derived from interviews with land managers in 2009 and field-based land cover and land use assessments made in 2007 and 2008 coupled with aerial videography flown at 2,000 m.a.s.l. in July 2008. This yielded information on the type of land-use, the specific cropping regime and/or presence of pasture for all time periods covered in this study (1994-2008). Land managers identified their fields on the 2008 CBERS-2 imagery. During processing, field site data were also located on the MODIS imagery, and then divided into training (80%) and validation (20%) data sets using random sampling. Once the data set was divided, a single, centrally located pixel was selected for each field mapped to create the spectral signature instead of a kernel of pixels in an attempt to reduce the influence of mixed edge pixels (Wardlow 2006). In Figures 50 and 51, individual profiles and averages of these phenology curves for each of the three time periods are shown for pasture and each cropping regime. Pastures in Bolivia are often very productive and usually have remaining intact or degraded vegetation giving rise to relatively high NDVI values in the summer and a steady decline as the dry, winter season progresses. Croplands, on the other hand, present a more dynamic range (Galford et al. 2008) as vegetation experiences one or two cycles per year of sowing, greening-up, flowering, maturity (maximum green leaf area), senescence, and harvest. Fields double cropped are easily distinguished by two, distinct curves corresponding to the summer and winter growing seasons. On the other hand, fields cropped only during the summer often experience longer growing seasons, but have lower NDVI values in the winter (compared to pasturelands) after harvest. Fallow fields are composed of a mixture of exposed bare and dry, crop stubble.

Identification of these distinct phenological cycles enabled us to calculate the following metrics for use as annual NDVI thresholds in the decision tree classifier: harmonic mean, minimum, maximum, and amplitude. According to DeFries et al. (1998), this suite of metrics had the highest accuracy compared to other available metrics when classifying land-cover and has also been used successfully by Zhang et al. (1997), and Wardlow (2005, 2007) in classification. In addition to these simple metrics, we also calculated the standard deviation of the harmonic mean (± 0.5) to account for the variable geographic differences between study regions mentioned in the previous section. Standard deviation was able to separate two or more modes which had similar NDVI values for a given date. Based on these variables, we used the decision tree structure to classify all 16-day composites which fell within the summer and winter growing seasons separately for each year (2001, 2007 and 2008) into four discrete categories: pasture, double cropped fields (cultivated in both summer and winter), single season crops (summer only), and bare soil cropland (annual fallow). An example of the decision tree used for 2007 is shown in Figure 52.

Accuracy assessment was based on the information obtained from semi-structured interviews with land-owners/ managers conducted in May and June 2009 and parcels mapped during field visits, which were not used in the classification procedure (i.e., 20% of ‘sites’): only 12 fields had cropland on their farms, five had pasture, and seven had a mix of cropland and pasture. In total these farms and ranches had approximately 28 fields under pasture or cropland. The land owners interviewed were drawn from the main groups found along the corridor: small-scale peasant farms; medium to large-scale, mechanized, owner-operator farms and/or ranches; and large-scale, mechanized, company-owned and managed farms and/or ranches. Information was gathered on crop types, cropping regimes during 2007, and the changes in regimes over time. The interviewees outlined their field boundaries on a detailed land-use map derived from 2007 CBERS-2 imagery. This resulted in high overall accuracy for each of the three time periods (between 91.64% and 92.98%) (Table 30). Kappa coefficients (κ) were slightly lower and ranged between 0.8465 and 0.8751, but still represented strong agreement that the classification products are significantly better than random class assignments. For the 2007 and 2008 classification products, relatively high commission and omission errors were due to the poor performance of the single, cropped summer regime and bare soil fields, which we ascribe to too few fields in these two categories being obtained from the interviews.

6.4.2 Mapping Natural Vegetation

Navarro and Ferreira's (2007) "Vegetation Map of Bolivia" is the most complete, up-to-date, and detailed digital map of natural vegetation for the entire country. Along the Corredor Bioceánico, 175 classes were mapped (Table 31). The authors used the GeoCover database (land-cover categorizations based on 30 m, Landsat TM imagery from 1990 to 2000) and topographic maps derived from digital elevation models for broad-scale mapping. More detailed classes relied on empirical fieldwork consisting of floristic-ecological inventories, which were georeferenced to botanical collections deposited in herbariaia in Santa Cruz and La Paz. Also included are deforested areas and human-influenced clearance which occurred prior to 1994. Classes completely deforested often account for the largest amount of change between time periods (persistence); therefore, classes which represented areas completely deforested were removed from our analysis. To determine the pathways of forest to cropland transition, we first resampled the dataset to 250 m and then intersected the land-cover classes derived by Navarro and Ferreira, and the land-use classes for each time period mapped from MODIS imagery (2001, 2007 and 2008).

6.5 RESULTS

LULCC in agricultural hotspots can occur in two ways: extensification and intensification. Extensification is the process of expanding new production onto areas of natural vegetation that were previously unused (Jepson and Millington, 2008; Keys and McConnell, 2005). Intensification usually involves the planting of more crops or managing more cattle within the same spatial boundaries on land already cleared of natural vegetation. For the purposes of our analysis, we defined intensification to include the replacement of one land-use by another within existing spatial boundaries, usually caused by a number of decision-making factors (e.g., more favorable economic outcome, government policies, changes in climate or soil fertility, etc.). Due to the distinct differences between extensification and intensification, the results are divided into two categories.

6.5.1 Forest to Agriculture Extensification: 1994-2008

Land-use classes derived from MODIS NDVI and land-cover classes mapped by Navarro and Ferreira (2007) were intersected to map and quantify modification pathways between 1994 and 2008. As 175 forest classes were mapped along the Corredor Bioceánico the LULCC analysis results are cumbersome. To simplify the results and increase manageability, we used a threshold and only report on natural vegetation classes (according to map unit) which lost the most area between the three time periods 1994-2001, 2001-2007, and 2007-2008.

In the Tierras Bajas, three classes account for the majority of natural vegetation lost between 1994 to 2008 (Table 32; Figure 53) to double cropped fields and pasture: (1) d9a – forests on clayey or silty soils poorly drained with Saó palms (*Diplokeleba floribunda-Trithrinax schizophylla*), which are concentrated in the central portion of the study area to the west of Tres Cruces; (2) d7an – transitional Chaco forest on the floodplains of intermittent streams with soils that are medium to imperfectly drained

(*Diplokeleba floribunda-Phyllostylon rhamnoides*); and (3) d7an+d9a+d14a – a mixture of the previous two classes, and hydrophytic forest in seasonal streams and flooded depressions in the northern Chaco (*Coccoloba guaranitica-Geoffroea spinosa*). The latter forest type is influenced by water that collects on an impermeable surface and is the most widespread Chaco vegetation in the region. Clearance of this class was found mainly in the eastern parts of the sub-region centered on the town of Pozo del Tigre.

In the Brazilian Shield, pasture was responsible for the majority of clearance that occurred from 2001 to 2008. In 2008, type d7c – transitional Chaco forest (*Ceiba samauma-Phyllostyllon rhamnoides*) located on floodplains of the Río Quimome with a restricted range extending to Lake Concepción – and d7c+d9h – transitional Chaco forest mixed with Palocruzal vegetation on ancient floodplains of the Otuquis and Quimome rivers (*Tabebuia nodosa-Lonchocarpus nudiflorens*) were the first and third, respectively, most common vegetation types cleared owing to the recent explosion of clearance in the colonies of Nuevo Mexico and Valle Hermosa (Table 33; Figure 54). This explains why this vegetation type was largely intact in 2001. The second largest vegetation class lost to pasture was c13b with 8.60%. This is Chiquitano-Chaco transitional forest (*Schinopsis brasiliensis-Lonchocarpus nudiflorens*) on poorly drained soils between the middle and lower basin of the Río Tucavaca. Just over half (54.25%) of all deforestation for double cropping also occurred among the vegetation classes d7c (23.97%), d7c+d9h (22.96%) and c13 (7.32%). The latter class, c13, consisting of Chiquitano-Chaco transitional forests on clayey or silty soils. The single cropping, summer regime was cultivated mainly at the expense of d14c (24.94%), semi-deciduous forest (*Lonchocarpus pluvialis-Ruprechtia exploratricis*) in seasonal streams and flooded depressions in the Chaco-Chiquitanía transition zones.

In the Pantanal, pasture was also the largest land-use class. From 1994 to 2008, 22-55% of all deforestation for pasture was in the c13b vegetation class (Table 34; Figure 55). Type c13a, Chiquitano-Chaco transitional forest (*Diplokeleba floribunda-Acosmium cardenasii*) on imperfectly drained soils of east-central Chiquitanía, and the composite of classes c13b+d14a+c14a were the next largest forest classes cleared for pasture with 15.50% and 12.26%, respectively. Consistently the largest forest class lost to double cropped fields was also c13b with between 44% and 47%. The second largest class cleared at the expense of this cropping regime was c13a.

6.5.2 Intensification of Pasture and Cropland Regimes: 2001-2008

In the Tierras Bajas, pasture dominated over half of all land-use in 2001 with 52.1% (5,973.9 km^2) and the double cropping regime constituted 44.4% (5,089.2 km^2) (Table 35). Both classes were widely dispersed throughout the sub-region leaving the only remaining large patches of vegetation east and south of the Rio Grande (Figure 56). Only 3.4% (392.2 km^2) was mapped as single-cropping, summer production and very little land was classified as bare soil cropland. Single-season, summer cropping was mainly found in Mennonite agricultural colonies. By 2007, land under pasture had decreased to 42.8% (5,112.5 km^2) and was largely replaced by intensive cropland cultivated twice per year. Fields double cropped increased to 52.2% (6,237.3 km^2) and those under single, summer cropping regimes increased slightly to 4.2% (502.8 km^2) as new lands were cleared and some parcels of pastureland west of the Rio Grande were given over to agriculture. For example, in the Mennonite colonies of Riva Palácio and Swift Current, much of the pastureland that was present in 2001 had been converted to single cropping, summer production in 2007. The following year pasture in the entire sub-region decreased slightly to 37.8% (4,776.6 km^2) although new lands were cleared to the south of the Morgenland Colony, north of the Oriente Colony, and to the northeast between the town of Pozo del Tigre and Lago Concepción. The double cropping regime increased to 59.3% (7,483.1 km^2) with the expansion occurring mainly at the expense of the forested area that remained between areas of existing agriculture and pasture. Single season, summer cropping decreased to 2.7% (335.8 km^2) of the landscape, and is likely due to rotational cycles.

In the Brazilian Shield, land use in 2001 remained at relatively smaller proportions of the landscape (Table 35). Pasture dominated the cleared area with 63.0% (353.1 km^2) and fields double cropped accounted for 33.7% (188.7 km^2). Pasture and doubled cropped parcels were found along the main highway and railroad, but concentrated mainly in the Mennonite colonies of Nuevo Esperanza and Holanda, north and east of the city of San José de Chiquitos, respectively (Figure 56). Summer, single cropping remained relatively small in comparison. By 2007, the area under pasture (62.6%, 652.9 km^2) and double cropping (32.6%, 339.4 km^2) had nearly doubled. Expansion took place largely in the newly established Mennonite colonies of Nuevo Mexico and Valle Hermosa west of San José and Berlin to the north. New pasture lands also opened up to the northeast and are associated with new Mennonite settlements in river valleys, especially the Tucavaca, but a small amount was related to traditional, small-scale peasant agriculture carried by Ayoreos and Chiquitanos south of the road and railway. In 2008, pasture experienced further significant gains and formed 74.2% (945.1 km^2) of all land use. Geographically, the distance remained similar to 2007. The area under the double cropping declined to 23.2% (though area was reduced by only 44.1 km^2) as parcels shifted to single, summer cropping and pasture production.

Results from the Pantanal show that in 2001, land use was also relatively nascent, and shared many similarities to the Brazilian Shield (Table 35). Pasture formed the majority at 83.5% (226.9 km^2) and was largely concentrated along the main highway and railroad near the Brazilian border. By 2007, clearance for pasture and cropland exploded along the access roads north of El Carmen and south to Puerto Suárez (Figure 56). Land use became more diverse as farmers took advantage of the wet, hot climate growing tropical crops such as hearts of palm, rice and sugar cane, in addition to the ubiquitous oilseeds and grains found elsewhere along the Corredor Bioceánico. Although the double cropping regime formed only 19.7% of the landscape, it now covered 109.3 km^2. This low proportion was largely the result of large clearance for pasture northeast of El Carmen and near the Brazilian border. By 2008, all land uses had increased in area. Pasture witnessed the largest increases in area as it grew to 534.5 km^2, largely the result of existing pasturelands increasing in size. The area under double cropping grew to 138.6 km^2.

6.6. DISCUSSION

6.6.1 Methodological Considerations

This study explored the use of MODIS, Landsat ETM+ and CBERS-2 imagery data, a vegetation map, ancillary GIS data, interview data, and on-site field studies, to record detailed natural vegetation to land-use modification pathways in the seasonal tropics of Santa Cruz Department in southeastern Bolivia from 1994 to 2008. The combination of these data sources and use of phenological information led to several methodological advances, and important insights regarding environmental damage along the Corredor Bioceánico.

First, this hybrid methodology allowed us to go beyond traditional classification of forest and non-forest to capture both detailed land-use extensification and intensification. LULC classes in many studies of land-use change in forested landscapes are conflated into a binary forest and non-forest classification scheme. If a binary scheme was used in this study, our end product would only indicate areas of deforestation, reforestation or no change. For example, the quantity and type of cropping and pasture that replaced a particular vegetation type would have been left unknown. More importantly, the intensification of cropland regimes would have been overlooked or at least obscured. For this purpose, we would have to turn to agricultural statistics. In the Department of Santa Cruz, these are normally producer organization censuses with the most detailed coming from the Cámara Agropecuaria del Oriente (Agricultural Chamber of the East) and Asociación De Productores De Oleaginosas y Trigo (Association of Oilseed and Wheat Producers). Both are normally given for *municipios* (analogous to U.S. counties) and provide only data on annual yield and crop and pasture area. They do not, however, provide spatially explicit information beyond this scale. From these data, we could only infer on the amount of pasture or amount and type of cropland regime.

The second methodological improvement is the documentation and verification of land-use for all three time periods mapped from MODIS imagery. An innovative feature of our methodology is the use of interview and on-site, field data to confirm the presence of pasture or a particular cropping regime dating back to 2001. Therefore, our accuracy assessment of the 2001 MODIS classified product is not simply an extrapolation of the 2007 and 2008 data, but instead represents actual conditions. Without this information, we would have to infer from later dates of imagery or rely on the agricultural statistics previously described. Either case could lead to a spurious accuracy assessment.

Third is that the results also elucidated the main environmental factors underlying the decision-making process – soil fertility and depth, abundant rainfall, gentle slopes, proximity to river valleys, and market opportunities which lead to agricultural intensification. While these drivers or constraints are well known within the LULC change literature (e.g., Geist and Lambin 2001, 2002, 2004; Lambin et al. 2003), identifying these are often only assumed or teased out during time-consuming interviews and focus groups. Additionally, knowing which factors take precedence over others will provide better input to spatial models which can tackle issues such as trajectory, consequences and future of LULC change.

On the other hand, there are also several drawbacks. First is the spatial and temporal resolution of the datasets used to classify land-use: 250 m, while relatively fine for time-series imagery such as MODIS, is coarse for detecting agricultural fields. In addition, the other data sources used in combination with MODIS imagery – CBERS-2 and Landsat TM – are set at 20 m and 30 m, respectively. Therefore, the forest/non-forest classified products from CBERS and Landsat had to be scaled up to 250 m, causing us to essentially lose the relatively final spatial detail of both CBERS and Landsat. In addition to the spatial scale of analysis, the temporal scale of the data used in this study should also be considered. Ideally, MODIS imagery would have been acquired sequentially from 2001 to 2008. However, MODIS NDVI for the 2002 to 2006 period had significant cloud contamination in at least 30-40% of all tiles covering the study region. Bi-weekly, 500 m MODIS and daily, 1 km AVHRR data sets are available, but are too coarse to detect the boundaries between pasture and types of cropland. The end result is that we are left with a significant gap between 2002 and 2006.

The second area of concern is the classification of land-cover classes. In this study, we used the vegetation map created by Navarro and Ferreira's (2007) "Vegetation Map of Bolivia" which represented natural vegetation for the year 1994. We initially attempted to use 1 km, daily AVHRR data in this study to map vegetation classes for the same time period. This was done using phenological methods similar to that performed during the classification of land-use classes from MODIS. However, this resulted in ambiguous vegetation classes due to the difficulty of separating green vegetation from senescent vegetation. Classes generated were therefore based on the length of time they were "green." We deemed these meaningless as they did not correlate well with other vegetation maps (e.g., floristic classes).

The third drawback is the classification of crop types. Though this methodology resulted in detailed cropland regime and forest to cropland transition maps, we were still unable to classify cropland into specific types (e.g., summer soybean or winter sunflower). While other studies have performed this task successfully (e.g., Wardlow 2007; Jakubauskas et al. 2002), they show that this is only possible through rigorous fieldwork or existing data by identifying crop type on several hundred (or even thousands) of individual fields in order to generate spectral signatures. With multiple crop types and at least two growing seasons, this would require extensive fieldwork. This type of fieldwork is possible in more developed countries but not time or cost feasible in southeastern Bolivia.

6.6.2 Environmental Change

The main findings in terms of percentage area cleared according to forest type is that farmers appear to be favoring transitional forest types on deep and poorly drained soils of alluvial plains. Several climatic and environmental variables account for the bias. These forests receive the most precipitation (1,000-1,100 mm), but lie on level terrain which is not completely seasonally inundated. Most agricultural lands lie on or are in close proximity to alluvial soils near rivers and streams on the most level terrain. They also provide the greatest range of ecosystem services (e.g., well-watered habitat for grazing animals, maintenance of soil health and fertility, prevention of soil erosion, regulation of river flows and groundwater supply). However, lands which provide the most benefit to wildlife are for the same reasons, attractive for human agriculture. Naturally, farmers are consciously aware of the factors which contribute to lands most suitable for agriculture. In addition, Cruceños and Mennonites take pride in their knowledge of plant cultivation. Both are well-known for agricultural efficiency and this is manifested through both innovative (new techniques such as direct tillage and the application of fertilizers, pesticides, and herbicides) and non-innovative (increase of crop frequency through a reduction of the fallow period [Keys and McConnell 2005]). Along the Corredor Bioceánico, this is shown by the intensification of maximizing production with two crops per year – soybeans in the summer and sunflower or sorghum in the winter. In the first few to several years, pasture is the dominant land-use, but is soon replaced by cropland. But what effect is this having on the environment?

The Tierras Bajas of the Corredor Bioceánico is heavily cultivated by any standard and the new pioneer fringe is pushing into the relatively uninhabited forests of Chiquitanía and Pantanal to the east. New frontiers are also pushing westward from the Pantanal putting remaining forest along the corridor at risk. Both environments are on the brink of a significant conversion to mechanized agriculture due to the availability of cheap, abundant land and the presence of underground aquifers for irrigation. These developments, however, have come at great cost to the hydrosphere (e.g., diversion of the Rio Grande, and smaller rivers and streams) and soil conditions (erosion, nutrient depletion, carbon loss, increase in albedo and overuse of agro-chemicals). The cost has been the destruction of habitat for humans as well as flora and fauna. The two largest ecoregions along the Corredor Bioceánico, the Chaco and Chiquitanía, are both listed among the world's 200 most sensitive (Wassenaar et al. 2007). During this study period, the trend has been widening gaps of forest clearance for agriculture along the boundaries. This transition zone, intact just two decades ago, had shrunk to half its original size in 2007 as a result of advantageous climatic and environmental factor. Environmentally, species movement and interaction between ecoregions is greatly hampered causing its functioning as an ecosystem to cease at the local level. Once home to numerous indigenous groups before completion of the railroad and opening of the lowlands in the 1950s (Weeks 1946), these forests have fallen before the tractor and pushed indigenous peoples deeper into eastern Bolivia, forced them to assimilate into mestizo culture (Mennonites generally do not intermix) or caused them extinction.

To the south and east, a modern and equally alarming trend is occurring that like that seen closer to the city of Santa Cruz. Results from this study illustrate the rapid frontier expansion of large-scale cultivation in the eastern Tierras Bajas. By 2007, colonization south from El Tinto was already threatening the northern boundary of South America's largest protected area (34,000 km^2) – Kaa-Iya National Park and Integrated Management Areas (IMA) – which together cosset the largest area of tropical dry forest under full-protected area status anywhere in the world (Winer 2003). The is a novel model of protected area design and management that puts community-based conservation into practice through being co-managed by the Bolivian government through agencies such as SERNAP (National Service of Protected Areas), the indigenous Izoceño-Guarani, and multiple conservation organizations such as the World Wildlife Fund. As pressure to continue producing lucrative soybeans and sunflower increases, those displaced from development, might well push settlement into the thinly settled northern IMA or even the park's core.

The current status of southeastern Bolivia's remaining forests east of the Tierras Bajas is also bleak. The Bolivian government is nearly finished upgrading the highway through paving and the construction of bridge and drainage infrastructure. When complete in 2011, the new highway will be the only paved, all-weather thoroughfare in central South America. It will connect the continent's agricultural heartlands of Santa Cruz and neighboring Mato Grosso do Sul, Brazil, more directly to international markets through Brazilian and Chilean ports. Evidence of this trend can already be seen in the Pantanal study region. In 2001, just over 200 km^2 of agriculture was present within 50 km of the highway and railroad. By 2008, the amount had increased to approximately 700 km^2 due to illegal colonization by Brazilians, land speculation, and high crop prices. More detailed imagery analysis (2005-2008) for emerging agricultural colonies north of the town of El Carmen show that annual deforestation rates are accelerating despite new government policies aimed at conservation (See Redo et al. 2010; Section 8). If deforestation reaches scales seen in the Tierras Bajas, it could be ecologically devastating for the region's indigenous inhabitants and the forests they depend on, as well as two more noteworthy national parks and integrated management areas – San Matías and Otuquis – protecting over 40,000 km^2 of one of the world's largest and most diverse wetlands. However, both protected areas are threatened as they skirt the northern and southern portions of the main highway and railroad. Threats include two natural gas pipelines which bisect the heart of each zone – Bolivia-Brazil and Cuiaba – as well as agricultural production and the potentially devastating dredging of the Paraguay River to increase agricultural shipments down-river to the Rio de la Plata.

6.7 CONCLUSION

In this paper, we have developed a method for quantifying and mapping the spatial location of detailed forest and crop classes in the seasonal tropics of Bolivia. This study also shows it is possible to incorporate several data sources and supplement one sensor's weakness with another's strength for use in mapping and quantifying changes in detailed LULC types. By going beyond classic classification schemes such as forest vs. non-forest or ecosystem approaches and assessing between changes in various types of forest and crop classes, we provide planners and conservationists with more than simply quality, accurate forest cover and change maps. These results can potentially provide decision-makers with more detailed insight as to the proximate causes or driving forces of change in addition to the most threatened forests remaining in the Tierras Bajas and those most likely to be cleared in the Brazilian Shield and Pantanal. This information is imperative for raising both government and public awareness so that more informed policy proposals can developed resulting more effective responses about landscape management and conservation (e.g., planning of future protected areas or effectiveness of existing units). In addition, scientists studying human-environment relationships can better understand the dynamic impact humans have on the environment. Data on phenology and the quantity and spatial distribution of vegetation is vital to terrestrial ecologists studying the influences of vegetation on animal distribution and dynamics (Pettorelli et al. 2005).

Finally, by focusing on one of the most dynamic regions in the Neotropics, we have advanced the basic scientific knowledge of LULC change in southern hemisphere semi-arid wooded ecosystems and provided a better understanding of the nature of human-environment relationships in one of the most dynamic, contemporary frontier regions in South America. If remote sensing and land change scientists are unsuccessful in identifying the most salient types of LULCC taking place, then they will also be unsuccessful in determining the proximate causes directly responsible for deforestation as well as researching and modeling change (Pontius et al. 2004). Without proper research, identification, and modeling, we will all fail to implement effective measures to slow deforestation and biodiversity loss, conserve natural habitat, and mitigate their effects on livelihoods (e.g., access to water supplies and forest products).

7. THE ROLE OF INDIVIDUALS, INSTITUTIONS AND ORGANIZATIONS IN LAND-USE AND LAND-COVER CHANGE[20]

7.1 INTRODUCTION

It is often argued that neoliberalism,[21] in the form of structural adjustment programs, have been the dominant link connecting drivers and patterns of land change for the last two decades (World Bank, 2005). Joseph Stiglitz, former Senior Vice President and Chief Economist of the World Bank, judged neoliberal economics to be the 'destroyer' of the environment (Stiglitz, 2002: 8). Studies from Latin America (e.g., Klak, 2008; Brannstrom, 2009; Pacheco, 2006; Hecht, 2005; Aide and Grau, 2004; Kaimowitz, et. al., 1999) suggest that environmental degradation in nations under neoliberal regimes has followed a generalized cause and effect chain owing to structural adjustment policies: (i) opening of new lands for colonization; (ii) influx of foreign colonists and investment; (iii) switch from communal to private property regimes; (iv) regional and global integration of markets for cash crop production; and (v) technological change in the form of genetically modified crops and greater access to machinery. These in turn opened up forested lands and grasslands to large-scale, mechanized cultivation of cash crops and directly caused the unprecedented

[20] This section has been submitted as a paper to *Geoforum*. The section numbers have been enumerated in sequence with this dissertation, the acknowledgements and abstract excluded, and the references merged in the References list for the entire dissertation.

[21] In its most basic form, neoliberalism has been defined as a political philosophy or worldview of free markets and less government (Liverman and Vilas 2006: 329). This philosophy or view is built on the argument that less government intervention will lead to a more efficient market and therefore, greater economic growth (Stiglitz, 2002). For a more thorough description of origins, components, and implementation in Latin America see McCarthy and Prudham (2004) and Gwynne and Kay (2000).

deforestation that has occurred in some parts of South America during the last two decades. Crop and livestock producers are now thought to be coerced or forced to make decisions such as choosing a certain crop variety or animal breed based predominantly on price as set by the global market; lack of access to natural resources; labor; capital; or institutions (rules-in-use).

My argument is not an attempt to dispute that neoliberal factors are not important in driving deforestation and that the era of neoliberalism did not cause some of the largest forest clearing in the 21st century. The aim is to show that the effects of institutions and organizations, changes in government policies, environmental influences, the decisions of the individual farmer, have been overlooked or ignored. In addition, previous models of the decision-making process and caused of land change for some parts of South America, particularly dry forest regions, are both incomplete and now outdated (e.g., Gasparri and Grau, 2009; Grau and Aide, 2009; Hecht, 2005; Grau et. al. 2005a, b; Steininger et al. 2001a, b). The global increases in commodity prices (i.e., income maximization) are not the only factors causing LULCC among both high-input, high-output agriculture systems[22] and peasant production. Similar to the point made by Ostrom (2007) in that overuse or destruction of resources is not attributable to a single cause, the factors which play an important role in LULCC are complex and multivariable including individuals, producer organizations and federations, seed and

[22] High-input, high-output agricultural systems have been previously described by Brannstrom (2010) for southern Brazil, and are synonymous with 'modern agriculture' (Pretty et al., 2001) or 'industrial agriculture' (Horrigan et al., 2002; Wilson, 2001). Under either name, crop production is typified by large amounts of inputs relying on outside industries to supply labor, tractors and irrigation equipment, fertilizers, pesticides, herbicides, modified seeds, and fuel, in an effort to maximize yields for commercial export (Pimentel et al., 1973).

machinery companies, national and international governments, and multi-regional trade blocs.

The Department of Santa Cruz in southeastern Bolivia serves as an exemplar (Figure 57). At 370,621 km^2, it is the largest of Bolivia's nine departments and occupies 33% of the total national territory. It is roughly the same size as the United Kingdom. Santa Cruz is also one of the most important agricultural regions in Bolivia as well as largest contemporary deforestation hotspot. The eastern lowlands of Santa Cruz are well endowed with forests and fertile soils, and it is here where large-scale, mechanized agriculture has taken hold in great quantity. Modern, mechanized commercial agriculture has expanded significantly in this region since the 1970s due to agricultural development and land colonization schemes which built on the high soil fertility and high rainfall; close proximity to Santa Cruz; and, more recently, upgraded highway and railroad links to transport produce to the Hidrovía Paraná-Paraguay and Pacific ports. The main crops are soybeans, wheat, maize or sesame in the summer growing season, and soybeans, sunflower, rice, sugar cane and sorghum in the drier, winter season. Two distinct groups of farmers/land managers can be identified: (i) large-scale, modern commercial farmers and ranchers under high-input, high-output systems, and (ii) small-scale traditional ranchers and farmers, mainly from the Chiquitano and Ayoreo indigenous groups. Today, Santa Cruz is the heart of Bolivia; the city of Santa Cruz has the largest population, the Department is the country's largest source of GDP, and most of the nation's industry is concentrated here. Foreign investments in the construction of highways, rail lines, and natural gas pipelines have been well underway to tap into the rich and relatively untouched natural resources of the Amazon Basin. The eventual aim is to strengthen Bolivia's weak transportation network by relieving the isolation of the still remote eastern Santa Cruz Department and linking it to national and international markets. Thus, Santa Cruz Department is seemingly a quintessential neoliberal frontier as described by Hecht (2005).

However, with the election of Evo Morales in 2005, Bolivia implemented policies which ended the era of neoliberal dominance. Common property regimes are strongly endorsed while privatization is actively discouraged. Modified agrarian reforms are underway and new fire policies have been implemented. Producer organizations such as ANAPO and CAO negotiate price for farmers; secure harvest destination; establish dialogue with seed and machine companies and firms; and also provide advice and even litigation support for land tenure. They are repealing the restriction of oilseed exports; repealing the prohibition of food exports; and assessing problems of credit regulations. Both are indirectly involved in supporting the movement for autonomy from the central government. Seed and machine companies, firms, and banks provide farmers with loans. Overall, the situation has more complex. It is in these contexts I seek to achieve the objectives of elucidating the causes of LULCC in southeastern Bolivia.

This research combines semi-structured interviews of key actors (individuals and organizations) conducted between January and June 2009, field surveys conducted between 2006 and 2009, and remotely-sensed satellite imagery at local and regional scales. Interviews were supplemented by an analysis of newspaper articles and unpublished government and producer organization documents. First, I provide a summary of evidence linking deforestation in Santa Cruz in the mid-1980s to neoliberalism. I then discuss the methodology behind key actor interviews. In the second part of the paper the focus migrates to the policy and regulatory changes implemented by the government since late 2005, and their affects on contemporary deforestation. The results and discussion that follow focus on the decision-making processes of individuals in relation to land change and finish with a discussion of government policies, organizations and federations, and their role.

7.2 LAND CHANGE LINKED TO NEOLIBERALISM

Nearly a decade has passed since Lambin et al. (2001) published a landmark article dispelling the myth that LULCC was driven largely by one or two factors – population and shifting cultivation. Two decades have transpired since Blaikie (1985) and Blaikie and Brookfield (1987) assessed the effects of institutions (rules-in-use), precipitation, soil erosion, and a lack of access to natural resources, labor or capital on land degradation. More recently, significant effort has been geared toward standardizing the multi-faceted underlying drivers and proximate causes of land change (Millington 2006; Geist et al., 2006; Rindfuss, 2008 and 2004; Lambin et al., 2006, 2003, and 2001) through the collection and analysis of case studies, many focused on humid tropical deforestation. Angelsen and Kaimowitz (1999), Geist and Lambin (2001 and 2002), and Lambin et al. (2001 and 2003) provided comprehensive reviews of hundreds of case studies from Amazônia, central Africa, and Southeast Asia. Geist and Lambin (2004) used 132 case studies to look for patterns in the driving forces of land change in dryland environments. More intensive, local studies have also emerged which concentrate on the role institutions play in explaining deforestation (e.g. Gibson et al., 2000; Sanderson 1994; Tucker and Ostrom 2005), while others focus on economic development and technological change (e.g. Bebbington and Bury 2009; Jepson 2006; Walker 2004; Angelsen et al., 2001), household characteristics (Walker, 2003; McCracken et al., 1999) or demographics (e.g. Perz, 2001).

Whether comprehensive or individual, all cases rebuke a single causation theory of land change and conclude that the drivers of deforestation cannot be solely attributed to one or two factors. They are immersed in a complex web of actors and processes which Geist and Lambin (2004: 817) call 'recurrent core variables.' At the underlying level they can include weak governments, corruption, competing territorial claims, accumulation of international capital, institutions, market opportunities, policy reforms, demographic change, infrastructure development, technological advances, and in some cases climatic factors. More direct or proximate causes, on the other hand, are too numerous to list. This wealth of literature raises questions about the need for another study to identify the factors associated with LULCC. The reasons are relatively straightforward. They lay in the notion that globalization as a driver of deforestation is linked to neoliberal policies manifested through trade blocs, the privatization of industry, and the distribution of large tracts of land were the only drivers of deforestation in the South American interior.

The case of the Bolivian lowlands of Santa Cruz suggests elements of such processes. By the 1981, Bolivia's economy was on the brink of total collapse. Interest rates had risen, hyperinflation skyrocketed, and the price of tin fell by half on top of declining demand. Tens of thousands were out of work. With little opportunity left in the economically- and environmentally-marginal Altiplano, they sought new lands and opportunity and descended down into the eastern lowland forests. Access to capital had also dried up and the nation's default on loans led to intervention by international lending organizations, which then became holders of the nation's multi-billion dollar debt. On the recommendation of World Bank and the International Monetary Fund, Bolivia underwent 'shock treatment' and embraced neoliberalism in the form of structural adjustment policies where the philosophy of 'market-rather than state-led solutions' through free trade and privatization of resources was stressed (Liverman and Silas, 2006: 328-329). Specific to Bolivia, several financial measures were enacted to halt the slide: currency devaluations; road construction; export tax rebates; reduction of import taxes; and suppression of price controls. The policy most relevant to deforestation was the accrual of foreign exchange through the increase of cash crop production. Under the World Bank's $56.4 million 'Lowlands of the East Project' which ran from 1990 to 1997, the following objectives were implemented to increase export earnings: (i) establishment of a regional land-use plan called the '*Plan de Uso de Suelos*' (Soil Use Plan) or PLUS, which is still closely followed by government agencies and producer's associations; (ii) facilitation of the sale of land to large-scale producers such as private companies; (iii) increase in the production of profitable agricultural commodities such as soybeans and sunflower; (iv) implementation of credit mechanisms to stimulate productivity through the provision of fiscal loans to purchase machinery for use in land clearing, cultivation, harvest storage facilities, and road improvements; and (v) opening of regional markets (World Bank, 1990).

The link between neoliberal policies and deforestation is difficult to establish, but nevertheless, "structural adjustment programs are charged with deepening environmental degradation" (Reed 1992: 143). Seven studies have previously reported on the quantity of land change in Santa Cruz during the era of neoliberalism (Killeen et al., 2007, 2008; Mertens, et al. 2004; Steininger et al., 2001a, b; Tucker and Townshend, 2000; and Davies, 1993). All show that deforestation rates rose steadily at first, and then rose sharply. Studies which look at the drivers of the unprecedented deforestation which occurred during this time period attribute structural adjustment policies. David Kaimowitz attributed deforestation solely to "soybean production for export, stimulated in part by improvements in road and railroad infrastructure" (Kaimowitz 1997: 540) and "structural adjustment, [which] contributed to large-scale forest clearing for soybean production for export" (Kaimowitz et al., 1999: 505). Susanna Hecht (2005: 375) argued "that the new context of globalization, structural adjustment, regional integration and rapid technological change contributed to accelerated forest cutting during the 1990s." Pablo Pacheco (2006: 222) contented that "the single most important factor that stimulated the large expansion of the soybean production [and subsequent, large-scale deforestation] was the preferential access of Bolivian producers to the Andean pact market." He further purported that "the implementation of the structural adjustment program based on fiscal and government policies stimulated the expansion of the agricultural frontier at rates of growth never before experienced in Bolivia [with] much of the frontier expansion [relying] on soybean production" (223). While not denying structural adjustment policies were instrumental in causing deforestation, they are not the only factors. These studies have overlooked individual farmers. They have ignored the fact that people make decisions based not only on needs but also on limitations of the environment and desires. They have also overlooked meso-scale institutions/organizations, which play an important role in determining or removing limitations.

7.3 THE POST-NEOLIBERAL ERA

The election of Evo Morales in December of 2005 witnessed changes in the political, economic, and social fabric of Bolivia. The last four years have represented a shift from an era dominated by neoliberalism to what has been termed post-neoliberalism (see Redo et al. 2010; Section 8). I define this as a hybrid blend of social democracy adopting elements of both neoliberal economics and socialist politics; thus, it should not be viewed as a different set of policies that have replaced neoliberalism, but instead as a shift to alternative or, in some cases, to the maintenance of neoliberal policies (Macdonald and Ruckert, 2009). Bolivia's post-neoliberalism is based on three related tenets: (i) organization of civil, peasant, and indigenous groups for greater participation in decision-making; (ii) resource expropriation from private corporations and colonial powers to state ownership (i.e., stronger government); and (iii) consolidation of state power to protect and serve social movements, thereby molding the state into an entity working for the people and kept in check by the people (see Redo et al. 2010; Section 8).

From 2006 to 2008, the Morales-led government initiated a new agrarian reform which has distributed portions of the nation's forest reserves to smallholders, titled indigenous territories, and called for the expropriation of farms and ranches which do not meet specified criteria. In the latest round of changes, prior regulations on the restriction of fire for the clearance of land have been rigorously enforced. New social and environmental goals have emerged and previous laws are being enforced. In the fight to overturn neoliberal policies, which are widely accepted as the largest driver of forest clearance, the post-neoliberal policies of land expropriation and re-distribution have fueled further deforestation. Many of the tenets of neoliberalism outlined by Pacheco (2006), Liverman and Vilas (2006), Hecht (2005), Angelsen and Kaimowitz (2001), Kaimowitz et al. (1999) and Kaimowitz (1997) that fueled deforestation in the last two decades are no longer applicable to southeastern Bolivia. In fact, some aspects of neoliberalism are the very anti-thesis of the Morales' administration's new political framework of land reform and fire suppression.

Privatization of public lands and state enterprises – once the centerpiece of structural adjustment policies – has now been replaced with the communal tenure model. Passed in 2006, the new Agrarian Reform law, N^{o} 3545 (including constitutional amendments passed in 2009), includes the distribution of fiscal (state-owned) lands to form communal properties. According to records made public by the National Institute of Agrarian Reform (INRA), of the nearly 135,000 km^2 which have been titled since 2006, 91% have been endowed by the State and are composed entirely of forest reserves. Sixty-eight percent of lands distributed through endowment have been in the form of traditional TCOs or new communal territories to *campesinos*, indigenous peoples, and syndicates. This law also states that producers must meet a Socio-Economic Function (SEF) whereby they intend to meet the 'best interests' or welfare for all residents or achieve economic development through the 'best use' of the land. They also must prove that a certain proportion of their property is in-use[23]. Land which does not comply can be expropriated and then reverted to the State for redistribution.

Land distribution to foreign colonists is also a relic of the neoliberal era and has virtually ceased. After the 1952 Agrarian Revolution, new land settlement schemes in the eastern lowlands precipitated hundreds of thousands of square kilometers being distributed to Bolivian nationals and foreigners from the United States, Brazil, and Mennonites in order to stimulate cash crop production. Today, many foreign colonists, including at least two that were interviewed for this study, were under either undergoing litigation over expropriation or expressed deep fear that their properties would be threatened with expropriation in the future. This has given rise to tenure insecurity. Capital availability has actually slowed down and in other cases regressed. Insecure tenure and a credit squeeze have both led to reduced investment. Fiscal incentives for

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[23] Area in cultivation for medium-size properties (50-500 hectares) must exceed 50% and 67% for agribusinesses (501-2,000 hectares). To calculate the projected area under cultivation, the effective area currently used is taken into account, in addition to the area under fallow in agricultural properties. The amount of land under production is measured by the area actually cultivated; for grazing lands, area under production corresponds to the number of cattle on-site – 5 hectares (0.05 km2) per head is the minimum requirement.

the cultivation and export of cash crops and favorable market conditions, both hallmarks of creating government revenue through foreign exchange, are also tenuous under the Morales' administration. In February 2008, Supreme Decree N^{o} 29538 was passed prohibiting the export of maize, and caused the selling price to drop below production costs. Negotiations between the Association of Oilseed and Wheat Producers (ANAPO) and the Viceministry of Agriculture caused the passage of Supreme Decree N^{o} 29746 in October of that same year capping the export of Bolivia maize (mainly to Peru) to a maximum of 150,000 tons (ANAPO, 2008). The rice industry was further hurt by government policies which de-stimulated production by prohibiting exports (Interview with Ignacio Landívar, President of the Association of Rice Producers, 21 May 2009). In March to April, 2008, the government implemented two decrees capping the export of soybean and sunflower in order to stabilize the rising cost of domestic vegetable oil. The areas planted and under production have fallen to levels not seen since 2000. Interviews with farmers in May 2009 show that price has fallen from a high of $420 to just $300. Clearly, conditions no longer favor large commercial producers.

As a result of the changes which have occurred since Morales took office, the socio-political climate of Santa Cruz is in turmoil. There is a great deal of mistrust between land-owners and representatives of the government. Posters and pamphlets litter the offices of Santa Cruz portraying Evo Morales as Joseph Stalin or Adolph Hitler. In the city's central plaza, protests draw hundreds of supporters who make speeches over loudspeakers. This often results in the formation of pro- and anti-Morales groups who participate in shouting matches or sometimes, violence. Efforts to walk the fine of neutrality and establish trust between myself and the interviewee are difficult and are discussed in the next sub-section.

7.4 FIELDWORK AND METHODOLOGY

A hybrid, semi-structured survey/interview was conducted from May to June of 2009 with 43 key actors in the Department of Santa Cruz. Approval for the interviews was obtained from the Texas A&M University Institutional Review Board (IRB). Overall, I conducted interviews with a total of 33 crop, animal, and hybrid producers over a wide ranging area of the Tierras Bajas as well as small portions of the Brazilian Shield bordering on the Pantanal. These 33 producers were spread out according to a wide range of farm size and type, nationalities, ages, and spatial locations in the Department of Santa Cruz (Table 36). I also carried out 10 interviews with various departmental crop and livestock producer organizations as well as with the regional state agency, the Institute of Agrarian Reform (INRA). These conversations ranged anywhere between thirty minutes and two hours, although most lasted approximately one hour. This information was supported by archival research of pertinent documents.

After careful consideration, I chose not to tape record interviews. This made sense as few respondents were willing to go on record considering the very sensitive political climate in Bolivia at this time. Instead, all interviews were transcribed on-site using pen and paper. To mitigate landowners' well-founded suspicions of foreign academics (Borrow-Strain, 2007), each respondent received a letter before each interview which included the following statements: (a) interviewer support from the university and advisor; (b) stated aims of the interviews; (c) benefits to the respondents; and (d) statement to protect privacy and anonymity. Names of the farmers, ranchers and owners remained confidential as the identities of the interviewees were not connected to the information gathered. Confidentiality was enforced by substituting arbitrary number codes for names and aggregating property location and boundaries into a regional classification scheme. All of these factors helped to establish trust between me and the interviewees.

The majority of respondents were selected based on the snow-ball technique (Neis et al., 1999; Ferguson and Messier 1997). This method is highly flexible and in this case, based on the referrals of presidents and executive committee members. In the case of Mennonite farmers, sampling was opportunistic and respondents were selected based on their willingness to converse with an outsider. They are significant actors in terms of impact on the environment, but due to their religious ideals and broad skepticism of outsiders, they are notoriously difficult to approach, much less interview. In fact, Mennonites have not been interviewed by an academic researcher since the early 1970s (Lanning, 1971). Serendipitously, I was able to locate a Mennonite dairy farmer who was formerly employed at the Mennonite Central Committee, a social and technical organization based in Santa Cruz and designed to help Bolivian Mennonites with a range of social services. With his help, I was able to enlist several Mennonite interviewees and while the selection of the sample may be biased, there is little choice when attempting to tackle the issue of interviewing “closed” societies as an outsider.

During the interviews and surveys, land managers were asked to recall aspects of forest clearance and what crops had been grown at five to ten year intervals between 1974 and 2008. Exact dates were selected based on corresponding satellite imagery. Respondents were then asked about their decision-making processes behind the selection of particular crops and/or livestock and changes in type over time through a variation of the following question – “What influenced your decision to plant a particular crop or select a certain animal?” Next, I requested they explain why they choose between crop and animal production or in some cases, choose to do both. Each land parcel was mapped on a 2008 CBERS-2 satellite image and received a unique identifier. Type of labor employed (percentages of household or hired help) and harvest destination (percentages destined for market, family/friends, or market) were also ascertained as well as information on the amount and type of credit, equipment, and seeds. Finally, a Likert scale was used to categorize responses which assessed a respondent’s opinion on pertinent land policies and threats and opportunities such as: the 2006 Agrarian reform (Law 3445); the 2007 law pertaining to the prevention and control of forest fires; difficulties obtaining credit, machinery, and seeds; outside threats and opportunities regarding adjacent landowners/communities; issues associated with the main highway and railway in the area, tertiary roads; and opinions on precipitation and soil quality.

Ten interviews with spokesman for international and domestic organizations as well as documentary and archival research of another 35 such organizations (for a total of 45) were also conducted. These revealed the organization’s role in the region’s historical and future of LULCC and also helped to gain a broader understanding of the collective decision-making rationale. The ten that were interviewed were selected based on their size and importance, but in the case of on-site interviews as well as documentary research, I recorded general information such as mission statement (initial need, goals, and objectives), years in operation and predecessors, number of employees and changes over time, spatial distribution or coverage of operations, and sources of funding. More specifically, I noted specifics on work or service conducted, major concerns and issues confronting the organization and its members, role or advice they give (if any) to member producers (e.g., soil rotation and management, windbreaks, methods of forest clearance, agrarian reform, and control of forest fires), and how they view their future role in the region.

The first analytical step applied to the data gathered was to develop a theory to explain the data through ‘coding,’ the process of examining the information gathered and defining the actions or events that are occurring in it or represented by it (Charmaz, 2001: 341). In addition to assessing the respondent’s actions and dialogue, this method also kept a nuance of objectivity by not introducing my own personal biases. In these cases, pre-conceived categories were already set in place by the structure of the protocol though sub-codes were sought out through focused coding. In other situations, I used *in vivo* coding from grounded theory in order to allow key theories to emerge (Charmaz, 2001). This was accomplished by taking responses directly from the discourse. Once analysis was complete, I was able to construct two conceptual models. The first outlines the underlying drivers and proximate cause of LULCC; the second is a figure showing the hierarchy of organizations which affect producers. These are discussed in the next section.

7.5 RESULTS AND DISCUSSION

Rates of deforestation by commercial agriculture have increased in some parts of Santa Cruz since 2005. Interviews I have conducted with a variety of stakeholders indicate that post-neoliberal policies – particularly the new Agrarian Reform laws and burning ban – have triggered forest clearance in the region. But these are two recent contributors to the underlying drivers of deforestation in Santa Cruz. Interviews with producers show that are other factors at play at both individual and organizational levels.

7.5.1 Individuals and Households

With 25.6% (45) of all responses, price was the most cited reason as to why producers choose a particular type of crop (Table 37). Of that 25.6%, Mennonite farmers accounted for approximately three-quarters of all responses for price, especially for soybean. Rising prices over the last decade appear to confirm these statements. Of the 13 major crop and animal types found in the lowlands of Santa Cruz, only sugarcane experienced a decline in price from 2000 to 2009 (Figure 58). However, nearly half of all crops experienced a significant reduction in value since 2007. For example, soybean and sunflower prices spiked in 2007, but declined markedly in 2008 due to government policies aimed at lowering the domestic price of cooking oil. Thus, the global market alone cannot account for increasing rates of deforestation as shown by the increases in area (Figure 59). In other cases, price increased and area decreased due to excessive flooding in the winter of 2007.

Tradition, the custom of continuing a certain agricultural systems or choosing a particular crop or animals within those systems due to family history or training, and choice (or inclination), were often noted by respondents are linked causes. Though seemingly obvious, they are also two of the most easily overlooked factors in a producer's decision making rationale and have rarely, if ever been noted in the LULCC literature. In the case of Santa Cruz, however, it ranked a close second to market concerns with price with 32 responses (18.2% of the total number of responses) and was most often associated with cattle ranchers and milk producers. For example, when one respondent was asked why he decided to graze cattle instead of cultivating crops, he replied:

> I tried [to grow crops] many years ago, but I hated it because I was not familiar with the soil, water requirements, etc. Then I said to myself – 'I am a cattle rancher…I have always been one and will continue to be so.' That's when I gave up on crop production…hopefully (May 31, 2009).

When I told one respondent that he could earn more money growing soybeans instead of producing milk, he replied:

> That doesn't matter to me. As long as I can feed my family I will continue to produce milk for market – it is the only thing I enjoy doing (May 24, 2009).

Sample responses such as these reveal that some farmers, at least to a certain degree, are not slaves to the market, but free to choose their production system based on family tradition or their own desires.

Other reasons are more pragmatic despite the producer's desires and regardless of market forces. In environmentally-fragile and less resilient regions such as Santa Cruz, farmers fight a continuous struggle against overuse, compaction, oversaturation, and drought in order to maintain soil fertility, moisture, and composition. Keeping pest infestations and diseases such as soybean rust to a minimum is also a major concern. Even if price is high, it may not be feasible to produce a high-value crop season after season. Over time, soil fertility declines and pest outbreaks become problematic, particularly in monoculture systems and humid environments such as Santa Cruz. Crops often must be rotated to avoid system uniformity. Sorghum and maize, for example, perform this function by adding nutrients and moisture back to the soil allowing farmers to plant higher value soy and sunflower the following season. In short, high-value soybean and sunflower, in some cases, cannot be planted season after season, year after year, even if price continues to climb higher.

This explains why the next most important reason behind tradition and inclination was soil rotation with 31 total responses (17.6%). According to some respondents, the soils of Santa Cruz are considered some of the best in the nation and even in South America. Regardless, they have significant limitations to crop production. The dominant soil type in the main agricultural zone in western Santa Cruz Department, the Tierras Bajas, are haplic ferralsols – weathered, light yellowish-brown soils resulting from the accretion of metal oxides (iron and aluminum) and are generally regarded for their low agricultural fertility by organizations such as the USDA. According to the

'*Plan de Uso de Suelos*' (Soil Use Plan) or PLUS[24], these lands are classified as high to moderate in terms of land-use potential, taking into account soil fertility, but also depth, texture, slope, salinity and chemical toxicity. Additions of lime and fertilizer, however, have pushed these soils toward the "high" category, and thus created a very productive crop-producing region. The Tierras Bajas has historically been the agricultural center of Santa Cruz Department. To the east in the Brazilian Shield, the proportion of deforestation is increasing in transitional forests along the Chaco-Chiquitano biome boundary. This trend is quickening with the recent Mennonite cultivation north and in wet-seasonal forests with moderate land-use potential. Towards the Brazil border of eastern Santa Cruz, new clearance is occurring in the Chiquitano-Pantanal transition zone for many of the same reasons as the Tierras Bajas, but on haplic fluvisols, which are high in nutrient content, and therefore suitable for a wide range of crops.

With 22 responses (12.5%), precipitation cannot be ignored as an important factor in the decision-making process. Southern portions of the Department of Santa Cruz are considered dry; often, precipitation determines which crops can be grown in such semi-arid environments without irrigation and chemical additives. For example, south of the city of Santa Cruz and the Santa Cruz-Puerto Suarez highway, producers are limited to sunflower, sorghum, cotton, and cattle. Too much rain though also has disadvantages. Northwest of the city of Santa Cruz, precipitation totals reach a maximum for the Department. Here, farmers interviewed noted that soybeans could be

[24] Created by the Santa Cruz Natural Resources Protection Project and funded by the World Bank in the mid-1990s, the PLUS map was designed to plan development in Santa Cruz by taking into account precipitation and soil fertility, depth, texture, slope, salinity and chemical toxicity. It is still closely followed by government agencies and producer associations.

easily grown in the winter in addition to summer. Often, adequate winter rainfall gave higher yields than summer yields due to an overabundance of rainfall thereby increasing profit. Another producer noted that he originally started with cattle, but excessive rainfall created miasmic conditions for meat and milk production. Disease killed off much of the herd and he switched to crop production. Abundant rainfall is another reason why rice dominates in the northwest portions of the Department.

Crops which require relatively fewer inputs are another determinant garnering 11 responses (6.3%). These are crops such as sorghum, soybeans, maize, cotton, and sugar cane as well as meat cattle. They require relatively less labor, management, and fertilizer, and are also relatively more productive (in terms of yield per hectare) than other crops. They also allow producers to diversify their plots by growing multiple crops in a season and possibly minimizing risk. The latter explanation is likely complementary to fewer inputs, but for others completely separate and thus, an important attribute of the decision-making process with 10 responses and 5.7%. Conditions in which minimizing risk is unrelated to fewer inputs usually involve cattle and other livestock. Cattle as a form of living capital is a centuries-old tradition in Bolivia and the rest of Latin America. In Santa Cruz, those who cited minimizing risk as their reason for holding livestock were largely hybrid producers. In times of drought, blight, or low prices for crops, livestock can be the producer’s “insurance policy” against the possibility of a reduced income. A total of eight (4.5%) hybrid producers who considered themselves predominantly ranchers cultivated solely maize and sorghum as animal feed.

Government policies, which both hamper and stimulate production, were also factors which determined whether farmers would choose to cultivate a particular crop or give up certain crop types (8 responses or 4.5%). In the Andean foothills west of Santa Cruz, indigenous communities are given incentives by the government to cultivate 'traditional' crops such as tomatoes, watermelons, and peanuts. However, in the case of maize, soybeans, sunflower, rice and soybeans, government policies enacted in the last two years have actually de-stimulated production in an attempt to control the internal price of these commodities or derivatives such as the domestic price of vegetable oil (see below). Surprisingly, crops such as maize, rice, and peanuts were infrequently cited solely for their ability to feed the producer's immediate household (5 responses or 2.8%).

7.5.2 Government Policies

Much has been made of the World Bank's $56.4 million 'Lowlands of the East Project' which ran from 1990 to 1997, and was designed to increase export sales (World Bank, 1990; Steininger et al., 2001; Hecht, 2005; Killeen et al., 2007). In the lowlands east of the Río Grande, the dense forests gave way to individual producers and private companies, which use high levels of capital investment (e.g., machinery and GM seeds) to grow agricultural commodities such as soybeans and sunflower on vast scales of production. Credit mechanisms to stimulate productivity through the provision of fiscal loans to purchase machinery for use in land clearing, cultivation, harvest storage facilities, and road improvements as well as the opening up regional markets under tariff preferences were also keys. Less well known (but arguably just as important) are the linkages between international governments and lenders, national bureaucracies, crop producer organizations and federations, seed and machine companies and firms, and individual producers. There is growing evidence (Kuemmerle et al., 2009; Brannstrom et al., 2008; Achard et al., 2006) that organizations and institutional[25] policy reforms play decisive roles in explaining deforestation dynamics, particularly during periods of societal and political change. A conceptual model illustrates the upward and downward linkages of the multiple levels of hierarchy that affect individual producers (Figure 60). As a schematic device, it is not meant to be complete, but is instead meant to show the multi-faced nature, complexity and challenges of defining the processes influencing decision-making. It also shows that individual farmers and meso-scale institutions and organizations are often underplayed factors amid the web of land change causes and drivers.

Agrarian Reform and Fire Policy. In 2006, during Morales first full year in office, a ‘new’ agrarian reform was enacted. Law N^{o} 3545 (including the January 2009 constitutional amendments) now states that properties which do not comply with the Socio-Economic Function (SEF) can be expropriated outright or reverted back to the State for redistribution. To avoid seizure or reversion, properties must be geared towards the ‘best interests’ or welfare of all residents, and second, owners must achieve

[25] Following Jepson et al. (2010), the term “institution” is defined as the formal and informal rules that shape access to natural resources. While often synonymous with property rights in the social science literature, the term can encompass property rights as well as contracts and policies. In this case, we focus on the policy aspect of institutions referring to the rules-in-use and their reformation and enforcement.

economic development through the ‘best use’ of the land (a full explanation of compliance measures can be found in Redo et al. 2010; Section 8). Land that is idle can be reported as unproductive and expropriated. Well over half of all financiers and farmers interviewed in the summer of 2009 expressed fears about land seizure. This climate of fear has led them to clear idle land to prove it is in some form of use. For example, forest which was once used to maintain surface water flow or simply because they enjoyed some of the last remnants of forest in the region are being cleared.

Another government policy aimed at conservation is the control of fire, still the main tool used to clear natural vegetation for crop production. Producers who burn without an authorized permit are fined $0.25 dollars per hectare. This policy represents a significant departure from those of the neoliberal period, when there was weaker regulation and enforcement. Regardless, as long as global demand and price for oilseeds remain high, farmers will continue to remove vegetation by burning the forest (the only means available) as the high crop returns outweigh the cost of fines. Interviews with producers in the region revealed a general consensus that the new policy was beneficial but they were worried simultaneously about what constituted ‘illegal’ burning. For example, so-called ‘traditional’ clearance on plots less than 50 hectares by indigenous groups/people is acceptable to the government, but it is still unclear whether traditional clearance is taken to mean slash-and-burn at small scales or who is considered ‘traditional’ by the government. Respondents were also worried that fires set by neighbors could spread to their properties and that they would be fined as well (in such cases, a person has 15 days after they appear on the Superintendent’s list to petition).

An additional injustice was felt to be that fines are set according to land title instead of fire intensity or the area burnt. In other words, if only a small corner of a property is burned, the fine is calculated according to the area of the entire property. This has particularly important implications for Mennonites who farm under a collective land title owned by the colony. If a single Mennonite farmer burns his land, the entire colony is penalized. This is a major reason Mennonites top the list of fines. A Mennonite farmer from near El Tinto remarked that his colony was fined and the entire colony had to contribute to the payment. More alarming is the fact that five of seven Mennonites interviewed in May and June 2009 (all representing separate colonies) were still unaware of the new law highlighting both limited institutional support, but also culpability among some leaders of Mennonites colonies for not being informed themselves and/or informing the people they lead. Others see the law as a contradiction, thus reinforcing their mistrust of the government's true intentions. Overall, however, many in the region are simply ignoring (or are unaware of) the resolution, thereby maintaining the status quo – deforestation for agriculture and pasture through the use of fire. One cattle rancher remarked that the bureaucratic process to obtain the permits was so long-winded and lengthy, and even then, one might not be approved. It was simply easier and cheaper to burn and then pay the fine.

7.5.3 Producer Organizations

The mediation between producer organizations and the government regarding environmental and land reform policies represents a hybrid form of governance, whereby the state or government has set policy objectives through legislation and non-state actors such as the Agricultural Chamber of the East (CAO) and ANAPO, the two largest and most important associations of producers, have determined policy means (Brannstrom, 2009: 146). ANAPO and CAO, however, are organizations that represent, defend, assist and advise crop producers in the Department of Santa Cruz, and are supported by a solid organizational structure – a highly trained and motivated staff, integrated systems, communication, and informatics. Both represent the interests of its members before the State as well as national and international institutions, and generally contribute to the socio-economic well-being of the country by promoting the growth of agriculture and agribusiness.

The linkage between producer organizations, companies/firms and individual producers is also important and sometimes both indirect and direct. Producer organizations often serve as middlemen between individuals (usually small and medium size producers) and companies/firms by negotiating prices, securing harvest destination, establishing dialogue with seed and machine companies and firms, as well as providing advice and even litigation support on the issue of land tenure. Seed and machine companies, firms, and banks on the other hand, provide loans (with an average of 12% interest) through a mortgage guarantee, usually in the form of property deeds, machinery or homes; agricultural chemicals such as fertilizers, pesticides, and herbicides; and genetically modified seeds. This is instructive since lending from commercial banks is a difficult and long process, especially considering that total lending declined 75% between 1998 and 2003 (Marconi and Mosley, 2003). For the small to medium-scale producer, obtaining funding from commercial banks is simply not a feasible option any longer.

One of the most significant forms of governance taken over by ANAPO is the preservation of the external market by repealing the restriction of oilseed exports. In March of 2008, the Government passed Supreme Decree N^{o} 29480 which banned the export of crude oil and refined soybean and sunflower, under the argument that the price of cooking oil was rising and unaffordable to many Bolivians. ANAPO and CAO petitioned the government to repeal the decree because it was causing serious economic damage, to not only the oil industry, but also to producers involved in the process of harvesting and delivery. Producers felt they could no longer negotiate fair prices. Actions took the form of a meeting based mainly on the justification that the decree offered no technical support, and the government was really making a political decision to weaken one of the main production facilities in Santa Cruz. In October 2008, at a meeting held with the Ministers of Agriculture and Planning, CAO reached an agreement to facilitate oilseed exports stored up to one million tons with the commitment of the industry to supply the domestic market in quantity and quality. Unfortunately, the Government has not fulfilled its commitment of one million tons and restrictions on oilseed exports are still ongoing at the time of this writing.

Producer organizations all over Santa Cruz are also repealing the prohibition of food exports. In February of 2008, the Government passed a decree prohibiting export in order to secure supplies for market demand, including corn, as important input for the production of chicken meat. A subsequent decree also prohibited the export of products from corn. Akin to double hammer blows, the dual restrictions cause enormous harm to farmers due to the substantial drop in the price of corn to values below the cost of production causing an over-supply of grain in the domestic market of at least 350 million tons. It also generated the collapse of collection centers which affected the storage of sunflower, and caused irreversible damage because many farmers could not deliver harvest, thus having to store their own. These problems were brought by ANAPO before the Ministry of Agriculture, asking for the full release of maize, whereas there was an oversupply of production, as the collection centers collapsed due to the storage of corn harvest during the winter of 2008. As a result, the government released the export of up to 150 million tons of maize grain and derivative products after verification of the domestic market supply. ANAPO is also protesting a new bill aimed at subsidizing the sale of wheat flour to 180 million tons. They see it as a disincentive for domestic wheat production, since the bill is aimed at subsidizing the production of other countries. ANAPO, on the other hand, is promoting a program to encourage the production of wheat by providing financing for producers.

The mediation between producer organizations and the State over production quotas has important implications for LULCC. Government policies aimed at reducing oilseed and corn exports could radically alter land-use in the region, and in some cases, land-cover. Some farmers interviewed have begun the switch to other crops (e.g., sesame seeds) or invested more in cattle production under the expectation that the restrictions will continue under the premise that government is trying to harm elite landowners in the region. In the case of a switch to less expansive crops such as sesame, this might actually result in reforestation since sesame requires less land compared to soybeans and sunflower. On the other hand, an investment in cattle might result in more deforestation in order to expand pasture production. In most cases, however, land-use change has resulted in property modification rather forest conversion.

In response to the Agrarian Reform Law, ANAPO has produced a pamphlet called the "Practical Guide to the Defense of Producer's Rights, which is aimed at helping producers understand the provisions of the law. They also provide a team of lawyers for producer to help with expropriation and titling. ANAPO has coordinated with the National Agricultural Federation (CONFEAGRO), the Ministry of Sustainable Development, Agriculture and Environment (MRDAMA), CAO, and the Federation of Cattle Producers in Santa Cruz (FEGASACRUZ) to guarantee land security in relation to meeting the requirements of the SEF. CAO also have a team of advisers, but not lawyers to advise the institutions. They feel that the government is eliminating private property and reverted land goes only to communities not to individuals, and that will require a lot of government support perpetuating the need for more state support.

ANAPO and CAO have also made headway in terms of technological development. They are lobbying for the use of genetically-modified (GM) soybeans, which within the current framework of the Constitution, is prohibited. GM seeds could cause an expansion of soybean production in the Department and cause significant deforestation. ANAPO also has requested funding from the Government of the Department of Santa Cruz to build levees along the Rio Grande to stop flooding linked to El Niño events. These events can cause serious damage to yearly output of oilseeds such as the events which occurred in 2008. To promote the development of biodiesel as an alternative energy source, ANAPO is working in conjunction with Bolivia-Argentina Association in which a project was organized to assess the technical and economic feasibility and assembly plants for biodiesel. CAO, on the other hand, has zero-tillage as one of its goals. 80% of medium to large-scale production is now zero tillage still unknown or major goal for them is to get the rest on this zero tillage scheme as most small-scale producers continue to use conventional tillage methods. The total switch to zero-tillage will have a significant effect on land-use modification as many farmers can intensively cultivate a single field for longer time periods compared to traditional cultivation, which causes soil compaction and loss of fertility. This could effectively increase total output per hectare. The effects on land-cover conversion, however, are unclear, but decrease the amount of land under cultivation and return some marginal lands to natural vegetation (Rolando Zabala, personal communications, 01 June 2007).

In 2008, Santa Cruz along with the three other richest departments in Bolivia – Beni, Pando and Tarija – have also followed suit in declaring autonomy from the central government. Each department has control over taxes, production, and certain internal laws. For example, Santa Cruz has now voted overwhelmingly to keep two-thirds of departmental tax revenues. The central government, however, has declared the votes illegal and it is unclear how the situation will unfold. Nevertheless, CAO have become key actors in the process and progress of departmental autonomy through several tenets: (i) active participation in the activities of the Civic Committee Pro Santa Cruz; (ii) monitoring and supporting the autonomy referendums of Santa Cruz, Pando, Beni, Tarija, and Chuquisaca; (iii) support the legislative departmental process; (iv) preparing and presenting proposals to committees of the associations; (v) opening a coordination office in Sucre; provide technical advisors; (vi) provide advice to the Cruceño Brigade of Constituents in Sucre; and (vi) contribution in developing the constitutional proposal of Bolivia drafted by the Cruceño institution. With autonomy, the land tenure situation in Bolivia appears to lean back towards privatization and less towards communal ownership. Investment in existing properties could increase and securing more land might become a viable option. The effects on LULCC, however, are difficult to determine as the reforms are still in pubescent stages.

7.6 CONCLUSION

This paper shows that previous models of deforestation drivers for dry forest regions such as southeastern Bolivia are both incomplete and now outdated. Producers in the region are seen as subservient to global increases in commodity prices (i.e., income maximization). While not denying structural adjustment policies and market forces were instrumental in causing deforestation, they are not the only factors driving land change in southeastern Bolivia. Interview results and archival research shows that the factors which play an important role in LULCC are complex and multivariable including individuals, producer organizations and federations, seed and machinery companies, national and international governments, and multi-regional trade blocs.

Only one-quarter of all respondents noted price as the dominant reason they made a decision. This was followed closely by tradition (18%), soil rotation (18%), precipitation (13%), requires few inputs (6 %), minimize risk (6%), use of animal feed (5%), government policies (5%), and subsistence use (3%). Producer organizations and federations often serve as middlemen between individual farmers and companies/firms by negotiating prices, securing harvest destination, establishing dialogue with seed and machine companies and firms, as well as providing advice and even litigation support for land tenure. Seed and machine companies, firms, and banks provide farmers with loans. Producer organizations such as ANAPO and CAO are directly involved in preservation of the external market by repealing the restriction of oilseed exports; repealing the prohibition of food exports; and assessing problems of credit regulations. Both are indirectly involved in supporting the movement for autonomy from the central government. Agrarian reform and fire policy also play a significant role in driving LULCC. New social and environmental goals have emerged during the transition from neoliberalism to post-neoliberalism. Properties which do not comply with the SEF can be expropriated outright or reverted back to the State for redistribution. Producers who burn without an authorized permit are fined. Both policies represent a significant departure from those of the neoliberal period, when there was weaker regulation and enforcement.

Overall, the opaque lens of neoliberalism has clouded the judgment of many researchers attempting to indentify the components of the decision making process. We often find it easy to determine that getting the maximum output with a minimal amount of input drives is the only motive. While price determined by the global market is not proportionally the most dominant motive, this study shows it is not the only motive.

8. DEFORESTATION DYNAMICS AND POLICY CHANGES IN BOLIVIA'S POST-NEOLIBERAL ERA[26]

8.1 INTRODUCTION

Over the last two decades concerted effort has been devoted to identifying the determinants of LULCC, and according to Rindfuss et al. (2008) such research is accelerating. The determinants of land change are diverse, and no other facet has received more attention than tropical deforestation (e.g. Rudel 2007; Keys and McConnell 2005; Walker 2004; and Angelsen and Kaimowitz 1999). Contemporary research, whether quantitative or qualitative, or comprehensive or case-specific, rebukes a single causation theory of land change and illustrates that causes are numerous, and knotted amid an intricate web of underlying drivers and proximate causes (Ostrom 2006 and 2007; Lepers et al. 2005; Geist and Lambin 2002). A key, but understudied strand (Rindfuss et al. 2008) is institutional[27] policy reform, as it plays a decisive role in explaining deforestation dynamics, particularly during periods of societal and political change (Kuemmerle et al. 2009; Brannstrom et al. 2008; Achard et al. 2006). By enabling or restraining particular crops or forms of agriculture, the agricultural frontier

[26] This section has been submitted as a paper to *Land Use Policy* (Authors: Redo, D., Millington, A.C. and Hindery, D.). The section numbers have been enumerated in sequence with this dissertation, the acknowledgements abstract excluded, and the references merged in the References list for the entire dissertation.

[27] Following Jepson et al. (2010), the term "institution" is defined as the formal and informal rules that shape access to natural resources. While often synonymous with property rights in the social science literature, the term can encompass property rights as well as contracts and policies. In this case, we focus on the policy aspect of institutions referring to the rules-in-use and their reformation and enforcement.

can expand, contract, or stagnate, thereby modulating the spatial distribution and rate of forest cover change.

The transition from import-substitution industrialization (ISI) to neoliberalism in Bolivia after the economic crises of the early 1980s is a prime example of how policy reforms can affect deforestation rates. Pacheco (2006) has compared the effects of this shift on agricultural expansion and changes in forest cover in lowland Bolivia up to 2000 and concluded that forest loss increased as policy changed. As we write, nine years later, there has been a second major shift in government land-use policies. Under neoliberalism, maximizing earning was paramount and achieved at the expense of the environment. In December 2005, the *Movimiento al Socialismo* (MAS) party led by Evo Morales was elected to office, representing a quasi-transition from right-center neoliberal economic policies (e.g., structural adjustment) implemented by previous administrations to what we term post-neoliberalism. We define this as a hybrid blend of social democracy adopting elements of both neoliberal economics and socialist politics; thus, it should not be viewed as a different set of policies that have replaced neoliberalism, but instead as a shift to alternative or, in some cases, to the maintenance of neoliberal policies (Macdonald and Ruckert 2009). Bolivia's post-neoliberalism is based on three related tenets: (i) organization of civil, peasant, and indigenous groups for greater participation in decision-making; (ii) resource expropriation from private corporations and colonial powers to state ownership (i.e., stronger government); and (iii) consolidation of state power to protect and serve social movements, thereby molding the state into an entity working for the people and kept in check by the people.

From 2006 to 2008, the Morales-led government initiated a new agrarian reform which has distributed portions of the nation's forest reserves to smallholders, titled indigenous territories, and called for the expropriation of farms and ranches which do not meet specified criteria. In the latest round of changes, prior regulations on the restriction of fire for the clearance of land have been rigorously enforced. New social and environmental goals have emerged and previous laws are being enforced, but has deforestation continued? Previous research (e.g. Liverman and Silas 2006; Kaimowitz and Angelsen 1998) has shown that strong government is better able to curtail deforestation. My aim is to extend Pacheco's analysis and update previous studies of deforestation in the region beyond 2004 (Killeen 2008) by incorporating the recent era of post-neoliberalism to examine if, and how, farmers have responded to policy changes through either compliance (e.g. proving "productive use") or non-compliance (ignoring bans on burning) with state policies. In terms of specific land change science questions, we seek answers to the following: have the policies of the MAS government introduced signals in the land-use change record? More specifically, have rates of forest clearance for agriculture changed since December 2005 and have the loci of agriculture-driven deforestation changed?

We attempt to answer these questions by focusing on the Corredor Bioceánico in the Department of Santa Cruz, the largest, and the most important agricultural region and, arguably, the most serious contemporary deforestation hotspot in Bolivia. The eastern lowlands of Santa Cruz are well endowed with forests, and it is here where changes in macroeconomic policies and political processes are likely to have had the greatest effects. Santa Cruz also continues to be the center of opposition to 'traditional Bolivia,' accentuating the political, economic, and cultural differences between the Altiplano and wealthier lowlands. Not surprisingly, Morales' policies have not been met with overall approval in Santa Cruz. The last four years have witnessed sporadic outbreaks of violence in the eastern lowlands, land expropriation coupled with the threat of future seizures, and the arrests and deaths of members of an alleged assassination plot.

Linking policy reforms to actual environmental change is a challenging task as most impacts are indirect. To overcome this, we combine remotely-sensed satellite imagery at local and regional scales, field surveys, and semi-structured interviews of key actors conducted between January and June 2009. Interviews were supplemented by an analysis of newspaper articles and unpublished government and producer organization documents. First we discuss deforestation in the eastern lowlands under neoliberalism. This is underpinned by evidence from satellite imagery dating back to the mid-1980s -- the beginning of the neoliberal period in Bolivia. In the second part of the paper the focus migrates to the policy and regulatory changes implemented by the government since Morales' election in late 2005, and their affects on land-use change based on satellite data acquired annually between 2005 and 2008. The discussion that follows links policy shifts since 2005 to forest-to-agriculture conversion in the Corredor Bioceánico between 2005 and 2008.

8.2 STUDY AREA

The Corredor Bioceánico is a continental transportation and natural gas pipeline artery connecting the departmental capital of Santa Cruz (population ~1 million) eastward to the Brazilian Atlantic, and westward to highland Bolivia and the Pacific ports in northern Chile. The highway, railroad, and pipeline bisect territories of indigenous peoples; relatively undisturbed, biologically-important ecoregions; and skirt three important national parks. Remotely sensed analyses focus on a 50 km north-south buffer centered on the main highway and railroad of the Corredor Bioceánico in southeastern Bolivia (Figure 61). With endpoints at the city of Santa Cruz and the Brazilian border, the area covers approximately 63,000 km^2, or 6% of Bolivia's total area. We have partitioned the Corredor Bioceánico into three sub-regions based on vegetation, topography, climate, and land-use in order to provide a sharper focus to my analysis.

From west to east, the first sub-region is the Tierras Bajas, covering 21,787 km^2 (Figure 62). It is well endowed with relatively, level terrain, generally fertile soils, abundant rainfall, two growing seasons, and close proximity to the city of Santa Cruz. Soybean, wheat and maize are the main summer crops, while soy, sunflower, rice, sugar cane and sorghum are grown in the drier, winter months. The second and largest (28,568 km^2) sub-region is the Brazilian Shield (Figure 61). This is an extension of the Brazilian Shield to the north, and underlain by sedimentary, igneous and metamorphic rocks of varying resistance to weathering and erosion. The area is undulating, with significant north-west to south-east trending mountain ranges. The soils are often shallow and acidic, but in the valleys deeper soils provide sites suitable for mechanized agriculture and are characterized by high-input, high-output agriculture systems[28]. The smallest sub-region, the Pantanal, covers the 12,671 km^2 adjacent to Brazil (Figure 61). The terrain slopes gently eastward to the large floodplain of the Río Paraguay. As we will show later, favorable terrain, soils and climate and its close proximity to the Hidrovía Paraná-Paraguay mean it is emerging as a new deforestation frontier along the 'Corridor'.

8.3 DATA DESCRIPTION AND METHODOLOGY

We created a time series of LULCC maps from remotely sensed imagery (Landsat MSS, Landsat TM, and Landsat ETM+) along the Corredor Bioceánico from 1986 to 2001 in order to assess land-use change during the neoliberal period (Table 38). For the post-neoliberal period (2006-2009), we used a hotspot analysis to focus on dynamic areas of change. Three areas were selected, each corresponding to one of the sub-regions. These 'hotspots' were chosen because (i) complete annual coverage of the Corredor Bioceánico is not available for 2005 and 2006; (ii) we wanted to contrast land-use change in an established area typical of Tierras Bajas, with areas of new cultivation in the Brazilian Shield and Pantanal; and by (iii) solely focusing on the entire corridor, important processes occurring the last few years would be obscured. We used CBERS-2

[28] High-input, high-output agricultural systems have been previously described by Brannstrom (2010) for southern Brazil, and are synonymous with 'modern agriculture' (Pretty et al. 2001) or 'industrial agriculture' (Horrigan et al. 2002; Wilson 2001). Under either name, crop production is typified by large amounts of inputs relying on outside industries to supply labor, tractors and irrigation equipment, fertilizers, pesticides, herbicides, modified seeds, and fuel, in an effort to maximize yields for commercial export (Pimentel et al. 1973).

(China-Brazil Earth Resources Satellite) imagery (Table 38) from 2005, 2006, 2007, and 2008 for this analysis. Initially launched in 1999, and with the second sensor following in 2003, CBERS is somewhat comparable to Landsat having two visible (0.45-0.52 μm, 0.52-0.59 μm) and two near-infrared (0.63-0.69 μm, 0.77-0.89 μm) bands, 20 m spatial resolution, and a 26 days nadir view temporal resolution (http://www.cbers.inpe.br/en/programas/cbers1-2.htm).

The Landsat and CBERS images were analyzed using the same image processing chain. All scenes were radiometrically corrected to remove atmospheric attenuation in order to address atmospheric scattering. The Chavez Cos(t) model was used as the data necessary to perform a full correction model (e.g. optical thickness of atmosphere and spectral diffuse sky irradiance) is not available. This model removes haze and estimates the effects of absorption and Rayleigh scattering (Chavez 1996) and all input parameters are available. Empirical line calibration was used to match brightness values between scenes. After stitching individual images together, we geometrically registered the mosaics using 1:50,000 topographic maps and GPS points acquired in-situ.

A maximum likelihood supervised classification rule was employed to map three classes: forest, agriculture, and savanna/bare ground. Developed areas and water bodies (rivers and lakes) were mapped through user-defined polygons (i.e., digitization). We created land-cover and land-use maps for the neoliberal and post-neoliberal time periods; inter-decadal maps; and change statistics matrices. Accuracy assessment was accomplished by reference to 176 locations visited in the summers of 2006 through 2008 along the entire length of the Corredor Bioceánico and aerial videography acquired from a light aircraft flown at 2,000 m.a.s.l. in 2006. At each location visited, a comprehensive land-cover and land-use survey was conducted. Site location was recorded and mapped in detail noting crop type or the vegetation formation. Crop or vegetation height was recorded, as were crop cover, crop maturity, tree density, and soil color. Landforms were also described. These measurements were repeated in the four cardinal directions for each location. Slightly over 700 samples were available for accuracy assessment. Each sample was mapped on a 2006-07 CBERS-2 mosaic and labeled polygons were used to represent the LULC assessments. 300 points were generated for random accuracy assessment through stratified random sampling of all five classes (60 per class) for each of the preceding time periods. The highest accuracy achieved was in the Tierras Bajas (99.92%) and the lowest in the Brazilian Shield (90.53%).

To link changes in LULC to policy reforms, we conducted 50 semi-structured, confidential interviews (43 on-site by lead author and 7 by telephone) with individual farmers and spokesmen for government agencies and producer organizations in 2009. Sampling was both purposive and opportunistic, and we used the “snowball” technique (Neis et al. 1999; Ferguson and Messier 1997) to select key actors. Responses from several types of farmers/land managers along the Corredor Bioceánico were elicited including, small-scale farms; medium-large, mechanized owner-operator farms; large, livestock ranches; and hybrid farms –mechanized owner-operated and livestock ranches. The goal was to determine which political, environmental, or social factors were behind their decision-making. In early interviews it became clear that two of the most important points of discussion were the recent Agrarian Reform (Law N^{o} 3445) and burning without a permit (Resolution #93/2007); therefore as we progressed with interviewing we made certain that we raised these. In addition to the interviews, archival research of published and unpublished documents (e.g., government policies and newspaper articles) was conducted to further support the analysis.

8.4 DEFORESTATION UNDER NEOLIBERALISM: 1985 - 2005

8.4.1 Structural Adjustment and Agrarian Reform (Law N^{o} 1715)

The foundation for neoliberalism was laid in the land-use policies of the 1950s. At that time, the Santa Cruz hinterland was still an isolated outpost of large-scale ranches and sugar producers far removed from the main urban centers of the Altiplano (highland plateau). In 1952, a nationalist revolution was fought to fragment these vast holdings, resulting in Law N^{o} 3464 (Table 39). The result was more than simply reformation; the vast eastern lowlands were opened for immigration. This coincided with the end of the region's isolation as the country's first roads were paved around this time. New land settlement schemes precipitated hundreds of thousands of square kilometers being distributed to Bolivian nationals and foreigners. Along what is now the Corredor Bioceánico, agricultural production increased and was further augmented as exports diversified under import-substitution industrialization policies aimed at subsidizing credit, government price control, and investment in infrastructure. During the 1970s, the Banzer administration had reorganized important land reform agencies and developed a well entrenched cult of cronyism by allowing friends of the government to acquire vast land holdings – many in Santa Cruz Department -- to supplement already substantial claims.

Despite State policies aimed at opening the frontier, a small domestic market and internal demand restrained the agricultural frontier and deforestation was relatively modest. By the mid-1980s, Bolivia's economy was on the brink of collapse. Tens of thousands miners, people relying on the mining industry, and civil servants became unemployed as interest rates rose, hyperinflation skyrocketed, and the price of tin fell by half on top of declining demand. The unemployed and underemployed descended from the economically and environmentally marginal Altiplano to the eastern lowland forests. Access to capital had all but dried up and the nation's default on loans led to intervention by international lenders, which became holders of the nation's multi-billion dollar debt. With World Bank funding and International Monetary Fund imposed conditions (Stiglitz 2002), Bolivia, like many other nations, underwent 'shock therapy' (rapid as opposed to 'gradualist' reform) and embraced neoliberalism in the form of structural adjustment policies beginning with Supreme Decree 21060. Broadly, the political philosophy adopted is one of market supremacy based on improving economic growth through fiscal austerity, trade liberalization, the privatization of resources, and curtailing government intervention in the economy (Liverman and Silas 2006; Stiglitz 2002). Specific to Bolivia, several financial measures were enacted to halt the downward spiral: currency devaluations; road construction; export tax rebates; reduction of import taxes; and suppression of price controls. The policy most relevant to land-use policy and deforestation was the accrual of foreign exchange through increased cash crop production. Under the World Bank's $56.4 million 'Lowlands of the East Project' which ran from 1990 to 1997, the following objectives were implemented to increase export earnings: (i) establishment of a regional land-use plan called the '*Plan de Uso de Suelos*' (Soil Use Plan) or PLUS[29], which is still closely followed by government agencies and producer's associations; (ii) facilitation of the sale of land to large-scale producers such as private companies; (iii) increase production of profitable agricultural commodities such as soybeans and sunflower; (iv) implementation of credit mechanisms to stimulate productivity through the provision of fiscal loans to purchase machinery for use in land clearing, cultivation, harvest storage facilities, and road improvements; and (v) opening up regional markets (World Bank 1990). Besides large-scale deforestation (see Section 4.2), another consequence of these policies was unequal land distribution in the eastern lowlands, which six years later, led to 'new' agrarian reform laws.

Due to the irregularities in land titling, the *Instituto Nacional de Reforma Agraria* (National Institute for Agrarian Reform or INRA) initiated Law N^{o} 1715 in 1996 in order to enforce and revise Law N^{o} 3464 (Table 39). Besides attempting to establish title regularization (Kaimowitz et al. 1999), the law (which was developed with World Bank funding) promoted privatization of land and set up a system of collective land titles for communal lands called *Tierras Comunitarias de Origen* or TCOs (World Bank 2001). It also set up new procedures for resolving land conflicts through the distribution of state lands to the landless as well as procedures to revert or expropriate properties

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[29] Created by the Santa Cruz Natural Resources Protection Project and funded by the World Bank in the mid-1990s, the PLUS map was designed to plan development in Santa Cruz by taking into account precipitation and soil fertility, depth, texture, slope, salinity and chemical toxicity. It is still closely followed by government agencies and producer associations.

back to the State based on two cases: (i) illegally obtained landholdings; and (ii) land which did not comply with the 'Socio-Economic Function' (SEF) or which was used against the 'collective interest' of the people. Land could be only be reverted if it was abandoned. However, the law only applied to medium and large-scale holdings, which were based on size and not on levels of capital input, technology or labor. Expropriation was the result of non-compliance with the SEF and compensation was paid to land owners based on the value of the land determined by the latest tax return. Land owners could avoid reversion by proving land was 'in-use' by simply paying property taxes, but this did not meet the criterion for 'productive use.' According to INRA, land was in compliance if it achieved family wellbeing or contributed to the economic development via owners' 'productive uses' in accordance with the land's capacity at best use (Köppen 2008: 14). This could be achieved through the sustainable use of land in the development of agriculture, forestry or other productive activities like conservation (protection of biodiversity or ecotourism) in accordance with the land's capacity at best use, for societal benefit, collective benefit and the owner's interest. However, meeting the SEF mattered little as the state did not have the institutional or bureaucratic backing to carry out expropriation, while bribes given to private officials contracted to assess productive use further stymied reform (Köppen 2008: 16). In some cases, pressure to secure land tenure caused some producers to clear forest in order to comply, which essentially promoted forest clearing and cultivation of crops or livestock to prove land was being productively used, preventing it from being reverted or expropriated by the State (see Discussion). Failure to adequately define 'productive use' kept land reforms from being effective and would help fuel a third agrarian reform 10 years later (see Section 5).

Open market competition also contributed to changes in land-use during this period. As Bolivia shifted away from the ISI model, barriers to export trade were dismantled as regional trade blocs began to form, such as the Andean Pact (now the Andean Community) and the Common Market of the South (MERCOSUR). The rationale was that markets and competition promoted efficiency through a reduction in tariffs on trade between member states. In this respect Bolivia has an advantage as a member and associated member of the Andean Community and MERCOSUR, respectively. In the case of the Andean Community, Bolivia is still granted tariff preferences, allowing trans-national corporations special access to member nations by not having to compete on the open market with countries such as Brazil, Argentina, and Paraguay where production and transportation are more cost efficient. MERCOSUR, on the other hand, attempts to reduce trade barriers by eliminating tariffs. Dual membership helps explain why Bolivia's main crops are oilseeds and the main export destinations are Andean nations.

8.4.2 Neoliberal Deforestation Dynamics along the Corredor Bioceánico

The rise of neoliberalism was one of the most important events in late twentieth century history, reshaping governments and causing significant changes in environmental management (Rudel 2007; Liverman and Vilas 2006). The impact of neoliberal structural adjustment policies and the 1996 Agrarian Reform law coupled with non-neoliberal aspects such as high global demand for agricultural commodities, preferential access to Andean Community members, and environmental factors (e.g., climate, soil and terrain conditions) that are advantageous for crop production in the Corredor Bioceánico, led to an unprecedented quickening of the pulse of deforestation in Bolivia (Killeen 2007a; Hecht 2005; Hindery 1997; World Bank 1993; Kaimowitz et al. 1997).

In only a decade, oilseed crops came to dominate the landscape and form a significant share of Bolivia's foreign exchange. Policies favoring large-scale producers caused production (and benefits) to become concentrated into the hands of a few hundred farmers, who employed a high degree of mechanization and relied on chemical inputs. For example, sunflower, which had not been grown previously, was introduced shortly after Bolivia embraced the neoliberal New Economic Policy (NEP) in 1985, and by 1996 nearly 1,000 km^2 was under cultivation (ANAPO 2007). All of these factors contributed to what Killeen et al. (2007a) aptly named a "perfect storm" for deforestation.

Most of the deforestation that took place during the neoliberal period occurred along the Corredor Bioceánico, as oilseeds produced along its margins could be shipped to nations of the Andean Community much faster via the Hidrovía Paraná-Paraguay. In the Tierras Bajas sub-region, approximately 8,000 km^2 of forest was lost to commercial agriculture between 1986 and 2001 (Figure 62; Table 40). By 1986, structural adjustment policies had taken hold, soybean had been introduced as a commercial crop, and there was a veritable land rush eastwards along what is now the 'Corridor', particularly along the existing Santa Cruz-Puerto Suarez highway and tertiary roads. In the 1990s, production east of the Rio Grande (the area of the land rush) grew mainly due to World Bank investment in the Eastern Lowlands Project, rising soybean prices, easy access to credit, and favorable environmental factors such as climate, soil and terrain. By 2001, little forest was left to be cleared in the Tierras Bajas, and cultivation had extended eastwards as far the Brazilian Shield. The ethnicities of the land-use change agents are mixed; they include Argentines, Brazilians, Bolivians, North Americans, mestizos, and Mennonite colonists who have their origins in Belize, Mexico, and Paraguay among others. The latter group live in a dozen or more colonies; including Riva Palacios, Swift Current, Santa Rita, Valle Esperanza, Tres Cruces, Manitoba, and El Tinto which range in area between 50 and 500 km^2.

In the central portion of the corridor, the Brazilian Shield sub-region, agriculture increased relatively little (1% , or approximately 400 km^2) during the same time period due to later initiation of mechanized agriculture in the region compared to the western Tierras Bajas, poorer soils, more dissected terrain, and less reliable rainfall (Figure 62; Table 40). While the increase was slight relative to the Tierras Bajas, the social and economic processes were similar. Land scarcity to the west and the wave of Mennonite immigration caused further deforestation in existing, small agricultural settlements north of the oldest town in the region – San José de Chiquitos. Ominously however, new agricultural and grazing areas had begun to appear further east near the military garrison town of Roboré by 2001.

During the era of neoliberalism, the Pantanal was developing as a new agricultural zone with approximately 200 km^2 of cropland and pasture (Figure 62; Table 40). From 1986 to 1994, clearance was concentrated along the highway. By 1994, these areas had generally increased in size, and embryonic clearance had begun along spur roads south of Puerto Suárez, and along secondary roads north of El Carmen. In 2001, further agricultural expansion had taken place in the same locations it had been seen in 1994, but the size of some fields (some as large as 50 km^2) indicate a shift from small-scale production to large-scale enterprises, mainly commercial grazing and sorghum.

8.5 POST-NEOLIBERAL POLICY CHANGES AND DEFORESTATION: 2005-PRESENT

8.5.1 The 'New' Agrarian Reform (Law N° 3545)

In 2006, during Morales first full year in office policies were implemented which signaled a shift toward post-neoliberalism. Exactly two decades after the second attempt at land reform, a third was initiated in 2006, when Law N° 3545 (Table 39) was brought into force to revise, insert new provisions, and effectively implement Law N° 1715 (itself an attempt to revise and implement Law N° 3464). The 'new' agrarian reform supposedly differs in that: (i) measures to comply with the SEF are more clearly defined; and (ii) regularization of the *saneamiento* (land titling) process is more transparent.

The Socio-Economic Function (SEF) set forth in Law N° 1715 was vague, thus leaving loopholes which allowed many to side-step the confiscation of their property. Supposedly, this situation has been rectified. Law N° 3545 (including the January 2009 constitutional amendments) now states that *campesino* (smallholder) farmers, small producers (<50 hectares), and indigenous communities meet the function when they intend to meet the 'best interests' or welfare for all residents or achieve economic development through the 'best use' of the land. It also allows for the sustainable use of the land in the development of agricultural activities and forestry as well as the conservation and protection of biodiversity, and eco-tourism, as long as it conforms with the 'best use' of the land, benefits society, and is in the 'best interest' of the owners (Article 2). Land which does not comply can be expropriated and then reverted to the State for redistribution. Compliance is determined by government appointed officials on-site every two years; a check-list of compliance measures is as follows (Defensor del Pueblo 2008; ANAPO 2008a):

(1) Best use of the land, whether agriculture, stock raising, or mixed, must be in accordance with the Departmental *Plan de Uso de Suelos* (Land-Use Plan);
(2) Area in cultivation for medium-size properties (50-500 hectares) must exceed 50% and 67% for agri-businesses (501-2,000 hectares). To calculate the projected area under cultivation, the effective area currently used is taken into account, in addition to the area under fallow in agricultural properties;
(3) The amount of land under production is measured by the area actually cultivated; for grazing lands, area under production corresponds to the number of cattle on-site – 5 hectares (0.05 km^2) per head is the minimum requirement
(4) Fallow is recognized as lands in rotation or under improvement; in the latter case, INRA officials should be shown proof such as machinery, fences, irrigation systems, etc.;
(5) Forestry, conservation and protection of biodiversity, research, and ecotourism are in compliance by respecting swamps, slopes greater than 45 degrees, windbreaks, riparian vegetation, lakes, and streams;
(6) Deforestation permits must be obtained by request from the *Superintendencia Forestal* (Forestry Superintendent); Illegal clearing are contrary to sustainable land use and do not constitute compliance with the SEF (Art II).
(7) Servitude of laborers is recognized as not fulfilling the SEF; therefore, the following actions should be taken to avoid charges of slavery or servitude:
    a. Do not make advance payments and avoid extending equity loans

b. Never give land as a form of payment
c. On days off, the worker must leave the workplace
d. Do not sponsor a worker or his family's marriage, baptisms, etc.
e. Do not put an employee's child on the payroll
f. Do not sell supplies (clothing, medicines, food, tools, etc.) to the workforce; ensure that more than one supplier can offer supplies

(8) Obligations to workers are as follows:

a. Contracted laborers (permanent and temporary) must have a fixed contract
b. Contracts must be registered
c. Workers must be enrolled in a health care system
d. Contribution to the Pension Fund Systems
e. Proof of worker payment signed by the laborers
f. On-site pharmaceutical facility in cases of 80 or more laborers; medical facility in cases of 200 or more laborers; and a hospital in cases of 500 or more laborers

Expropriated properties are not put on the open market as in 1996, but surrendered to the State, and distributed, according to Presidential authority to indigenous and *campesino* communities without a 'sufficient amount' of land, marked as some form of protected area, or put under works of public interest (Article 59). Smallholdings, however, will be given to the social organization with jurisdiction in the region (Köppen 2008). Compensation is no longer based on property tax, but instead market value (as determined by the Supervisory Authority for Agriculture). Current land holdings, including large-scale holdings obtained by legal title, are grandfathered in assuming that they meet the SEF.

Law N^{o} 3545 also attempts to rectify the discriminatory land tenure arrangements that have plagued Bolivia for centuries through the *saneamiento* process. For this purpose, a legal cadastre has been created and managed in a GIS. During the period of Law N^{o} 1715 (1996-2005), just over 93,000 km^{2} were titled at a cost of $88 million.

This is one of the most successful regularization processes in Latin America where approximately 94,500 km^2 have been titled in the last 3 years alone, at a cost of just over $10 million (MDRAyMA and INRA, 2008). While seemingly vast, these values are misleading considering that Bolivia covers 1,098,581 km^2 and 88% of Santa Cruz has not been regularized. Ambitious deadlines set by the Morales' administration target 2013 for completion of *saneamiento*.

8.5.2 Regulatory Changes to Bolivia's Fire Policy (Resolution #93/2007)

Under neoliberalism, deforestation and associated burning were weakly regulated and enforced, despite national fire education programs and the use of colorful mascots such as "Smokey the Tapir" (McDaniel et al. 2005). However, under the Morales administration, legislative, regulatory and constitutional changes have been instituted and are aimed at conservation through increased control and subsequent fines.

Criminalization is outlined in Resolution #93/2007, entitled "Administration, Authorization and Monitoring of Controlled Grassland Fires," and has sparked interagency action from several government agencies, the police and armed forces, as well as local and regional governmental entities. International players are also involved, including GTZ and the Brazilian National Institute for Space Research (INPE). Bolivia's Vice-ministry of the Environment is working with INPE using satellite imagery to detect fires and relay the information to INRA to identify and penalize violators who burn without a permit. Permits currently cost $14 per 100 hectares. In many ways, the campaign is strikingly similar to the 1998 Brazilian fire policy, “Amazon Fire and Deforestation Monitoring and Control Project,” a conservation oriented policy designed after the devastating fires of 1997 that attempted to control forest fires by prescribing permits and dictating specific locations where fires could be set (Sorrensen 2009).

8.5.3 Post-Neoliberal Deforestation Dynamics along the Corredor Bioceánico

We consider three possible scenarios to illustrate rates of forest-to-agriculture conversion in relation to policies set forth by Evo Morales: (i) a business-as-usual scenario in which the Morales’ administration’s policies have had no measurable effect on the rates of forest to agriculture conversion before they came to power; (ii) post-2005 policies have slowed down rates of land clearance; and (ii) these policies have accelerated forest clearance. Two possibilities exist with respect to the loci of deforestation: either entirely new areas of forest clearance have appeared since 2005 or it is occurring in close proximity to existing agricultural areas.

We examined a 637 km^2 rectangular area to the west of the town of Tres Cruces in the Tierras Bajas (Figure 61). This site was chosen for analysis as it is one of the oldest settled areas along the Corredor Bioceánico. It is characteristic of the Tierras Bajas: it is dominated by export-oriented farms cultivated by mestizo Bolivians, Brazilians and Mennonites (it includes part of the long-established colonies of Rosenort and Nueva Holanda). It can be seen on Figure 63 that many fields are relatively long and narrow, and separated by windbreaks of forest vegetation. As settlement had begun in the 1980s agriculture was well established by 2005 and constituted 77% of the landscape

(Table 41). This high proportion of cultivated made it a likely candidate area in which to see reforestation, and, in fact, the forest area increased by approximately 9 km^2 in 2006 (equal to a 6.8% increase in forest area). In the following two years, 32 km^2 were lost, the vast majority of which occurred from 2007 to 2008. By the end of 2008, agricultural land comprised 88% of the area. By examining Figure 63 it can be seen that this forest-to-agriculture conversion occurred in two relatively large patches in the north-east of the area, four medium-sized fields in the west, and many of the linear windbreaks were made narrower.

In the Brazilian Shield sub-region a 650 km^2 area was selected which focused on the Mennonite colonies that appeared near the end of the neoliberal era (Figure 61). These consist of the Mennonite colonies of Nuevo México and a portion of Valle Hermosa. In 2005, only 37 km^2 of the area had been deforested (Table 41). Most of the clearance was in the form of straight, parallel roads cut into the primary forest and small farmsteads (Figure 64): 94% of the study area (613 km^2) was still composed of intact forest. From 2005 to 2006, large rectangular agricultural fields appeared between these roads as more forest was cleared to expose soils for cultivation and the amount of cleared land increased over 50%. In the next two years, the trend of cutting roads into primary forest and clearing forest between them to create fields accelerated. By 2008, 200 km^2 of forest had been lost, compared to 37 km^2 in 2005.

The third area studied, in the Pantanal sub-region, is larger than the other two. It covers 3,600 km^2 in the northeast of the Corredor Bioceánico and is known as Rincón del Tigre (Figure 61). Irregular boundaries were drawn (Figure 65) to capture both *mestizo* expansion north of the town El Carmen and the establishment of pasture further east close to the border with Brazil: both are new frontiers of colonization. The amount and rates of deforestation do not appear as dramatic as those in the Brazilian Shield, but the size of the area (3,600 km^2 compared to 650 km^2) has to be borne in mind (Table 41). From 2005 to 2006, the area under forest decreased by approximately 50 km^2, representing a 1.3% loss. Figure 65 shows that losses in this year were associated with new agricultural fields near the town of El Carmen (the same areas which experienced deforestation in 2001). The following year the rate of forest loss decreased slightly to 0.8%, but increased to 3.8% from 2007 to 2008. By 2008 the amount of forest lost had approached 130 km^2. While some forest loss in during this time can still be attributed to deforestation around El Carmen, most resulted from Brazilian farmers and ranchers moving into the north-east of the region from Mato Grosso do Sol (El Deber, 2005). Close to the Brazilian border nearly 100 km^2 of forest lost were the result of a single field being cleared in less than one year! According to El Deber (2006), forest-to-agriculture conversion along the Brazilian border is attributed to illegal acquisition of lands by Brazilians.

8.6. DISCUSSION

In the previous section data on recent deforestation rates and spatial vignettes of land-use change in key locations along the Corredor Bioceánico were provided. However, by themselves, they do not signal aspects of the land-use change record which are related to policy shifts brought about by the *Movimiento al Socialismo* (MAS) government of President Morales. In this section the influences of regulatory changes in burning policies and land reform passed and implemented by the MAS government in the last few years on land-use decision making and land-use change are discussed. This is done in conjunction with information from interviews with key respondents conducted in May and June 2009. The focus of the discussion is an attempt to answer the question: Are the recent patterns and rates of forest-to-agriculture conversion in this agricultural frontier attributable to policy changes?

Recent studies have shown that the strength of institutions (in this case, government policy) can be important in determining deforestation rates (e.g. Jepson 2006; Tucker and Ostrom 2005; Gibson et al. 2000). Though their role is often ambiguous and complex (Lambin et al. 2003), at a general level, when institutions are weak or corrupt and forest management policies are poorly enforced, increased forest loss is facilitated. Liverman and Silas (2006) present a general argument that on the one hand reduced state intervention has meant less environmental regulation, and on the other when state institutions provide strong oversight they are better able to reduce bad environmental outcomes like deforestation. The Corredor Bioceánico largely presents contradictory evidence to this orthodox position. In post-Morales' Bolivia, stronger government (where the state defines the means and objectives: Brannstrom, 2009; Jordan et al. 2005) has been manifested through institutions such as INRA[30] which have been empowered. Yet, at the same time, deforestation initially showed no significant difference to that during the neoliberal era, but very recently rates of forest loss have

[30] INRA is simultaneously a national and a departmental organization, as it is an arm of national government, and has semi-autonomous offices in each department of the country.

accelerated. Here then, strong management and a combination of dangerous policies and mistrust has had the unintended consequence of increasing forest loss.

The first year of detailed results presented in this paper (2005-2006) were a transitional year as the MAS government was elected in December 2005, a month or so into the summer growing season. The deforestation rates and areas of active deforestation along the Corredor Bioceánico were similar to the years that immediately preceded it: we can term this business-as-usual. Deforestation did not increase markedly from 2006 to 2007, thought it might have been expected too given that, as we argue below, the policies of the national government have created conditions which encourage forest-to-agriculture conversion along the entire Corredor Bioceánico. We attribute this 'apparent depression' in expected deforestation to the severe floods in the eastern lowlands of Bolivia during the 2006-2007 austral summer. Deforestation rates increased markedly in all sub-regions from 2007 to 2008.

Significantly, during the tenure of Morales' government hotspots of rapid forest-to-agriculture cover have appeared in primary forest in the Brazilian Shield and Pantanal sub-regions to the east of the Tierras Bajas: areas Hecht (2005) and Pacheco (2006) deemed natural barriers the advance of agricultural advancement only a few years ago: "There will be little expansion of the agricultural frontier [beyond central and northern Santa Cruz] due to mechanized agriculture" (Pacheco 2006: 216).

8.6.1 Linking Agrarian Reform to Deforestation

Law N^{o} 3545 has directly contributed to the high rates of deforestation experienced during the post-neoliberal period. One of the most quantifiable aspects has been the distribution of fiscal (state-owned) lands to form communal properties. It began between May and August of 2006 when President Morales symbolically delivered tractors, trucks, and water pumps at Ucureña; the same city in Cochabamba Department where former president Paz Estenssoro handed land deeds to landless smallholders who were veterans of the 1952 revolution. Emulating his predecessor, he also presented 2,300 land titles amounting to 30,000 km^2 to 60 indigenous communities, with a promise of an additional 200,000 km^2 (BBC News 2006). In August 2007, another 5,166 titles (7,000 km^2) were distributed at Ucureña with the promise of an additional 60,000 km^2 (El Deber 2007).

Over the last two years, those promises have largely been kept, but where and what is the ‘promised land’? Scattered over the entire eastern lowlands, approximately a third is thought to have been in State ownership. The other two-thirds was reportedly land in the eastern lowlands ‘owned’ by individuals and companies who illegally held title or who had not acquired one (Enzinna 2006). However, according to records made public by INRA, of the nearly 135,000 km^2 which have been titled since 2006, 91% have been endowed by the State and are composed entirely of forest reserves located a long way from urban centers in Beni, Santa Cruz, and Pando. Nonetheless, although only 21% of the land in Santa Cruz Department has been endowed, the total area still amounts to 21,150 km^2.

Sixty-eight percent of lands distributed through endowment have been in the form of TCOs or communal territories to *campesinos*, indigenous peoples, and syndicates. These are the lands which are scattered throughout the eastern lowlands, mainly Santa Cruz and Beni; though there is some in the Altiplano in Oruro and Potosi Departments. Overall, the general consensus among large landowners interviewed is that too much land has been claimed, and eventually titled by indigenous peoples, since INRA's primary mission when distributing land is to "give priority to indigenous communities and peasants" (Article 17). In fact, as of 2008, nearly 18% of Bolivia's territory was claimed by indigenous groups; in total they formed 3% of Bolivia's total population (van Schaick 2009). Köppen (2008) and some respondents interviewed claim that TCOs are in effect completely independent of authority once they obtain land title, and that the sanctions that apply to other land owners in terms of land-use decisions (e.g., leaving land in fallow, use of fire as a clearance tool) are not reported and can, anyway, be ignored by TCOs without the government taking action.

In addition to endowments, many TCOs have been formed through consolidation where individual, indigenous or *campesino* title holders have pooled their titles and receive a communal TCO. However, the consolidation process is akin to a one-way street. Once a TCO is granted it is illegal to sell the land and if the individual leaves the community, they relinquish any land claims. Another issue of concern voiced among medium-large property owners is that preferential treatment is given to TCO inhabitants when assessing socio-economic compliance. They argue that communal lands are granted thousands of hectares for 'traditional' hunting and collection of medicinal plants.

These lands technically meet the government's socio-economic requirements, but many respondents stated emphatically that the same would not hold true for a non-indigenous soybean producer who might protect large tracts of forested land for conservation. By way of contrast, indigenous respondents complained they accounted for a significantly smaller proportion of forest clearance, and that large-scale farmers in the region are encroaching on their ancestral territories, making the region more arid because of the changes in microclimate and hydrological functioning through deforestation. Though it is too early to assess the debate of common (new forms of TCOs) vs. private (e.g., see Tucker 1999) in causing deforestation, the situation in the eastern lowlands will eventually provide an interesting case.

Morales' land 'reform' has received favorable press in the international media with claims of true 'reform' in the sense that the injustices of the past have been rectified. Public records prove otherwise as very little of the 'reformed' land has actually been reverted from large land owners (Table 42). Even then, much of the land claimed to have been expropriated is tied up in litigation. Therefore, the government's new law can be seen not so much as a radical reform, but rather as a release valve for appeasing smallholder land claims. However, many pro-Morales supporters see this as true reform and a tangible victory. As of June 2009, no land directly along the main highway in the Corredor Bioceánico had been expropriated or reverted. Yet, nearly all farmers interviewed in the summer of 2009 expressed fears about land seizure – they perceive it to be the greatest threat to their livelihoods. This climate of fear has led to the most direct, and currently the greatest, contributor to deforestation by individuals and companies under the reform. This, in their minds, is underpinned by the arbitrary use of 'productive' land and SEF criteria that could be used as weapons of retaliation against landowners. This has led them to clear land to prove it is in some form of use. Often, 'best use' and 'best interest' of the owner(s) are not synonymous terms. INRA officials interviewed at the Santa Cruz office in 2009 affirmed that the government does not recognize forest clearing by fire in order to obtain property titles:

> Deforestation is not accepted as an indicator that the land is being worked, but rather that the land is being destroyed (15 January 2009).
>
> These people who are clearing more land than is needed don't know the law; they could have their land taken away (21 June 2009).

17 of 33 interviews with financiers and farmers illustrate contradictions to INRA's stated position, arguing that Law N^{o} 3545 was 'highly' threatening to their properties. For example, a financier who provides credit to farmers along a 200 km^2 stretch of the Corredor Bioceánico noted several cases where farmers are clearing forest "to comply with Law N^{o} 3545." A committee member of one of Santa Cruz's leading agricultural producer organizations, who is also a producer with over 10 km^2 of riparian vegetation along the Corredor Bioceánico, asserted that in the past, they held land in forest to maintain surface water flow or simply because they enjoyed some of the last remnants of forest in the region. Now, however, they have cleared this land for production so that the laborers they employ will not complain to officials that the land is idle. A further group of landowners who hold 100 km^2 of forest (one of the largest blocks of contiguous forest south of the highway) asserted that they have, and will continue to deforest to meet the conditions of reform. In addition, land that is idle can be

reported as unproductive and expropriated. The Association of Oilseed and Wheat Producers (ANAPO 2008a) recommends that owners with less than 0.5 km^2 not leave their land fallow, nor reside anywhere else for more than two years, for fear of being reported. Whether INRA's tenets that one does not need to clear forest to comply with the new law is a moot point; clearly, mistrust of the INRA's 'true intentions' are having unintended consequences.

8.6.2 Linking Deforestation to Fire Prevention

Resolution #93/2007 was designed to prevent unauthorized clearance of forest and grasslands by fire. As shown in Table 43, a report produced by the Supervisory Authority for Agriculture maintains satellite-based regulation of unpermitted fires under the Morales' administration helped reduce fires by 43% between 2004 (pre-MAS) and 2007 (post-MAS). Still, 740 violators were identified, and the state anticipates recuperating over $4 million through fines, which it plans to invest in restoration of deforested areas through the National Forest Development Fund (El Deber, 2008). Once fires are located on satellite imagery or are reported on a toll-free hotline, violators are identified from land tenure maps and fined equivalent to $0.25 dollars per hectare. For example, based on satellite monitoring carried out from September 16 to 30, 2007, the Supervisory Authority for Agriculture, fined owners of 41 properties on average $4,875; individual amounts ranging from $256 to $34,089. Of these, 33 were from the Department of Santa Cruz, and the remainder from the Beni. All properties appear to be owned by large-scale commercial farmers, including three Mennonite colonies located in Santa Cruz.

In addition to data on violators, data on the number of fire permits also suggests that the government is cracking down on deforestation and burning by agribusiness (Table 43). Between 2003 and 2005, 399 permits authorizing fires were granted. In 2006, no permit requests were granted, and in 2007 it was reported that none were requested. A representative interviewed at the Supervisory Authority for Agriculture indicated that all agents of deforestation are monitored, whether indigenous groups, smallholders or commercial farmers. It is important to note that large-scale commercial farmers and ranchers account for most burning and deforestation in Santa Cruz and Beni, and that the municipalities with the highest number of fires between 2004 and 2007 were located in these two departments.

This policy represents a significant departure from those of the neoliberal period, when there was weaker regulation and enforcement. The situation in the Brazilian Amazon may illustrate what could be happening in Bolivia. There, when land tenure is insecure, access to credit is difficult, and the threat of expropriation is high existing land policies still hold sway and thwart efforts to prevent fires regardless of how well anti-burning policies are conceived and implemented (Sorrensen 2009). While this applies to small-scale, swidden cultivators, the same principles apply to systems of mechanized agriculture. Regardless, as long as global demand and price for oilseeds remain high, farmers will continue to remove vegetation by burning the forest (the only means available) as the high crop returns outweigh the cost of fines.

Interviews with producers in the region revealed a general consensus that the new policy was beneficial but they were worried simultaneously about what constituted ‘illegal’ burning. For example, so-called ‘traditional’ clearance on plots less than 50 hectares by indigenous is acceptable to the government, but it is still unclear whether traditional clearance is taken to mean slash-and-burn at small scales or who is considered ‘traditional’ by the government. Respondents were also worried that fires set by neighbors could spread to their properties and that they would be fined as well (in such cases, a person has 15 days after they appear on the Superintendent’s list to petition). An additional injustice was felt to be that fines are set according to land title instead of fire intensity or the area burnt. In other words, if only a small corner of a property is burned, the fine is calculated according to the area of the entire property. This has particularly important implications for Mennonites who farm under a collective land title owned by the colony. If a single Mennonite farmer burns his land, the entire colony is penalized. This is a major reason Mennonites top the list of fines. A Mennonite farmer from near El Tinto remarked that his colony was fined and the entire colony had to contribute payment. More alarming is the fact that 5 of 7 Mennonites interviewed in May and June 2009 (all representing separate colonies) were still unaware of the new law highlighting both limited institutional support, but also culpability among some leaders of Mennonites colonies for not being informed themselves and/or informing the people they lead. Others see the law as a contradiction, thus reinforcing their mistrust of the government’s true intentions. One interviewee responded:

> Meeting the SEF requires the land be ‘productive.’ Often, this can only be achieved through the use of fire to clear vegetation. If the government denies the

> land owner a permit and the land is not being used productively, it can be reverted back to the State (14 June 2009).

Overall, however, many in the region are simply ignoring (or are unaware of) the resolution, thereby maintaining the status quo – deforestation for agriculture and pasture through the use of fire. One cattle rancher remarked that the bureaucratic process to obtain the permits was so long-winded and lengthy, and even then, one might not be approved. It was simply easier and cheaper to burn and then pay the fine.

8.7 CONCLUSION

Our aim was to determine whether policies introduced by the Morales' government can be seen as signals in the land-use change record. Specifically, have rates of forest clearance for agriculture and the loci of agricultural-driven deforestation changed since post-neoliberalism has dominated land-use policy in Bolivia? Our results show that rates of deforestation by commercial agriculture has increased in some parts of the Corredor Bioceánico during the time the MAS government has been in control, this has been most notable in the Brazilian Shield and Pantanal sub-regions, in areas which had just begun to emerge as new agricultural zones by 2001. Between 2007 and 2008, in particular, forest clearance has accelerated markedly. However, forest clearance was not restricted to the relatively well forested parts of the Corredor Bioceánico; the remaining forests in the Tierras Bajas were rapidly being cleared at the same time. Interviews we have conducted with a variety of stakeholders indicate that the post-neoliberal policies – particularly the new Agrarian Reform laws and a burning ban – have triggered an acceleration of forest clearance along the Corredor Bioceánico.

Given a continuation of increased regulation and stronger enforcement of forest clearing and burning – the key elements of 'strong' Morales-led government in this context -- our prognosis is that deforestation rates will continue to increase wherever agricultural zones incorporate much new forest (i.e., in the Brazilian Shield and the Pantanal), and the last vestiges of forest in the Tierras Bajas will soon be lost. In the Brazilian Shield, there is a natural brake on continued deforestation, simply the availability of terrain with high land capability ratings. The remainder may be spared, but much is already under extensive grazing. However, the Pantanal has better natural endowments and is likely to replicate the Tierras Bajas. The future then hinges on the degree to which the current administration provides oversight, and whether provisions for sustainable land-use present in the newly approved constitution are implemented. The current government, which was re-elected in January, 2010, faces a paradox in the context of deforestation. In the fight to overturn neoliberal policies, which are widely accepted as the largest driver of forest clearance, the post-neoliberal policies of land expropriation and re-distribution have fueled further deforestation. This perverse outcome is also at odds with the concept of more regulated use of natural resources which President Morales is trying to encourage.

What happens in Bolivia will be observed intensely by Latin American governments and their people, and a cadre of scholars worldwide, as other Latin American countries make a political journey from neoliberal, center and center-right to post-neoliberal center-left and left, and more landowners find themselves caught between increasingly more powerful peasant movements and state governments who threaten land reform and distribution (Borrow-Strain, 2007). The era of neoliberalism witnessed staggering levels of deforestation across the continent, as many countries enter a left-wing post-neoliberal world are their forests destined to become a distant memory? And as scholars reflect on late twentieth century neoliberalism, will we ultimately consider it as a precursor of something worse in terms of environmental damage?

9. SUMMARY AND CONCLUSIONS

My key research findings have shown that overall, large-scale deforestation has occurred along the Corredor Bioceánico mainly as a consequence of the expansion of mechanized commercial production of oil-seed crops such as soybeans and sunflower. The significance of these findings is that agriculture-driven deforestation is pushing into sensitive areas threatening globally-important ecosystems such as those in the Chaco, Chiquitano and Pantanal as well as some of the nation's and continent's largest protected areas. In addition, farmers appear to be favoring transitional forest types on deep and poorly drained soils of alluvial plains for agriculture, and attempting to maximize production by producing two crops per year – soybeans in the summer and sunflower or sorghum in the winter. Rates of forest loss match or exceed those of more publicized or well-known regions such as Rondônia and Mato Grosso, Brazil. Moreover, rates of forest loss are accelerating linearly with time due to the policies implemented by incumbent president Evo Morales. Finally, just over one-quarter of all respondents interviewed, noted price or market forces as the dominant reason they made a decision to clear land for crops or animal production. They also noted traditional, environmental and climatic variables as important in the decision making process. The remainder of this section summarizes the key research findings from Sections 5-8.

9.1 KEY RESEARCH FINDINGS

9.1.1 Land-Use and Land-Cover Change

- **Deforestation along the Corredor Bioceánico, 1975-2008:** Over the 33-year study period, approximately 12,000 km^2 of forest were lost among the three sub-regions – which is an area nearly the size of Connecticut. Forest loss was greatest in the Tierras Bajas (10,000 km^2), followed by the Brazilian Shield with (1,200 km^2), and the Pantanal (650 km^2). The agricultural frontier has extended well beyond the agricultural 'expansion zone' of the Tierras Bajas into the Chiquitano and Pantanal forests, which were once thought impervious to large-scale, mechanized agriculture (Hecht 2005; Pacheco 2006). In addition, evidence suggests that agriculture-driven deforestation is pushing into noteworthy protected areas such as Kaa-Iya del Gran Chaco, San Matías and Otuquis National Parks and Integrated Management Areas.

  Among the three 'hotspots' assessed (Tres Cruces, Nuevo México, Rincón del Tigre), deforestation for commercial agriculture in Santa Cruz continues. In the case of Nuevo México and Rincón del Tigre rates accelerated after Morales took power. These changes can be directly linked to the Morales' administration's recent Agrarian Reform and pro-environmental regulations. This trend counters recent studies which have shown that stronger oversight or more government (in this case, government policy) lowers deforestation rates.

- **Land Change among Classes:** The intensification of pasture and cropland regimes varied from 2001 to 2008. In the Tierras Bajas, pasture was initially the dominant land-use, but is gradually replaced by the double cropping regime by 2007 and 2008.

In the Brazilian Shield and Pantanal, pasture is still the dominant land-use although both pasture and the double cropping regime continued to increase in area. Overall, farmers appear to be favoring transitional forest types on deep and poorly drained soils of alluvial plains.

In the Tierras Bajas, three classes account for the majority of natural vegetation lost between 1994 and 2008, mainly to the double cropping regime: (i) Chaco forest with Saó palm poorly drained on clay or silty clay soils; (ii) transitional Chaco forest on medium to imperfectly drained floodplain soils; and (iii) floodplain forest of south-central Chiquitanía on well-drained soils. In the Brazilian Shield, transitional Chaco forest; Chiquitano-Chaco transitional forest; and transitional Chaco forest mixed with Palocruzal vegetation on ancient floodplains of the Río Otuquis and Quimome were the three most dominant types of natural vegetation lost to pasture. In the Pantanal, Chiquitano-Chaco transitional forest on imperfectly drained soils of east-central Chiquitanía was the dominant vegetation class lost to pasture.

- **Extending the Land Change Record with CBERS Imagery:** CBERS imagery is one of a number of potential sources that help to fill the gap in the land change record created by the failure of Landsat ETM's SLC in 2006. It has several advantages or characteristics: (i) it can extend the land change record forward in time without the loss of information (until 2009); (ii) imagery is free of charge to the public; (iii) contains bandwidths in the visible and infrared ranges; and (iv) has a relatively fine spatial resolution of 20 m. Therefore, CBERS is well suited for observation of phenomena and objects where details such as small holder and industrial agriculture can be captured simultaneously.

However, CBERS imagery comes with problems of its own. Available scenes are limited to the continent of South America and the Caribbean, and portions of East Asia. Artifacts caused by systematic distortion must be corrected before processing began. These problems can be overcome through the relatively straightforward statistical correction procedure outlined in Section 5. What cannot be overcome is the loss of the CCD camera post-July 2009. CBERS-4 will not be launched until 2011 and the Landsat Data Continuity Mission is not scheduled to be launched until 2012. Clearly, land change scientists will have to turn a limited source of other medium-resolution satellites.

9.1.2 Land-Use and Land-Cover Change Causes and Drivers

- **Neoliberalism:** The neoliberal period witnessed some of the largest forest clearing in Bolivia. From 1952 to 1985, the vast eastern lowlands were opened for immigration; the country's first roads were paved; new land settlement schemes precipitated land distribution; and agricultural production increased. After 1985, Bolivia underwent neoliberal reform and attempted to accrue foreign exchange through increased cash crop production. However, other factors were responsible for forest clearance.
- **Role of Individual Producers:** As proximate causes**,** individual producers have a direct and therefore, significant effect on LULC according to the decisions they make. During interviews, only one-quarter of all respondents noted price as the

dominant reason they made a decision. This was followed closely by tradition (18%), soil rotation (18%), precipitation (13%), requires few inputs (6 %), minimize risk (6%), use of animal feed (5%), government policies (5%), and subsistence use (3%).

- **Role of Organizations and Federations:** Producer organizations and federations also influence LULC. They often serve as middlemen between individual farmers and companies/firms by negotiating prices, securing harvest destination, establishing dialogue with seed and machine companies and firms, as well as providing advice and even litigation support for land tenure. Seed and machine companies, firms, and banks provide farmers with loans. Producer organizations such as ANAPO and CAO are directly involved in preservation of the external market by repealing the restriction of oilseed exports; repealing the prohibition of food exports; and assessing problems of credit regulations. Both are indirectly involved in supporting the movement for autonomy from the central government.
- **Role of Government:** The 2006 Agrarian Reform and Resolution #93/2007 (fire policy) also play a significant role in driving contemporary LULCC. New social and environmental goals have emerged during the transition from neoliberalism to post-neoliberalism. Properties which do not comply with the Socio-Economic Function (SEF) can be expropriated outright or reverted back to the State for redistribution. Producers who burn without an authorized permit are fined. Both policies represent a significant departure from those of the neoliberal period, when there was weaker regulation and enforcement.

- **Agrarian Reform:** The 2006 Agrarian Reform law has directly contributed to the high rates of deforestation experienced during the post-neoliberal period. Over half of all financiers and farmers interviewed in the summer of 2009 expressed fears about land seizure. This climate of fear has led them to clear idle land to prove it is in some form of use.
- **Fire Prevention:** The new fire policy has also had an effect on deforestation. Many farmers in the region are simply ignoring, are unaware of, or defying the resolution, thereby maintaining the status quo – deforestation for agriculture and pasture through the use of fire. The majority of respondents viewed it as simply easier and cheaper to burn and then pay the fine.

9.2 RESEARCH OBJECTIVES AND IMPLICATIONS

At this stage, it is appropriate to consider to what extent I met my research objectives and answered the questions I posed in the introductory section. I also consider the implications for the wider LULCC community.

9.2.1 Map and Quantify the Spatial Patterns of LULCC

The purpose of Objective 1 is to map and quantify the spatial patterns of LULCC from 1975 to 2008 along eastern Bolivia's portion of the Corredor Bioceánico using a time-series of medium resolution Landsat (MSS, TM, and ETM+) and CBERS-2 and 2B data, and coarse resolution MODIS NDVI data. Specific questions answered in this objective are:

(i) Can the land change record be extended at low cost without the loss of information using CBERS-2 and 2B imagery?

The Landsat archive has been providing users with imagery for decades and is unequalled 35-year record of imagery, but with the failure of the SLC in 2006 this once reliable sensor has forced land change scientists to turn elsewhere. This research shows that CBERS-2 and -2B helps to fill this gap and can extend the land change record forward in time without the loss of information. CBERS provides imagery free of charge in bandwidths in the visible and infrared ranges, and at a relatively fine spatial resolution of 20 m. Therefore, it is well suited to observation of phenomena and objects in areas where small holder and industrial agriculture can be captured simultaneously. However, CBERS imagery comes with problems of its own. Available scenes are limited to the continent of South America and the Caribbean, and portions of East Asia. Artifacts caused by systematic distortion must be corrected before processing began. Regardless, these problems can be overcome through the relatively straightforward statistical correction procedure outlined in Section 5.

(ii) What types of forest are being converted to pasture or a particular cropping regime, where and why; and what types of land-use modification changes have occurred?

In Section 6, we have developed a method for quantifying and mapping the spatial location of detailed forest and crop classes in the seasonal tropics of Bolivia. Results show it is possible to incorporate several data sources and supplement one sensor's weakness with another's strength for use in mapping and quantifying changes in detailed LULC types. By going beyond classic classification schemes such as forest vs. non-forest or ecosystem approaches and assessing between changes in various types of forest and crop classes, the resulting change maps can potentially provide decision-makers with more detailed insight as to the proximate causes or driving forces of change in addition to the most threatened forests remaining in the Tierras Bajas and those most likely to be cleared in the Brazilian Shield and Pantanal. This information is imperative for raising both government and public awareness so that more informed policy proposals can developed resulting more effective responses about landscape management and conservation (e.g., planning of future protected areas or effectiveness of existing units). In addition, scientists studying human-environment relationships can better understand the dynamic impact humans have on the environment. Data on phenology and the quantity and spatial distribution of vegetation is vital to terrestrial ecologists studying the influences of vegetation on animal distribution and dynamics (Pettorelli et al. 2005). Finally, by focusing on one of the most dynamic regions in the Neotropics, this paper has advanced the basic scientific knowledge of LULC change in southern hemisphere semi-arid wooded ecosystems and provided a better understanding of the nature of human-environment relationships in one of the most dynamic, contemporary frontier regions in South America.

9.2.2 Understanding Drivers and Causes of LULCC

The purpose of Objective 2 is to understand the socio-economic and political drivers of change and develop a conceptual model of drivers by linking social science to image processing techniques. Specific hypotheses tested in this objective were:

(i) The effects of institutions and organizations, changes in government policies, physical and climatic influences, and individual land-use decisions, rather than economic factors as argued by Hecht et al., are the most important drivers of land change.

The hypothesis should neither be accepted nor rejected (i.e., accept alternative hypothesis). Instead it should be reformulated because results show that while structural adjustment policies and market forces were instrumental in causing deforestation, they are not the only factors driving land change in southeastern Bolivia. Interview results and archival research shows that the factors which play an important role in LULCC are complex and multivariable including individual decisions, producer organizations and federations, seed and machinery companies, national and international governments, and multi-regional trade blocs.

Only one-quarter of all respondents noted price as the dominant reason they made a decision. This was followed closely by tradition (18%), soil rotation (18%), precipitation (13%), requires few inputs (6 %), minimize risk (6%), use of animal feed (5%), government policies (5%), and subsistence use (3%). Producer organizations and federations often serve as middlemen between individual farmers and companies/firms by negotiating prices, securing harvest destination, establishing dialogue with seed and machine companies and firms, as well as providing advice and even litigation support for land tenure. Seed and machine companies, firms, and banks provide farmers with loans. Producer organizations such as ANAPO and CAO are directly involved in preservation of the external market by repealing the restriction of oilseed exports; repealing the prohibition of food exports; and assessing problems of credit regulations. Both are indirectly involved in supporting the movement for autonomy from the central government. Agrarian reform and fire policy also play a significant role in driving LULCC. New social and environmental goals have emerged during the transition from neoliberalism to post-neoliberalism. Properties which do not comply with the SEF can be expropriated outright or reverted back to the State for redistribution. Producers who burn without an authorized permit are fined. Both policies represent a significant departure from those of the neoliberal period, when there was weaker regulation and enforcement.

While price determined by the global market is not proportionally the most dominant driver, this study shows it is not the only underlying motive. Therefore, the null hypothesis should be restated as: The effects of economic factors, institutions and organizations, changes in government policies, physical and climatic influences, and individual land-use decisions, are all important drivers of land change.

(ii) The rise to power of Evo Morales' government and their land-use policies has introduced signals in the land-use change record. More specifically, the rates of forest clearance for agriculture changed since December 2005 and the loci of agriculture-driven deforestation have changed.

Results from Section 8 show that the hypothesis should be accepted. Rates of deforestation for commercial agriculture have increased in some parts of the Corredor Bioceánico during the time the MAS government has been in control. This has been most notable in the Brazilian Shield and Pantanal sub-regions, in areas which had just begun to emerge as new agricultural zones by 2001. Between 2007 and 2008, in particular, forest clearance has accelerated markedly. However, forest clearance was not restricted to the relatively well forested parts of the Corredor Bioceánico; the remaining forests in the Tierras Bajas were rapidly being cleared at the same time. Interviews I have conducted with a variety of stakeholders indicate that the post-neoliberal policies – particularly the new Agrarian Reform laws and a burning ban – have triggered an acceleration of forest clearance along the Corredor Bioceánico.

Given a continuation of increased regulation and stronger enforcement of forest clearing and burning my prognosis is that deforestation rates will continue to increase wherever agricultural zones incorporate much new forest (i.e., in the Brazilian Shield and the Pantanal), and the last vestiges of forest in the Tierras Bajas will soon be lost. In the Brazilian Shield, there is a natural brake on continued deforestation, simply the availability of terrain with high land capability ratings. The remainder may be spared, but much is already under extensive grazing. However, the Pantanal has better natural endowments and is likely to replicate the Tierras Bajas. The future then hinges on the degree to which the current administration provides oversight, and whether provisions for sustainable land-use present in the newly approved constitution are implemented. The current government, which was re-elected in January, 2010, faces a paradox in the context of deforestation. In the fight to overturn neoliberal policies, which are widely accepted as the largest driver of forest clearance, the post-neoliberal policies of land expropriation and re-distribution have fueled further deforestation. This outcome is also at odds with the concept of more regulated use of natural resources which President Morales is trying to encourage.

REFERENCES

ADEPA (Asociación de Productores de Algodón). *Anuario Estadístico*. 2007. Santa Cruz, Bolivia.

Abbot, J.I.O. and K. Homewood. 1999. A history of change: causes of *miombo* woodland decline in a protected area in Malawi. *Journal of Applied Ecology* 36: 422-433.

Achard, F. and F. Blasco. 1990. Analysis of vegetation seasonal evolution and mapping of forest cover in west Africa with the use of NOAA AVHRR data. *Photogrammetric Engineering and Remote Sensing* 56: 1359-1365.

Achard, F. and C. Estreguil. 1995. Forest classification of Southeast Asia using NOAA AVHRR data. *Remote Sensing of the Environment* 54: 198-208.

Achard, F., H.D. Eva, J.H. Stibig, P. Mayaux, J. Gallego, T. Richards, and J.P. Malingreau. 2002. Determination of deforestation rates of the world's humid tropical forests. *Science* 297: 99-1002.

Achard, F., D. Mollicone, H.J. Stibig, D. Aksenov, L. Laestadius, Z.Y. Li, P. Popatov and A. Yaroshenko. 2006. Areas of rapid forest-cover change in Boreal Eurasia. *Forest Ecology and Management* 237 (1-3): 322-334.

Adámoli, J., E. Sennhauser, J. Acero, and A. Rescia. 1990. Stress and disturbance: vegetation dynamics in the dry Chaco region of Argentina. *Journal of Biogeography* 17: 491-500.

Aguirre, C.B. 2000. Wetlands in Bolivia: Pantanal preservation and sustainable development. In *The Pantanal: Understanding and Preserving the World's Largest Wetland*, ed. F.A. Swarts, 43-54. St. Paul, MN: Paragon House.

Aide, T.M. and H.R. Grau. 2004. Globalization, migration and Latin American ecosystems. *Science* 305: 1915-1916.

Altstatt, A., Kim, S., Rodas, O., Yanosky, A., Townshend, J., Tucker, C., Clay, R. and Musinsky, J. 2006. Change in the subtropical forest of eastern Paraguay during the 1990s [PowerPoint Report]. College Park, MD: The Global Land Cover Facility, University of Maryland Institute for Advanced Computer Studies.

Alves, D.S. 2002. Space-time dynamics of deforestation in Brazilian Amazônia. *International Journal of Remote Sensing* 23 (14): 2903-2908.

Alves, D.S. 2003. Land use intensification and abandonment in Rondônia, Brazilian Amazônia. *International Journal of Remote Sensing* 24 (4): 899-903.

ANAPO (Asociación De Productores De Oleaginosas y Trigo). 2002. *Anuario Estadístico – 2002*. Unidad de Servicios y Comunicaciones – UsyC, Santa Cruz, Bolivia.

ANAPO (Asociación De Productores De Oleaginosas y Trigo). 2007. *Anuario Estadístico – 2007*. Unidad de Servicios y Comunicaciones – UsyC, Santa Cruz, Bolivia.

ANAPO (Asociación De Productores De Oleaginosas y Trigo [Association of Oilseed and Wheat Producers]). 2008a. *Guía Práctica Defensa de los Derechos de los Productores (Practical Guide to the Defense of Producer's Rights)*. Santa Cruz, Bolivia.

ANAPO (Asociación De Productores De Oleaginosas y Trigo [Association of Oilseed and Wheat Producers]). 2008b. *Memoria Anual – 2008*. Santa Cruz, Bolivia.

Angelsen, A. and D. Kaimowitz. 1999. Rethinking the causes of deforestation: lessons from economic models. *The World Bank Research Observer* 14 (1): 73-98.

Angelsen, A., D. van Soest, D. Kaimowitz, and E. Bulte. 2001. Technological change and deforestation: a theoretical overview. In *Agricultural Technologies and Tropical Deforestation*, ed. A. Angelsen and D. Kaimowitz, 19-34. Wallingford, U.K.: CABI.

APA (Asociación de Productores de Algodón). *Anuario Estadístico*. 1973. Santa Cruz, Bolivia.

Barber, R.G. 1995. Soil degradation in the tropical lowlands of Santa Cruz, eastern Bolivia. *Land Degradation and Rehabilitation* 6: 95-107.

Bassett, T.J. and K.B. Zuéli. 2000. Environmental discourses and the Ivorian savanna. *Annals of the Association of the American Geographers* 90 (1): 67-95.

Batistella, M., M. Guimarães, M.E. de Miranda, H.R. Vieira, G.S. Valladares, J.A. de C. Mangabeira, and M.C. de Assis. 2002. *Monitoramento da expansão agropecuária na região Oeste da Bahia*. Documentos 20, Embrapa Monitoramento por Satélite, Campinas, Brazil.

BBC News. 2006 (03 August). Morales seeks radical land reform. London, UK.

Bebbington, A. and J.T. Bury. 2009. Institutional challenges for mining and sustainability in Peru. *Proceedings of the National Academy of Sciences* 106 (41): 17296-17301.

Becqué, R., A.B.A. Harrilall, M. Hartman, D. Husbands, A. van Kuijk, S. Nokta, S. Morel, and P. Da Silva. 2007. Strategic environmental assessment (SEA) of transport infrastructure initiatives (focus on IIRSA) in Guyana. Inter-American Development Bank Draft Report, 9S0230.

Beltran, A. 2000. *Indigenous and Traditional Peoples and Protected Areas: Principles, Guidelines, and Case Studies*. World Commission on Protected Areas (WCPA), Best Practice Protected Area Guidelines Series 4: 31-39.

Bender, H.S., M.W. Friesen, M. Ediger, I Hiebert, and M. Gerald. 1987. Bolivia: Global Anabaptist Mennonite Encyclopedia Online. *Global Anabaptist Mennonite Encyclopedia Online*. http://www.gameo.org/encyclopedia/contents/B665.html (last accessed 26 February 2009.

Bender, P. (Soil Scientist and member of MCC Staff). Personal Communication, 02 June 2009.

Beneria-Surkin, J. 2003. Decentralization questioned: the structuring and articulation of Guarani participation in conservation and development in Izozog, Bolivia. Unpublished Dissertation, University of California – Los Angeles.

Bensebaa, K., G.J. Francis Banon, and L.M. Garcia Fonseca. 2004. On-orbit spatial resolution estimation of CBERS-1 CCD imaging system from bridge images. *Proceedings of the International Society for Photogrammetry and Remote Sensing (ISPRS)*. Istanbul, Turkey, 12-23 July 2004.

BICECA (Building Informed Civic Engagement for Conservation in Andes-Amazon). 2006. *El Corredor vial de integración Bolivia-Brasil (Construcción Carretera Santa Cruz-Pailón-San José-Puerto Suarez)*, http://www.biceca.org/es/Project.overview.61.aspx (last accessed 28 May 08).

Blaikie, P. 1985. *The Political Economy of Soil Erosion in Developing Countries*. Essex, U.K.: Longman Development Studies.

Blaikie, P. and H. Brookfield. 1987. *Land Degradation and Society*. London, U.K.: Methuen.

Boletta, P.E., A.C. Ravelo, A.M. Planchuelo and M. Grilli. 2006. Assessing deforestation in the Argentine Chaco. *Forest Ecology and Management* 228: 108-114.

Boletín Informativo: Estación Experimental Agrícola de Los Llanos. 1961. *Los resultados de investigaciones agrícolas en "Los Llanos" al servicio de Bolivia*, No. 1 (March).

Borrow-Strain, A. 2007. Intimate Enemies: Landowners, Power, and Violence in Chiapas, Mexico. Durham, NC: Duke University Press.

Boyd, D.S. and F.M. Danson. 2005. Satellite remote sensing of forest resources: three decades of research development. *Progress in Physical Geography* 29 (1): 1-26.

Bradley, A.V. 2005. Land-use and land-cover change in the Chapare region of Bolivia. Unpublished Ph.D. Dissertation, University of Leicester, U.K.

Bradley, A.V. and A.C. Millington. 2008. Coca and colonists: quantifying and explaining forest clearance under coca and anti-narcotics policy regimes. *Ecology and Society* 13 (1): Art. 31.

Bradley, B.A., R.W. Jacob, J.F. Hermance and J.F. Mustard. 2007. A curve fitting procedure to derive inter-annual phonologies from time series of noisy satellite NDVI data. *Remote Sensing of Environment* 106: 137-145.

Brannstrom, C.B., W. Jepson, A.M. Filippi, D. Redo, Z. Xu, and S. Ganesh. 2008. Land change in the Brazilian savanna (Cerrado), 1986-2002: comparative analysis and implications for land-use policy. *Land Use Policy* 25: 579-595.

Brannstrom, C.B. 2009. South America's neoliberal agricultural frontiers: places of environmental sacrifice or conservation opportunity. *Ambio* 38 (3), 141-149.

Brannstrom, C.B. 2010. A Q-method analysis of environmental governance in Brazil's northeastern soy frontier. Unpublished.

Brondizio, E.S., E.F. Moran, P. Mausel, and Y. Wu. 1994. Land-use change in the Amazon estuary: patterns of Cabloco settlement and landscape management. *Human Ecology* 22 (3): 249-278.

Brondizio, E.S. 2005. Intraregional analysis of land-use change in the Amazon. In *Seeing the Forest for the Trees: Human-Environment Interactions in Forest Ecosystem*, ed. E.F. Moran and E. Ostrom, 223-252. Cambridge, MA: The MIT Press.

Brown, J.C., W.E. Jepson, and K.P. Price. 2004. Expansion of mechanized agriculture and land-cover change in southern Rondônia, Brazil. *Journal of Latin American Geography* 3 (1): 96-102.

Brown, J.C., W.E. Jepson, J.H. Kastens, B.D. Wardlow, J.M. Lomas, and K.P. Price. 2007. Multitemporal, moderate-spatial-resolution remote sensing of modern agricultural production and land modification in the Brazilian Amazon. *GIScience and Remote Sensing* 44 (2): 117-148.

Bryant, D., D. Nielsen and L. Tangley. 1997. *The Last Frontier Forests: Ecosystems and Economies on the Edge*. Baltimore, MD: WRI Publications.

Bucher, E.H. 1983. Chaco and Caatinga: South America arid savannas, woodlands and thickets. In *Ecology of Tropical Savannas*, ed. B. Huntley and B. Walker, 48-79. Heidelberg, Germany: Springer-Verlag.

Bucher, E.H. and P.C. Huszar. 1999. Sustainable management of the Gran Chaco of South America: ecological promise and economic constraints. *Journal of Environmental Management* 57: 99-108.

Bullock S.H., H.A. Mooney and E. Medina (ed.). 1995. Seasonally Dry Tropical Forests. London, U.K.: Cambridge University Press.

CAO (Cámara Agropecuaria del Oriente). 2002. *Evaluación del Desempeño del Sector Agropecuario*. Santa Cruz, Bolivia.

CAO (Cámara Agropecuaria del Oriente). 2003. *Evaluación del Desempeño del Sector Agropecuario*. Santa Cruz, Bolivia.

CAO (Cámara Agropecuaria del Oriente). 2007. *Evaluación del Desempeño del Sector Agropecuario*. Santa Cruz, Bolivia.

CAO (Cámara Agropecuaria del Oriente). 2008. *Evaluación del Desempeño del Sector Agropecuario*. Santa Cruz, Bolivia.

Cardille, J.A. and J.A. Foley. 2003. Agricultural land-use change in Brazil Amazônia between 1980 and 1995: evidence from integrated satellite and census data. *Remote Sensing of Environment* 87: 551-562.

Castillo, O. (Chief of Party, Kaa-Iya Project and Bolivia Regional Coordinator for Peru, Bolivia, and Paraguay of the Wildlife Conservation Society). Personal Communication, 04 August 2007.

Censo Agropecuario. 1950. La Paz, Bolivia: Ministerio de Hacienda.

Charmaz, K. 2001. Grounded Theory. In *Contemporary Field Research: Perspectives and Formulations*, ed. R.M. Emerson, 335-352. Long Grove, IL: Waveland Press, Inc.

Chander, G. 2007. *Landsat Data Gap Study, Technical Report: Initial Data Characterization, Science Utility and Mission Capability Evaluation of Candidate Landsat Mission Data Gap Sensors*. Sioux Falls, SD: USGS and EROS.

Chavez, P.S. 1996. Image-based atmospheric corrections revisited and improved. *Photogrammetric Engineering and Remote Sensing* 60: 571-583.

CIAT (Centro de Investigación Agrícola Tropical). 2008. *33 Años: Memoria Institucional, 1975-2008*. Santa Cruz, Bolivia: Autonomous Department of Santa Cruz.

CIFOR (Center for International Forestry Research). 1995. *PLUS – Precipitation map of the Department of Santa Cruz, Bolivia*. Santa Cruz, Bolivia: Santa Cruz Natural Resources Protection Project.

Crist, R.E. 1946. Bolivia: land of contrasts. *American Journal of Economics and Society* 5 (3): 297-325.

Crossley, J.C. 1961. Santa Cruz at the cross-roads: a study of development in eastern Bolivia. *Tijdschrift voor economische en sociale geografie* (*Journal of Economic and Social Geography*) 52: 197-206; 230-241.

Council on Hemispheric Affairs. 2009 (June 17). Testing time for Obama's Colombia Free Trade Agreement. Washington, D.C.

Davies, D. 1993. Estimation of deforestation east of the Rio Grande, Bolivia, using Landsat satellite imagery. Unpublished Master's Thesis, Cranfield Institute of Technology, Silsoe College, Silsoe, U.K..

Defensor del Pueblo. 2008. *Ley No 3545 (Ley del 28 de noviembre de 2006): Modificación de la Ley No. 1715 Reconducción de la Reforma Agraria*. La Paz, Bolivia.

de Oliveira Lino, C., M.G. Rodrigues Lima and G.L. Hubscher. 2000. CBERS – an international space cooperation program. *Acta Astronautica* 47 (2-9): 559-564.

DeFries, R., M. Hansen, J.R.G. Townshend, and R. Sohlberg. 1998. Global land cover classifications at 8-km spatial resolution: the use of training data derived from Landsat imagery in decision tree classifiers. *International Journal of Remote Sensing* 19 (16): 3141-3168.

DeFries, R. and A.S. Belward. 2000. Global and regional land cover characterization from satellite data: an introduction to the special issue. *International Journal of Remote Sensing* 21 (6-7): 1083-1092.

DeFries, R., R.A. Houghton, M. Hansen, C. Field, D.L. Skole, and J. Townshend. 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 90s. *Proceedings of the National Academy of Sciences* 99 (22): 14256-14261.

DeFries, R., A.J. Hansen, A.C. Newton and M.C. Hansen. 2005. Increasing isolation of protected areas in tropical forests over the past twenty years. *Ecological Applications* 15 (1): 19-26.

Dinerstein, E., D.M. Olson, D.J. Graham, A.L. Webster, S.A. Primm, M.P. Bookbinder, and G. Ledec. 1995. *A Conservation Assessment of the Terrestrial Ecosystems of Latin America and the Caribbean*. Washington, D.C.: The World Wildlife Fund and The World Bank.

Dros, J.M. 2004. Managing the soy boom: two scenarios of soy production expansion in South America. Amsterdam, The Netherlands: Worldwildlife Fund and AIDEnvironment.

El Deber. 2004 (Wednesday, March 10). En la civilización, pg. B3. *El Deber*. Santa Cruz, Bolivia.

El Deber. 2005 (25 December). La 'ilegalidad' se impone en la frontera con Brasil Negocio. *El Deber*. Santa Cruz, Bolivia.

El Deber. 2006a (09 August). INRA denuncia 'tráfico de tierras' en Tucavaca Acciones. *El Deber*. Santa Cruz, Bolivia.

El Deber. 2006b (22 March). Noticias. *El Deber*. Santa Cruz, Bolivia.

El Deber. 2007 (03 August). INRA iniciará revolución agraria en SantaCruz. *El Deber*. Santa Cruz, Bolivia.

El Deber. 2008a (Friday, June 13). Sambu hará entrega parcial del Puente Paila. *El Deber*. Santa Cruz, Bolivia.

El Deber. 2008b (Tuesday, July 15). Accleran corredores viales, pg. 6-7. *El Deber*. Santa Cruz, Bolivia.

ENTRIX. 1999. *Supplemental Environmental Assessment, Cuiabá Pipeline – Bolivian Portion, Phase I Direct Impacts*. Houston, TX: ENTRIX, Inc.

Enzinna, W. 2006 (7 August). Let them have tractors, new steps in Bolivia's agrarian reform. Narco News Bulletin. Published online at *www.narconews.com/*.

Etter, A., C. McAlpine, K. Wilson, S. Phinn and H. Possingham. 2006. Regional patterns of agricultural land use and deforestation in Colombia. *Agriculture, Ecosystems and Environment* 114: 369-386.

Etter, A. and C. McAlpine. 2008. Modeling unplanned landcover change across scale: a Colombian case. In *Land Use Change: Science, Policy and Management*, ed. R.J. Aspinall and M. J. Hill, 81-98. Boca Raton, FL: CRC Press.

Eva, H.D., A.S. Belward, E.E. De Miranda, C.M. Di Bella, V. Gond, O. Huber, S. Jones, M. Sgrenzaroli, and S. Fritz. 2004. A land cover map of South America. *Global Change Biology* 10: 732–745.

FAO (Food and Agriculture Organization). 2005. *Global Forest Resources Assessment 2005: Progress Towards Sustainable Forest Management*. FAO Forestry Paper 147. Rome, Italy: FAO.

FAO (Food and Agriculture Organization). 2007 (29 June). *Informe Especial: Misión FAO/PMA de Evaluación de Cultivos y Suministros de Alimentos en Bolivia*. Rome, Italy: FAO.

FEGASACRUZ (Federación de Ganaderos de Santa Cruz). *Anuario Estadístico*. 2008. Santa Cruz, Bolivia.

FENCA - Federación Nacional de Cooperativas Arroceras. *Anuario Estadístico*. 2007. Santa Cruz, Bolivia.

Fearnside, P.M. 2001. Soybean cultivation as a threat to the environment in Brazil. *Environmental Conservation* 28 (1): 23-38.

Fearnside, P.M. 2002. Avança Brasil: environmental and social consequences of Brazil's planned infrastructure in Amazonia. *Environmental Management* 30 (6): 735-747.

Fearnside, P.M. 2005. Deforestation in Brazilian Amazonia: history, rates, and consequences. *Conservation Biology* 19 (3): 680-688.

Fearnside, P.M. 2006. BR-319: Brazil's Manaus-Porto Velho highway and the potential impact of linking the arc of deforestation to central Amazonia. *Environmental Management* 38: 705-716.

Fearnside, P.M. 2007. Brazil's Cuiabá-Santarém (BR-163) highway: the environmental cost of paving a soybean corridor through the Amazon. *Environmental Management* 39: 601-614.

Ferguson, M.A.D. and F. Messier. 1997. Collection and analysis of traditional ecological knowledge about a population of Arctic Tundra Caribou. *Arctic* 50 (1): 17-28.

Fifer, J.V. 1967. Bolivia's pioneer fringe. *Geographical Review* 57 (1): 1-23.

Fifer, J.V. 1982. The search for a series of small successes: frontiers of settlement in eastern Bolivia. *Journal of Latin American Studies* 14 (2): 407-432.

Fretz, J.F. 1960. A visit to the Mennonites in Bolivia. *Mennonite Life* 15: 13-18.

Frey, R. 1995. Flora and vegetation of "Las Piedritas" and the margin of Laguna Caceres, Puerto Suarez, Bolivian Pantanal. *Bulletin of the Torrey Botanical Club* 122 (4): 314-319.

Friedl, M.A. and C.E. Brodley. 1997. Decision tree classification of land cover from remotely sensed data. *Remote Sensing of Environment* 61: 399-409.

Friedl, M.A., D.K. McIver, J.C.F. Hodges, Z.Y. Zhang, D. Muchoney, A.H. Strahler, C.E. Woodcock, S. Gopal, A. Schneider, A. Cooper, A. Baccini, F. Gao, and C. Schaaf. 2002. Global land cover mapping from MODIS: algorithms and early results. *Remote Sensing of Environment* 83: 287-302.

Fuller, D.O. 2006. Tropical forest monitoring and remote sensing: a new era of transparency in forest governance? *Singapore Journal of Tropical Geography* 27: 15-29.

FVSA (Fundación Vida Silvestre Argentina, The Nature Conservancy, Fundación desde el Chaco, Wildlife Conservation Society – Bolivia). 2005. *Evaluación ecoregional del Gran Chaco Americano*. Buenos Aries, Argentina.

Galford, G.L., J.F. Mustard, J. Melillo, A. Gendrin, C.C. Cerri and C.E.P. Cerri. 2008. Wavelet analysis of MODIS time series to detect expansion and intensification of row-crop agriculture in Brazil. *Remote Sensing of Environment* 112: 576-587.

Gao, X., A.R. Huete, W. Ni, and T. Miura. 2000. Optical-biophysical relationships of vegetation spectra without background contamination. *Remote Sensing of Environment* 74: 609-620.

Gao, X., H.R. Huete and K. Didan. 2003. Multisensor comparisons and validation of MODIS vegetation indices at the semiarid Jornada Experimental Range. *IEEE Transactions on Geoscience and Remote Sensing* 41 (10): 2368-2381.

Gasparri, N.I. and H.R. Grau. 2009. Deforestation and fragmentation of Chaco dry forest in NW Argentina (1972-2007). *Forest Ecology and Management* 258: 913-921.

Geist, H.J. and E.F. Lambin. 2001. *What drives tropical deforestation? A meta analysis of proximate and underlying causes of deforestation based on sub-national case study evidence*. LUCC Report Series Number 4, CIACO. Louvain-la-Neuve, Belgium, University of Louvain.

Geist, H.J. and E.F. Lambin. 2002. Proximate causes and underlying driving forces of tropical deforestation. *BioScience* 52 (2): 143-150.

Geist, H.J. and E.F. Lambin. 2004. Dynamic causal patterns of desertification. *BioScience* 54 (9): 817-829.

Geist, H.J., W. McConnell, E.F. Lambin, E. Moran, D. Alves, T. Rudel. 2006. Causes and trajectories of land-use/cover change. In *Land-Use and Land-Cover Change: Local Processes and Global Impacts*, ed. E.F. Lambin and H.J. Geist, 41-70. Berlin, Germany: Springer-Verlag.

Gentry, A. 1995. Diversity and floristic composition of Neotropical dry forests. In *Seasonally dry tropical forests*, ed. S.H. Bullock, H.A. Mooney, and E. Medina, 146-194. Cambridge, MA: Cambridge University Press.

Gerold, G. 2004. Soil: the foundation of biodiversity. In *Biodiversity: The Richness of Bolivia: State of Knowledge and Conservation*, ed. P.L. Ibisch and G. Mérida, 17-30. Ministry of Sustainable Development. Editorial FAN: Santa Cruz, Bolivia.

Gibson, C.C., M. McKean, and E. Ostrom. 2000. Explaining deforestation: the role of local institutions. In *People and Forests: Communities, Institutions and Governance*, ed. C.C. Gibson, M. McKean, and E. Ostrom, 1-27. Cambridge: MIT Press.

Gilruth, P.T. and C.F. Hutchinson. 1990. Assessing deforestation in the Guinea highlands of West Africa using remote sensing. *Photogrammetric Engineering and Remote Sensing* 56 (10): 1375-1382.

Gómez, E. 1974. Economic analysis of the agricultural sector in Santa Cruz, Bolivia. Unpublished Dissertation, Utah State University.

Grainger, A. 2008. Difficulties in tracking the long-term global trend in tropical forest area. *Proceedings from the National Academy of Sciences* 105 (2): 818-823.

Grau, H.R. 2005a. Agriculture expansion and deforestation in seasonally dry forests of north-west Argentina. *Environmental Conservation* 32: 140-148.

Grau, H.R. 2005b. Globalization and soybean expansion into semiarid ecosystems of Argentina. *Ambio* 34 (3): 265-266.

Grau, H.R., N.I. Gasparri, and T.M. Aide. 2008. Balancing food production and nature conservation in the Neotropical dry forests of northern Argentina. *Global Change Biology* 14: 985-997.

Grau, H.R. and T.M. Aide. 2009. Globalization and land-use transitions in Latin America. *Ecology and Society* 13 (2): 36 [online] URL: http://www.ecologyandsociety.org/vol113/iss2/art16/.

Guillermoprieto, A. 2008. Bolivia's new order. *The National Geographic*, July 2008.

Hamerschlag, K. 1999. The Bolivia-Brazil pipeline: a "model" project? Bank Information Center, http://www.bicusa.org/bicusa/issues/misc_resources/454.php, (last accessed 27 May 2008).

Hagen, S.C., B.H. Braswell, S. Frolking, W.A. Salas, and X. Xiao. 2002. Determination of subpixel fractions of nonforested area in the Amazon using multiresolution satellite sensor data. *Journal of Geophysical Research* 107 D20: 8049.

Hamandawana, H., F. Eckardt and S. Ringrose. 2007. Proposed methodology for georeferencing and mosaicking Corona photographs. *International Journal of Remote Sensing* 28: 5-22.

Hansen, M.C., R. Dubayah, and R. DeFries. 1996. Classification trees: an alternative to traditional land cover classifiers. *International Journal of Remote Sensing* 17 (5): 1075-1081.

Hansen, M.C., R. DeFries, J.R.G. Townshend, and R. Sohlberg. 2000. Global land cover classification at 1-km spatial resolution using a classification tree approach. *International Journal of Remote Sensing* 21(6&7): 1331-1364.

Hansen, M.C., Y.E. Shimabukuro, P. Potapov, and K. Pittman. 2008a. Comparing annual MODIS and PRODES forest cover change for advancing monitoring of Brazilian forest cover. *Remote Sensing of Environment* 112: 3784-3793.

Hansen, M.C., S.V. Stehman, P.V. Potapov, T.R. Loveland, J.R.G. Townshend, R.S. DeFries, K.W. Pittman, B. Arunarwati, F. Stolle, M.K. Steininger, M. Carroll, and C. DiMiceli. 2008b. Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data. *Proceedings from the National Academy of Sciences* 105 (27): 9439-9444.

Heath, D.B. 1959. Camba: a study of land and society in eastern Bolivia. Unpublished Dissertation, Yale University, New Haven.

Heath, D.B, C.J. Erasmus, and H.C. Buechler. 1969. *Land Reform and Social Revolution in Bolivia*. Praeger Publishers: New York, NY.

Hecht, S.B. 1985. Environment, development and politics: capital accumulation and the livestock sector in eastern Amazonia. *World Development* 13(6): 663–84.

Hecht, S.B. 2005. Soybeans, development and conservation on the Amazon frontier. *Development and Change* 36 (2): 375-404.

Hecht, S.B. and C.C. Mann. 2008. How Brazil outfarmed the American farmer. *Fortune Magazine*, January 16, 2008. http://money.cnn.com/2008/01/16/news/international/brazil_soy.fortune/index.htm, (last accessed 09 June 2008).

Hindery, D. 1997. The effects of structural adjustment on deforestation in the Bolivian Amazon. Unpublished Master's Thesis, University of California, Los Angeles.

Hindery, D. 2003. Multinational Oil Corporations in a Neoliberal Era: Enron, Shell, and the Political Ecology of Conflict over the Cuiabá Pipeline in Bolivia's Chiquitanía. Unpublished Dissertation, The University of California, Los Angeles.

Hindery, D. 2004. Social and environmental impacts of World Bank/IMF-funded economic restructuring in Bolivia: an analysis of Enron and Shell's hydrocarbon projects. *Singapore Journal of Tropical Geography* 25 (3): 281-303.

Hiraoka, M. 1974. Pioneer settlement in eastern Bolivia. Unpublished Dissertation, The University of Wisconsin-Milwaukee.

Hirsch, S.M. 2001. The *Capitanía* of the Izozo: the struggle for political autonomy among the Guarani Indians of eastern Bolivia. In *Peoples of the Gran Chaco*, ed. E.S. Miller, 61-80. Westport, CT: Bergin & Garvey.

Horrigan, L., Lawrence, R.S. and Walker, P. 2002. How sustainable agriculture can address the environmental and human health harms of industrial agriculture. *Environmental Health Perspectives* 110 (5), 445-456.

Hostetler, J.A. 1951. The Amish family in Miffin County, Pennsylvania. Unpublished Master's Thesis, Pennsylvania State College.

Huete, A., K. Didan, T. Miura, E.P. Rodriguez, X. Gao, and L.G. Ferreira. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment* 83: 195-213.

IADB (Inter-American Development Bank). 2004. Santa Cruz-Puerto Suárez Corridor Project Phase One (BO-0036). www.iadb.org/IDBDocs.cfm?docnum=412220, (last accessed 17 Sept 07).

Ibisch, P.L., G. Rauer, D. Rudolph, and W. Barthlott. 1995. Floristic, biogeographical and vegetational aspects of Pre-Columbian rock outcrops (inselbergs) in Eastern Bolivia. *Flora* 190: 299-314.

Ibisch, P.L., S.G. Beck, B. Gerkmann, and A. Carretero. 2003. Ecoregions and ecosystems. In *Biodiversity: The Richness of Bolivia*, ed. P.L. Ibisch and G. Mérida, 47-88. Editorial Fundación Amigos de la Naturaleza (FAN): Santa Cruz, Bolivia.

INE (Instituto Nacional de Estadística). 1992. *Estadística de Población 1992*. www.ine.gov.bo/, (last accessed 20 Sept 07).

INE (Instituto Nacional de Estadística). 2001. *Estadística de Población 2001*. www.ine.gov.bo/, (last accessed 20 Sept 07).

INE (Instituto Nacional de Estadística). 2006. *Estadística de Población 2006*. www.ine.gov.bo/, (last accessed 20 Sept 07).

ISRIC (International Soil Reference and Information Centre). *Soil and Terrain Database for Latin America and Caribbean (SOTERLAC)*. 2005. Wageningen, The Netherlands.

ITC (International Institute for Aerial Survey and Earth Sciences). 1973. *Soil Monolith Paper No. 1: Chromic Luvisol, Botswana*. Enschede, The Netherlands.

Izquierdo, A.E. and H.R. Grau, H.R. 2009. Agriculture adjustment, land-use transition and protected areas in Northwest Argentina. *Journal of Environmental Management* 90: 858-865.

Jakubauskas, M.E., D.R. Legates and H. Kastens. 2002. Crop identification using harmonic analysis of time-series AVHRR NDVI data. *Computers and Electronics in Agriculture* 37: 127-139.

Janzen, D.H. 1988. Tropical dry forests: the most endangered major tropical ecosystem. In *Biodiversity*, ed. E.O. Wilson, 130-137. Washington, D.C.: National Academy Press.

Jensen, J.R. 2006. *Remote Sensing of the Environment: An Earth Resource Perspective*. Upper Saddle River, NJ: Prentice Hall.

Jepson, W.J. 2005. A disappearing biome? Reconsidering land-cover change in the Brazilian savanna. *The Geographical Journal* 171 (2): 99-111.

Jepson, W.J. 2006. Producing a modern agricultural frontier: firms and cooperatives in eastern Mato Grosso, Brazil. *Economic Geography* 82 (3): 289-316.

Jepson, W.J. and A.C Millington. 2008. The changing countryside. In *Land-Change Science in the Tropics: Changing Agricultural Landscapes*, ed. A.C. Millington and W.J. Jepson, 1-10. Norwell, MA: Springer.

Jepson, W.J., J.C. Brown, and M. Koeppe. 2008. Agricultural intensification on Brazil's Amazonian soybean frontier. In *Land-Change Science in the Tropics: Changing Agricultural Landscapes*, ed. A.C. Millington and W.J. Jepson, 73-92. Springer: Norwell, MA.

Jepson, W.J., C.B. Brannstrom and A.M. Filippi. 2010. Access regimes and regional land change in the Brazilian Cerrado, 1972-2002. *Annals of the Association of American Geographers* 100 (1): 87-111.

Jianning, G., Y. Jin, Z. Yong, X. Jianyan, P. Zhiqiang and H. Minghui. 2005. Study of the relative radiometric correction of CBERS satellite CCD image. *Science in China Series E (Engineering and Materials Science)* 48 (1): 12-28.

Jordan, A., K. Rüdiger, W. Wurzel and A. Zito, A. 2005. The rise of 'new' policy instruments in comparative perspective: Has governance eclipsed government? Political Studies 53, 477-496.

Junwu, T., M.A. Chaofei, N.I.U. Shengli, W. Xiaomei, S. Qingjun and D. Jing. 2005. The primary results of quantitative ocean color retrieval in China coastal areas with CBERS CCD data. *Science in China Series E (Engineering and Materials Science)* 48 (1): 161-176.

Justice, C.O., J.R.G. Townshend, B.N. Holben, and C.J. Tucker. 1985. Analysis of the phenology of global vegetation using meteorological satellite data. *International Journal of Remote Sensing* 6 (8): 1271-1318.

Kaimowitz, D. 1997. Factors determining low deforestation: the Bolivian Amazon. *Ambio* 26 (8): 537-540.

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

Kaimowitz, D., G. Thiele and P. Pacheco. 1999. The effects of structural adjustment on deforestation and forest degradation in lowland Bolivia. *World Development* 27 (3): 505-520.

Keeling, D.J. 2002. Transportation challenges for Latin America in the 21st century. In *Latin America in the 21st Century: Challenges and Solutions*, ed. G. Knapp, 77-103. Austin, TX: University of Texas Press

Keeling, D.J. 2008. Latin America's transportation conundrum. *Journal of Latin American Geography* 7 (2): 133-154.

Kennard, D.K. 2002. Secondary forest succession in a tropical dry forest: patterns of development across a 50-year chronosequence in lowland Bolivia. *Journal of Tropical Ecology* 18: 53-66.

Keys, E. and McConnell, W.J. 2005. Global change and the intensification of agriculture in the tropics. Global Environmental Change 15, 320-337.

Killeen, T.J. 1991. Range management and land-use practices in Chiquitanía, Santa Cruz, Bolivia. *Rangelands* 13 (2): 59-63.

Killeen, T.J. 1993. Guía de arboles de Bolivia. Herbario Nacional de Bolivia, La Paz, and Missouri Botanical Garden, St. Louis, MO.

Killeen, T.J., A. Jardim, F. Mamani, and N. Rojas. 1998. Diversity, composition and structure of a tropical semideciduous forest in the Chiquitanía region of Santa Cruz, Bolivia. *Journal of Tropical Ecology* 14: 803-827.

Killeen, T.J. 2007a. *A Perfect Storm in the Amazon Wilderness: Development and Conservation in the Context of the Initiative for the Integration of the Regional Infrastructure of South America (IIRSA)*. Arlington, VA: Center for Applied Biodiversity Science (CABS), Conservation International.

Killeen, T.J., V. Calderon, L. Soria, B. Quezada, M.K. Steininger, G. Harper, L.A. Solórzano, and C.J. Tucker. 2007b. Thirty years of land-cover change in Bolivia. *Ambio* 36 (7): 600-606.

Killeen, T.J., A. Guerra, M. Calzada, L. Correa, V. Calderon, L. Soria, B. Quezada and M.K. Steininger. 2008. Total historical land-use change in Eastern Bolivia: who, where, when, and how much? *Ecology and Society* 13(1): 36 [online] URL: http://www.ecologyandsociety.org/vol113/iss1/art36/.

Kimbrell, A. 2002. *The Fatal Harvest Reader: The Tragedy of Industrialized Agriculture*. Washington, D.C.: Island Press.

Klak, T. 2008. Neoliberal exports and regional vulnerability. In *Placing Latin America: Contemporary Themes in Human Geography*, ed. E.L. Jackiewicz and F.J. Bosco, 31-49. Lanham, MD: Rowan and Littlefield Publishers.

Klein Goldewijk, K. 2001. Estimating global land use change over the past 300 years: the HYDE database. *Global Biogeochemical Cycles* 15 (2): 417-434.

Klein, H.S. 2003. A Concise History of Bolivia. Cambridge University Press, Cambridge, UK.

Knorn, J., A. Rabe, V.C. Radeloff, T. Kuemmerle, J. Kozak and P. Hostert. 2009. Land cover mapping of large areas using chain classification of neighboring Landsat satellite images. *Remote Sensing of Environment* 113: 957-964.

Köppen, V. 2008. *Land regularization, land titling and cadastre in rural Bolivia with special regard to communal and indigenous lands*. Eschborn, Germany: German Technical Cooperation (GTZ).

Krüger, J.P. 2006. Waldkonversion und Bodendegradation im tropischen Tiefland von Ostbolivien – GIS – gestützte Analyse zur Regionalisierung der Bodendegradation im Department Santa Cruz. *EcoRegio* 17: 182S.

Kuemmerle, T., Kozak, J., Radeloff, V.C. and Hostert, P. 2009. Differences in forest disturbance among land ownership types in Poland during and after socialism. *Journal of Land Use Science* 4 (1-2), 73-83.

Lambin, E.F., B.L. Turner II, H.J. Geist, S.B. Agbola, A. Angelsen, J.W. Bruce, O.T. Coomes, R. Dirzo, G. Fischer, C. Folke, P.S. George, K. Homewood, J. Imbernon, R. Leemans, L. Xiubin, E.F. Moran, M. Mortimore, P.S. Ramakrishnan, J.F. Richards, H. Skanes, W. Steffen, G.D. Stone, U. Svedin, T.A. Veldkamp, C. Vogel, and J. Xu. 2001. The causes of land cover change: moving beyond the myths. *Global Environmental Change* 11: 261-269.

Lambin, E.F., H.J. Geist, and E. Lepers. 2003. Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environmental Resources* 28: 205-241.

Lambin, E.F., H. Geist, and R.R. Rindfuss. 2006. Introduction: local processes with global impacts. In *Land-Use and Land-Cover Change: Local Processes and Global Impacts*, ed. E.F. Lambin and H.J. Geist, 1-8. Berlin, Germany: Springer-Verlag.

Landívar, I. (President of the Association of Rice Producer). Personal Communication, 21 May 2009)

Lanning, J.W. 1971. The old colony Mennonites of Bolivia. Unpublished Master's Thesis, Texas A&M University, College Station, TX.

Leonard, O.E. 1948. *Santa Cruz: a socio-economic study of an area in Bolivia*. Foreign Agricultural Report No. 31, Office of Foreign Relations, U.S. Department of Agriculture, Washington D.C.

Lepers, E., E.F. Lambin, A.C. Janetos, R. DeFries, F. Achard, N. Ramankutty, and R.J. Scholes. 2005. A synthesis of information on rapid land-cover change for the period 1981-2000. *BioScience* 55 (2): 115-124.

Liverman, D.M. and S. Vilas. 2006. Neoliberalism and the environment in Latin America. *Annual Review of Environment and Resources* 31: 327-363.

Lobell, D.B. and G.P. Asner. 2004. Cropland distributions from temporal unmixing of MODIS data. *Remote Sensing of Environment* 93: 412-422.

Locklin,C.C. and B. Haack. 2003. Roadside measurements of deforestation in the Amazon area of Bolivia. *Environmental Management* 31 (6): 774-783.

Loveland, T., B.C. Reed, J.F. Brown, D.O. Ohlen, Z. Zhu, L. Yang, and J.W. Merchant. 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *International Journal of Remote Sensing* 21 (6&7): 1303-1330.

Loveland, T., G. Gutman, M. Buford, K. Chatterjee, C. Justice, C. Rogers, B. Stokes and J. Thomas. 2003. Land-Use/Land-Cover Change. In *Strategic Plan for the Climate Change Science Program*. Climate Change Science Program and the Subcommittee on Global Change Research, July 2003.

Lunetta, R.S., J.F. Knight, J. Ediriwickrema, J.G. Lyon and L.D. Worthy. 2006. Land-cover change detection using multi-temporal MODIS NDVI data. *Remote Sensing of the Environment* 105: 142-154.

Maass, J.M. 1995. Conversion of tropical dry forest to pasture and agriculture. In *Seasonally Dry Tropical Forests*, ed. S.H. Bullock, H.A. Mooney and E. Medina, 399-416. Cambridge, U.K.: Cambridge University Press.

Macdonald, L. and A. Ruckert. 2009. *Post-Neoliberalism in the Americas*. Basingstoke, Hampshire, England: Palgrave, Macmillan.

Maffei, L., E. Cuéllar, and A. Noss. 2004. One thousand jaguars (*Panthera Onca*) in Bolivia's Chaco? Camera trapping in the Kaa-Iya National Park. *Journal of the Zoological Society of London* 262: 295-304.

Malingreau, J.P. 1986. Global vegetation in dynamics: satellite observations over Asia. *International Journal of Remote Sensing* 7: 1121-1146.

Malingreau, J.P. and C.J. Tucker. 1988. Large-scale deforestation in the southeastern Amazon Basin of Brazil. *Ambio* 17 (1): 49-55.

Mares, D.R. 2006. Natural gas pipelines in the Southern Cone. In *Natural Gas and Geopolitics: From 1970 to 2040*, ed. D.G. Victor, A.M. Jaffe, and M.H. Hayes, 169-201. Cambridge, U.K.: Cambridge University Press.

Mather, K.F. 1922. Along the Andean front in southeastern Bolivia. *Geographical Review* 12 (3): 358-374.

Matheson, W. and S. Ringrose. 1994a. The development of image processing techniques to assess changes in green vegetation cover along a climatic gradient through Northern Territory Australia. *International Journal of Remote Sensing* 15 (1): 17-47.

Matheson, W. and S. Ringrose. 1994b. Assessment of degradation features and their development into the post-drought period in the west-central Sahel using Landsat MSS. *Journal of Arid Environments* 26: 181-199.

Mayaux, P., T. Richards and E. Janodet. 1999. A vegetation map of Central Africa derived from satellite imagery. *Journal of Biogeography* 26: 353-66.

Mayaux, P., E. Bartholomé, S. Fritz and A. Belward. 2004. A new land-cover map of Africa for the year 2000. *Journal of Biogeography* 31: 861-877.

McCarthy, J. and S. Prudham. 2004. Neoliberal nature and the nature of neoliberalism. *Geoforum* 35: 275-283.

McCracken, S.D., E.S. Brondizio, D. Nelson, E.F. Moran, A.D. Siqueria, and C. Rodriguez-Pedraza. 1999. Remote sensing and GIS at farm property level: demography and deforestation in the Brazilian Amazon. *Photogrammetric Engineering and Remote Sensing* 65 (11): 1311-1320.

McDaniel, J., Kennard, D., and Fuentes, A. 2005. Smokey the Tapir: Traditional fire knowledge and fire prevention campaigns in lowland Bolivia. *Society and Natural Resources* 18 (10), 921-931.

MDRAyMA (Ministry of Rural Development, Agriculture, Environment) and INRA (National Institute for Agrarian Reform). 2008. *Informe de Gestión 2007*. La Paz, Bolivia.

Medalla, E. 2009 (20 July). Authorities will likely have to expand Pacific ports beyond plans, says MOP official. Santiago, Chile: Business News Americas.

Mertens, B. and E.F. Lambin. 1997. Spatial modelling of deforestation in southern Cameroon. *Applied Geography* 17 (2): 143-162.

Mertens, B. and E.F. Lambin. 2000. Land-cover-trajectories in southern Cameroon. *Annals of the Association of American Geographers* 90 (3): 467-494.

Mertens, B., D. Kaimowitz, A. Puntodewo, J. Vanclay, and P. Mendez. 2004. Modeling deforestation at distinct geographic scales and time periods in Santa Cruz, Bolivia. *International Regional Science Review* 27 (3): 271-296.

Messina, J.P., S.J. Walsh, C.F. Mena, and P.L. Delamater. 2006. Land tenure and deforestation patterns in the Ecuadorian Amazon: conflicts in land conservation in frontier settings. *Applied Geography* 26: 113-128.

Miles, L., A.C. Newton, R.S. DeFries, C. Ravilious, I. May, S. Blyth, V. Kapos, and J.E. Gordon. 2006. A global overview of the conservation status of tropical dry forests. *Journal of Biogeography* 33: 491-505.

Miller, E.S. 1985. Marking Mennonite identity: a structuralist approach separation. *The Conrad Grabel Review* 3 (3): 251-263.

Miller, E.S. 1995. *Nurturing Doubt: From Mennonite Missionary to Anthropologist in the Argentine Chaco*. Urbana and Chicago, IL: University of Illinois Press.

Millington, A. and J.R.G. Townshend. 1988. *Biomass Assessment: Woody Biomass in the SADCC Region*. London, U.K.: Earthscan Publications.

Millington, A.C., P.J. Styles and R.W. Critchley. 1992. Mapping forests and savannas in sub-Saharan Africa form advances very high resolution radiometer (AVHRR) imagery. In *Nature and Dynamics of Forest-Savanna Boundaries*, ed. P.A. Furley, J. Proctor and J.A. Ratter, 37-62. New York, N.Y.: Chapman and Hall.

Millington, A.C., X.M. Velez-Liendo, and A.V. Bradley. 2003. Scale dependence in multitemporal mapping of forest fragmentation in Bolivia: implications for explaining temporal trends in landscape ecology and applications to biodiversity conservation. *ISPRS Journal of Photogrammetry and Remote Sensing* 57: 289-299.

Millington, A.C. 2006. Introductory essay: land-cover change. In *Our Earth's Changing Land: An Encyclopedia of Land-Use and Land-Cover Change,* ed. H. Geist, xl-xlviii. Westport, CT: Greenwood Press.

Minchin, J.B. 1881. Eastern Bolivia and the Gran Chaco. *Proceedings of the Royal Geographical Society and Monthly Record of Geography, New Monthly Series* 3 (7): 401-420.

Moffett, M. 2009 (12 February). Commodity price dive hits Latin economies. *The Wall Street Journal*. New York, NY.

Montes de Oca, I. 1997. *Geografía y Recursos Naturales de Bolivia*. La Paz, Bolivia: EDOBOL.

Moran, E.F., E. Brondizio, P. Mausel and Y. Wu. 1994. Integrating Amazonian vegetation, land-use, and satellite data. *Bioscience* 44 (5): 329– 338.

Morello, J. and G. Hortt. 1985. Changes in the areal extent of arable farming, stock raising and forestry in the South American Chaco. *Applied Geography and Development* 25: 109.

Morton, D.C., R.S. DeFries, Y.E. Shimabukuro, L.O. Anderson, F. Del Bon Espírito-Santo, M. Hansen, and M. Carroll. 2005. Rapid assessment of annual deforestation in the Brazilian Amazon using MODIS data. *Earth Interactions* 9: 1-22.

Morton, D.C., R.S. DeFries, Y.E. Shimabukuro, L.O. Anderson, E. Arai, F. del B. Espirito-Santo, R. Freitas and J. Morisette. 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proceedings of the National Academy of Sciences* 103: 14637-14641.

Moulin, S., L. Kergoat, N. Viovy and G. Dedieu. 1997. Global-scale assessment of vegetation phenology using NOAA/AVHRR satellite measurements. *Journal of Climate* 10: 1154-1170.

Murphy, P.G. and A.E. Lugo. 1986. Ecology of tropical dry forest. *Annual Review of Ecology and Systematics* 17: 67-88.

Nagendra, H., C. Tucker, J. Southworth, M. Karmacharya, and B. Karna. 2004. Monitoring parks through remote sensing: studies in Nepal and Honduras. *Environmental Management* 34 (5): 748-760.

Navarro, G. and E. Ferreira. 2007. *Mapa de Vegetación de Bolivia*, *1:250,000* (Digital Edition). The Nature Conservancy (TNC). Santa Cruz, Bolivia (ISBN: 978-99954-0-168-9).

Neis, B., D.C. Schneider, L. Felt, R.L. Haedrich, J. Fischer, and J.A. Hutchings. 1999. Fisheries assessment: what can be learned from interviewing resource users? *Canadian Journal of Fisheries and Aquatic Sciences* 56 (10): 1949-1963.

Nelson, G.C. and D. Hellerstein. 1997. Do roads cause deforestation? Using satellite images in econometric analysis of land use. *American Journal of Agricultural Economics* 79 (1): 80-88.

Nelson, R. and B. Holben. 1986. Indentifying deforestation in Brazil using multiresolution satellite data. *International Journal of Remote Sensing* 7 (3): 429-448.

Nepstad, D., G. Carvalho, A.C. Barros, A. Alencar, J.P. Capobianco, J. Bishop, P. Moutinho, P. Lefebvre, U.L. Silva Jr., and E. Prins. 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. *Forest Ecology and Management* 154: 395-407.

Noss, A.J., I. Oetting, and R.L. Cuéllar. 2004. Hunter self-monitoring by the Isoseño-Guaraní in the Bolivian Chaco. *Biodiversity and Conservation* 14: 2679-2693.

Nyerges, A.E. and G.M. Green. 2000. The ethnography of landscape: GIS and remote sensing in the study of forest change in West African Guinea savanna. *American Anthropologist* 102 (2): 271-289.

Ostrom, E. and Nagendra, H. 2006. Insights on linking forests, trees, and people from the air, on the ground, and in the laboratory. *Proceedings of the National Academy of Sciences* 103 (51), 19224-19231.

Ostrom, E. 2007. A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences* 104 (39): 15181-15187.

OTAI (Organización de Técnicos de la Agroindustria). 2007. Santa Cruz, Bolivia.

Pablo López, R. and C. Zambrana-Torrelio. 2006. Representation of Andean dry ecoregions in the protected areas of Bolivia: the situation in relation to the new phytogeographical findings. *Biodiversity and Conservation* 15 (7): 2163-2175.

Pacheco, P. 2001. *The role of forestry in poverty alleviation: Bolivia*. Country Profile for the Forum on The Role of Forestry in Poverty Alleviation. Rome, Italy: FAO (Forestry Department).

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

Pacheco, P. 2006. Agricultural expansion and deforestation in lowland Bolivia: the import substitution versus the structural adjustment model. *Land Use Policy* 23: 205-225.

Parker, T.A., A.H. Gentry, R.B. Foster, L.H. Emmons and J.V. Remsen, Jr. 1993. *The lowland dry forests of Santa Cruz, Bolivia: A global conservation priority*. Washington, D.C.: Conservation International.

Painter, M. and W.L. Partridge. 1989. Lowland settlement in San Julian, Bolivia – project success and regional underdevelopment. In *The Human Ecology of Tropical Land Settlement in Latin America*, ed. D.A. Schumann and W.L. Partridge, 341-377. Boulder, CO: Westview Press.

Pató, Z. 2000. *Piping the forest: The Bolivia-Brasil gas pipeline*. CEE Bankwatch Network. http://bankwatch.org/documents/pipeline.pdf, (last accessed 20 May 08).

Pedelty, J., S. Devadiga, E. Masuoka, M. Brown, J. Pinzon, C. Tucker, E. Vermote, S. Prince, J. Nagol, C. Justice, D.R. Junchang, Jr., C. Schaaf and J. Liu. 2007. Generating a long-term land data record from the AVHRR and MODIS instruments. *Proceedings of IGARSS 2007* (pp. 1021-1025). Barcelona, Spain. July 23-27, 2007.

Pennington, R.T., D.E. Prado, and C.A. Pendry. 2000. Neotropical seasonally dry forests and Quaternary vegetation changes. *Journal of Biogeography* 27: 261-273.

Pérez Flores, D. (President of the Association of Oilseed and Wheat Producers). Personal Communication, 25 May 2009

Perz, S.G. 2001. Household demographic factors as life cycle determinants of land use in the Amazon. *Population Research and Policy Review* 20: 159-186.

Perz, S.G., C. Aramburú and J. Bremner. 2005. Population, land use and deforestation in the Pan Amazon Basin: a comparison of Brazil, Ecuador, Perú and Venezuela. *Environment, Development and Sustainability* 7: 23-49.

Pettorelli, N., J.O. Vik, A. Mysterud, J-M. Gaillard, C.J. Tucker and N.C. Stenseth. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology and Evolution* 20 (9): 503-510.

Pickup, G., V.H. Chewings, and D.J. Nelson. 1993. Estimating changes in vegetation cover over time in arid rangelands using Landsat MSS data. *Remote Sensing of the Environment* 43: 243-263.

Pimentel, D., L.E. Hurd, A.C. Bellotti, M.J. Forster, I.N. Oka, O.D. Sholes and R.J. Whitman. 1973. Food production and the energy crisis. *Science* 182: 443-449.

PLUS (Plan de Uso de Suelos). 1995. Precipitation map of the Department of Santa Cruz, Bolivia. Center for International Forestry Research (CIFOR): Bogota, Indonesia.

PLUS (Plan de Uso de Suelos). 1996. Soil map of the Department of Santa Cruz, Bolivia. Center for International Forestry Research (CIFOR): Bogota, Indonesia.

Pontius, Jr., R.G., E. Shusas and M. McEachern. 2004. Detecting important categorical changes while accounting for persistence. *Agriculture, Ecosystems and Environment*, 101: 251-268.

Ponzoni, F.J. and B.F. Carneiro Albuquerque. 2008. Pre-launch absolute calibration of CCD/CBERS-2B sensor. *Sensors* 8: 6557-6565.

Prado, D.E. 1991. A critical evaluation of the floristic links between chaco and caatingas vegetation in South America. Unpublished Dissertation, University of St. Andrews, Scotland.

Prado, D.E. 1993. What is the Gran Chaco vegetation in South America? I. A review. Contribution to the study of flora and vegetation of the Chaco. V. *Candollea* 48: 145-172.

Pretty, J., C. Brett, D. Gee, R. Hine, C. Mason, J. Morison, M. Rayment, G. Van Der Bijl and T. Dobbs. 2001. Policy challenges and priorities for internalizing the externalities of modern agriculture. *Journal of Environment and Planning* 44 (2): 263-283.

PROMASOR (Productores de Maíz y Sorgo). 2007. Santa Cruz, Bolivia.

Quesada, M., G.A. Sanchez-Azofeifa, M. Alvarez-Añorve, K.E. Stoner, L. Avila-Cabadilla, J. Calvo-Alvarado, A. Castillo, M.M. Espírito-Santo, M. Fagundes, G.W. Fernandes, J. Gamon, M. Lopezaraiza-Mikel, D. Lawrence, L.P. Cerdeira Morellato, J.S. Powers, F. de S. Neves, V. Rosas-Guerrero, R. Sayago and G. Sanchez-Montoya. 2009. Succession and management of tropical dry forests in the Americas: Review and perspectives. *Forest Ecology and Management* 258: 1014-1024.

Rafiqpoor, D. and P.L. Ibisch. 2004. The history of the Plio-Pleistocene epoch and the generation of topographical elevations. In *Biodiversity: The Richness of Bolivia: State of Knowledge and Conservation*, ed. P.L. Ibisch and G. Mérida, 10-12. Ministry of Sustainable Development, Santa Cruz, Bolivia: Editorial Fan.

Rafiqpoor, D., C. Nowicki, R. Villarpando, H. Sommer, A. Jarvis, P. Jones, and P.L. Ibisch. 2004. Climate: the abiotic factor that most influences the distribution of biodiversity. In *Biodiversity: The Richness of Bolivia: State of Knowledge and Conservation*, ed. P.L. Ibisch and G. Mérida, 31-44. Ministry of Sustainable Development, Santa Cruz, Bolivia: Editorial Fan.

Ramankutty, N. and J.A. Foley. 1999. Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochemical Cycles* 13 (4), 997-1027.

Ramankutty, N., L. Graumlich, F. Achard, D. Alves, A. Chhabra, R.S. DeFries, J.A. Foley, H. Geist, R.A. Houghton, K. Klein Goldewijk, E.F. Lambin, A.C. Millington, K. Rasmussen, R.S. Reid, and B.L. Turner II. 2006. Global land-cover change: Recent progress, remaining challenges. In *Land-Use and Land-Cover Change: Local Processes and Global Impacts*, ed. E.F. Lambin and H.J. Geist, 9-39. Berlin, Germany: Springer-Verlag.

Rasmussen, K., B. Fog, and J.E. Madsen. 2001. Desertification in reverse? Observations from northern Burkina Faso. *Global Environmental Change* 11: 271-282.

Redekop, C. 1971. Church history and the contrasystem: a case study. *Church History* 40 (1): 57-68.

Redo, D. 2005. Forest cover change in the highlands of Intibucá and La Paz, Honduras, at different spatial scales. Unpublished Master's Thesis, University of Southern Mississippi.

Redo, D., J.O. Bass and A.C. Millington. 2009. Forest dynamics and the importance of place in western Honduras. *Applied Geography* 29: 92-111.

Redo, D. and A.C. Millington. 2010. Beyond Forest and Non-Forest: A Time-Series Analysis of Forest to Agriculture Transition in the Bolivian Seasonal Tropics. Unpublished.

Redo, D., A.C. Millington, and D. Hindery. 2010. Deforestation Dynamics and Policy Changes in Bolivia's post-Neoliberal Era. Unpublished.

Reed, D. 1992. *Structural Adjustment and the Environment*. Boulder, CO: Westview Press.

Reed, B.C., J.F. Brown, D. VanderZee, T.R. Loveland, J.W. Merchant and D.O. Ohlen. 1994. Measuring phenological variability from satellite imagery. *Journal of Vegetation Science* 5 (5): 703-714.

Ribera, M.O., M. Libermann, S. Beck and M. Moraes. 1994. *Mapa de la vegetación y áreas protegidea de Bolivia. 1:1,500,000*. La Paz and Santa Cruz, Bolivia: Centro de Investigaciones y Manejo de Recursos Naturales (CIMAR) and Universidad Autónoma Gabriel René Moreno (UAGRM).

Rindfuss, R.R., S.J. Walsh, B.L. Turner II, J. Fox, and V. Mishra. 2004. Developing a science of land change: challenges and methodological issues. *Proceedings from the National Academy of Sciences* 101 (39): 13976-13981.

Rindfuss, R.R., B. Entwisle, S.J. Walsh, L. An, N. Badenoch, D.G. Brown, P. Deadman, T.P. Evans, J. Fox, J. Geoghegan, M. Gutmann, M. Kelly, M. Linderman, J. Liu, G.P. Malanson, C.F. Mena, J.P. Messina, E.F. Moran, D.C. Parker, W. Parton, P. Prasartkul, D.T. Robinson, Y. Sawangdee, L.K. Vanwey and P.H. Verburg. 2008. Land use change: complexity and comparisons. *Journal of Land Use Science* 3 (1): 1-10.

Ringrose, S., C. Vanderpost, and W. Matheson. 1996. The use of integrated remotely sensed and GIS data to determine causes of vegetation cover change in southern Botswana. *Applied Geography* 16 (3): 225-242.

Ringrose, S., A.C. Chipanshi, W. Mateson, R. Chanda, L. Motoma, I. Magole, and A. Jellema. 2002. Climate- and human-induced woody vegetation changes in Botswana and their implications for human adaptation. *Environmental Management* 30 (1): 98-109.

Robbins, P. 2001. Fixed categories in a portable landscape: the causes and consequences of land-cover categorization. *Environment and Planning A* 33: 161-179.

Rogan, J. and D. Chen. 2004. Remote sensing technology for mapping and monitoring land-cover and land-use change. *Progress in Planning* 61: 301-325.

Rojas, F. 2004. Partnering for services in Santa Cruz. In *Leadership and Innovation in Subnational Government*, ed. T. Campbell, 259-294. Washington, D.C.: World Bank Publications.

Romecin, E. 1929. Agricultural adaption in Bolivia. *Geographical Review* 19 (2): 248-255.

Rudel, T.K. 2007. Changing agents of deforestation: from state-initiated to enterprise driven processes, 1970-2000. *Land Use Policy* 24: 35-41.

Rudolph, W.E. 1944. South America: the railroad from Corumbá to Santa Cruz. *Geographical Review* 34 (2): 329-330.

Rumiz, D. (Coordinator of Santa Cruz Wildlife Conservation Society). Personal Communication, 04 August 2007.

Sakamoto, T., M. Yokozawa, H. Toritani, M. Shibiyama, N. Ishitsuka and H. Ohno. 2005. A crop phenology detection method using time-series MODIS data. *Remote Sensing of the Environment* 96 (3-4): 366-374.

Sakamoto, T., C.V. Phung, A. Kotera, K.D. Nguyen and M. Yokozawa. 2009. Analysis of rapid expansion of inland agriculture and triple rice-cropping areas in a coastal area of the Vietnamese Mekong Delta using MODIS time-series imagery. *Landscape and Urban Planning* 92 (1): 34-46.

Sampaio, E.V.S.B. 1995. Overview of the Brazilian Caatinga. In *Seasonally dry tropical forests*, ed. S.H. Bullock, H.A. Mooney and E. Medina, 35-63. Cambridge, U.K.: Cambridge University Press.

Sanábria Fernández, H. 1958. En busca del dorado: la colonización del oriente boliviano por los cruceños. Santa Cruz, Bolivia.

Sánchez-Azofeifa, G.A., K.L. Castro, B. Rivard, and M.R. Kalascka. 2003. Remote sensing research priorities in tropical dry forest environments. *BioTropica* 35 (2): 134-142.

Sanderson, S. 1994. Political-economic institutions. In *Changes in Land-Use and Land-Cover: A Global Perspective*, ed. W. Meyer and B.L. Turner II, 329-355. Cambridge, U.K.: Cambridge University Press.

Sanjines, D. 2005. *La aplicación del proceso de reforma agraria en las tierras bajas de Bolivia*. Agro Nuevo 7, July 2005.

Schimel, D.S. 2010. Drylands in the Earth system. *Science* 327 (5964): 418-419.

SERNAP (Servicio Nacional de Áreas Protegidas). 2000. *Información técnica del Sistema Nacional de Áreas Protegidas de Bolivia*. Ministerio de Desarrollo Sostenible Planificación.

Skole, D.L. and C. Tucker. 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978-1988. *Science* 260 (5116): 1905-1910.

Snader, K. 2005. Characteristics of effective Mennonite Central Committee Development volunteers in Bolivia. Unpublished Master's Thesis, The University of Guelph.

SNAP (Servicio Nacional de Áreas Protegidas). 2001. Plan de Manejo Parque Nacional y Área Natural de Manejo Integrado Kaa-Iya del Gran Chaco. Santa Cruz, Bolivia: SNAP.

Sorrensen, C. 2009. Potential hazards of land use policy: conservation, rural development and fire use in the Brazilian Amazon. *Land Use Policy* 26: 782-791.

Southworth, J., H. Nagendra, L.A. Carlson, and C. Tucker. 2004. Assessing the impact of Celaque National Park on forest fragmentation in western Honduras. *Applied Geography* 24: 303-322.

Spichiger, R. and L. Ramella. 1989. The forests of the Paraguayan Chaco. In *Tropical Forests: Botanical Dynamics, Speciation and Diversity*, ed. L.B. Holm-Nielson, I.C. Neilson, and H. Balsev, 259-270. London, U.K.: Academic Press, Harcourt Brace Jovanovich.

Stearman, A.M.L. 1976. The highland migrant in lowland Bolivia: regional migration and the department of Santa Cruz. Unpublished Dissertation, The University of Florida.

Steininger, M.K., C.J. Tucker, J.R.G. Townshend, T.J. Killeen, A. Desch, V. Bell, and P. Ersts. 2001a. Tropical deforestation in the Bolivian Amazon. *Environmental Conservation* 28 (2): 127-134.

Steininger, M.K., C.J. Tucker, P. Ersts, T.J. Killeen, Z. Villegas, and S.B. Hecht. 2001b. Clearance and fragmentation of tropical deciduous forest in the Tierras Bajas, Santa Cruz, Bolivia. *Conservation Biology* 15 (4): 856-866.

Stibig, H.J., F. Achard, and S. Fritz. 2004. A new forest cover map of continental southeast Asia derived from SPOT-VEGETATION satellite imagery. *Applied Vegetation Science* 7 (2): 153-162.

Stiglitz, J.E. 2002. *Globalization and Its Discontents*. New York, N.Y.: W.W. Norton and Company.

Stone, T.A., I.F. Brown, and G.M. Woodwell. 1991. Estimation, by remote sensing, of deforestation in central Rondônia, Brazil. *Forest Ecology and Management* 38: 291-304.

Storie, R.E. 1973. Preliminary study of Bolivian soils. *Soil Science Society of America Journal* 17: 128-131.

Sunderland, R. 2002. Indigenous people and conservation in the Bolivian Chaco. Unpublished Master's Thesis, The University of Wisconsin – Madison.

Swarts, F.A. 2000. *The Pantanal: Understanding and Preserving the World's Largest Wetland*, ed. F.A. Swarts. St. Paul, MN: Paragon House.

Sydenstricker-Neto, J., A.W. Parmenter, and S.D. DeGloria. 2000. Participatory reference data collection methods for accuracy assessment of land-cover change maps. In *Remote Sensing and GIS Accuracy Assessment*, ed. R.S. Lunetta and J.G. Lyon, 75-90. Boca Raton, FL: CRC Press.

Taber, A., G. Navarro and M.A. Arribas. 1997. A new park in the Bolivian Gran Chaco – an advance in tropical dry forest conservation and community-based management. *Oryx* 31: 189-198.

Tappan, G.G., A. Hadj, E.C. Wood and R.W. Lietzow. 2000. Use of Argon, Corona, and Landsat imagery to assess 30 years of land resource changes in West-Central Senegal. *Photogrammetric Engineering and Remote Sensing* 66: 727-735.

The New York Times. 1995 (January 5). New Highways Open a Rich Bolivian Region, pg. NA. New York, NY: The New York Times.

Thiele, G. 1995. The displacement of peasant settlers in the Amazon: the case of Santa Cruz, Bolivia. *Human Organization* 54 (3): 273-282.

Tigner, J.L. 1982. Review: Japanese settlement in eastern Bolivia and Brazil. *Journal of Interamerican Studies and World Affairs* 24 (4): 496-517.

Tucker, C.J., B.N. Holben, and T.E. Goff. 1984b. Intensive forest clearing in Rondônia, Brazil, as detected by satellite remote sensing. *Remote Sensing of Environment* 15: 255-261.

Tucker, C.J., J.R.G. Townshend, and T.E. Goff. 1985. African land-cover classification using satellite data. *Science* 227 (4685): 369-375.

Tucker, C.J. and J.R.G. Townshend. 2000. Strategies for monitoring tropical deforestation using satellite data. *International Journal of Remote Sensing* 21 (6&7): 1461-1471.

Tucker, C.J., J.E. Pinzon, and M.E. Brown. 2004. Global Inventory Modeling and Mapping Studies (GIMMS) satellite drift corrected and NOAA-16 incorporated Normalized Difference Vegetation Index (NDVI), Monthly 1981-2003. University of Maryland.

Tucker, C.J. and E. Ostrom. 2005. Multidisciplinary research relating to institutions and forest transformations. In *Seeing the Forest and the Trees: Human-Environment Interactions in Forest Ecosystems*, ed. E.F. Moran and E. Ostrom, 81-103. Cambridge, MA: MIT Press.

Tucker, C.M. 1999. Private versus common property forests: forest conditions and tenure in a Honduran community. *Human Ecology* 27 (2): 201–230.

Turner, B.L. II, D. Skole, S. Sanderson, G. Fischer, L. Fresco, and R. Leemans. 1995. Land-Use and Land-Cover Change; Science/Research Plan. IGBP Report No. 35, HDP Report No. 7. Stockholm, Sweden and Geneva, Switzerland: IGBP and HDP.

Turner, B.L. II, S.C. Villar, D. Foster, J. Goeghegan, E. Keys, P. Klepeis, D. Lawrence, P.M. Mendoza, S. Manson, Y. Ogneva-Himmelberger, A.B. Plotkin, D.P. Salicrup, R.R. Chowdhury, B. Savitsky, L. Schneider, B. Scmook, and C. Vance. 2001. Deforestation in the southern Yucatán peninsular region: an integrative approach. *Forest Ecology and Management* 154: 353-370.

USDA (United States Department of Agriculture). 2005. *Foreign Agricultural Service Commodity Intelligence Report, Bolivia: Agricultural Overview*. http://www.fas.usda.gov/pecad/highlights/2005/10/bolivia_12oct2005/, (last accessed 09 June 2008).

USDA (United States Department of Agriculture). 2008a. *Foreign Agricultural Service Commodity Intelligence Report, World Agricultural Production*. http://www.fas.usda.gov/wap/circular/2008/08-03/productionfull03-08.pdf, (last accessed 09 June 2008).

USDA (United States Department of Agriculture). 2008b. Foreign Agricultural Service, Oilseeds: World Markets and Trade. http://www.fas.usda.gov/oilseeds/circular/2008/May/oilseed.pdf, (last accessed 09 June 2008).

Vadjunec, J., L. Schneider, and B.L. Turner II. 2002. Land change science: the contributions of Latin Americanist geographers to global environmental change and sustainability research. In *Latin America in the 21st Century: Challenges and Solutions*, ed. G. Knapp, 171-205. Austin, TX: University of Texas Press.

Van Giles, H.A.M.J. and A.V.L. Armand Ugon. 2006. What drives conversion of tropical forest in Carrasco Province, Bolivia? *Ambio* 35(2): 81-85.

Van Schaick, A. 2009 (28 April). Landowners' rebellion: slavery and *saneamiento* in Bolivia. Upside Down World. Online: http://upsidedownworld.org/main/.

Vargas Ríos, M.T. and K. Hamerschlag. 2001. The Santa Cruz – Puerto Suárez transportation project. Bank Information Center, http://www.bicusa.org/en/Article.1318.aspx, (last accessed 27 May 2008).

Vides-Almonacid, R., S. Reichle and F. Padilla. 2007. Planificación Ecorregional del Bosque Seco Chiquitano. Santa Cruz, Bolivia: FCBC and The Nature Conservancy.

Viña, A. and J. Cavelier. 1999. Deforestation rates (1938-1988) of tropical lowland forests on the Andean foothills of Colombia. *Biotropica* 31 (1): 31-36.

Viña, A., F.R. Echavarria, and D.C. Rundquist. 2004. Satellite change detection analysis of deforestation rates and patterns along the Colombia – Ecuador border. *Ambio* 33 (3): 118-125.

Walker, R., E.F. Moran, and L. Anselin. 2000. Deforestation and cattle ranching in the Brazilian Amazon: external capital and household processes. *World Development* 28 (4): 683-699.

Walker, R.T. 2003. Mapping Process to Pattern in the Landscape Change of the Amazonian Frontier. *Annals of the Association of American Geographers* 93(2): 376-398.

Walker, R. 2004. Theorizing land-cover and land-use change: the case of tropical deforestation. *International Regional Science Review* 27 (3): 247-270.

Wardlow, B.D. 2005. An evaluation of time-series MODIS 250-meter vegetation index data for crop mapping in the U.S. Central Great Plains. Unpublished Dissertation, University of Kansas, Lawrence, KS.

Wardlow, B.D. 2006. Using USDA crop progress data for the greenup onset date calculated from MODIS 250-meter data. *Photogrammetric Engineering and Remote Sensing* 72 (11): 1225-1234.

Wardlow, B.D. 2007. Analyzing of time-series MODIS 250 m vegetation index data for crop classification in the U.S. Central Great Plains. *Remote Sensing of Environment* 108: 290-310.

Wassenaar, T., P. Gerber, P.H. Verburg, M. Rosales, M. Ibrahim, and H. Steinfeld. 2007. Projecting land use changes in the Neotropics: the geography of pasture expansion into forest. *Global Environmental Change* 17: 86-104.

Weeks, D. 1946. Bolivia's agricultural frontier. *Geographical Review* 36 (4): 546-567.

WEF (World Economic Forum). 2008. *Global Competiveness Report, 2007-2008*. Geneva, Switzerland: World Economic Forum.

Wessels, K.J., R.S. DeFries, J. Dempewolf, L.O. Anderson, A.J. Hansen, S.L. Powell, and E.F. Moran. 2004. Mapping regional land cover with MODIS data for biological conservation: examples from the Greater Yellowstone Ecosystem, USA and Pará State, Brazil. *Remote Sensing of Environment* 92: 67-83.

Williams, R.G. 1986. *Export Agriculture and the Crisis in Central America*. Chapel Hill, NC: The University of North Carolina Press.

Wilson, G.A. 2001. Productivism and to post-productivism…and back again? Exploring the (un)changed natural and mental landscapes of European agriculture. *Transactions of the Institute of British Geographers* 26 (1): 77-102.

Winer, N. 2003. Co-management of protected areas, the oil and gas industry and indigenous empowerment – the experience of Bolivia's Kaa-Iya del Gran Chaco. *Policy Matters* 12: 181-191.

Wolfe, R.E., M. Nishihama, A.J. Fleig, J.A. Kuyper, D.P. Roy, J.C. Storey, and F.S. Patt. 2002. Achieving sub-pixel geolocation accuracy in support of MODIS land science. *Remote Sensing of Environment* 83: 31-49.

World Bank. 1990. *Sustainable Development, Issues in Adjustment Lending Policies. Divisional Paper No. 1989-6*. Washington, D.C.: Environment Department, Policy and Research Division.

World Bank. 1993 . *Natural Resource Management in Bolivia: 30 Years of Experience*. Washington, D.C.: Operations Evaluation Department.

World Bank. 2001. *Bolivia-National Land Administration Project (Project BOPE6197).* Report No. PID541. Washington, D.C.: Field Office La Paz, World Bank.

WWF World Wildlife Fund. 2009a. *Chaco* (NT0210). http://www.worldwildlife.org/wildworld/profiles/terrestrial/nt/nt0210_full.html, (last accessed 22 September 2009).

WWF – World Wildlife Fund. 2009b. *Chiquitano dry forests* (NT0212). http://www.worldwildlife.org/wildworld/profiles/terrestrial/nt/nt0212_full.html, (last accessed 22 September 2009).

Xiao, X., S. Boles, J.Y. Liu, D.F. Zhuang, S. Frokling, C. Li, W. Salas and B. Moore III. 2005. Mapping paddy rice agriculture in southern China using multi-temporal MODIS images. *Remote Sensing of Environment* 95 (4): 480-492.

Xiao, X., S. Boles, S. Frokling, C. Li, J.Y. Babu, W. Salas and B. Moore III. 2006. Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images. *Remote Sensing of Environment* 100 (1): 95-113.

Zabala, R. (President of ANAPO). Personal Communication, 01 June 2009.

Zak, M.R., M. Cabido, and J.G. Hodgson. 2004a. Do subtropical seasonal forests in the Gran Chaco, Argentina, have a future? *Biological Conservation* 120: 589-598.

Zak, M.R., M. Cabido, D. Cáceres and S. Díaz. 2004b. What drives accelerated land cover change in central Argentina? Synergistic consequences of climatic, socioeconomic, and technological factors. *Environmental Management* 42: 181-189.

Zhan, X., R.A. Solhberg, J.R.G. Townshend, C. DiMiceli, M.L. Carroll, J.C. Eastman, M.C. Hansen, and R.S. DeFries. 2002. Detection of land cover changes using MODIS 250 m data. *Remote Sensing of Environment* 83: 336-350.

Zhou, G. and K.C. Jezek. 2002. Satellite photographs mosaics of Greenland from the 1960s era. *International Journal Remote Sensing* 23: 1143-1159.f

APPENDIX A

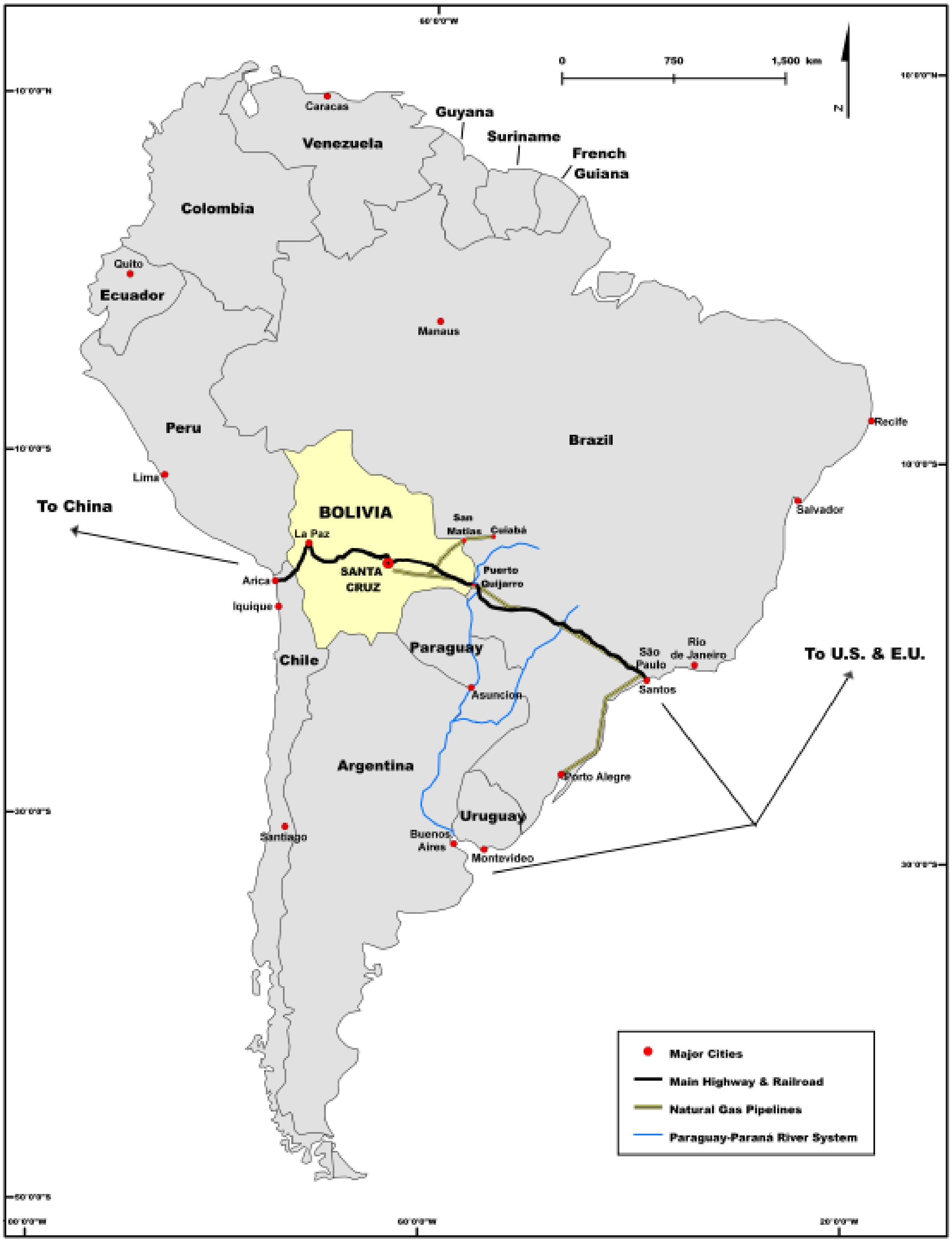


Figure 1. Map of South America showing the Corredor Bioceánico. Arrows denote export routes from Arica, Chile to China and the Rio Paraguay and Santos, Brazil, to MERCOSUR countries, the United States and the European Union.

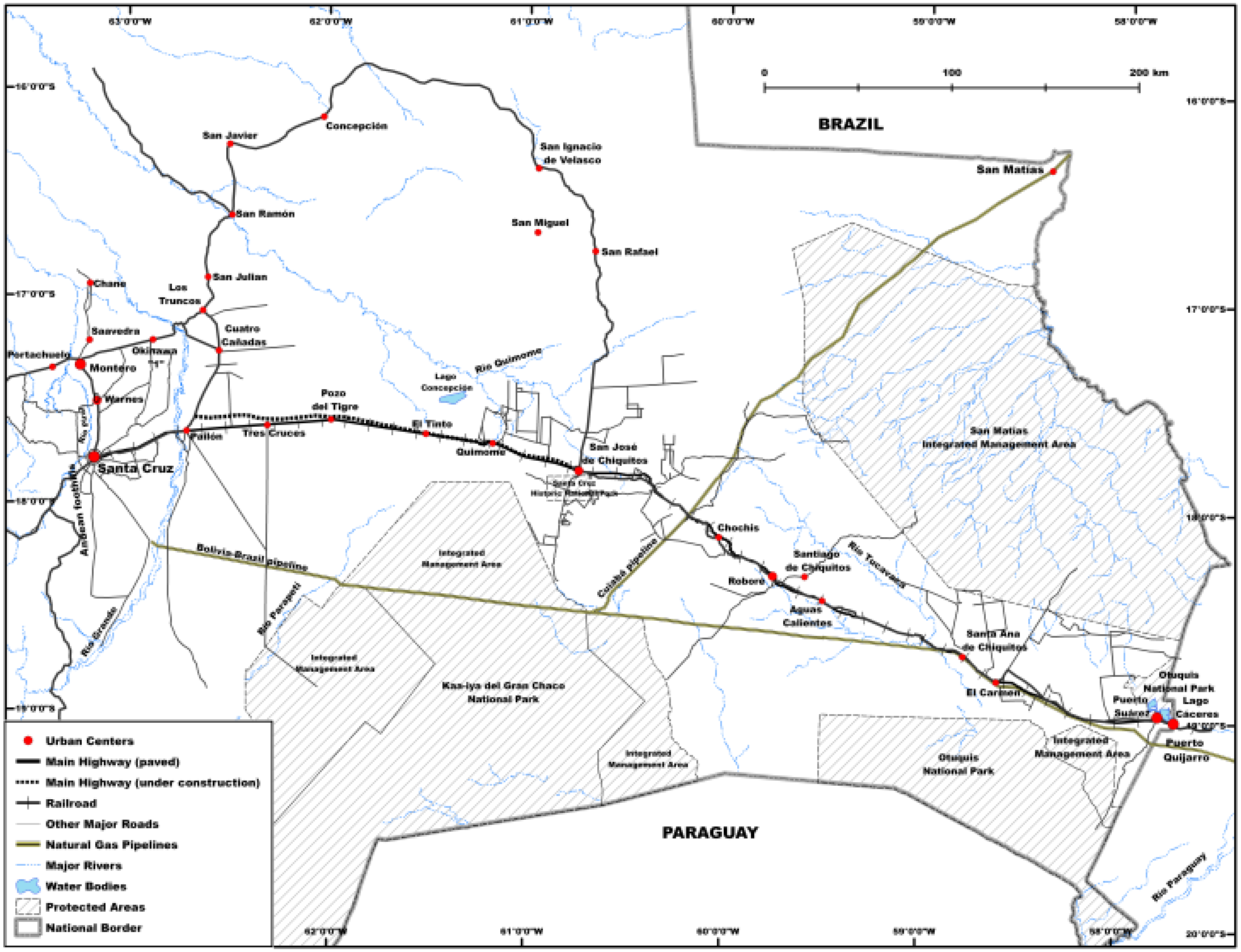


Figure 2. Location map of Santa Cruz Department in southeastern Bolivia.

Table 1

Comparison of peer-reviewed LCLU change studies.

Author(s)	***Time Period***	***Area (km^2)***	***Sensors***	***Classes†***	***Forest Loss±***	
					Annual Rate	***Total (km^2)***
Davies 1993	1975-1991	15,659	Landsat MSS/TM	PF, SF, F, A, P	0.1-4.4%	2,605
Tucker & Townshend 2000	1992-1994	784,759	Landsat TM	F, NF	NA	28,208
Steininger et al. 2001a	1984-1994	700,000	Landsat MSS/TM	F, NF	0.8-1.2%	40,235
Steininger et al. 2001b	1975-1998	19,533	Landsat MSS/TM	F, NF, WA, C	0.4-4.6	9,400
Mertens et al. 2004	1989-1994	364,615	Landsat TM	F, NF	0.3%	5,117
Killeen et al. 2007	1976-2004	720,915	Landsat MSS-ETM+	F, S, G, WE, WA	0.5%	45,411
Killeen et al. 2008	1975-2004	729,024	Landsat MSS-ETM+	F, S, G, WE, WA	0.4%	46,183

†Classes:

PF = Primary Forest	NF = Non-Forest	S = Scrubland	WA = Water
SF = Secondary Forest	A = Agriculture	G = Grassland	C = Cloud
F = Forest	P = Pasture	WE = Wetland	NA = Not available

± Includes all forest classes

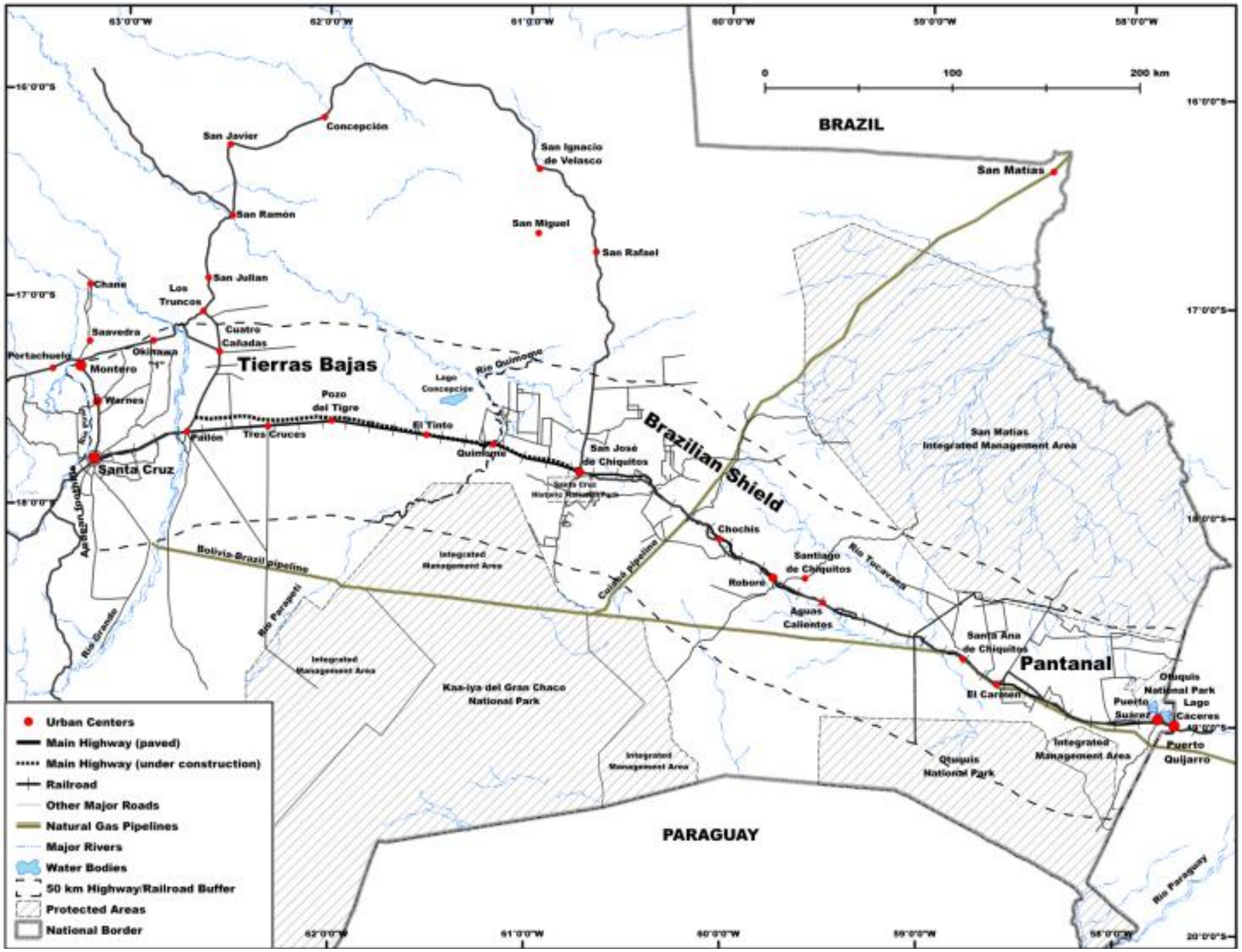


Figure 3. The Corredor Bioceánico of southeastern Bolivia. A 50-km buffer north and south of the main highway (dashed lines) has been used to demarcate the study area. Internal boundaries are defined by the Andean foothills and the Río Piraí to the west, Río Quimome and western ranges of the Brazilian Shield in the center and the Bolivia-Brazil border in the east (see text).

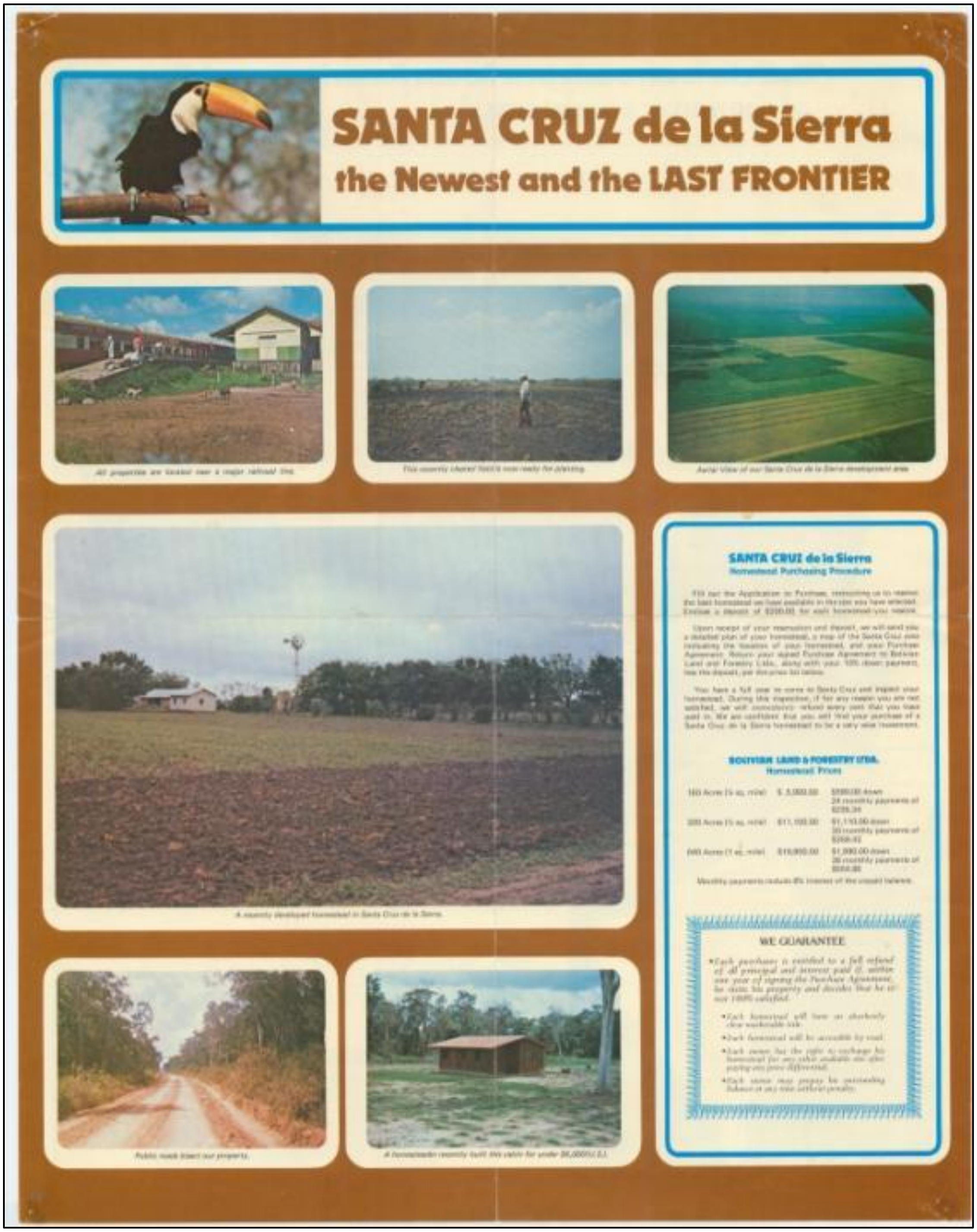


Figure 4. Promotion pamphlet (front side). Produced in the late 1970s, it advertises the Santa Cruz region as the "newest and last frontier." To obtain the desired acreage, the prospective buyer needed to fill out the application and send in a cash deposit. The new owner then had one full year to inspect the purchase (Pamphlet courtesy of Andrew Millington).

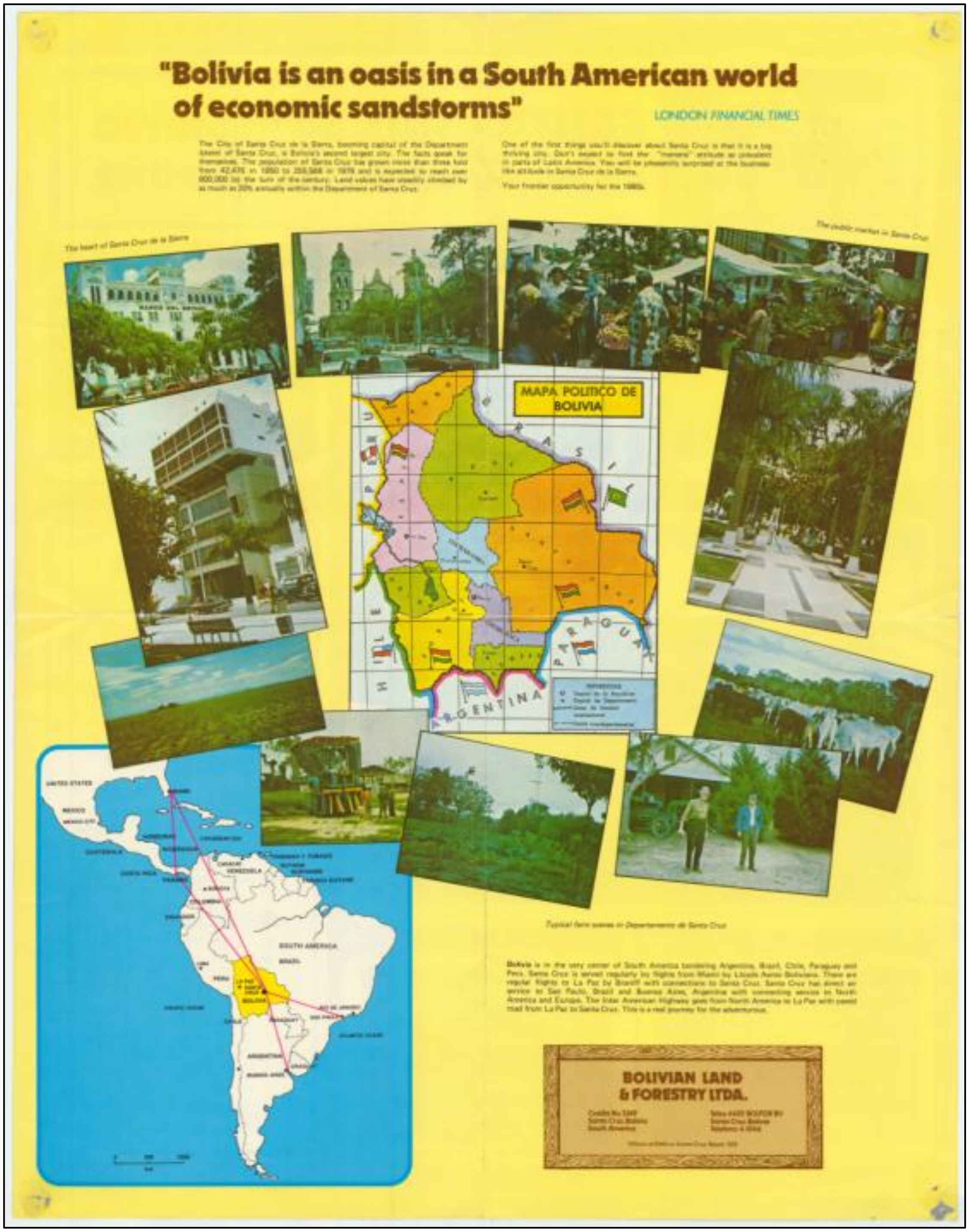


Figure 5. Promotion pamphlet (back side). Produced in the late 1970s, it advertises the city of Santa Cruz as progressive in terms of business attitude and with several national and international flight connections to South, Central, and North America (Pamphlet courtesy of Andrew Millington).

Figure 6. Aerial view of the town of Quimome. The city is located near the western extent of the Brazilian Shield (July 2008).

Figure 7. Chochis Tower. Rising several hundred meters from the otherwise level floor, the rock spire is located outside of the town of Chochis (July 2008). A popular tourist destination for those few who travel the Corredor Bioceánico, the tower is also famous for the fact that residents of the town climb its base once a year for religious purposes, recreation, and as a test of strength.

Figure 8. Lago Cáceres. The lake straddles the border between Bolivia and Brazil (July 2008).

Figure 9. Santa Cruz – Puerto Suarez highway in early stages of construction. This stretch is between Tres Cruces and Pozo del Tigre (August 2006).

Figure 10. Aerial view of the Río Grande. This photo is looking south at the new (top) and old (bottom) railroad bridges. The city of Pailón can be seen on the left-hand side (east) of the photograph (July 2008).

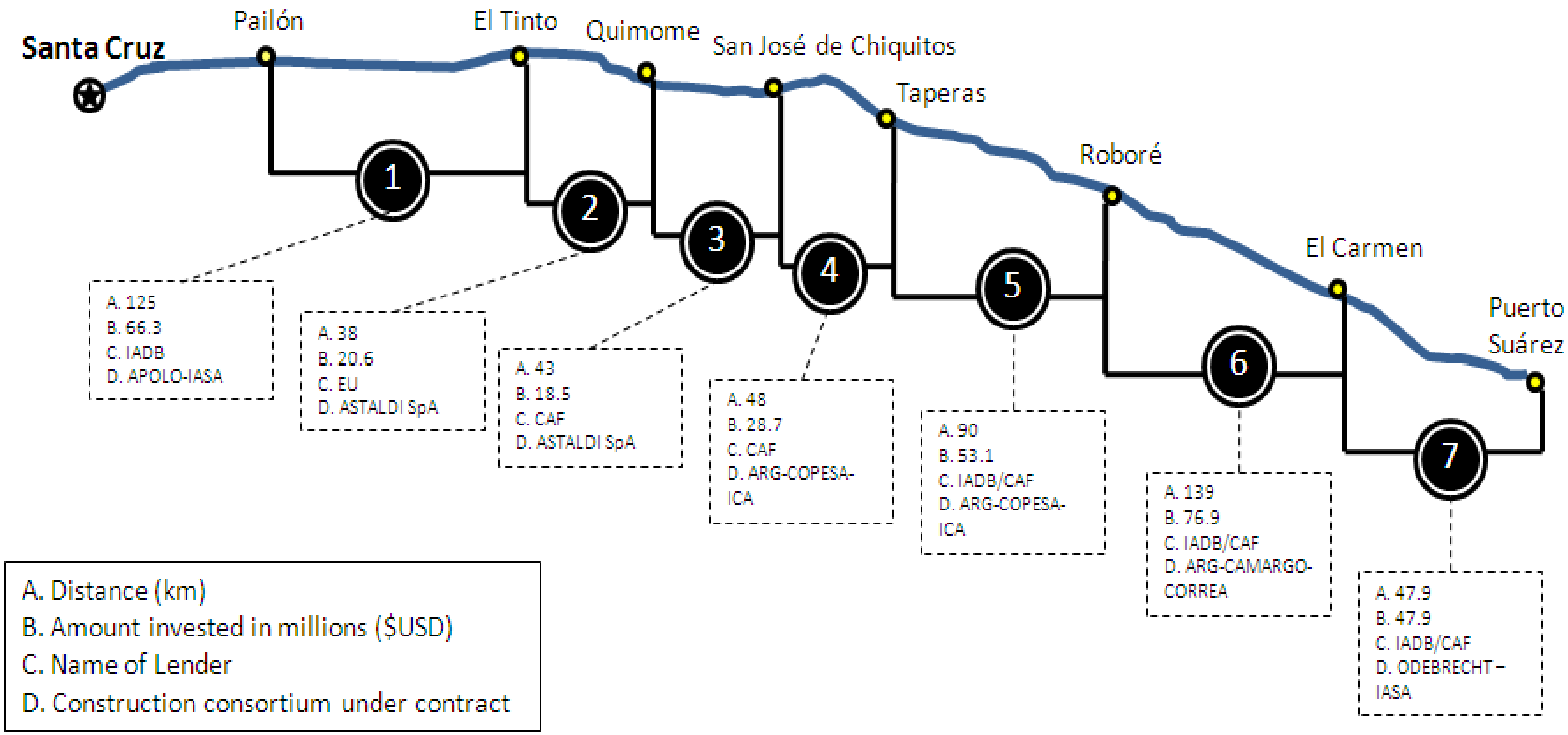


Figure 11. Construction plans along the Santa Cruz-Puerto Suárez highway. The highway is partitioned into seven sections according to distance (km), amount invested (millions of $USD), name of lender organization, and construction consortium under building contract.

Figure 12. New highway construction between El Tinto and Quimome (July 2008).

Figure 13. Challenges with constructing a bridge over the Rio Quimome (July 2008).

Figure 14. Portion of the Bolivia-Brazil pipeline in Santa Ana de Chiquitos (July 2008).

Figure 15. Portion of the Cuiabá pipeline buried underground (photos courtesy of D. Hindery, August 2008).

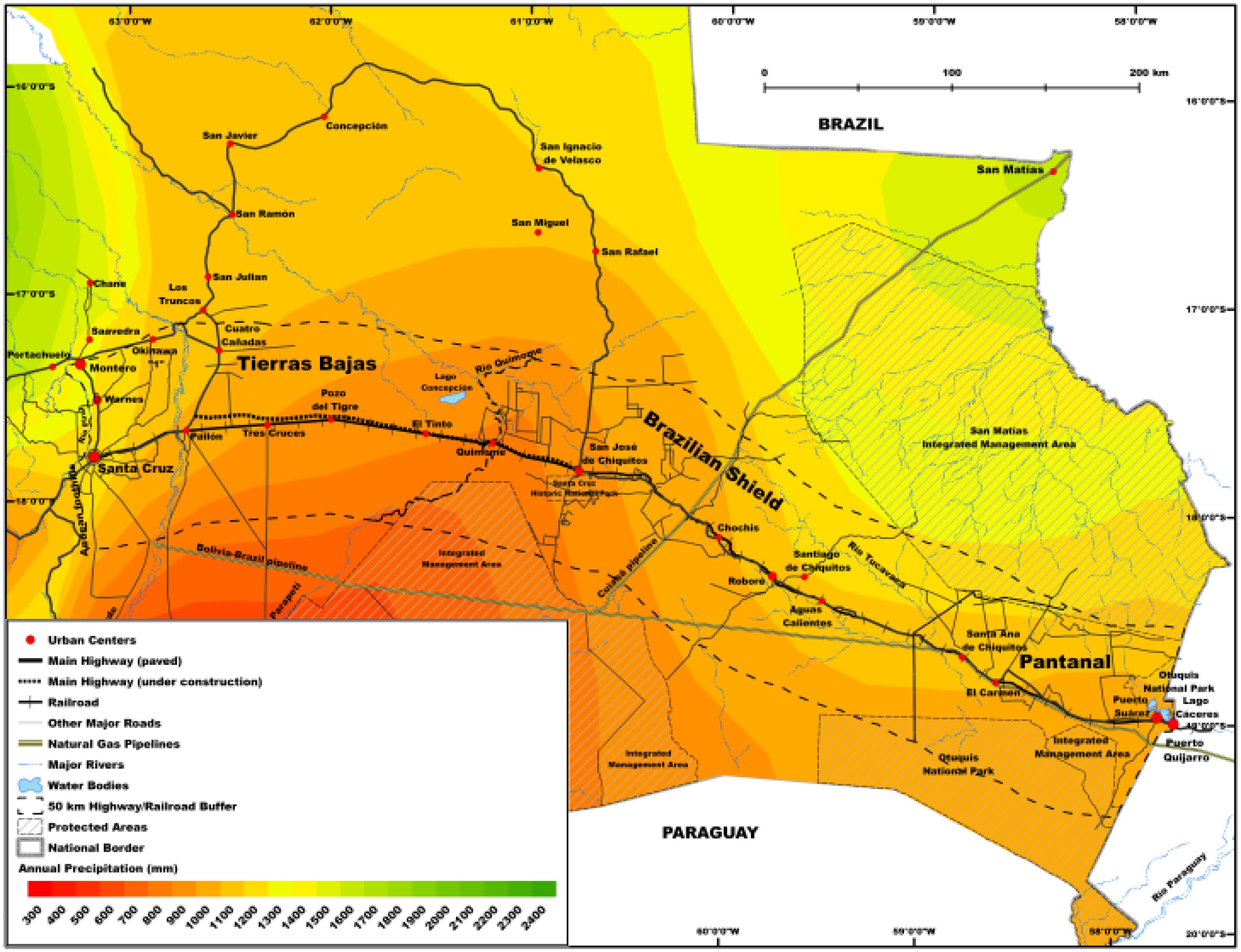


Figure 16. Annual precipitation for the Corredor Bioceánico (Adapted from PLUS 1995).

Figure 17. Example of windbreak agriculture near the town of El Tinto (July 2008).

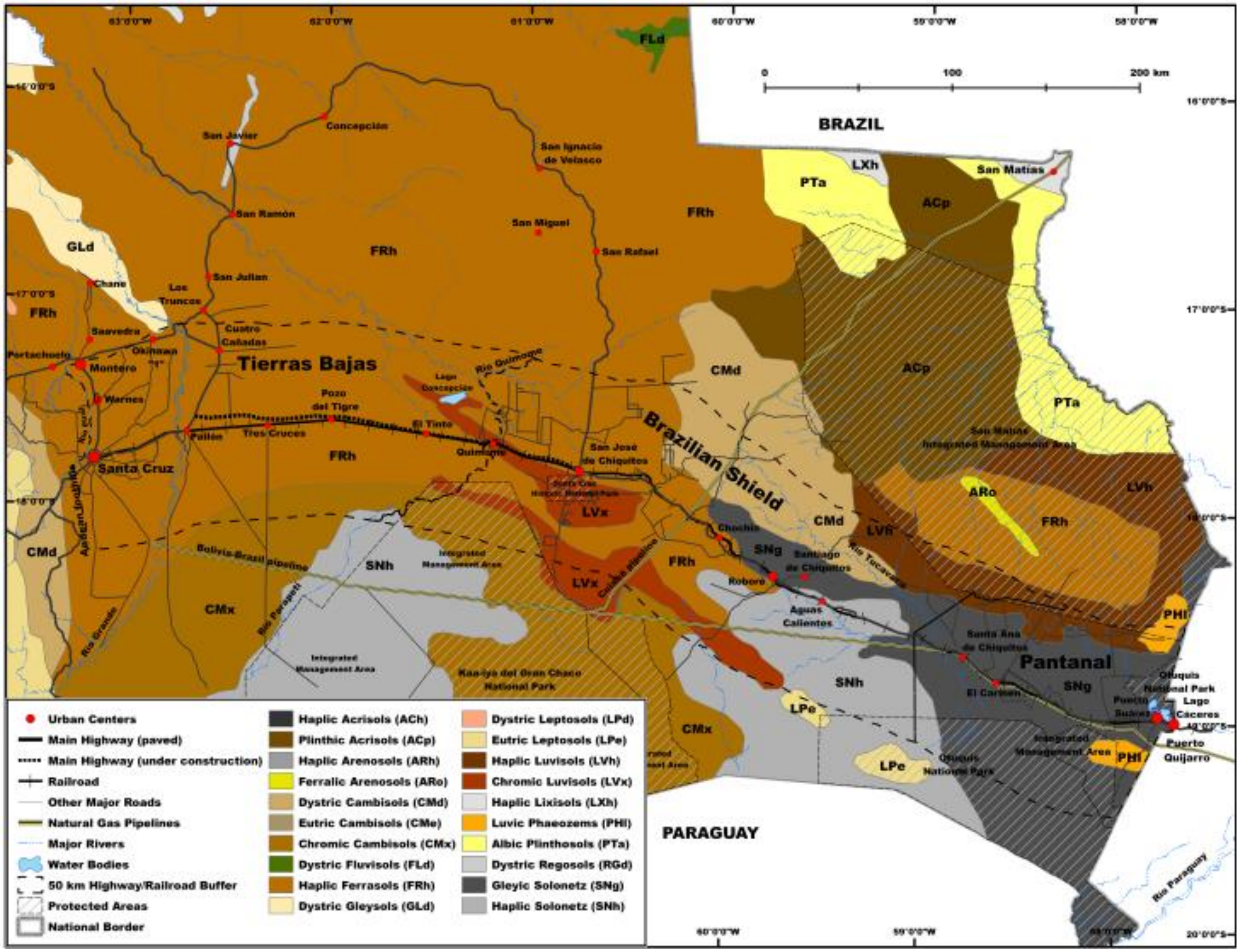


Figure 18. Soil types along the Corredor Bioceánico. This map uses the FAO Classification Scheme (Adapted from the Soil and Terrain Database for Latin America and the Caribbean [SOTERLAC], ISRIC 2005).

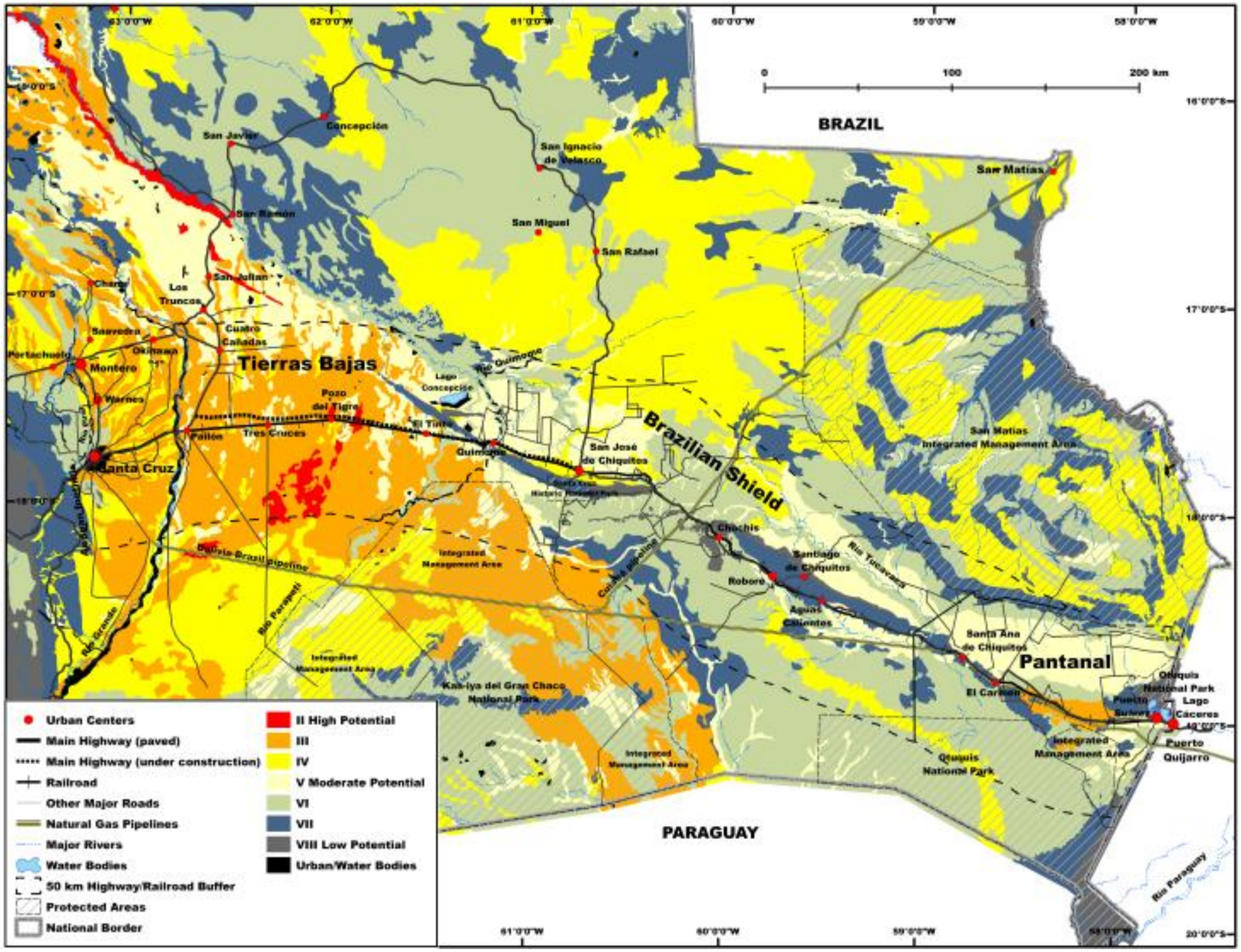


Figure 19. Land-use potential for agriculture (Adapted from PLUS 1996).

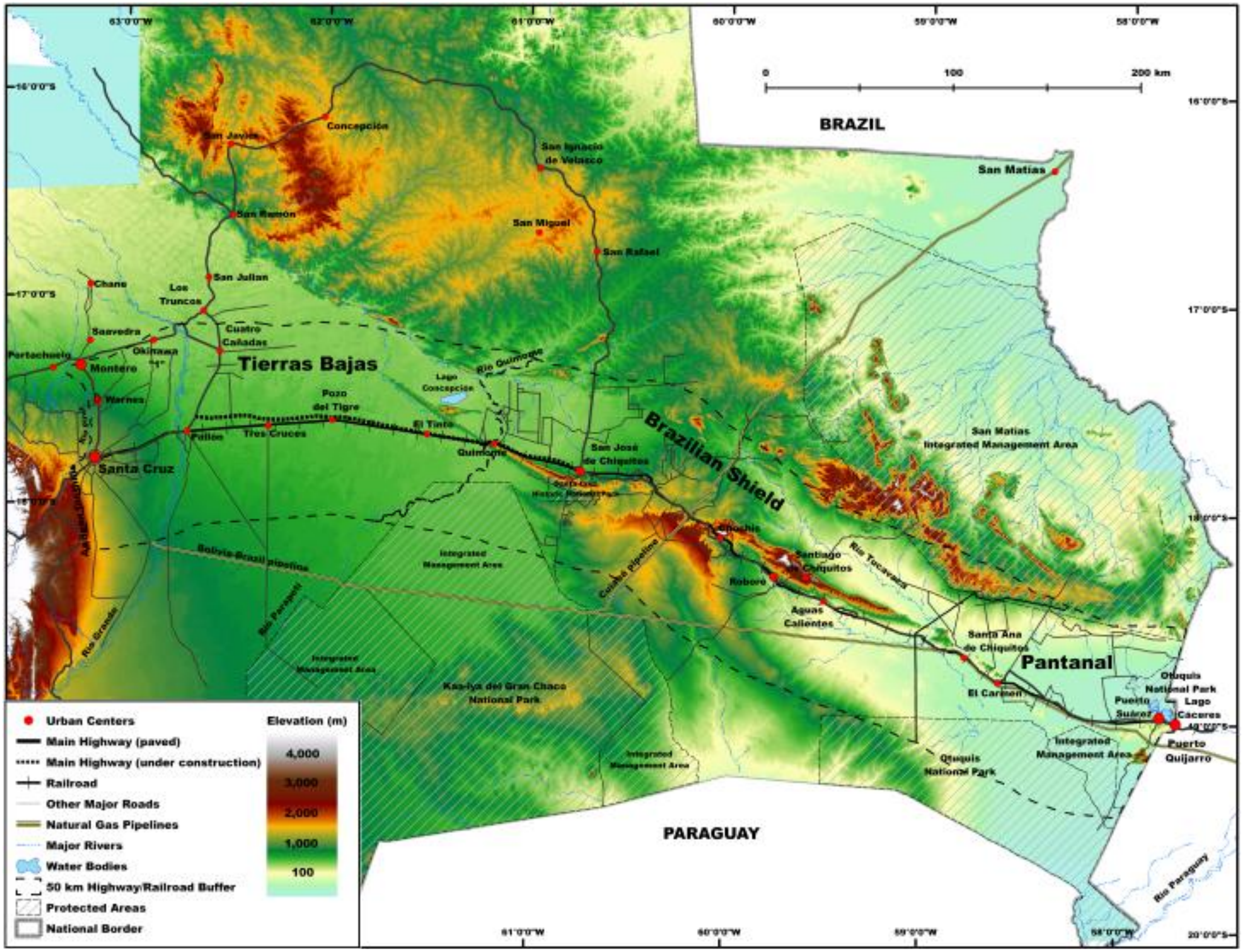


Figure 20. Elevation (Adapted from 90-meter SRTM data acquired from the Maryland Global Land-Cover Facility).

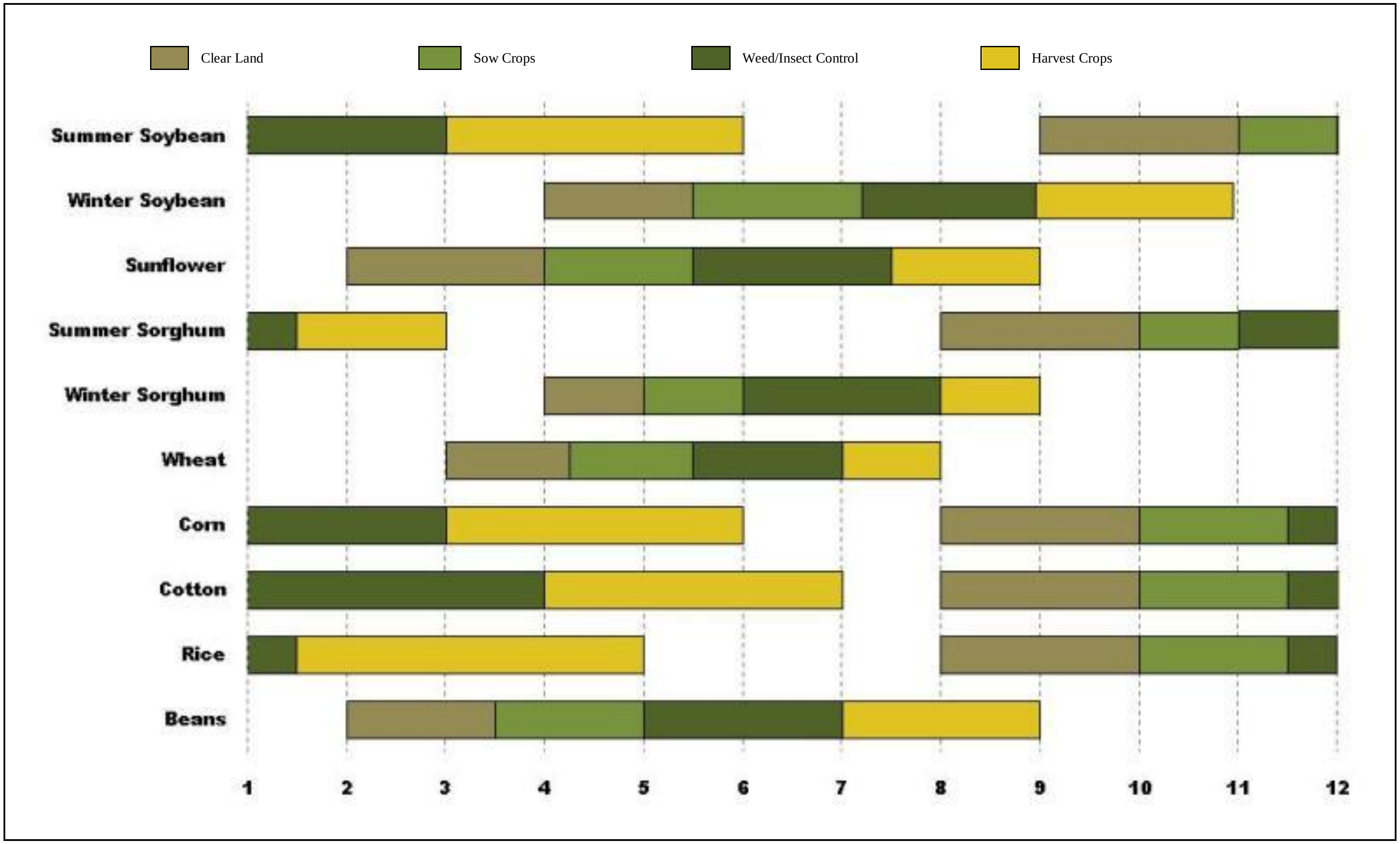


Figure 21. Crop calendar for the Department of Santa Cruz. This map illustrates the growing cycles of the main summer and winter crop types (in descending order of relative area).

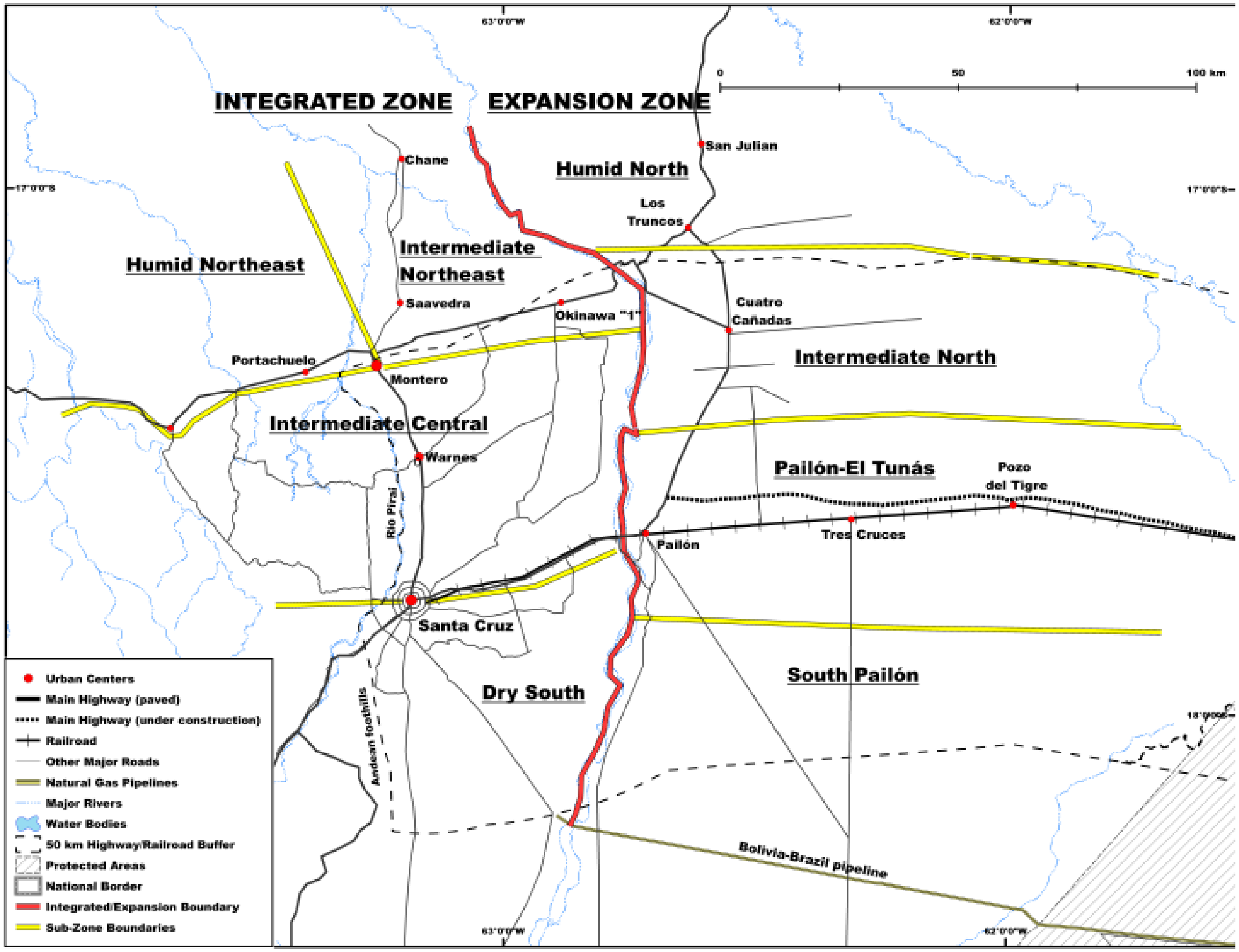


Figure 22. Agricultural zones of the Tierras Bajas. The region is divided into two distinct zones based on age with the Rio Grande as a convenient dividing line: (1) the western, older and wetter "integrated" zone and (2) the eastern, younger and drier "expansion" zone. Zones are further subdivided into sectors based on precipitation and geographic location (ANAPO 2007).

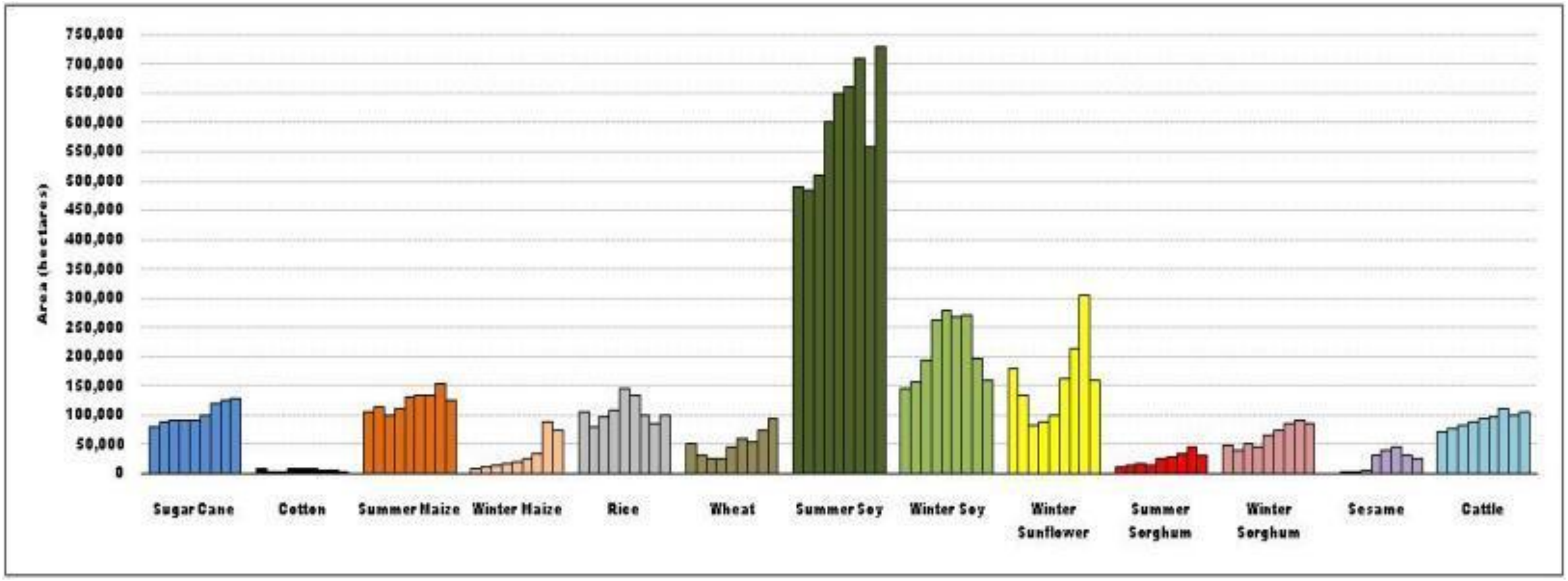


Figure 23. Bar graph showing the major commercial crop areas. Each bar for each crop type represents a year between 2000 and 2009 (ANAPO 2008; CAO 2008).

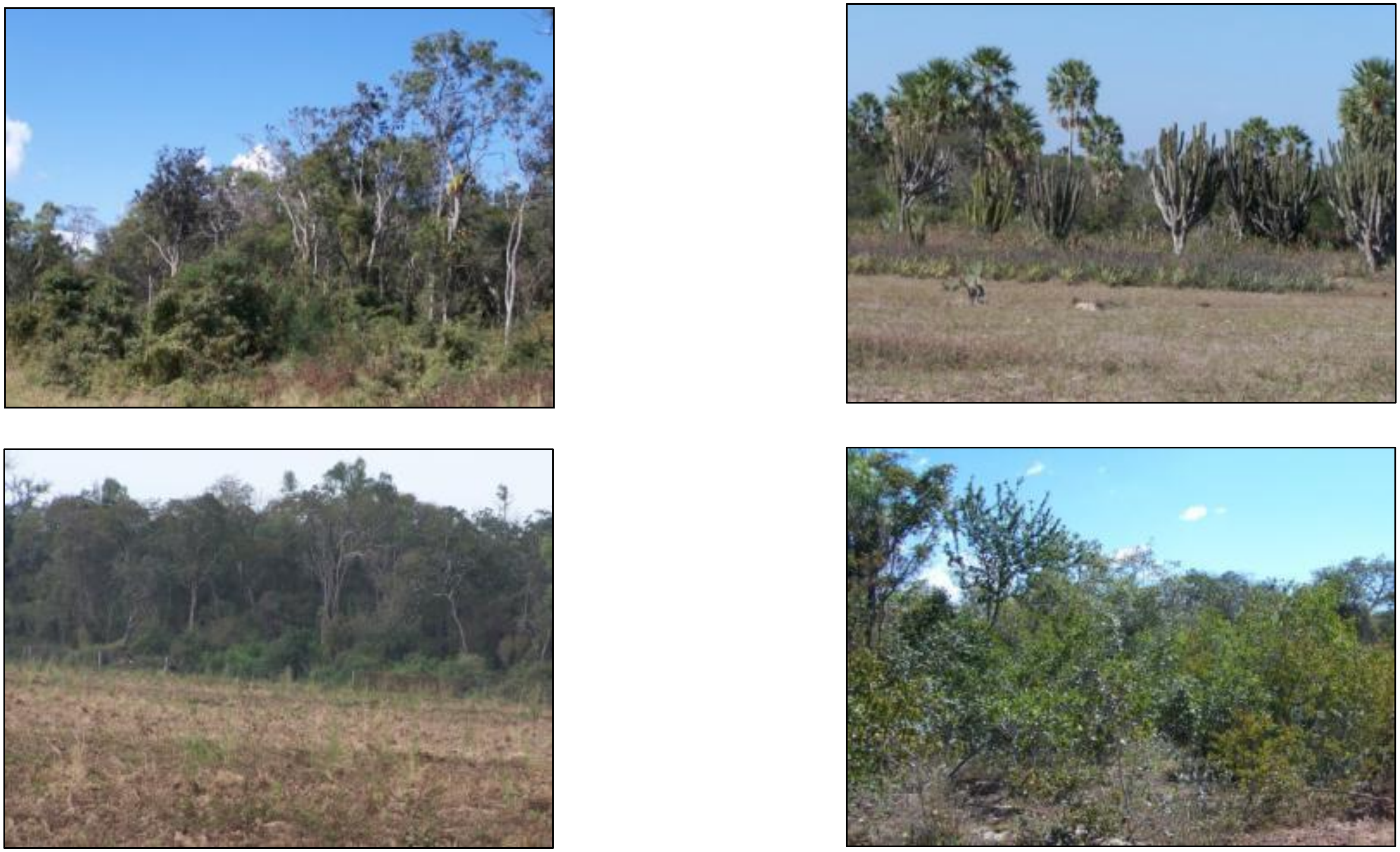


Figure 24. Examples of Chaco woodland. Top left photograph: Transitional Chaco forest north of Tres Cruces (July, 2008); Top right photograph: Flooded Chaco forest and savanna south of Pailón (August, 2007); Bottom left photograph: Chaco forest with Saó Palm south of Pailón (July, 2008); Bottom Right photograph: Chaparral woodland south of Quimome (August, 2007). Forest classifications are based on Navarro and Ferreira (2007).

Figure 25. Example of semi-deciduous, sub-humid Chiquitano forest. This photograph was taken north of San Jose de Chiquitos (July, 2008). Forest classification based on Navarro and Ferreira (2007).

Table 2
Characteristics of CBERS and SPOT sensors.

	CBERS-1, -2 and 2B				SPOT 1, 2 and 3 HRV		
Band	*Spectral Res.*	*Spatial Res. (CCD)*	*Spatial Res. (WFI)*	*Spatial Res. (IRMSS)*	*Band*	*Spectral Res.*	*Spatial Res.*
Blue	0.45-0.52 µm	20 x 20 m	--	--	Blue	--	--
Green	0.52-0.59 µm	20 x 20 m	260 x 260 km	--	Green	0.50-0.59 µm	20 x 20 m
Red	0.63-0.69 µm	20 x 20 m	--	--	Red	0.61-0.68 µm	20 x 20 m
NIR	0.77-0.89 µm	20 x 20 m	260 x 260 km	--	NIR	0.79-0.89 µm	20 x 20 m
PAN	0.51-0.73 µm	10 x 10 m	--	--	PAN	0.51-0.73 µm	10 x 10 m
PAN	0.50-1.10 µm	--	--	80 x 80m	--	--	--
MIR	1.55-1.75 µm	--	--	80 x 80m	--	--	--
MIR	2.08-2.35 µm	--	--	80 x 80m	--	--	--
TIR	10.4-12.5 µm	--	--	160 x 160 m	--	--	--
	Sensor	Linear Array	Linear Array	Linear Array		*Sensor*	Linear Array
	Swath	120 km	890 km	120 km		*Swath*	60 km
	Revisit	26 days	3-5 days	26 days		*Revisit*	26 days
	Orbit	Sun-synchro.	Sun-synchro.	Sun-synchro.		*Orbit*	Sun-synchro.
	Launch	Oct. 4, 1999 – Sept. 19, 2007	Oct. 4, 1999 – Sept. 19, 2007	Oct. 4, 1999 – Sept. 19, 2007		*Launch*	Feb. 21, 1986 – Sept. 26,1993
	Cost	Free	Free	Free		*Cost*	$1,200 USD

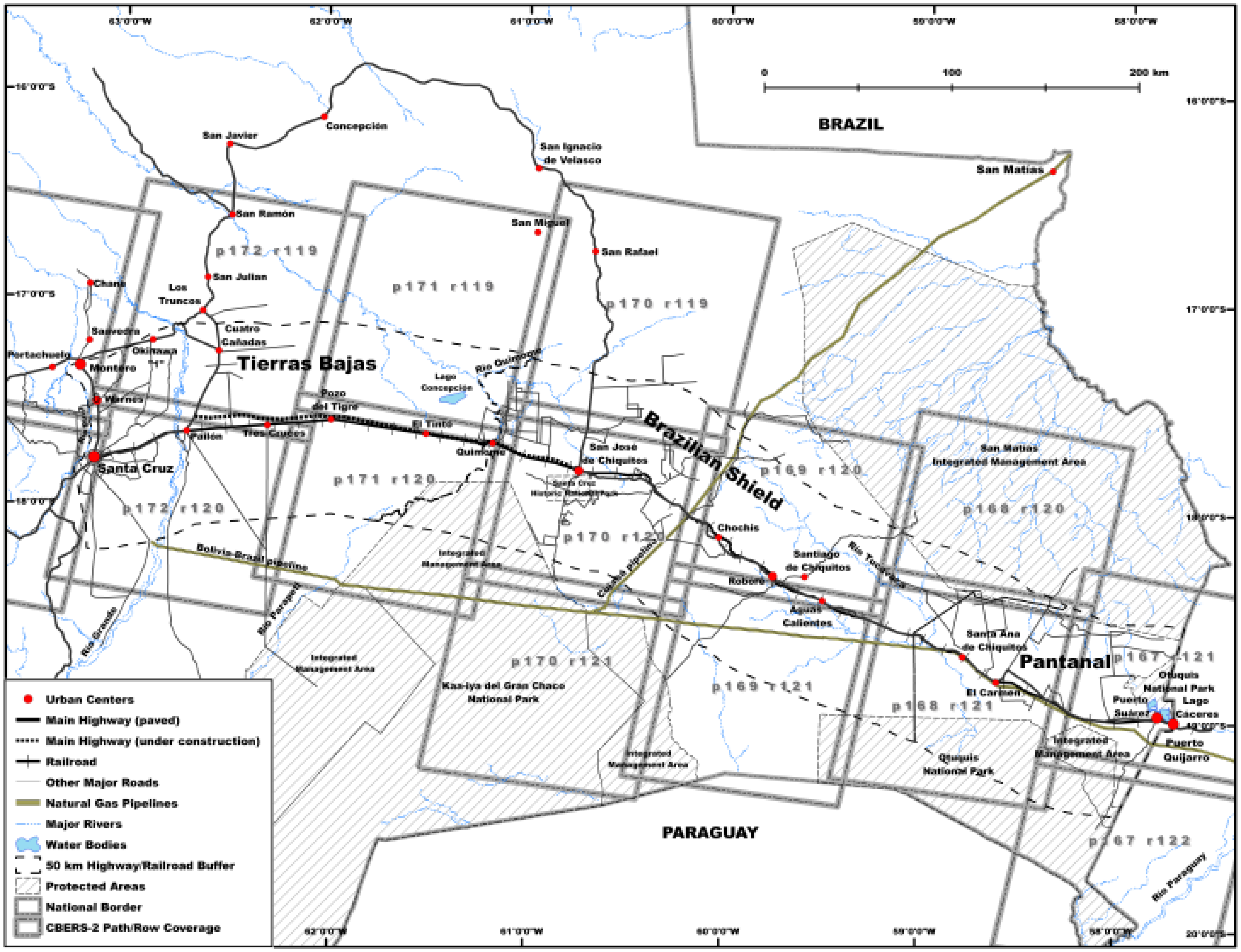


Figure 26. Location of 2005-08 CBERS-2 and -2B scenes.

Table 3

Description CBERS imagery used in classification.

Path/Row	*Dates*	*Location in Mosaic*	*Radiometrically Corrected*	*Distortion Removed*
173/119	20-Jul-06	Tierras Bajas	x	
	26-Aug-08		x	x
173/120	19-Jul-07	Tierras Bajas	x	x
	26-Aug-08		x	x
173/121	19-Jul-07	Tierras Bajas	x	
172/119	09-Oct-06	Tierras Bajas	x	
	20-Oct-08		x	
172/120	10-Oct-05		x	
	09-Oct-06		x	x
	31-May-07		x	x
	20-Oct-08		x	x
172/121	23-Jul-06	Tierras Bajas	x	x
171/119	29-Jun-07	Tierras Bajas & Brazilian Shield	x	
	27-Sep-08		x	x
171/120	17-Sep-05		x	
	30-Jun-06		x	
	29-Jun-07		x	x
	27-Sep-08	Tierras Bajas & Brazilian Shield	x	
170/119	06-Jun-07	Brazilian Shield	x	
	21-Nov-08		x	
170/120	30-Jul-05		x	x
	03-Jul-06		x	
	06-Jun-07		x	
	21-Nov-08	Brazilian Shield	x	x
170/121	02-Jul-07	Brazilian Shield	x	
	21-Nov-08		x	
169/120	09-Jun-07		x	x
	16-Jul-08	Brazilian Shield	x	x
169/121	09-Jun-07	Brazilian Shield	x	x
	16-Jul-08		x	
168/120	12-Jun-07	Brazilian Shield & Pantanal	x	x
	19-Jul-08		x	
168/121	05-Aug-05		x	x
	04-Aug-06		x	
	12-Jun-07		x	x
	19-Jul-08	Brazilian Shield & Pantanal	x	x
167/121	13-Jul-05		x	
	07-Aug-06		x	x
	15-Jun-07		x	
	18-Aug-08	Pantanal	x	
167/122	15-Jun-07	Pantanal	x	x
	18-Aug-08		x	x

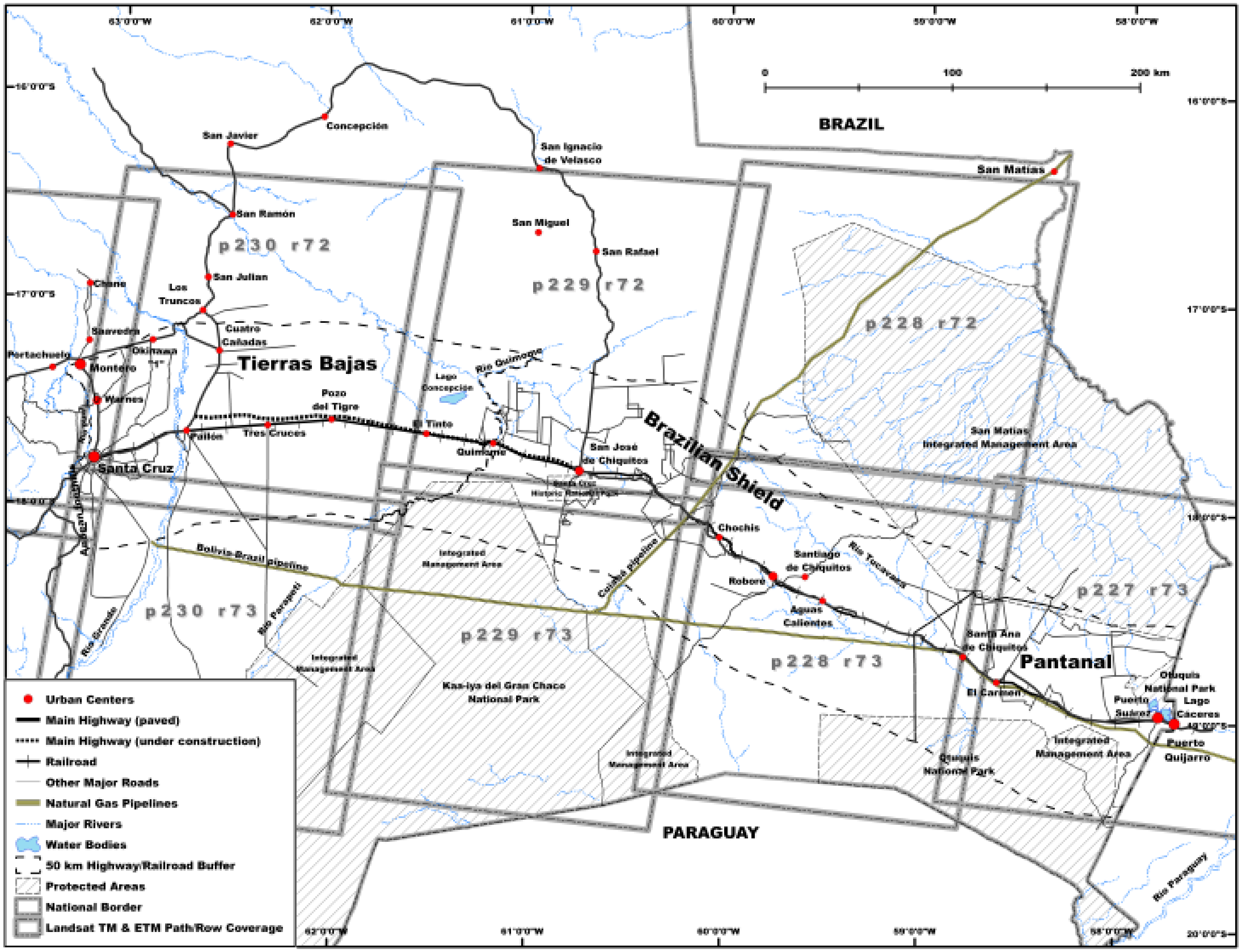


Figure 27. Location of 1986-89 Landsat TM and 2000-01 Landsat ETM+ scenes.

Table 4

Description of Landsat TM and ETM+ imagery used in classification.

Path/Row	***Dates***	***Location in Mosaic***	***Radiometrically Corrected***
227/73	10-May-89	Pantanal & Brazilian Shield	x
	17-Jun-94		x
	12-Jun-01		x
228/72	24-Oct-86	Brazilian Shield	x
	21-Jun-93		x
	07-Sep-01		x
228/73	24-Oct-86	Pantanal & Brazilian Shield	x
	21-Jun-93		x
	31-Mar-01		x
229/72	16-Jul-88	Tierras Bajas & Brazilian Shield	x
	17-Jul-94		x
	25-Jul-00		x
229/73	27-Jul-86	Brazilian Shield	x
	17-Jul-94		x
	25-Jul-00		x
230/72	26-May-87	Tierras Bajas	x
	19-Jun-93		x
	07-Dec-00		x
230/73	02-Jul-86	Tierras Bajas	x
	10-Jul-92		x
	01-Aug-00		x
231/72	25-Jul-86	Tierras Bajas	x
	09-Jul-92		x
	11-Aug-01		x
231/73	25-Jul-86	Tierras Bajas	x
	29-Aug-93		x
	11-Aug-01		x

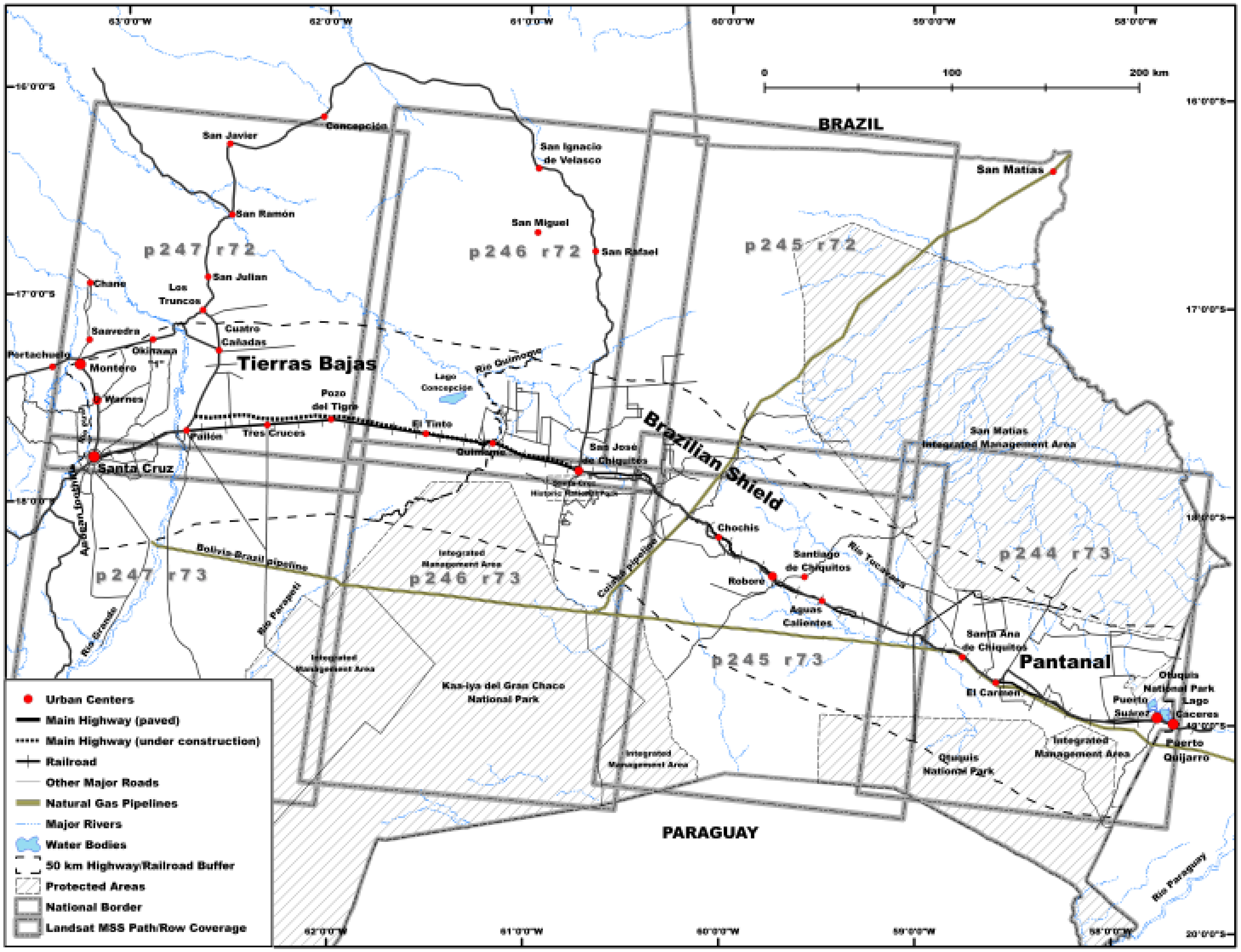


Figure 28. Location of 1975 Landsat MSS scenes.

Table 5
Description of Landsat MSS imagery used in classification.

Path/Row	*Dates*	*Location in Mosaic*	*Radiometrically Corrected*
244/73	27-May-75	Brazilian Shield & Pantanal	x
245/72	21-Jul-75	Brazilian Shield	x
245/73	21-Jul-75	Brazilian Shield	x
246/72	16-Jun-75	Tierras Bajas & Brazilian Shield	x
246/73	27-Aug-75	Tierras Bajas & Brazilian Shield	x
247/72	17-Jun-75	Tierras Bajas	x
247/73	17-Jun-75	Tierras Bajas	x

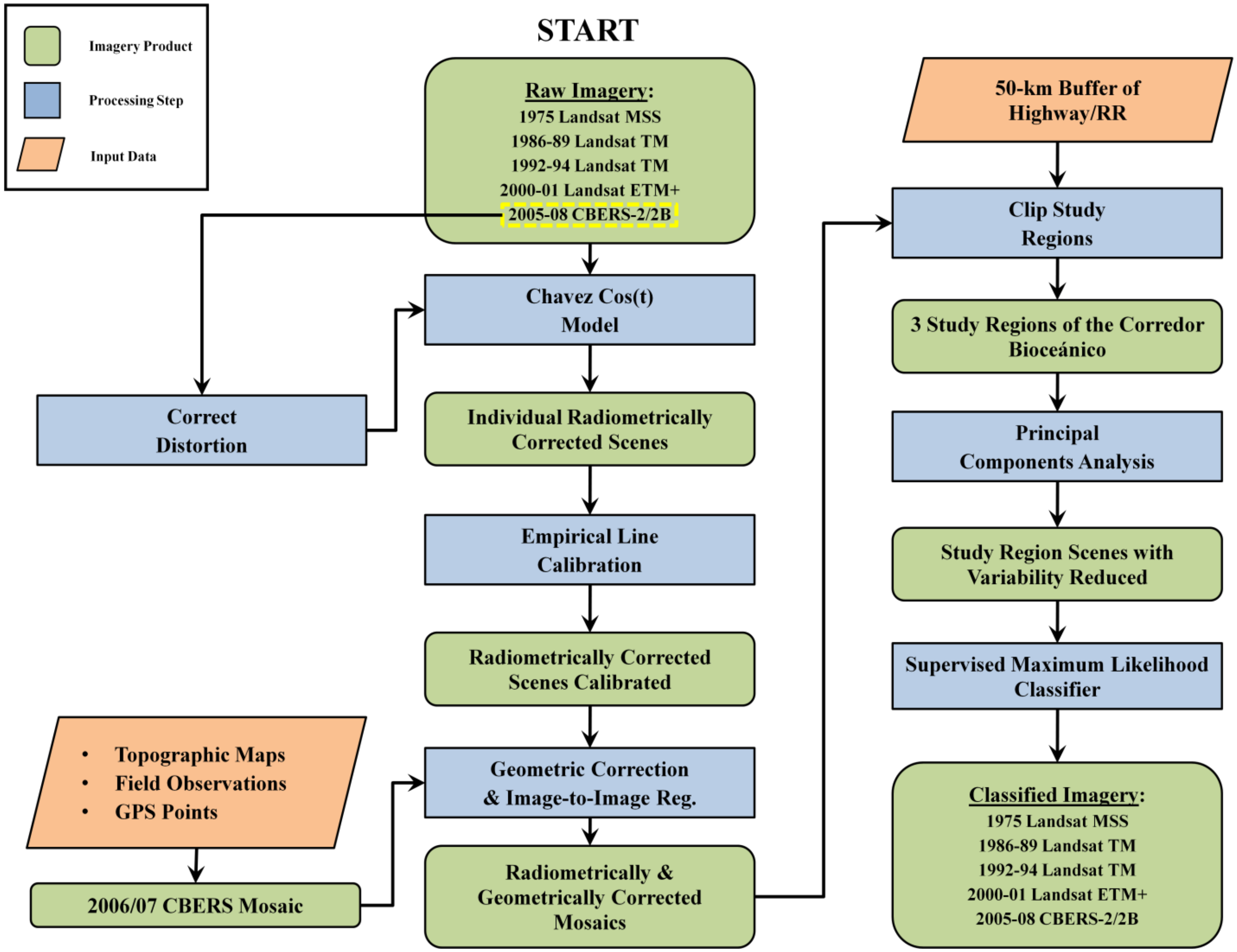
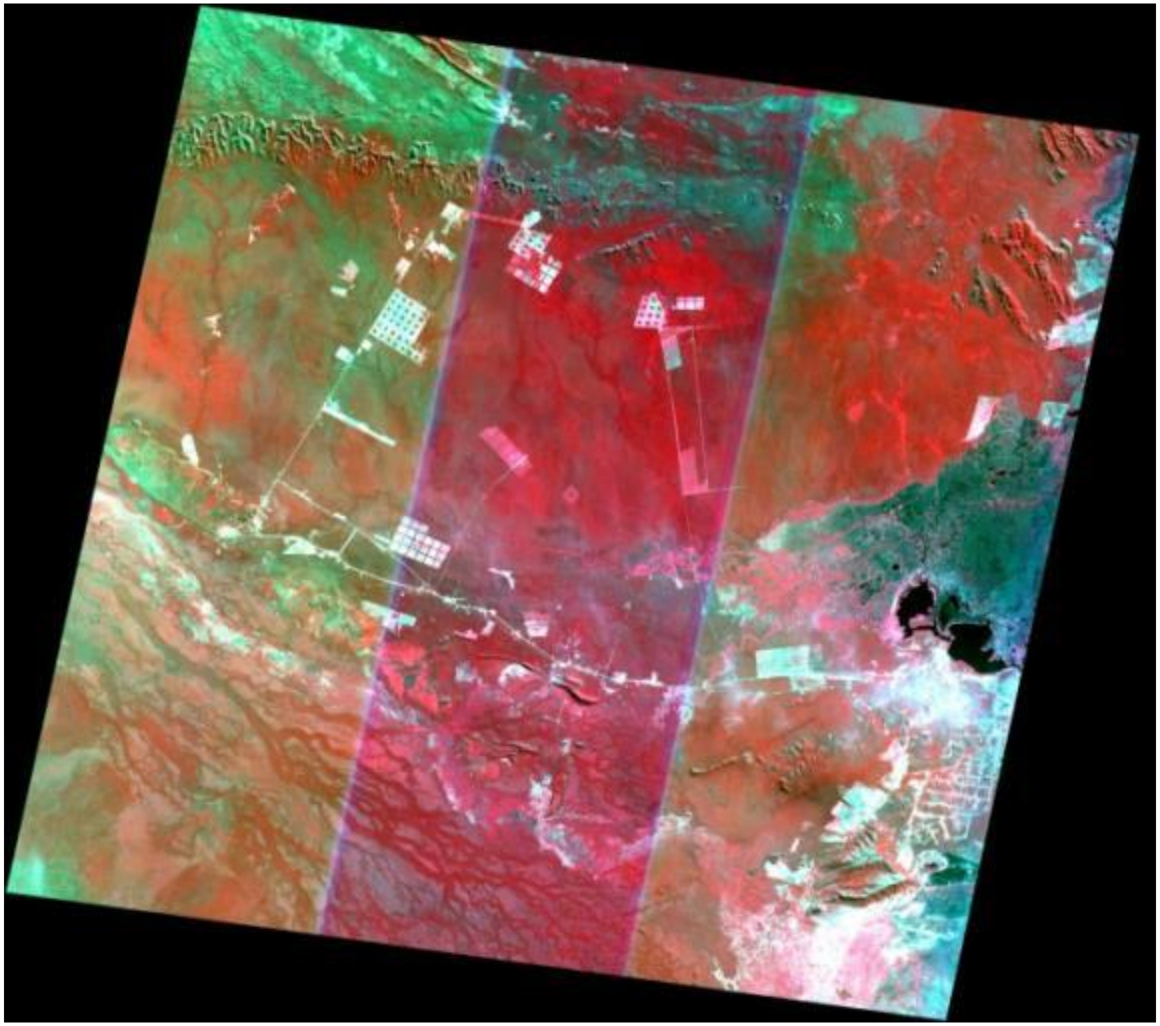


Figure 29. Methodology for processing satellite imagery.



Sensor:	CBERS-2 CCD
Composite:	Color-Infrared
Path:	167
Row:	121
Location:	Bolivia-Brazil Border
Date:	June 15, 2006
Datum:	WGS 1984
Projection:	UTM Zone 21
Source:	Brazilian National Institute of Space Research website

Figure 30. CBERS-2 scene illustrating systematic distortion.

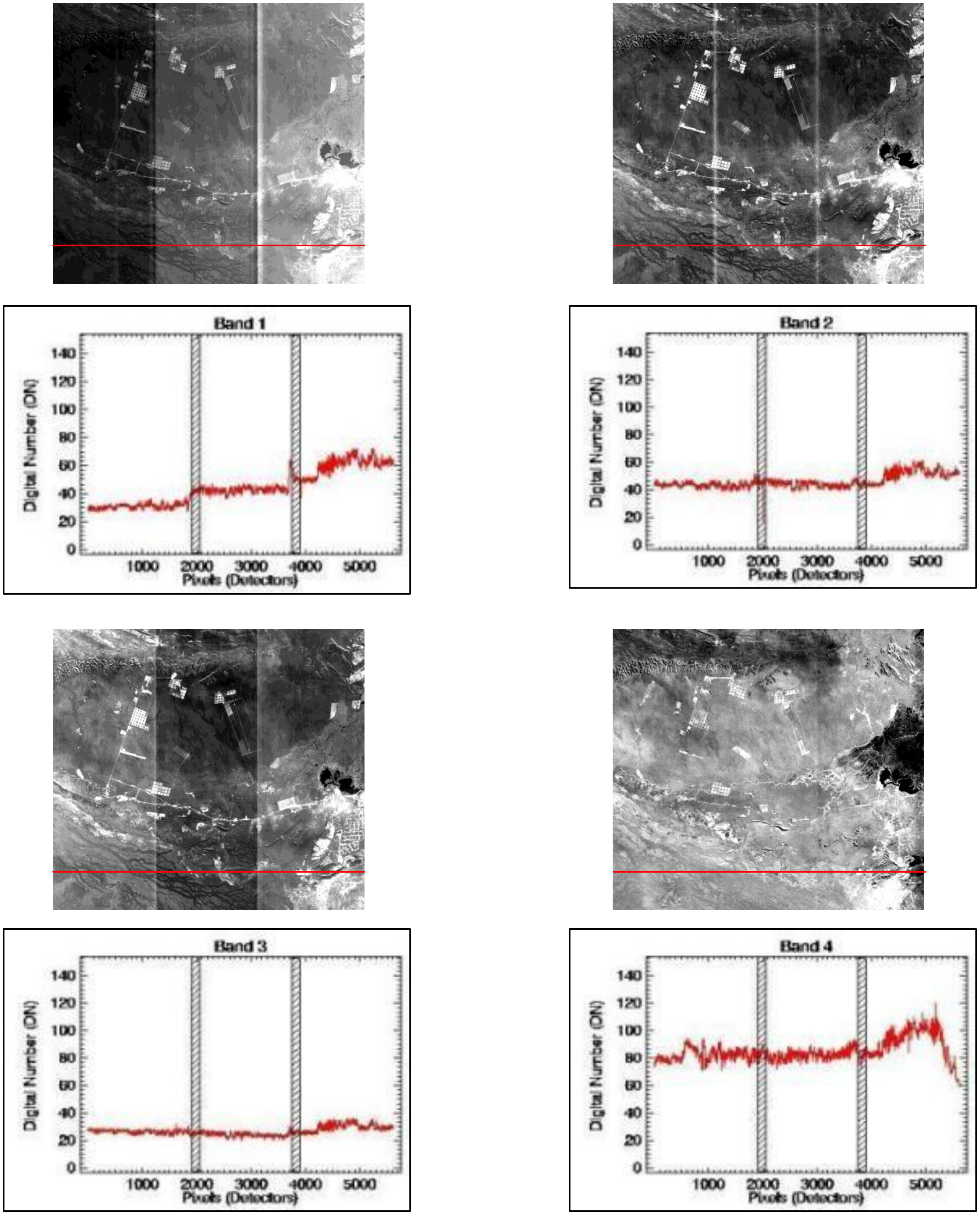


Figure 31. CBERS-2 histograms illustrating systematic distortion. Horizontal bars indicate regions of overlap. Red lines on images indicate location of transect used to generate histograms.

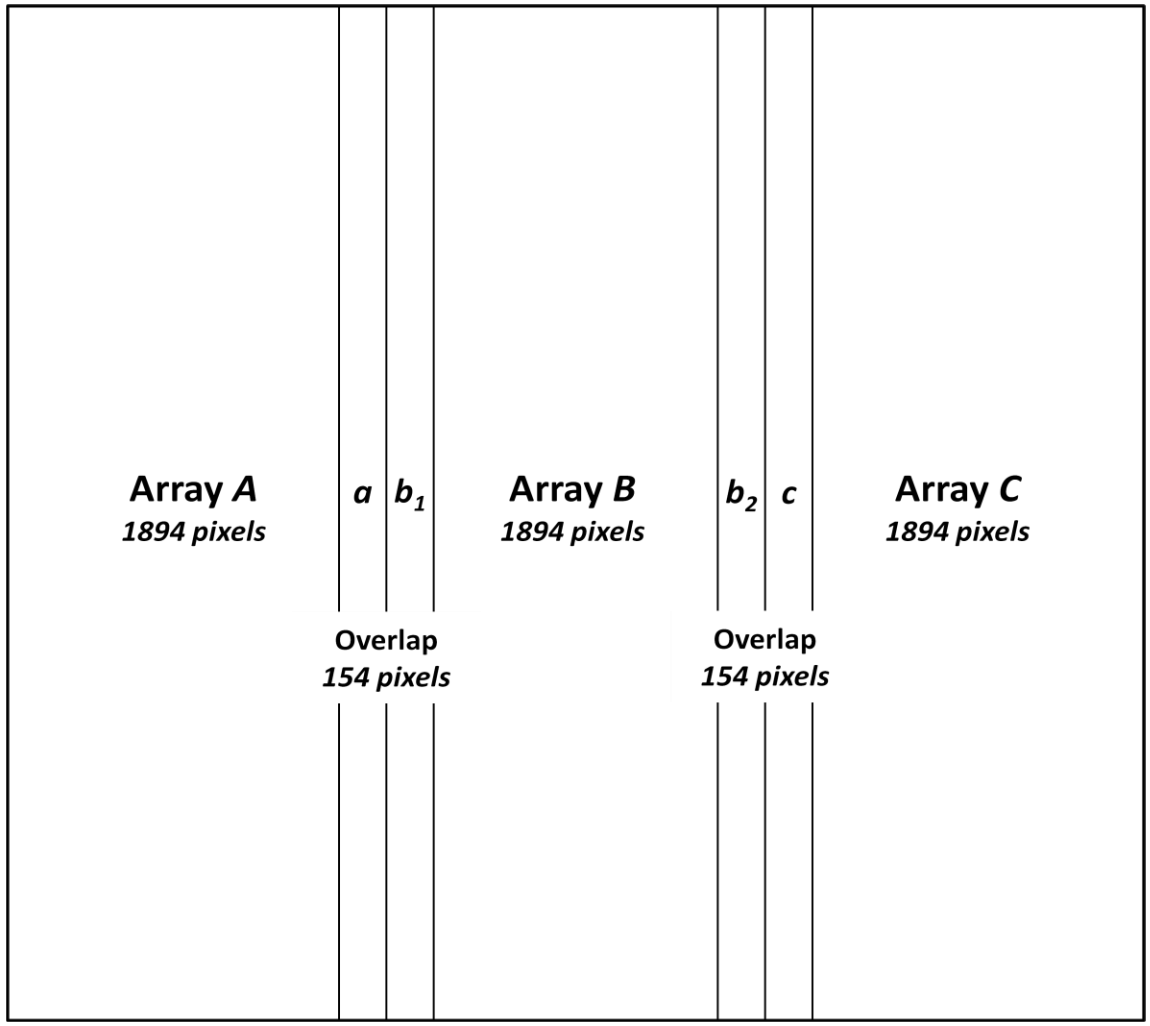


Figure 32. Diagram of a CBERS-2 CCD scene. It is partitioned into large sub-regions and smaller sub-regions based on the natural separation of each of the three, 9-km arrays. 6,130 pixels are received in each line for each band; 14 pixels in Array C are not received by the collecting station; 154 pixels are overlap between arrays Figure B and B-C and 8 pixels are dark. Thus, the final image contains 5,798 pixels (adapted from Jianning et al. 2005 and Fonseca et al. 2004).

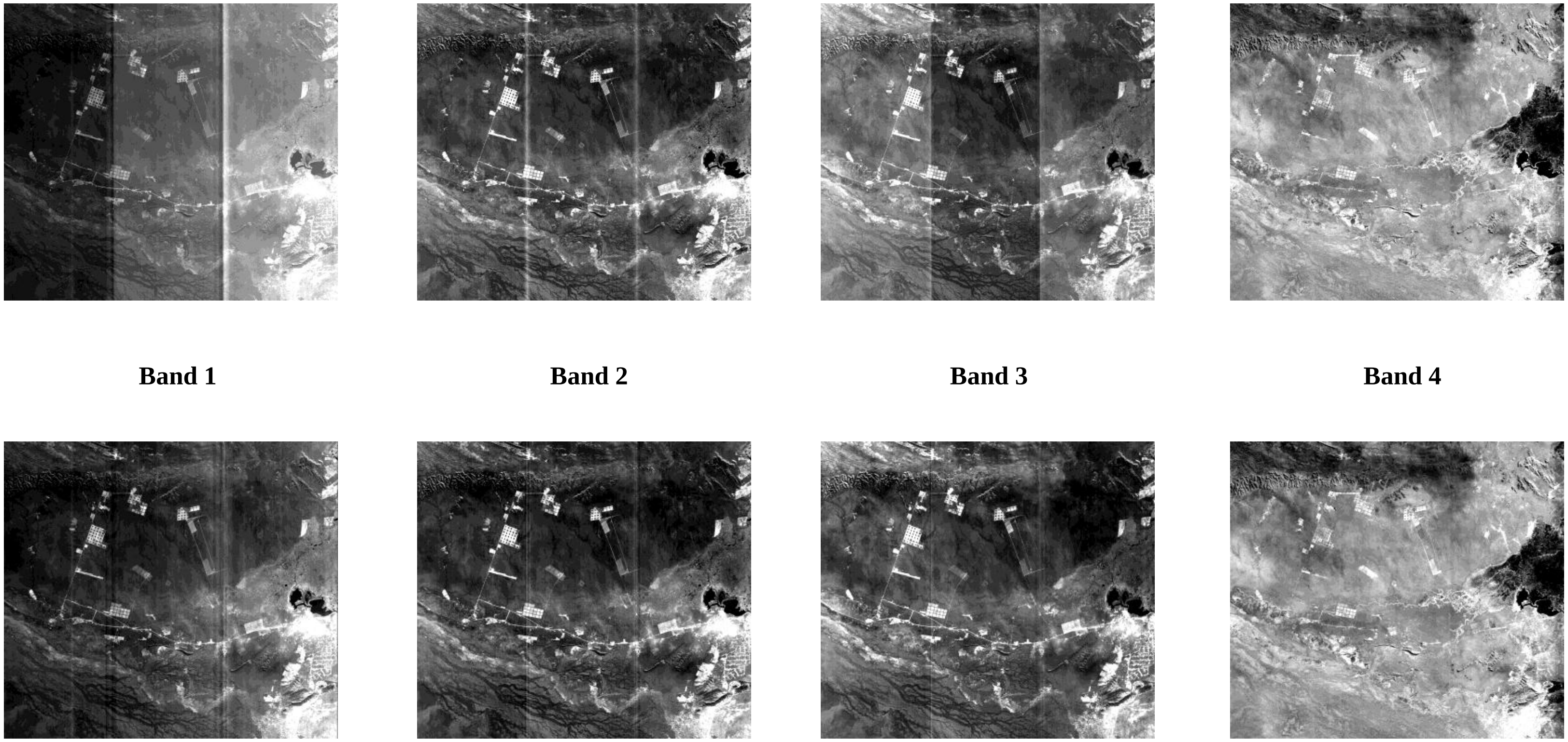


Figure 33. Comparison of uncorrected/corrected CBERS-2 scene by bands.

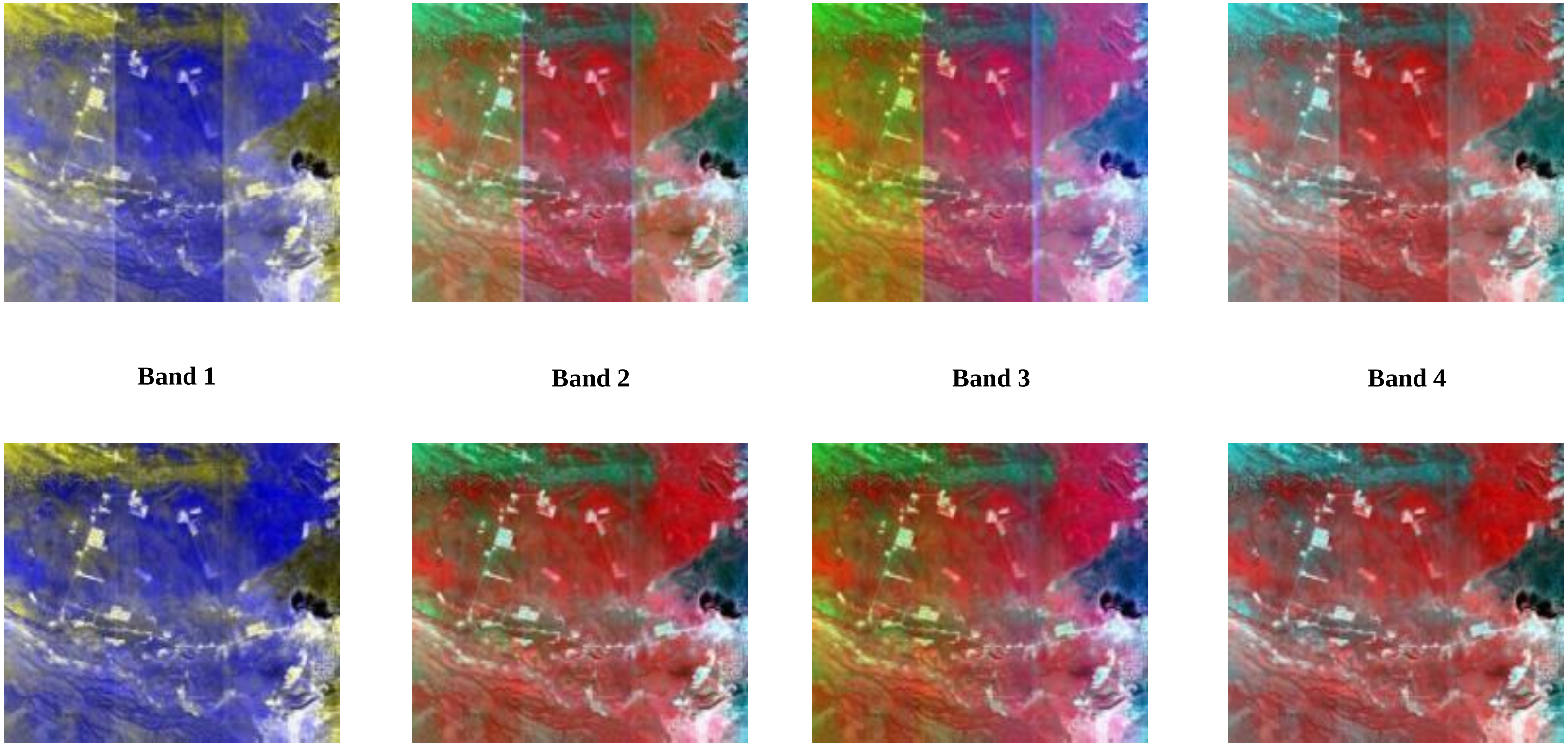


Figure 34. Comparison of uncorrected/corrected CBERS-2 scene by composites.

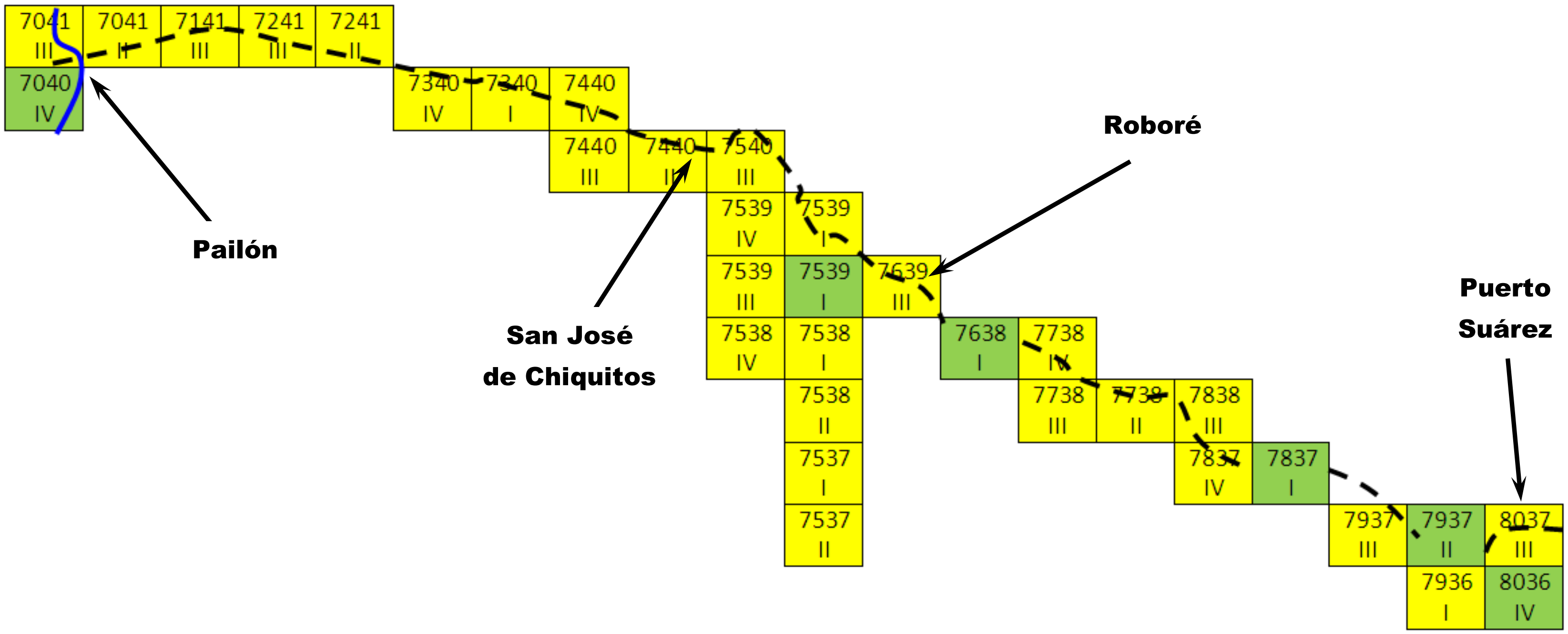


Figure 35. 1:50,000 topographic maps covering the Corredor Bioceánico. Maps acquired are shown in yellow. The railroad is shown in the dashed, black line while the Rio Grande is denoted in blue.

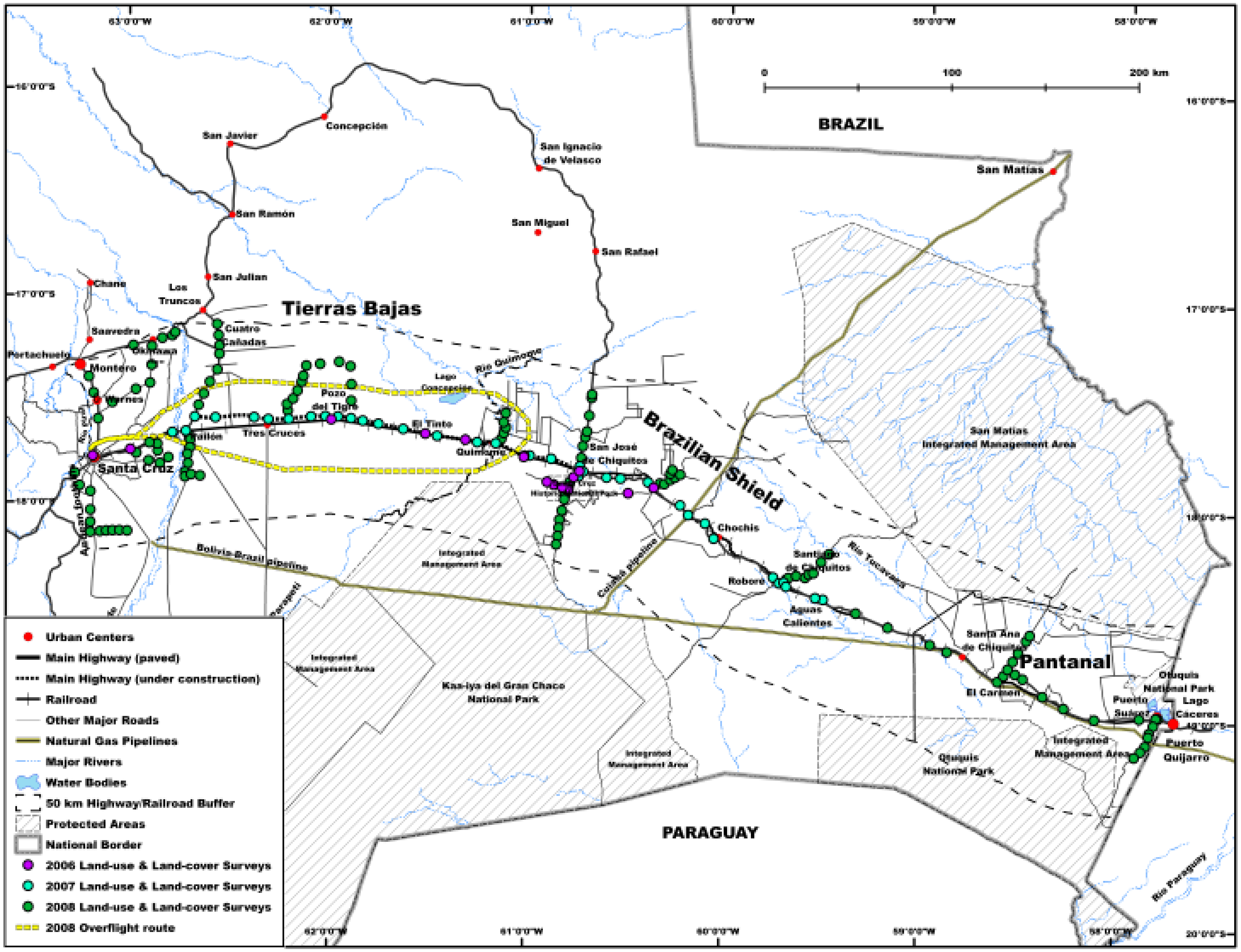


Figure 36. Location of land-cover and land-use surveys. All surveys were conducted from 2006 to 2008.

Table 6
Sample accuracy assessment example.

LAND-USE AND LAND-COVER RECORDING SHEET

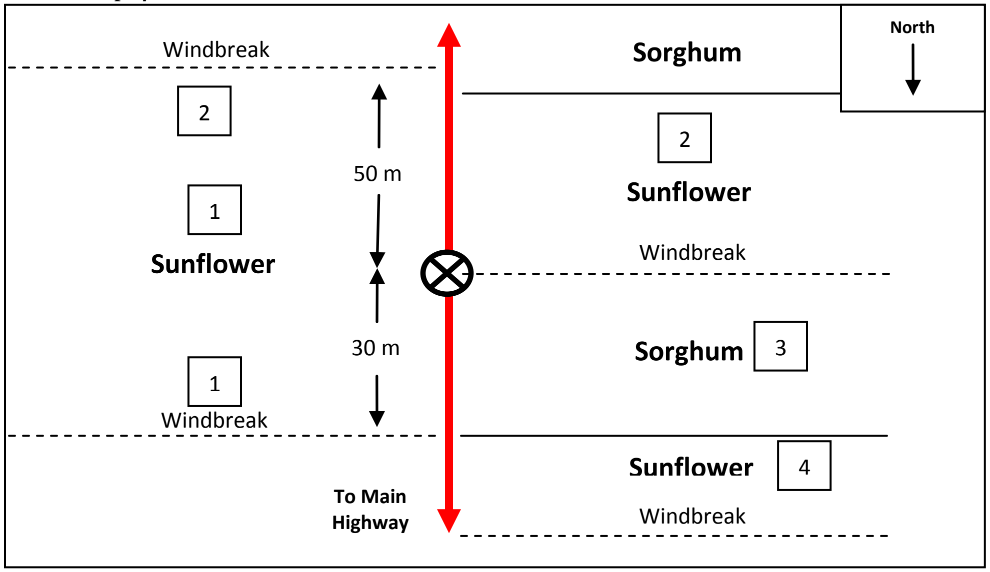
Date	06/30/08
Observer	**Danny R.**

GPS Coordinates (UTM 20S)
617229
8081931

Notes:

Photo Sequence	
1.	**N**
2.	**E**
3.	**S**
4.	**W**

Sketch Map of Location



Check you include: N arrow, scale, prominent landmarks/features, label cover/use type

TOPOGRAPHY	
Slope Angle:	**0**
Slope Form:	Convex; Concave; Rectilinear; **None**
Slope Aspect:	**None**
Soil:	**% Bare Rock: 0** **% Stone/Gravel: 0** **Median Size (cm): % BR: 0 % S/G: 0** **Color: 10YR 8/2 Texture: Very fine/Silty** Dry Moist Waterlogged **% Vegetation ground cover: 100** **Vegetation type:** Crop; Grasses; Herbs **Overcover:** Shrubs; Trees; Grass; None
Landforms:	River Channel; Standing Water; Marsh/Swamp; Plateau; Mountain; Valley; Hill; Mountain Divide; Interfluve; Floodplain; River Terrace; Grassland **Describe stream bed if present: None** **Depression**: None: Basin; Blowout; Graben; Pit Crater; Pothole **Erosion Type:** None; Sheet; Gully; Rill **Rock Exposure Present/Type: None**

Table 6. Continued

CROP FIELD #	1	2	3	4
Crop Type:	**Sunflower**	**Sunflower**	**Sorghum**	**Sunflower**
Crop Height:	**0.75m**	**2.5m**	**1.0m**	**0.50m**
Maturity/Health:	**young/healthy**	**mature/healthy**	**young/healthy**	**very young/healthy**
Crop Density:	**very dense**	**very dense**	**dense**	**dense**

VEGETATION SITE #	1	2
VEGETATION TYPE:		
Forest/Woodland (WL)	✔	✔
Shrubland (SL)		
Grassland (GL)		
Wooded GL/Shrubby GL		
Grassy or Shrubby WL		
Grassy or Woody SL		
Tree Species Present:	Unknown	unknown
Tree Height:	Canopy: 12m Understory: 3-4m	Canopy: 14m Understory: 3-4m
Tree Density:	Basal Area: 2; Angle of Sweep: 45; # of trees: 3	Basal Area: 2; Angle of Sweep: 45; # of trees: 8
% Cover:	100	100
Texture:	Dense	Dense
Phenology:	Canopy: In leaf Senescent Flowering Understory: In leaf Senescent Flowering	Canopy: In leaf Senescent Flowering Understory: In leaf Senescent Flowering
Evidence of Use:	NONE; Recent Burning; Wood Collection (felling, lopping, gathering); Hunting; Apiculture; Fruit trees; Apiculture (Bees); Wax	NONE; Recent Burning; Wood Collection (felling, lopping, gathering); Hunting; Apiculture; Fruit trees; Apiculture (Bees); Wax

Table 7
2008 CBERS-2B accuracy assessment results.

Tierra Bajas [a]	*Producers Accuracy (%)*	*Users Accuracy (%)*	*Commission (%)*	*Omission (%)*
Forest	99.91	99.99	0.01	0.09
Agriculture	99.94	99.45	0.55	0.06
Bare Ground/Savanna	100.00	98.98	1.02	0.00
Water Bodies	100.00	99.97	0.03	0.00
Infrastructure	100.00	99.88	0.12	0.00
Brazilian Shield [b]	*Producers Accuracy (%)*	*Users Accuracy (%)*	*Commission (%)*	*Omission (%)*
Forest	89.99	95.29	4.71	10.01
Agriculture	91.34	89.04	10.96	8.66
Bare Ground/Savanna	87.02	63.95	36.05	12.98
Water Bodies	--	--	--	--
Infrastructure	96.20	99.58	0.42	3.80
Pantanal [c]	*Producers Accuracy (%)*	*Users Accuracy (%)*	*Commission (%)*	*Omission (%)*
Forest	94.47	99.63	0.37	5.53
Agriculture	96.06	94.85	5.15	3.94
Bare Ground/Savanna	100.00	46.92	53.08	0.00
Water Bodies	100.00	100.00	0.00	0.00
Infrastructure	100.00	100.00	0.00	0.00

[a] Overall Accuracy = 99.2; Kappa Coefficient = 0.99
[b] Overall Accuracy = 90.5; Kappa Coefficient = 0.84
[c] Overall Accuracy = 97.5; Kappa Coefficient = 0.96

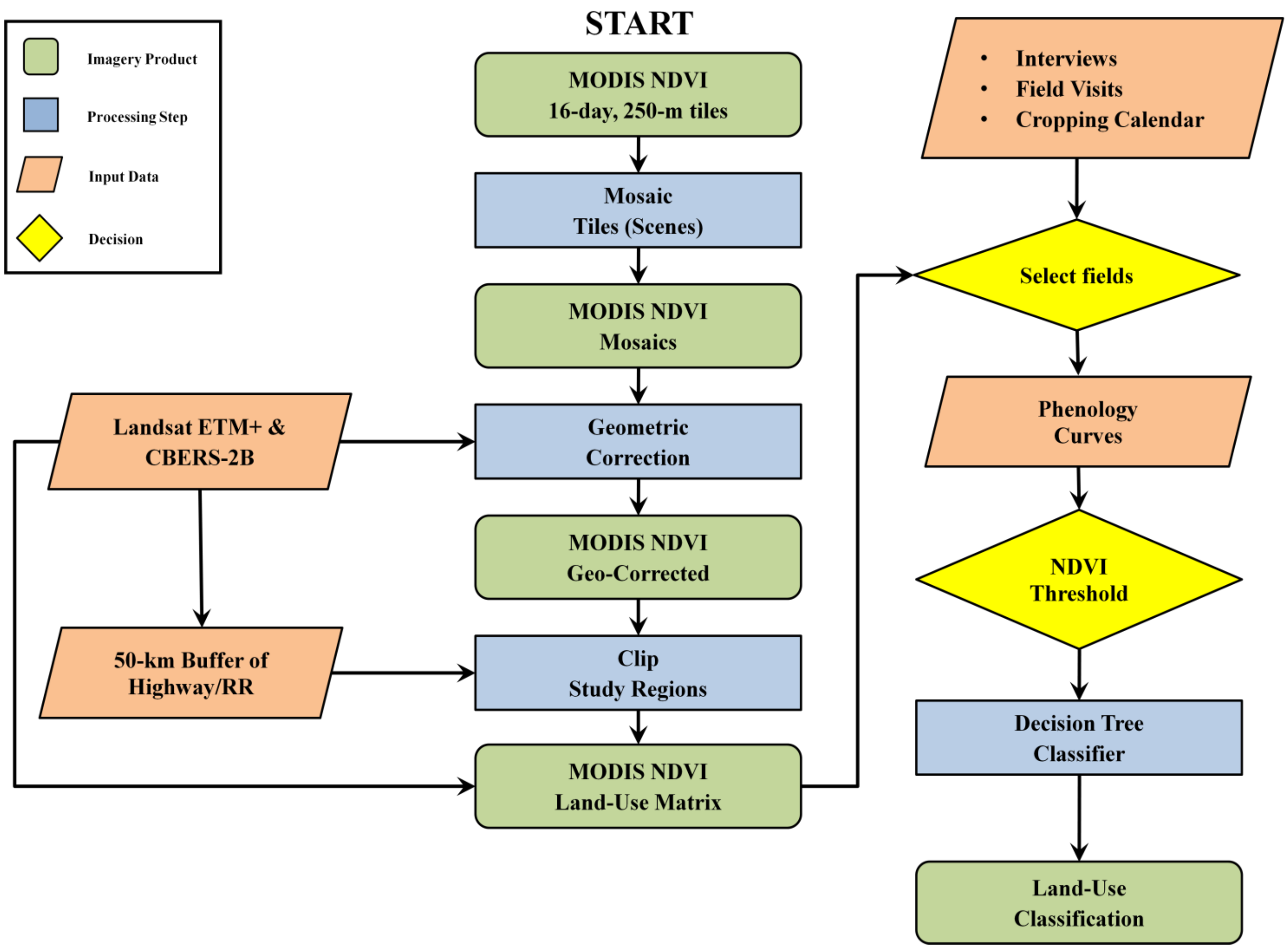


Figure 37. Methodology for classifying cropland from MODIS NDVI imagery.

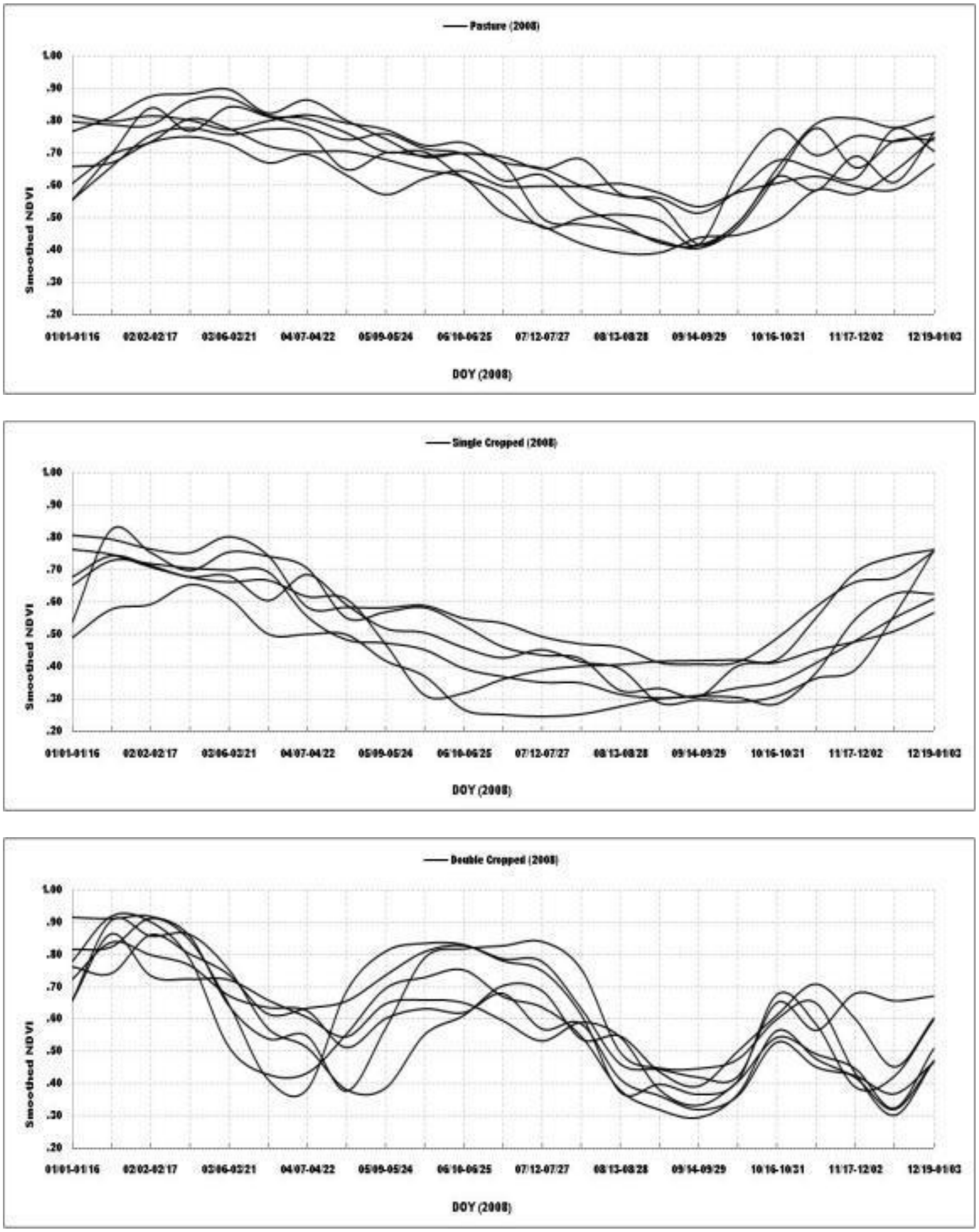


Figure 38. Phenology curves representing individual values. These curves are derived from seven test sites under pasture and double and single cropped fields for 2008.

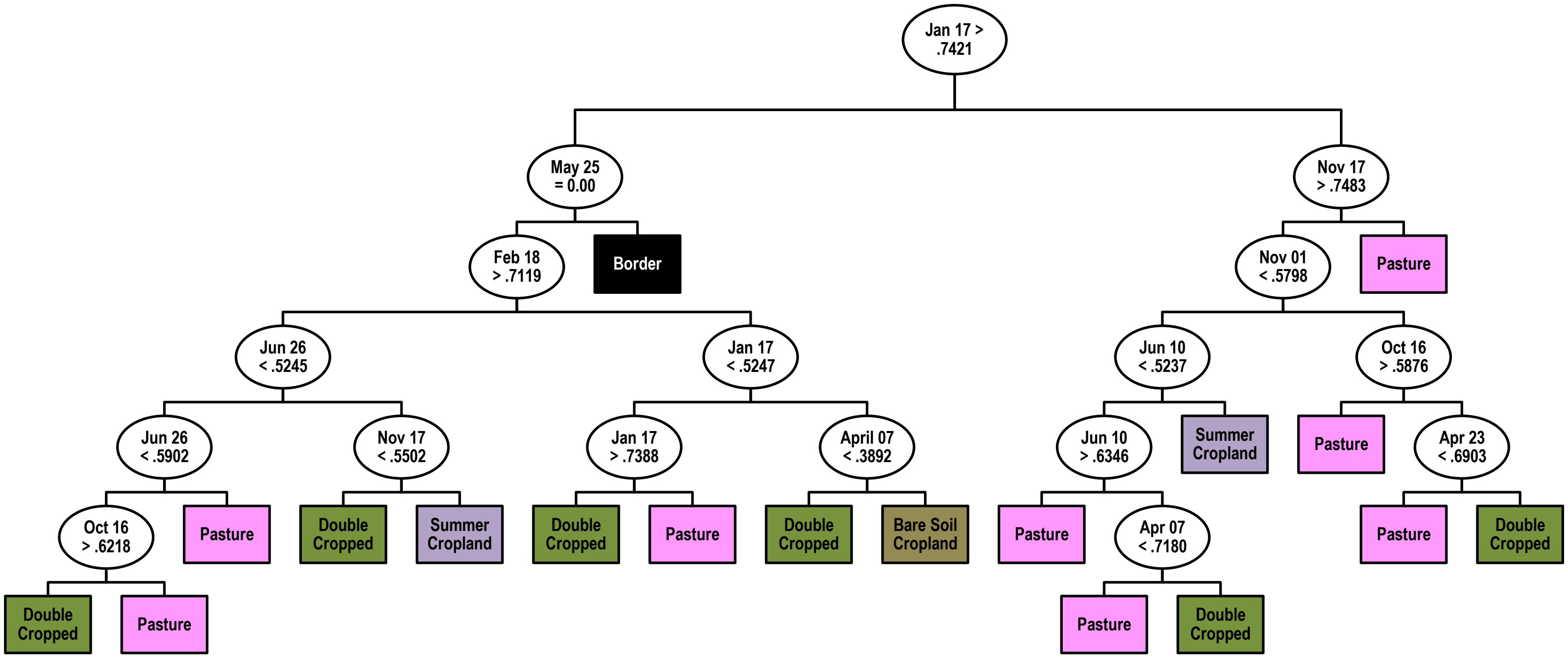


Figure 39. Final decision tree classifier for the year 2007. Circular boxes represent mathematical decisions while rectangular boxes represent final land-use classes.

Table 8
Land-use classification accuracy for 2001, 2007 and 2008.

2001 [a]	*Producer's Accuracy (%)*	*User's Accuracy (%)*	*Commission (%)*	*Omission (%)*
Pasture	98.03	95.13	4.87	1.97
Double Cropped	83.50	90.76	9.24	16.50
Single Crop, Summer	89.11	89.11	10.89	10.89
Annual Fallow	92.00	85.19	14.81	8.00
2007 [b]	*Producer's Accuracy (%)*	*User's Accuracy (%)*	*Commission (%)*	*Omission (%)*
Pasture	96.37	94.94	5.06	3.63
Double Cropped	87.63	90.91	9.09	12.37
Single Crop, Summer	79.31	74.19	25.81	20.69
Annual Fallow	93.33	93.33	6.67	6.67
2008 [c]	*Producer's Accuracy (%)*	*User's Accuracy (%)*	*Commission (%)*	*Omission (%)*
Pasture	96.61	93.44	6.56	3.39
Double Cropped	86.73	88.83	11.17	13.27
Single Crop, Summer	77.78	77.78	22.22	22.22
Annual Fallow	75.00	100.00	0.00	0.00

[a] Overall Accuracy = 92.98%; Kappa Coefficient = 0.8751
[b] Overall Accuracy = 92.44%; Kappa Coefficient = 0.8544
[c] Overall Accuracy = 91.64%; Kappa Coefficient = 0.8465

Table 9
Vegetation classes defined by Navarro and Ferreira (2007).

Vegetation Class:	Vegetation Description:	Dominant Species or Variant:	Spatial Distribution:
a7as	Transitional Chaco forest on floodplain soils medium to imperfectly drained	*Diplokeleba floribunda-Phyllostylon rhamnoides*	Main Series and most widespread transitional Chaco vegetation of the alluvial plain
b15	Human-influenced vegetation: pasture, cropland, fallow land, urban areas, roads, and communication lines		
b5bc	Swamp forest of Bibosi and Cosorió	*Ficus trigona-Erythrina fusca*	Low forest of the Várzea swamps with permanent water
b6	Successional, whitewater riparian vegetation communities of the Beni lowlands (plains), which colonize river banks and abandoned flood channels		Amazonian white water
c1 **c1+c2+c9** **c1+c2a+c5d+c9a** **c1+c2d+c9** **c1+c5d** **c1+c9**	Subhumid semi-deciduous forests of Chiquitanía on well-drained soils; Forest group which is seasonally rainy and represents the natural potential vegetation zone of soils moderately deep, well to medium drained		
c10+c14a+c18 **c10+c14a+d14**	Riparian forests of the Chiquitano Precambrian Shield. These forests develop on river banks that dissect the shield, have direct contact with the water, and are inundated during floods		
c13 **c13+d14a+d12**	Chiquitano-Chaco transitional forest on medium to poorly drained, clayey or silty soils		Chiquitanía-Chaco transition zone
c13a	Chiquitano-Chaco transitional forest on imperfectly drained soils of east-central Chiquitanía	*Diplokeleba floribunda-Acosmium cardenasii*	Wide distribution along the southern boundary of the Chiquitaniá mountain ranges
c13b **c13b+d14a** **c13b+d14a+c14a** **c13b+d14b+d14c**	Chiquitano-Chaco transitional forest on poorly drained soils of east Chiquitanía	*Schinopsis brasiliensis-Lonchocarpus nudiflorens*	Contact zone between the middle and lower basin of the Río Tucavaca
c14 **c14+d14** **c14+d14a**	Ecological system consisting of several types of seasonally flooded forests		Transition zone between Chiquitanía and the Chaco, mainly in the south
c14a	Chaco-eastern Chiquitano transitional, flooded forests		Floodplain of the upper and middle Rio Tucavaca (east of the Chiquitos Province)
c14a+d14a **c14a+d4a**	Chaco-eastern Chiquitano transitional, flooded forests + Forest on seasonal streams and depressions		
c17 **c17+c18** **c17+c1e**	Set of herbaceous pampas grasses, typical of oligotrophic soils temporarily flooded to varying degrees depending on the topography, mainly by water from depressions		Chiquitanía
c18	Neotropical aquatic and marsh vegetation of permanent water bodies, including permanent swamps, lagoons and backwaters of rivers.		
c1a **c1a+d14c** **c1a+d7an+d9a+d14** **c1a+d7an+d9a+d14b**	Floodplain forest of south-central Chiquitanía on well-drained soils	*Machaerium scleroxylon-Acosmium cardenasii*	Southern boundary of the Chiquitanía toward the Chaco, in the central province of Chiquitos, on soils well-drained
c1b+c13a	Floodplain forest of east Chiquitanía on well-drained soils	*Machaerium scleroxylon-Acosmium cardenasii*	Areas with well-drained soils on alluvial plains of the watersheds of the Middle Rio Otuquis and Lower Tucavaca
c1e **c1e+c5e+c17+c18** **c1e+c9e+c17+c18**	Chiquitano forest on the wind-blown, sandy, alluvial soils of Santa Cruz	*Erythrina dominguezii-Astronium urundeuva*	Sandy soils of the ancient alluvial plain of the Rio Piraí, west and northwest of the city of Santa Cruz

Table 9. Continued

Vegetation Class:	Vegetation Description:	Dominant Species or Variant:	Spatial Distribution:
c1g	Chiquitano forest on sandy soils of southeastern Chiquitanía		Peneplain mountain ranges with sandy, wind-blown tops to the northeast of Cerro Chovoreca, toward Roboré (Cordillera Province), in the transition zone toward the Chaco
c1h	Chiquitano forest on mountain ranges of eastern Chiquitanía		Limestone and sandstone hills in the region of Puerto Suárez (G. Busch Province)
c1h+c13a+a	Chiquitano forest on mountain ranges of eastern Chiquitanía + Chiquitano-Chaco transitional forest on imperfectly drained soils of east-central Chiquitanía		
c1h+c5g+c13a	Chiquitano forest on mountain ranges of eastern Chiquitanía + Transitional Cerrado of southeastern Chiquitanía-Pantanal	Preliminary set of *Qualea grandiflora-Styra*	
c1i **c1i+c2g**	Forest on deep soils of east-central Chiquitanía + Hydrophyte (aquatic) forests of the valleys of eastern Chiquitanía	*Machaerium scleroxylon-Schinopsis brasiliensis*	San José and Santiago mountain ranges, on deep soils well-drained of mountain slopes and foothills
c1i+c9 **c1i+c9+c16**	Forest on deep soils of east-central Chiquitanía + Semideciduous, phreatophytic and hydrophytic forest on rocky limestone soils of eastern Chiquitanía		
c1i+c9b	Forest on deep soils of east-central Chiquitanía + Hydrophytic forest of the valleys of eastern Chiquitanía		
c1j+c5e+c9e	Transitional Chiquitano forest of the lower Subandean south of Santa Cruz	*Schinopsis haenkeana-Aspidosperma cylindrocarpon*	Andean foothills south-southwest of the city of Santa Cruz, below 1000 - 1200 m
c2 **c2+c9** **c2+c9+c13b**	Lowland Chiquitano forest on rocky or sandy soils (Savannah, "Pampa-Monte"). Semi-deciduous forests with a canopy of 10-16 m developed on excessively drained, shallow soils		
c2a+c5d	Lowland forest on stony soils of central Chiquitanía + Sclerophyllous chaparral and savanna woodlands of Chiquitanía on well-drained soils	*Machaerium acutifolium-Astronium urundeuva*	Shallow, rocky soils of central Chiquitanía + Cerrado of south Chiquitanía
c2b	Lowland forest on sandy soils of eastern Chiquitanía	*Pterodon emarginatum-Terminalia argentea*	Undulating low ridges with wind-blown, sandy tops between Roboré and San Jose de Chiquitos, on the lower slopes of the mountain ranges
c2d	Lowland forest on sandy soils of east-central Chiquitanía	*Schinopsis brasiliensis-Aspidosperma tomentosum*	Pampa or Cerrado distributed on shallow rocky soils of the Chiquitaniá mountain ranges
c2e	Lowland forest on sandy soils of southern Chiquitanía		Pampa or Cerrado distributed on sandy, rocky soils on mountain ranges or rolling hills with wind-blown tops to the south of San José de Chiquitos
c2e/c6	Lowland forest on sandy soils of southern Chiquitanía / Sclerophyllous chaparral		
c2e+c17	Lowland forest on sandy soils of southern Chiquitanía / Sclerophyllous chaparral + Oligotrophic flooded grassy savannas of Chiquitanía		
c2g **c2g+c5**	Lowland forest on rocky limestone soils of eastern Chiquitanía	*Commiphora leptophloeos-Pseudobombax longiflorum*	Pampa-Monte or Cerrado distributed on stony, shallow soils of the hills and mountains
c3	Transitional Chiquitano-Chaco forest on well-drained soils. Forest group which is semi-deciduous and are the floristic and ecological transition of Chiquitanía toward the Chaco		
c3a	Dry transitional Chiquitano-Chaco forest on well-drained soils. Forest with a deciduous canopy with a medium height of 12-16 m distributed in the southern extreme of Chiquitanía	*Athyana weinmannifolia-Acosmium cardenasii*	
c3b	Sub-humid transitional Chiquitano-Chaco forest on well-drained soils.	*Athyana weinmannifolia-Schinopsis brasiliensis*	Chiquitano forest which transitions to Chaco forest in sub-humid areas seasonally rainy south of the Chiquitos Province
c3c+c9e	Transitional Chiquitano-Chaco forest in Preandean Santa Cruz	Preliminary set of *Aspidosperma cylindrocarpon-Diplokeleba floribunda*	Lowland, easternmost sub-Andean foothills of southern Santa Cruz in the northeast of the Cordillera Province
c4	Transitional Chiquitano-Amazônia forest on soils well-drained. Chiquitanos forests climatophilous (natural potential vegetation) with a semi-deciduous to seasonal evergreen canopy 22-26 m in average height		Distributed in northern Chiquitanía

Table 9. Continued

Vegetation Class:	Vegetation Description:	Dominant Species or Variant:	Spatial Distribution:
c5 **c5+c7b**	Sclerophyllous chaparral and savanna woodlands of Chiquitanía on well-drained soils. Cerrado formation on ancient tuff-lateritic substrates or stones, well-drained, which include lowland forests		
c5b	Mountainous Cerrado of east-central Chiquitanía	Preliminary set of *Callisthene hassleri-Pterodon emarginatus*	Mountain ranges of San José (eastern), Ipiás y Santiago
c5d	Sclerophyllous chaparral and savanna woodlands of Chiquitanía on well-drained soils: Cerrado of southern Chiquitanía	*Priogymnanthus hasslerianus-Callisthene fasciculata*	Mountain ranges of the Lomerío region to the south of Concepción
c5g	Cerrado of Chiquitanía transitioning southeast to the Pantanal	Preliminary set of *Qualea grandiflora-Styrax subargenteus*	Isolated hills and low mountains in the region of Puerto Suárez, on very stony soils and rock slabs
c6	Sclerophyllous chaparral of Chiquitanía transitioning to the Chaco on sand (Abayoy). Lowland forests and scrublands, semi-dense, developed on low, rolling peneplains with wind-blown, sandy ridge tops		
c6a	Abayoy Chaparral on sandstone substrates	*Tabebuia selachidentata-Terminalia argentea*	Sandy soils on rocks of Paleozoic sandstone
c6aq **c6aq+c3aq**	Abayoy Chaparral on sandstone substrates, pyrogenic variation transitioning to burned zones		
c6c	Abayoy Chaparral on the sloping, sandstone outer edges of the Chochis Plateau	*Copaifera langsdorfii-Terminalia fagifolia*	Plateaus of the foothills of Chochís and Ipiás, between the mountain ranges of San José and Santiago
c9 **c9+c13a** **c9+c14**	Semideciduous, phreatophytic and hydrophytic forest of Chiquitanía (CES406.233). Forest group distributed in the valley bottoms and lower slopes of the river valleys of Chiquitanía and in the floodplain of Santa Cruz		
c9a	Hydrophytic forest of the valleys of central Chiquitanía	*Cariniana ianeirensis-Vitex cymosa*	
c9a+c10	Hydrophytic forest of the valleys of central Chiquitanía + Riparian forests of the Chiquitano Precambrian Shield	*Cariniana ianeirensis-Vitex cymosa*	Forests developed on river margins that dissect the shield, have direct contact with the water, and are inundated during floods
c9b	Hydrophytic forest of the valleys of eastern Chiquitanía	Series to be determined	
c9b+c13b	Hydrophytic forest of the valleys of eastern Chiquitanía + Chiquitano-Chaco transitional forest on poorly drained soils of east Chiquitanía	c13b = *Schinopsis brasiliensis-Lonchocarpus nudiflorens*	Before the previous series in the contact zone between the middle/lower basin of Río Tucavaca
c9b+d14	Hydrophytic forest of the valleys of eastern Chiquitanía + tropical high forest of the northern Chaco	Series to be determined	
c9d	Hydrophytic forest of the valleys of southern Chiquitanía	Series to be determined	
c9e & c9ee **c9e/d7an** **c9e+d9** **c9e+d9ic**	Mesophytic-phreatophytic floodplain forests of the wind-blown alluvial plains of Santa Cruz	*Albizia niopoides-Gallesia integrifolia*	Potential climax forest of central and southern plains of Santa Cruz on well-drained deep soils
ca	Human-influenced vegetation complex: Vegetation heavily influenced or transformed by human action, including extensive cropland, pasture, fallow land, and deforested areas		
ca+ c1e+c9e	Human influenced vegetation + Chiquitano forest on the wind-blown, sandy alluvial soils of Santa Cruz	*Erythrina dominguezii-Astronium urundeuva*	Sandy soils on the ancient alluvial floodplains of the Río Piraí, to the west
ca+(c9e+d7as+d9i+c1e) **ca+c9e**	Human influenced vegetation + Mesophytic-phreatophytic floodplain of the wind-blown alluvial plains of Santa Cruz	*Albizia niopoides-Gallesia integrifolia*	Potential climax forest of central and southern plains of Santa Cruz on well-drained deep soils
ca+c1e+c17+c18	Human influenced vegetation + Chiquitano forest on the wind-blown, sandy alluvial soils of Santa Cruz + Oligotrophic flooded grassy savannas of Chiquitanía	*Erythrina dominguezii-Astronium urundeuva*	
d12 **d12+d14a**	Flooded palm forest of the northern Chaco. Ecological system of Chaco palm forest comprising associations dominated by the Carandá Palma (*Copernicia alba*)		

Table 9. Continued

Vegetation Class:	Vegetation Description:	Dominant Species or Variant:	Spatial Distribution:
d12a **d12a+d14** **d12a+d15a** **d12a+d15a+d19** **d12a+d19** **d12a+pa3** **d12a+pa3+pa4**	Carandá palm forest of low-medium flooding in the northern Chaco	*Microlobium paraguensis-Copernicia alba*	Palms with trees and shrubs, seasonally flooded by full to semi-flowing water, interrupted and partly mineralized
d12c **d12c+d14+pa4** **d12c+d14a** **d12c+d14b** **d12c+d14c** **d12c+pa4**	Carandá palm forest of medium-high flooding in the Chaco-Pantanal-Chiquitanía transition	*Triplaris gardneriana-Copernicia alba*	Palms flooded six months or more a year by river overflow by water, interrupted and partly mineralized
d13 **d13+d18**	Flooded vegetation of the salt flats of the northern Chaco. This system includes several types of herbaceous vegetation, shrubs and trees that grow in clear, saline soils		Seasonally flooded areas of the northern Chaco
d13a **d13a+d15+d19** **d13a+d18**	Carandá palms developed on saline soils of the northeastern Chaco. Chaco palms developed in moderately saline soils and temporarily flooded	*Prosopis ruscifolia-Copernicia alba*	Distributed in the northwest of Chaco
d13c	Carandá palms of the salt marshes of San José, San Miguel y Santiago; Palms restricted to the beaches around the salt marshes of southern Bolivian Chaco	*Lophocarpinia aculeatifolia-Copernicia alba*	
d14 **d14+pa4**	Hydrophytic forest of the northern Chaco (502,258). Joint forest characteristics of the drainage system and seasonal to ephemeral flooding in the northern Gran Chaco		Distributed in streams, creeks or temporary creeks
d14a **d14a+d1** **d14a+d14c** **d14a+d14d** **d14a+d15a**	Forest in seasonal streams and flooded depressions in the northern Chaco	*Coccoloba guaranitica-Geoffroea spinosa*	Represents the type of hydrophytic Chaco forest most widespread in Bolivia and northern Paraguay, in areas of preferred human development
d14b **d14b+d15a+d18** **d14b+d18+d19** **d14b+d9h**	Seasonally flooded forests of the Chaco-Chiquitanía-Pantanal transition. Vegetation series homologous to the previous series	*Zygia pithecollobioides-Geoffroea spinosa*	Located within ecological and biogeographical transition belt between the northeastern Chaco and the southern Pantanal
d14c	Forest in seasonal streams and flooded depressions in the Chaco-Chiquitanía transition. Semi-deciduous forest with an irregular canopy 15-18 m in height, emerging 20-22 m	*Lonchocarpus pluvialis-Ruprechtia exploratricis*	
d15a **d15a+d16+d17a** **d15a+d19**	Flooded forests of the swamps of the northeastern Chaco	*Crataeva tapia-Albizia inundata*	Distributed mainly in the Izozog swamps and along the axis of the Parapetí River
d16	Successional scrub and riparian forests of the Chaco. They are species-poor communities		Set of lowland forests and shrub or bush developed in sandy or muddy beaches of the great Chaco rivers
d18	Open, flooded savannas of the northern Chaco. Ecological system comprising a set of grassland savannas or seasonally flooded fields		Distributed throughout the east of the northern Chaco
d7a **d7a+d7aa** **d7a+d7b** **d7a+d9** **d7a+d9a**	Transitional Chaco forest on floodplain soils medium to imperfectly drained	*Diplokeleba floribunda-Phyllostylon rhamnoides*	Main Series and most widespread vegetation transitional Chaco vegetation of the floodplain
d7a/d9a	Transitional Chaco forest on floodplain soils medium to imperfectly drained / Forest on soils poorly drained with Palma Saó		
d7aa	Transitional Chaco forest on floodplain soils medium to imperfectly drained	Variant of some sandy soils	

Table 9. Continued

Vegetation Class:	Vegetation Description:	Dominant Species or Variant:	Spatial Distribution:
d7aa+d7an	Transitional Chaco forest on floodplain soils medium to imperfectly drained + Transitional Chaco forest on floodplain soils medium to imperfectly drained	Variant of some sandy soils	
d7af	Transitional Chaco forest on floodplain soils medium to imperfectly drained	Variant influenced with water that collects on an impermeable surface	
d7af+d15a	Transitional Chaco forest on floodplain soils medium to imperfectly drained + Flooded forest of the swamps of the northeastern Chaco	d7af = Variant influenced with water that collects on an impermeable surface; d15a = *Crataeva tapia-Albizia inundata L.*	
d7an	Transitional Chaco forest on floodplain soils medium to imperfectly drained	*Diplokeleba floribunda-Phyllostylon rhamnoides*	Main Series and most widespread transitional Chaco vegetation of the floodplain
d7an/d9a	Transitional Chaco forest on floodplain soils medium to imperfectly drained / Forest on soils poorly drained with Palma Saó	d7an = Variant with phreatic influence; d9a = *Diplokeleba floribunda-Trithrinax schizophylla*	
d7an+a	Variant influenced with water that collects on an impermeable surface + Human-influenced vegetation complex		
d7an+d14a	Transitional Chaco forest on floodplain soils medium to imperfectly drained + Forest in seasonal streams and flooded depressions in the northern Chaco	d14a = *Coccoloba guaranitica-Geoffroea spinosa*	
d7an+d7aa+d14a		d14a = Variant of some stony soils	
d7an+d7b+d14a	Transitional Chaco forest on floodplain soils medium to imperfectly drained + Transitional Chaco forest on floodplain soils well to medium drained	d7an = Variant influenced with water that collects on an impermeable surface	
d7an+d9a **d7an+d9a+c1a** **d7an+d9a+d14a** **d7an+d9a+d14b**	Transitional Chaco forest on floodplain soils medium to imperfectly drained + Forest on soils poorly drained with Palma Saó	d7an = Variant influenced with water that collects on an impermeable surface; d9a = *Diplokeleba floribunda-Trithrinax schizophylla*	
d7b **d7b+d14a**	Transitional Chaco forest on floodplain soils medium to imperfectly drained. These type of forests develop on soils which are sandy-loam to moderately free of medium sandy-loam	*Diplokeleba floribunda-Schinopsis quebracho-colorado*	
d7c **d7c+d9** **d7c+d9h**	Transitional Chaco forest on floodplains of the Río Quimome. Transitional Chaco forest with a restricted range extending to the ancient floodplains of the Río Quimome, east to Lake Concepción	*Ceiba samauma-Phyllostyllon rhamnoides*	
d9	Forests on poorly drained soils of the northwestern Chaco. Ecological system which groups several types of lowland forests and shrublands developed on fine textured soils		Distributed in topographic depressions of the alluvial plains
d9a-d15	Forest on soils poorly drained with Palma Saó. Forest on clay or poorly drained, silty clay soils of the northern Bolivian Chaco	*Diplokeleba floribunda-Trithrinax schizophylla*	
d9i	Palocruzal vegetation of the floodplains of Santa Cruz. Low forest, developed on silty clay soils very poorly drained, somewhat salty	*Machaerium latifolium-Tabebuia nodosa*	
da	Human-influenced vegetation complex		
da+d7an	Human-influenced vegetation + Transitional Chaco forest on floodplain soils medium to imperfectly drained	Variant of the north	
da+d7an+d9a	Human-influenced vegetation complex + Transitional Chaco forest on floodplain soils medium to imperfectly drained + Forest on soils poorly drained with Palma Saó	d7an= Variant of the north; d9a = *Diplokeleba floribunda-Trithrinax schizophylla*	

Type 1
Tierras Bajas: medium-large, mechanized owner-operated farms

Type 2
Tierras Bajas and Brazilian Shield: large, modern ranches

Type 3
Tierras Bajas and Brazilian Shield: hybrid mechanized farms and modern ranches

Figure 40. Three types of farms/land managers interviewed.

Table 10
Mechanized, owner-operated farms survey instrument.

Location: ______________________________

Date: ________________________

Survey #:________

Table 10. Continued

SECTION I: Household Information

Household Members (Note: “household” is defined as a group of people, connected by family or kinship ties, in which individuals EITHER (a) live in the same dwelling(s) for most of the year or (b) live outside the dwelling but provide regular income or sustenance to the household, such as remittances)

No.	***Age***	***Gender***	***Relation to respondent***	***Birthplace/ Citizenship***	***Current Residence***	***Marital Status***	***Income Earner or Sustenance Provider***	***Remittances***
1		___Male ___Female	Respondent			___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
2		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
3		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
4		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
5		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
6		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No

Table 10. Continued

Section II: Summer Cultivation (not adjacent to house)

		Area		*Crop Cycle (month)*					*Harvest*		*Labor*	*Harvest Destination (%)*		
2007/08	*Crop/Animal Type*	*Hectares*	*% Irrigated*	*Soil Prep*	*Plant*	*Fertilizer/ Pesticide*	*Harvest*	*Fallow*	*Amount (mT/ha)*	*Selling price ($USD/mT)*	*Labor (%)*	*Household*	*Market*	*Others*
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
3											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
4											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2002/03														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
1994/95														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
1974/75														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op

Why did you change main crops?

2002-2007: ____

1994-2002: ____

1974-1994: ____

Did any government incentives or policies (or laws) influence crop type? ______ YES ______ NO; if yes, list reasons and sort in order of importance.

____

____

Did price influence a change in crop? ______ YES ______ NO

Do you (or did you) cultivate crops in winter?

Table 10. Continued

Section III: Winter Cultivation (not adjacent to house)

		Area		*Crop Cycle (month)*					*Harvest*		*Labor*	*Harvest Destination (%)*		
2007/08	***Crop/Animal Type***	***Hectares***	***% Irrigated***	***Soil Prep***	***Plant***	***Fertilizer/ Pesticide***	***Harvest***	***Fallow***	***Amount (mT/ha)***	***Selling price ($USD/mT)***	***Labor (%)***	***Household***	***Market***	***Others***
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
3											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
4											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2002/03														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
1994/95														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
1974/75														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op

Why did you change main crops?

2002-2007: ____

1994-2002: ____

1974-1994: ____

Did any government incentives or policies (or laws) influence crop type? ______ YES ______ NO; if yes, list reasons and sort in order of importance.

____

____

Did price influence a change in crop? ______ YES ______ NO

Table 10. Continued

Section IV: Credit and Technology

	Credit (%)	*Technology*		
2007/08		***Type (%)***	***Equipment (#)***	***Seeds***
1	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
2	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
3	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
4	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
2002/03				
1	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
2	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
1994/95				
1	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
2	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
1974/75				
1	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
2	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N

Terms of Loan:

Harvest: ____

Interest Rate: ____

Table 10. Continued

Section V: Threats and Opportunities

Rank	*Threats/Opportunities*	*Weight*	*Explanation*
	Agrarian Reform (Law Nº 3545)	1 2 3 4 5 DK	
	Prevention/control of forest fires	1 2 3 4 5 DK	
	Loan/Credit Acquisition	1 2 3 4 5 DK	
	Access to Seeds or Machinery	1 2 3 4 5 DK	
	Adjacent land owners	1 2 3 4 5 DK	
	Highway	1 2 3 4 5 DK	
	Railroad	1 2 3 4 5 DK	
	Decrease in rainfall	1 2 3 4 5 DK	
	Decreasing soil quality	1 2 3 4 5 DK	

1 = Very Poor/Unimportant/Low
5 = Very good/Important/High
DK = Don't know

Table 11
Modern ranches survey instrument.

Location: ______________________________

Date: ______________________

Survey #:________

Table 11. Continued

SECTION I: Household Information

Household Members (Note: “household” is defined as a group of people, connected by family or kinship ties, in which individuals EITHER (a) live in the same dwelling(s) for most of the year or (b) live outside the dwelling but provide regular income or sustenance to the household, such as remittances)

No.	***Age***	***Gender***	***Relation to respondent***	***Birthplace/ Citizenship***	***Current Residence***	***Marital Status***	***Income Earner or Sustenance Provider***	***Remittances***
1		___Male ___Female	Respondent			___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
2		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
3		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
4		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
5		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
6		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No

Table 11. Continued

SECTION II: Livestock

Animal/Product	*Number*	*Area (hectares)*	*Forage*	*Labor (%)*	*Slaughter (Harvest)*		*Destination (%)*		
					Amount (mT/ha; liters/day; eggs or chicks/day)	*Selling price ($USD/mT; $USD/L; SUSD/chick or egg)*	*Household*	*Family/Friends*	*Market*
1a. Chicken (eggs)			___Purchased feed ___Scraps	__Household __Hired					___Consumer ___Intermediary
1b. Chicken (meat)			___Purchased feed ___Scraps	__Household __Hired					___Consumer ___Intermediary
2. Pigs			___Purchased feed ___Scraps	__Household __Hired					___Consumer ___Intermediary
3a. Cattle (milk)			___Purchased feed ___Pasture ___Crops ___Forest	__Household __Hired					___Consumer ___Intermediary
3b. Cattle (meat)			___Purchased feed ___Pasture ___Crops ___Forest	__Household __Hired					___Consumer ___Intermediary
4. Goats			___Purchased feed ___Scraps ___Browse	__Household __Hired					___Consumer ___Intermediary
5. Other ______			___Purchased feed ___Scraps ___Browse	__Household __Hired					___Consumer ___Intermediary

Did any government incentives or policies (or laws) influence your decision to graze cattle instead of growing crops? List reasons and sort in order of importance.

____

____

Did price influence your decision? ______YES ______NO

Did soil quality (or lack of) influence your decision? ______YES ______NO

Did precipitation (or lack of) influence your decision? ______YES ______NO

Are you considering growing crops in the future? ______YES ______NO

Why or why not? ____

Table 11. Continued

Section III: Credit and Technology

	Credit (%)	***Technology***		
2007/08		***Type (%)***	***Equipment (#)***	***Seeds***
1	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
2	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
3	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
4	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
2002/03				
1	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
2	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
1994/95				
1	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
2	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
1974/75				
1	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N
2	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Silos	__________Origin Chemically treated? ___Y ___N

Terms of Loan:

Harvest: ____

Interest Rate: ____

Table 11. Continued

Section IV: Threats and Opportunities

Rank	***Threats/Opportunities***	***Weight***	***Explanation***
	Agrarian Reform (Law Nº 3545)	1 2 3 4 5 DK	
	Prevention/control of forest fires	1 2 3 4 5 DK	
	Loan/Credit Acquisition	1 2 3 4 5 DK	
	Access to Seeds or Machinery	1 2 3 4 5 DK	
	Adjacent land owners	1 2 3 4 5 DK	
	Highway	1 2 3 4 5 DK	
	Railroad	1 2 3 4 5 DK	
	Decrease in rainfall	1 2 3 4 5 DK	
	Decreasing soil quality	1 2 3 4 5 DK	

1 = Very Poor/Unimportant/Low
5 = Very good/Important/High
DK = Don’t know

Table 12
Hybrid producers survey instrument.

Location: ______________________________

Date: ______________________

Survey #:________

Table 12. Continued

SECTION I: Household Information

Household Members (Note: “household” is defined as a group of people, connected by family or kinship ties, in which individuals EITHER (a) live in the same dwelling(s) for most of the year or (b) live outside the dwelling but provide regular income or sustenance to the household, such as remittances)

No.	***Age***	***Gender***	***Relation to respondent***	***Birthplace/ Citizenship***	***Current Residence***	***Marital Status***	***Income Earner or Sustenance Provider***	***Remittances***
1		___Male ___Female	Respondent			___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
2		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
3		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
4		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
5		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No
6		___Male ___Female				___Single ___Married ___Cohabit ___Widow ___Divorce/Sep.	___Yes ___No	___Yes ___No

Table 12. Continued

Section II: Summer Cultivation (not adjacent to house)

		Area		*Crop Cycle (month)*					*Harvest*		*Labor*	*Harvest Destination (%)*		
2007/08	***Crop/Animal Type***	***Hectares***	***% Irrigated***	***Soil Prep***	***Plant***	***Fertilizer/ Pesticide***	***Harvest***	***Fallow***	***Amount (mT/ha)***	***Selling price ($USD/mT)***	***Labor (%)***	***Household***	***Market***	***Others***
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
3											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
4											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2002/03														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
1994/95														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
1974/75														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op

Why did you change main crops?

2002-2007: ____

1994-2002: ____

1974-1994: ____

Did any government incentives or policies (or laws) influence crop type? ______ YES ______ NO; if yes, list reasons and sort in order of importance.

____

____

Did price influence a change in crop? ______ YES ______ NO

Do you (or did you) cultivate crops in winter?

Table 12. Continued

Section III: Winter Cultivation (not adjacent to house)

		Area		*Crop Cycle (month)*					*Harvest*		*Labor*	*Harvest Destination (%)*		
2007/08	***Crop/Animal Type***	***Hectares***	***% Irrigated***	***Soil Prep***	***Plant***	***Fertilizer/ Pesticide***	***Harvest***	***Fallow***	***Amount (mT/ha)***	***Selling price ($USD/mT)***	***Labor (%)***	***Household***	***Market***	***Others***
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
3											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
4											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2002/03														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
1994/95														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
1974/75														
1											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op
2											___Household ___Hired		___Consumer ___Intermediary	___TNC ___Co-op

Why did you change main crops?

2002-2007: ____

1994-2002: ____

1974-1994: ____

Did any government incentives or policies (or laws) influence crop type? ______ YES ______ NO; if yes, list reasons and sort in order of importance.

____

____

Did price influence a change in crop? ______ YES ______ NO

Table 12. Continued

SECTION IV: Livestock

Animal/Product	*Number*	*Area (hectares)*	*Forage*	*Labor (%)*	*Slaughter (Harvest)*		*Destination (%)*		
					Amount (mT/ha; liters/day; eggs or chicks/day)	*Selling price ($USD/mT; $USD/L; SUSD/chick or egg)*	*Household*	*Family/Friends*	*Market*
1a. Chicken (eggs)			___Purchased feed ___Scraps	__Household __Hired					___Consumer ___Intermediary
1b. Chicken (meat)			___Purchased feed ___Scraps	__Household __Hired					___Consumer ___Intermediary
2. Pigs			___Purchased feed ___Scraps	__Household __Hired					___Consumer ___Intermediary
3a. Cattle (milk)			___Purchased feed ___Pasture ___Crops ___Forest	__Household __Hired					___Consumer ___Intermediary
3b. Cattle (meat)			___Purchased feed ___Pasture ___Crops ___Forest	__Household __Hired					___Consumer ___Intermediary
4. Goats			___Purchased feed ___Scraps ___Browse	__Household __Hired					___Consumer ___Intermediary
5. Other ______			___Purchased feed ___Scraps ___Browse	__Household __Hired					___Consumer ___Intermediary

Did any government incentives or policies (or laws) influence your decision to graze cattle instead of growing crops? List reasons and sort in order of importance.

____

____

Did price influence your decision? ______YES ______NO

Did soil quality (or lack of) influence your decision? ______YES ______NO

Did precipitation (or lack of) influence your decision? ______YES ______NO

Are you considering growing crops in the future? ______YES ______NO

Why or why not? ____

Table 12. Continued

Section V: Credit and Technology (Crops)

	Credit (%)	***Technology***		
2007/08		***Type (%)***	***Equipment (#)***	***Seeds***
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
2002/03				
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
1994/95				
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
1974/75				
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N

Terms of Loan:

Harvest: ____

Interest Rate: ____

Table 12. Continued

Section VI: Credit and Technology (Livestock)

	Credit (%)	***Technology***		
2007/08		***Type (%)***	***Equipment (#)***	***Seeds***
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
2002/03				
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
1994/95				
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
1974/75				
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N
	_____Government ______Firms _____Cooperatives ______Self _____Colony	______Conventional ______Direct Tillage	______Tractors ______Trucks ______Cooling Tank	___________Origin Chemically treated? ___Y ___N

Terms of Loan:

Harvest: ____

Interest Rate: ____

Table 12. Continued

Section VII: Threats and Opportunities

Rank	***Threats/Opportunities***	***Weight***	***Explanation***
	Agrarian Reform (Law Nº 3545)	1 2 3 4 5 DK	
	Prevention/control of forest fires	1 2 3 4 5 DK	
	Loan/Credit Acquisition	1 2 3 4 5 DK	
	Access to Seeds or Machinery	1 2 3 4 5 DK	
	Adjacent land owners	1 2 3 4 5 DK	
	Highway	1 2 3 4 5 DK	
	Railroad	1 2 3 4 5 DK	
	Decrease in rainfall	1 2 3 4 5 DK	
	Decreasing soil quality	1 2 3 4 5 DK	

1 = Very Poor/Unimportant/Low
5 = Very good/Important/High
DK = Don't know

Table 13
Respondents according to type of producers.

Type of Producer								
Crop-Only Producer				Animal-Only Producer		Hybrid Producer		
2-1*	2-5	2-9	2-13	5-1	5-5	6-1	6-5	6-9
2-2	2-6	2-10	2-14	5-2	5-6	6-2	6-6	6-10
2-3	2-7	2-11	2-15	5-3 (a, b)	5-7	6-3	6-7	
2-4	2-8	2-12		5-4	5-8	6-4	6-8	

*This table uses a coding system in which the first number corresponds to a producer type and second number according to amount of producers. The system is used to protect the anonymity of producers.

Table 14
Age and race of respondents.

Age					Race						
30-44	45-59		60-79	N.A.	Latino		Hispanic		Indigenous	White	N.A.
2-4	2-2	5-3 (a,b)	2-1	2-10	2-2	5-3 (a.b)	2-2	5-3 (a.b)	2-2	2-3	2-10
2-6	2-3	5-4	6-6	2-13	2-6	5-4	2-6	5-4	2-12	2-4	2-13
2-9	2-5	5-7	6-7	5-5	2-7	5-7	2-7	5-8	2-14	2-5	5-5
2-12	2-7	6-1		5-6	2-8	5-8	2-8	6-3		2-15	5-6
2-14	2-8	6-2			2-9	6-3	2-9	6-5		6-1	
5-8	2-11	6-3			2-11	6-5	2-11	6-8		6-2	
6-9	2-15	6-4			5-1	6-8	5-1	6-9		6-4	
	5-1	6-5			5-2	6-8	5-2			6-6	
	5-2	6-8								6-7	

Table 15

Birthplace of respondents.

Birth (by country)													
Bolivia (Department)						Argentina	Belize	Brazil	Canada	Mexico	U.K.	U.S.A	N.A.
Beni	*Cochabamba*	*La Paz*	*Potosi*	*Santa Cruz*									
2-14	2-2	6-8	2-9	2-1	5-2	2-6	2-15	5-7	6-1	2-3	6-7	6-2	2-10
	6-9			2-4	5-3 (a,b)		6-4			2-5			2-13
				2-7	5-4					6-6			5-5
				2-8	5-8								5-6
				2-11	6-3								
				2-12	6-5								
				5-1									

Table 16
Farm size (in hectares) of respondents.

Farm Size (ha)								
Small (< 50)	Medium (51-500)				Large (> 501)			
2-2	2-4	2-15	5-4	6-9	2-1	2-13	5-7	6-4
2-3	2-6	5-1	5-5		2-7	2-14	5-8	6-5
2-5	2-8	5-2	6-1		2-10	5-3 (b)	6-2	6-7
2-12	2-9	5-3 (a)	6-6		2-11	5-6	6-3	6-8

Table 17

Farm location of respondents. All categories are based on classification scheme used by CAO.

Location									
Tierras Bajas Integrated Zone				Tierras Bajas Expansion Zone				Brazilian Shield	Pantanal
Humid Northeast	*Intermediate Northeast*	*Intermediate Central*	*Dry South*	*Humid North*	*Intermediate North*	*Pailón-Tunás*	*South Pailón*	*South*	*North*
2-9	2-7	2-2	2-3	2-5	2-1	2-10	5-6	5-3 (a)	5-8
6-3	2-11	2-6	2-8	6-6	2-4	2-15		5-3 (b)	
6-5		2-12	5-1		2-13	5-5			
		5-2	6-1		2-14				
		5-4	6-7		5-7				
		6-9	6-8		6-2				
					6-4				

Table 18

Crop production according to date, farm size, and cropping regime.

	2007/08								
	< 50 ha			51-500 ha			> 500 ha		
	Double	*Summer*	*Winter*	*Double*	*Summer*	*Winter*	*Double*	*Summer*	*Winter*
Soybean		2-3	6-7	2-9	2-1		2-7	2-10	
				2-14	2-4		6-3	2-13	
					2-5			6-5	
					2-15			6-8	
					6-2				
					6-4				
					6-6				
Sunflower			2-4			2-1			2-10
			2-9			2-4			2-13
						6-4			
						6-8			
Wheat			2-9			2-1			2-13
						6-5			
						6-8			
Sorghum		2-3	2-4		6-6	2-1	2-10		2-13
		2-11	2-5			2-15			6-5
		6-1	2-8			6-2			
						6-3			
						6-4			
						6-6			
						6-8			
Maize	2-15	2-2	6-6	2-9	2-1	2-14		2-13	
		2-11			6-7				
		2-12							
		6-9							
Sugar	2-8			2-11					
	6-9			6-5					
Cotton								2-13	
Sesame		2-8	6-7						
		6-9							
Rice		2-9			2-6				
		2-11			2-7				
		2-12			6-2				
Peanuts		2-2							
		2-12							

Table 18. Continued

	2006/07								
	< 50 ha			51-500 ha			> 500 ha		
	Double	*Summer*	*Winter*	*Double*	*Summer*	*Winter*	*Double*	*Summer*	*Winter*
Soybean		2-3	6-7	2-9	2-1		2-7	2-10	
				2-14	2-4		6-3	2-13	
					2-15			6-5	
					6-4			6-8	
					6-6				
Sunflower			2-9			2-1			2-10
						6-4			2-13
						6-8			
Wheat			2-9			2-1			2-13
						6-5			
						6-8			
Sorghum		2-11	2-5		6-6	2-1	2-10		2-13
		6-1	2-8			2-15			2-10
						6-3			6-5
						6-4			
						6-6			
						6-8			
Maize	2-15	2-2	6-6		2-1	2-14		2-13	
		2-5			6-7				
		2-11							
		6-9							
Sugar	2-8			2-11					
	6-9			6-5					
Cotton		2-3						2-13	
Sesame		2-8	6-7						
		6-9							
Rice		2-9			2-6				
		2-11			2-7				
					6-3				
Peanuts		2-2							

Table 18. Continued

	2002/03								
	< 50 ha			51-500 ha			> 500 ha		
	Double	*Summer*	*Winter*	*Double*	*Summer*	*Winter*	*Double*	*Summer*	*Winter*
Soybean		2-3	6-7	2-9	2-1		2-7	2-13	
		2-5		2-14	2-15		6-3	6-8	
					6-4				
					6-6				
					6-9				
Sunflower			2-9			2-1			2-13
						2-4			
						6-4			
						6-8			
Wheat			2-9		2-4	2-1			2-13
						6-3			
						6-5			
						6-8			
Sorghum		2-11	2-4		6-6	2-1			2-13
		6-1	2-5			2-15			2-10
			2-8			6-3			6-5
						6-4			
						6-6			
						6-8			
Maize	2-15	2-2	6-6		2-1	2-14		2-10	
		2-11			6-7	6-3		2-13	
Sugar	2-8			2-11					
Cotton		2-3						2-13	
Sesame		2-8	6-7						
Rice		2-9			2-6			6-5	
		2-11			2-7				
Peanuts									

Table 18. Continued

	1994/95								
	< 50 ha			51-500 ha			> 500 ha		
	Double	*Summer*	*Winter*	*Double*	*Summer*	*Winter*	*Double*	*Summer*	*Winter*
Soybean		2-3		2-9	2-1		2-7	2-13	
				2-14	2-15			6-8	
					6-4				
					6-6				
					6-9				
Sunflower			2-9			2-1			2-13
						6-4			
						6-8			
Wheat			2-9		2-4	2-1			2-13
						6-5			
						6-6			
						6-8			
Sorghum		2-11	2-8			2-1			2-13
						2-15			2-10
						6-4			6-5
						6-8			
Maize	2-15	2-2	6-6			2-14		2-10	
		2-11						2-13	
		6-4							
Sugar	2-8			2-11					
Cotton		6-6						2-13	
Sesame		2-3							
		2-8							
Rice		2-9			2-7				
		2-11							
Peanuts									

	1974/75								
	< 50 ha			51-500 ha			> 500 ha		
	Double	*Summer*	*Winter*	*Double*	*Summer*	*Winter*	*Double*	*Summer*	*Winter*
Soybean									
Sunflower									
Wheat						6-6			
Sorghum									
Maize									
Sugar									
Cotton		6-6							
Sesame									
Rice									
Peanuts									

Table 19
Animal production according to date, farm size, and number of head.

				2007/08					
	≤ 50 ha			51-500 ha			≥ 500 ha		
	0-499	*500-999*	*1,000+*	*0-499*	*500-999*	*1,000+*	*0-499*	*500-999*	*1,000+*
Dairy Cattle	5-4			5-1	6-7				
	6-1			5-2					
	6-9			6-5					
Meat Cattle	5-3 (a)			5-2	5-4	5-8	5-3 (b)		5-6
	6-1			6-4	6-3				5-7
				6-6					6-2
				6-9					6-5
									6-8
Chickens	6-1		5-5						
			6-9						
Other Animals †	5-3 (b)			6-8					
	6-1								

† Other Animals includes sheep, pigs, and buffalo

				2006/07					
	≤ 50 ha			51-500 ha			≥ 500 ha		
	0-499	*500-999*	*1,000+*	*0-499*	*500-999*	*1,000+*	*0-499*	*500-999*	*1,000+*
Dairy Cattle	5-4			5-1	6-7				
	6-1			5-2					
	6-9			6-5					
Meat Cattle	5-3 (a)			5-2	5-4		5-3 (b)		5-6
	6-1			6-4	6-3				5-7
				6-6					6-2
				6-9					6-5
									6-8
Chickens	6-1		5-5						
			6-9						
Other Animals †	5-3 (b)								
	6-1								

† Other Animals includes sheep, pigs, and buffalo

					2002/03				
	< 50 ha			51-500 ha			> 500 ha		
	0-499	*500-999*	*1,000+*	*0-499*	*500-999*	*1,000+*	*0-499*	*500-999*	*1,000+*
Dairy Cattle	5-4			5-1	6-7				
	6-1			5-2					
	6-9			6-5					
Meat Cattle	6-1			5-2	5-4				5-6
				6-4	6-3				5-7
				6-6					6-2
				6-9					6-5
									6-8
Chickens	6-1		5-5						
			6-9						
Other Animals †	6-1								
	5-4			5-1	6-7				

† Other Animals includes sheep, pigs, and buffalo

					1994/95				
	< 50 ha			51-500 ha			> 500 ha		
	0-499	*500-999*	*1,000+*	*0-499*	*500-999*	*1,000+*	*0-499*	*500-999*	*1,000+*
Dairy Cattle	5-4			5-1					
	6-1			5-2					
	6-9			6-5					
				6-7					
Meat Cattle	6-1			5-2	5-4				5-6
				6-6	6-3				5-7
				6-9					6-2
									6-5
									6-8
Chickens	6-1		6-9						
Other Animals †	6-1								

† Other Animals includes sheep, pigs, and buffalo

Table 19. Continued

	1974/75								
	< 50 ha			51-500 ha			> 500 ha		
	Double	*Summer*	*Winter*	*Double*	*Summer*	*Winter*	*Double*	*Summer*	*Winter*
Dairy Cattle				6-7					
Meat Cattle									
Chickens			5-1						
Other Animals †									

† Other Animals includes sheep, pigs, and buffalo

Table 20

Rationale for Crop or Animal Choice and Change (Part I).

	Minimize Risks		**Price/Market**			**Precipitation**				**Requires Less Input ╫**				**Soil Tillage/Rotation †**			**Disease**	**Government Policy ±**			
	Choice	Switch	Choice	Switch		Choice		Switch		Choice		Switch		Choice	Switch		Switch	Choice		Switch	
		↑	+	↑	↓	+	-	↑	↓	↑	↓	↑	↓	+	↑	↓		↑	↓	↑	↓
Soybean		6-5 6-7 6-9	2-1 2-5 2-9 2-15 6-3 6-5 6-8	2-4 2-7 6-4 6-7				2-7(-) 2-10(+)	6-5(+)	2-3		6-6		2-3 2-9 2-13	2-7						2-1
Sunflower		2-1			2-4									2-1 2-4 2-10 6-8							2-9
Wheat			2-1 6-5		2-4				2-15(-) 6-3(-) 6-6(-)					2-1 2-9 6-8		2-4					
Sorghum			2-1 2-11 6-5						2-1(+)	6-5				2-1 2-4 2-8 2-10 2-15 6-3 6-8							2-1
Maize			2-1 2-2 2-9 2-11	5-8	6-4	5-8			2-10(-)				6-4	2-5 2-9 2-13 2-15	2-9			2-2			2-1
Sugar			2-11					6-5(+)		2-8											
Cotton			2-13		2-3 6-6								6-6			2-3 2-15					
Sesame			2-8 6-10													2-3					
Rice			2-6 2-9 2-11	2-7 6-5				2-6(-) 2-7(-)	6-3(-) 6-5(+)					2-9	2-7						2-6
Peanuts			2-2 2-12															2-2			
Other Crops*			2-2 2-8 2-9	5-8		2-12		2-9(+) 5-8(-)						2-12 6-9				2-2			

Table 20. Continued

	Minimize Risks		Price/Market			Precipitation				Requires Less Input ╫				Soil Tillage/Rotation †			Disease	Government Policy ±			
	Choice	Switch	Choice	Switch		Choice		Switch		Choice		Switch		Choice	Switch		Switch	Choice		Switch	
		↑	+	↑	↓	+	-	↑	↓	↑	↓	↑	↓	+	↑	↓	↓	↑	↓	↑	↓
Dairy Cattle			6-5 6-7							6-1 6-7											
Meat Cattle	5-3 5-8 6-4 6-6 6-8 6-9		5-3 5-6 6-2 6-5			5-3 6-3	5-6		2-7(-)	6-1											
Chickens			5-5														5-1				
Other Animals**	5-3 6-1 6-7		5-3			5-3															

↑ To
↓ From
\+ Increase
\- Decrease
* Chia Seeds, Citrus, Tomatoes, Watermelon, Beans
** Sheep, Pigs & Buffalo
╫ Labor, time, and chemicals (fertilizer, herbicide, pesticide)
† Maintain soil fertility, moisture, composition & keeps pests/disease to a minimum; zero tillage system
± Includes support through funding & training as well as export limitation

Table 21
Rationale for Crop or Animal Choice and Change (Part II).

	Quantity			Benefits Other Crops		Animal Feed		Prevent Secondary Growth			Pleasure	Tradition		Subsistence			
	Choice	Switch	Switch	Choice	Switch	Choice	Switch	Choice	Switch		Choice	Choice	Switch	Choice		Switch	
	+	↑	↓	+	↑	+	↑		↑	↓				+	-	↑	↓
Soybean								6-2				2-14					
Sunflower												2-1					
Wheat												2-1					
Sorghum	6-5	6-4				6-1 6-2 6-7	6-6					2-1 6-11	5-4				
Maize				2-1 2-2		2-8 2-15 6-7 6-9						2-2 2-11 2-14	5-4	2-2			
Sugar												2-8 2-11 6-9					
Cotton												2-13					
Sesame																	
Rice								6-2				2-11		2-12			
Peanuts												2-2		2-2			
Other Crops*												2-2 2-8 2-12		2-2			
Dairy Cattle												5-1 5-2 5-4 6-1					
Meat Cattle												5-2 5-3 5-4 5-7 5-8 6-1 6-6					
Chickens																	
Other Animals**											6-7	5-2 5-3		5-3			

↑ To
↓ From
\+ Increase
\- Decrease
* Chia Seeds, Citrus, Tomatoes, Watermelon, Beans
** Sheep, Pigs & Buffalo

Table 22
Threats/Problems (-) and Benefits/Opportunities (+).

	Law Nº 3545		Resolution #93/2007		Access to Credit		Access to Equipment		Corredor Bioceánico		Precipitation		Soil Quality	
Ranking	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)
1	2-13 5-7			5-7	6-3		5-4 6-3			1-11	5-2	6-3		6-3 6-4
2	2-1 5-8	2-12	6-1 6-3		2-6 5-1 6-4 6-9		6-4 6-9				2-3 5-1 5-6 5-8 6-2 6-4 6-7		2-12 2-14 5-1 5-4 6-7	2-4 5-2 6-2
3	2-5		2-11 5-8 6-4	2-1	6-8					5-3	2-4 2-8 2-9 2-10 2-11 2-14 5-3 6-1		2-3 2-11 6-5 6-9	
4	2-7 5-2 6-3 6-4 6-5		2-7 2-13 5-2 5-4		2-1 2-12 2-14 6-1		2-1 2-2 2-14 5-3			5-8	2-5 2-12 6-5 6-6 6-9		2-9 6-1	2-2
5	2-6 2-9 2-10 2-11 2-14 2-15 5-1 5-3 5-4 6-2 6-7 6-8	2-2	2-9 2-14 2-15 5-3 6-2	2-2 2-6 6-8 6-9	5-3 6-7		6-7				2-6 2-7 5-7		2-6	2-15
Note: Rankings #6, #7, and #8 are considered neutral.														
6	2-3 2-4 2-8 5-5 5-6 6-1 6-6 6-9		2-5 2-8 2-12 5-5 5-6		2-3 2-4 2-5 2-7 2-8 2-9 2-10 2-11 2-13	2-15 5-2 5-4 5-5 5-8 6-2 6-5 6-6	2-3 2-4 2-5 2-7 2-8 2-9 2-10 2-11 2-13	2-15 5-2 5-5 5-8 6-2 6-5 6-6 6-8	2-3 2-4 2-5 2-6 2-8 2-10 2-14	2-15 5-4 5-5 6-2 6-6 6-8	2-1 2-2 2-15 5-4 5-5		2-1 2-5 2-7 2-8 2-10 5-5 5-6 5-7 5-8	
7			2-3 2-4 6-5 6-6		5-7		5-1		5-6		2-13 6-8		2-13 5-3 6-6 6-8	
8			2-10 5-1 6-7		5-6		2-10 2-12 5-6 5-7 6-1		2-1 2-2 2-7 2-9 2-11 2-12 2-13 5-1	5-2 5-7 6-1 6-3 6-4 6-5 6-7 6-9				

1 Very Important/Low
2 Poor/Low-Medium
3 Fair/Semi-important/Medium
4 Good/Medium-High
5 Very Good/Important/High
6 No Opinion or Problem
7 Does Not Know
8 Does Not Apply

Table 23

Organization Information, Part I: Type, Coverage/Distribution, Years in Operation, and Operational Status.

	Type:							Coverage/Distribution:				Source of Funding:					Years in Operation:						Status (2009):	
	Producer:		State	NGO	Finance	Trade	Comm.	Global	National	Dep	Local	Fees	Donation	Agency	State	Internal	0-5	6-10	11-15	16-20	21 +	NA	Active	Defunct
	Fed	Ass																						
ADEPA		X							X			X							X				X	
AGASAJO	X										X	X									X		X	
ANAPO		X								X			X							X			X	
ASFI			X		X				X						X		X						X	
ASOFIN			X		X				X						X			X					X	
ASPAR		X								X		X							X				X	
BCB					X				X			X									X		X	
BDP					X			X				X										X	X	
BID					X			X								X					X		X	
BTAM			X					X							X					X				X
CAF					X			X								X					X		X	
CAN																							X	
CAO									X						X						X		X	
CBF			X		X				X					X	X					X				X
CIAGRO							X	X								X					X		X	
CI				X				X					X	X							X		X	
CIAT				X				X					X	X	X						X		X	
CIFOR				X				X					X	X	X					X			X	
CIPCA				X					X				X								X		X	
CONFEAGRO	X		X						X						X		X						X	
CORDECRUZ			X							X					X					X				X
CUMAT				X					X				X	X	X							X		X
FAN				X							X				X						X		X	
FCBC				X						X			X	X				X					X	
F.C.S.C.	X									X		X									X		X	
FEGASACRUZ	X									X					X	X					X		X	
FIDEPLE	X									X		X									X		X	
FONDESIF			X		X				X						X									
FUNDACRUZ				X						X			X	X					X				X	
GTZ			X					X							X				X				X	
IADB					X			X								X					X		X	
INRA			X						X						X							X	X	
ME & FP			X		X				X						X								X	
MERCOSUR						X		X								X				X			X	
MCC				X				X					X	X							X		X	
MDP			X						X						X						X		X	
MDRA & MA			X						X						X						X		X	
MH & E			X						X						X						X		X	
MMA & A			X						X						X						X		X	
MNK				X					X					X							X		X	
PROMASOR		X								X		X	X	X							X		X	
SERNAP			X						X						X			X					X	
SRNA			X						X						X					X			X	
YPFB			X						X					X	X	X					X		X	

Table 24

Organization Information, Part II: Work/Service.

	Work/Service: Markets/ Price		State Policy	Land Titling/ Classification	Crop/ Animal Development	Credit/ Funding	Infrast-ucture	Organization Cooperation	Fuel Availability/Costs	Consumer Products	Gender Issues	Urban Dev.	Rural Dev.	Health		Biodiversity	Climate	Ext. Service	PA's/ Eco-tourism
	Ext.	Int.												Human	Crop/ Animal				
ADEPA	X	X						X	X										
AGASAJO	X	X		X	X			X											
ANAPO	X	X		X	X		X	X	X									X	
ASFI						X													
ASOFIN						X		X											
ASPAR	X	X		X	X	X	X	X										X	
BCB						X													
BDP								X											
BID						X													
BTAM					X			X										X	
CAF						X													
CAN																			
CAO	X	X		X	X	X	X	X	X						X			X	
CBF					X											X			
CIAGRO										X								X	
CI								X								X		X	
CIAT					X			X							X	X		X	
CIFOR								X								X	X	X	
CIPCA								X			X			X					
CONFEAGRO		X		X		X		X										X	
CORDECRUZ							X	X				X						X	
CUMAT				X															
FAN																X	X	X	X
FCBC								X								X			X
F.C.S.C.	X			X	X	X		X	X										
FEGASACRUZ	X	X		X	X	X		X		X					X			X	
FIDEPLE	X	X		X	X	X		X		X					X			X	
FONDESIF													X						
FUNDACRUZ					X										X			X	
GTZ					X								X						
IADB						X													
INRA				X									X						
ME & FP			X																
MERCOSUR	X	X	X																
MCC				X	X						X	X	X	X	X			X	
MDP			X	X			X	X				X	X					X	
MDRA & MA	X	X	X	X				X					X			X	X	X	X
MH & E	X	X	X				X	X	X										
MMA & A			X					X				X	X			X	X		X
MNK								X								X	X		X
ODA							X	X	X			X	X	x				X	
PROMASOR				X	X														
SERNAP			X													X	X	X	X
SRNA			X	X									X						
YPFB	X	X	X																

Table 25
Organization Information, Part III: Major Concerns and Conservation/Protection.

	Major Concerns:							Conservation/Protection:						
	Funding	Land Titling/ Security	Regional/ National Trade	Fuel Cost/ Availability	Export Growth	Agricultural Production	Social	Agricultural Intensification	Sustainable Development	Forest	Fauna	Social	Windbreaks/ Crop Rotation	None
ADEPA	X	X		X	X	X		X						
AGASAJO	X	X				X								
ANAPO	X	X	X	X	X	X		X					X	
ASFI														X
ASOFIN														X
ASPAR	X		X		X	X		X						
BCB	X		X											X
BDP	X													X
BID	X													X
BTAM						X	X	X						
CAF	X								X					
CAN														
CAO	X	X	X	X	X	X	X	X	X				X	
CBF						X		X	X	X				
CIAGRO														X
CI										X	X			
CIAT						X		X	X	X				
CIFOR									X	X	X			
CIPCA							X		X					
CONFEAGRO		X	X	X	X		X					X		
CORDECRUZ	X						X							X
CUMAT									X					
FAN										X	X			
FCBC	X									X	X			
F.C.S.C.	X	X	X	X	X	X		X						
FEGASACRUZ		X				X			X				X	
FIDEPLE	X	X			X	X	X		X					
FONDESIF	X													X
FUNDACRUZ						X		X	X					
GTZ						X	X		X					
IADB	X													X
INRA		X					X							X
ME & FP	X													
MERCOSUR			X											X
MCC	X					X	X	X	X			X	X	
MDP														
MDRA & MA		X		X	X		X		X	X	X	X		
MH & E		X	X	X	X		X		X	X				
MMA & A				X	X				X	X	X	X		
MNK									X	X	X			
ODA	X		X		X		X					X		
PROMASOR	X													X
SERNAP									X	X	X			
SRNA							X					X		
YPFB	X		X	X	X									X

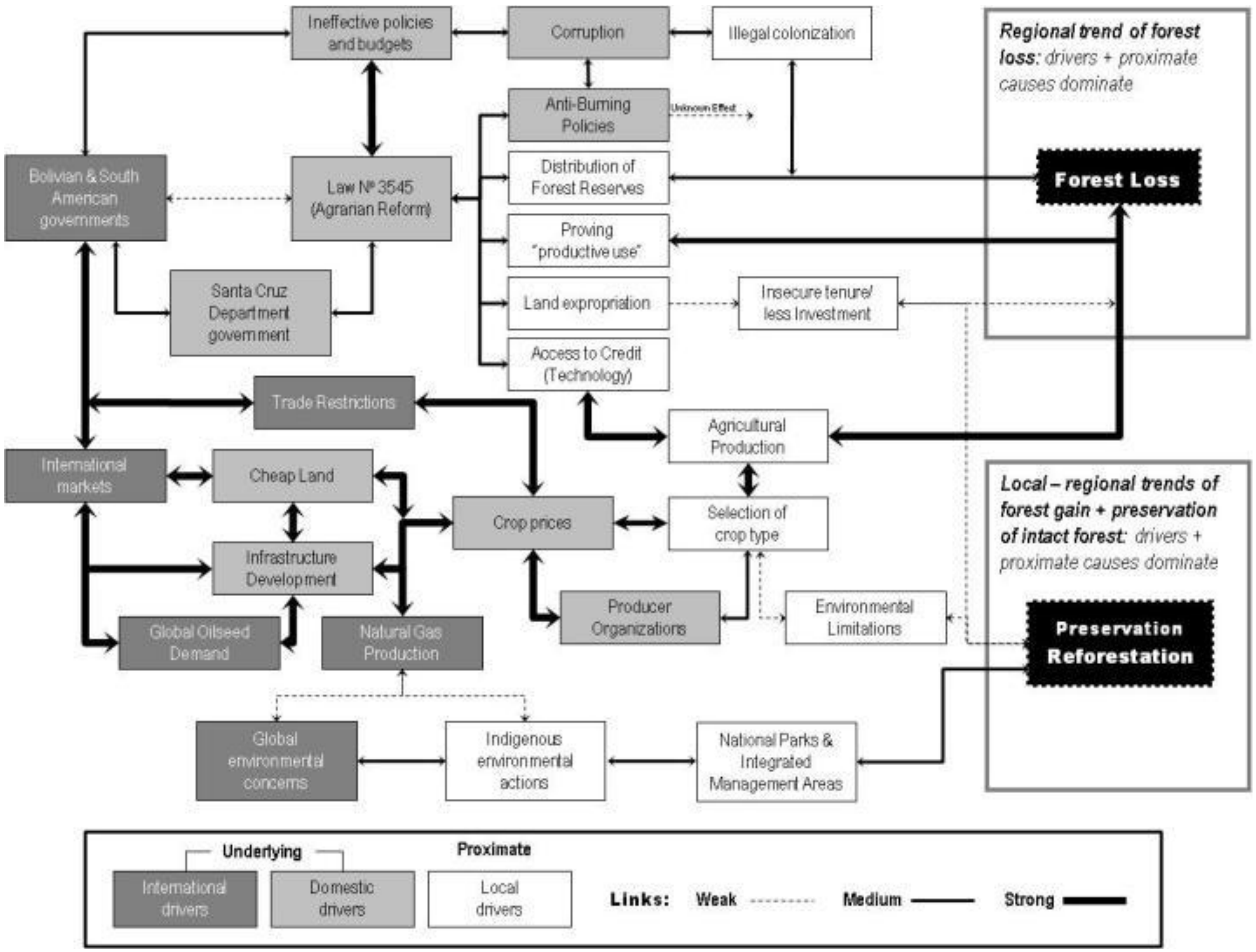


Figure 41. Conceptual model of the driving forces of LULCC.

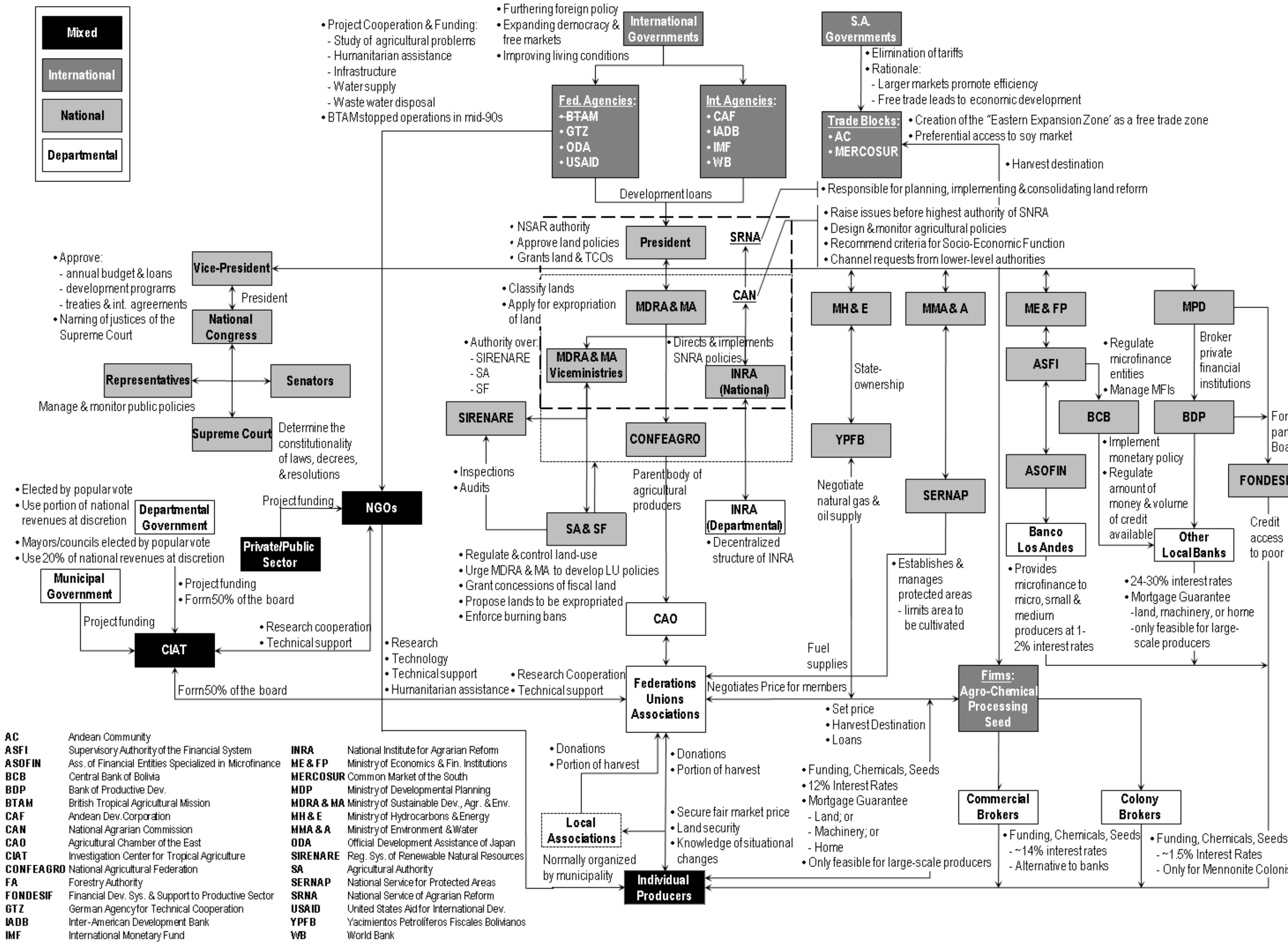


Figure 42. Organizational structure of actors.

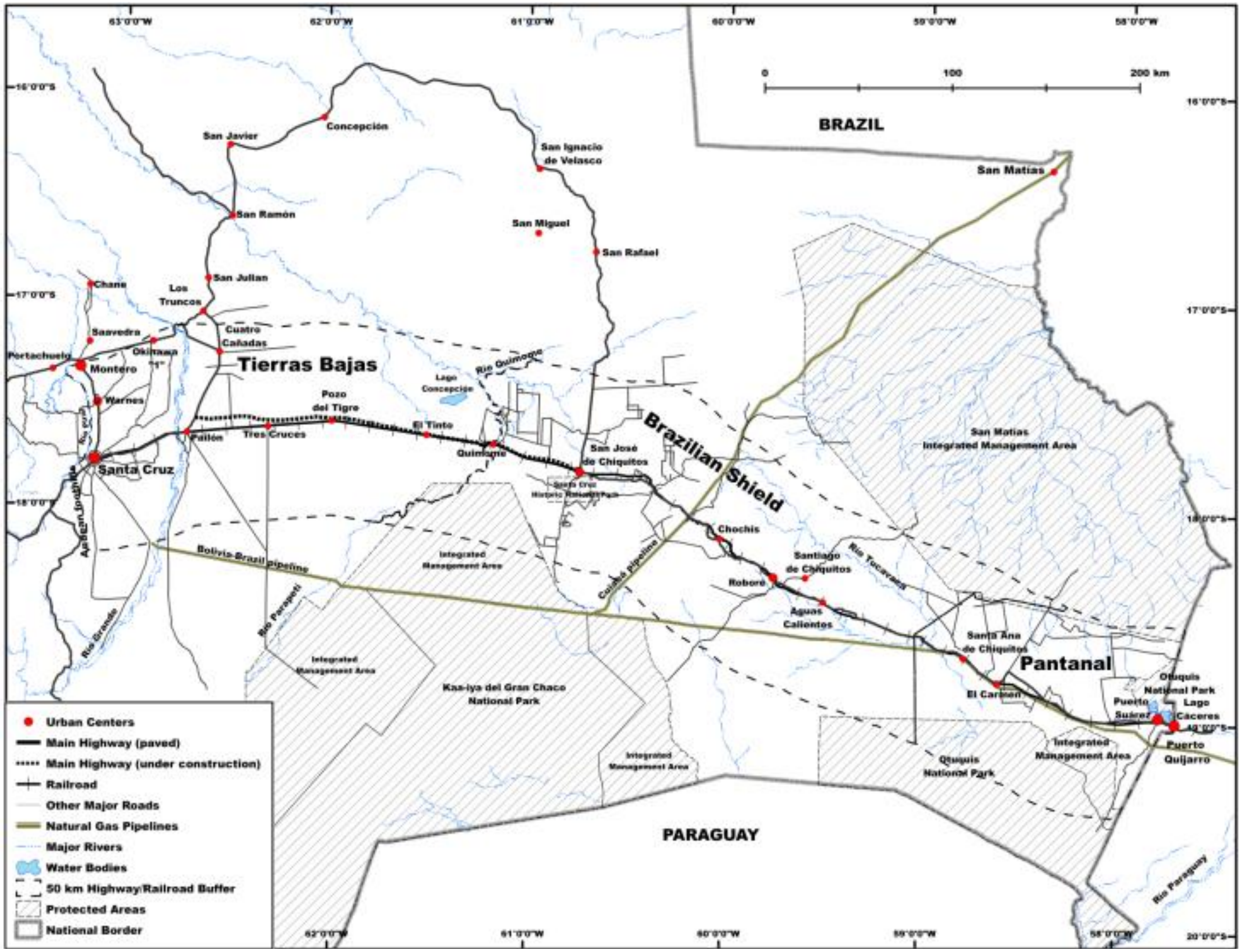


Figure 43. The Corredor Bioceánico of southeastern Bolivia. A 50-km buffer north and south of the main highway (dashed lines) has been used to demarcate the study area. Internal boundaries are defined by the Andean foothills and the Río Piraí to the west, Río Quimome and western ranges of the Brazilian Shield in the center and the Bolivia-Brazil border in the east (see text).

Table 26

Comparison of CBERS, IRS and SPOT sensors.

CBERS-1, -2 and -2B			IRS P6 (RESOURCESAT-1) LISS 3			SPOT 1, 2 and 3 HRV		
Band	*Spectral Res.*	*Spatial Res. (CCD)*	*Band*	*Spectral Res.*	*Spatial Res.*	*Band*	*Spectral Res.*	*Spatial Res.*
Blue	0.45-0.52 µm	20 x 20 m	Blue	--	--	Blue	--	--
Green	0.52-0.59 µm	20 x 20 m	Green	0.52-0.59 µm	24 x 24 m	Green	0.50-0.59 µm	20 x 20 m
Red	0.63-0.69 µm	20 x 20 m	Red	0.62-0.68 µm	24 x 24 m	Red	0.61-0.68 µm	20 x 20 m
NIR	0.77-0.89 µm	20 x 20 m	NIR	0.77-0.86 µm	24 x 24 m	NIR	0.79-0.89 µm	20 x 20 m
PAN	0.51-0.73 µm	10 x 10 m	PAN	--	--	PAN	0.51-0.73 µm	10 x 10 m
MIR	--	--	MIR	1.55-1.70 µm	24 x 24 m	--	--	--
Sensor Type		Linear Array Pushbroom	**Sensor Type**		Linear Array Pushbroom	**Sensor Type**		Linear Array Pushbroom
Swath Width		113 km	**Swath Width**		140 km	**Swath Width**		60 km
Revisit Time		26 days	**Revisit Time**		24 days	**Revisit Time**		26 days
Orbit Path		Sun-synchronous	**Orbit Path**		Sun-synchronous	**Orbit Path**		Sun-synchronous
Launch Date		Oct. 04, 1999 – Sept. 19, 2007	**Launch Date**		October 17, 2003	**Launch Date**		Feb. 21, 1986 – Sept. 26, 1993
Tasking Capability		None	**Tasking Capability**		None	**Tasking Capability**		None
Cost Per Scene		None	**Cost Per Scene**		USD $2, 750	**Cost Per Scene**		USD $1,200-1,900

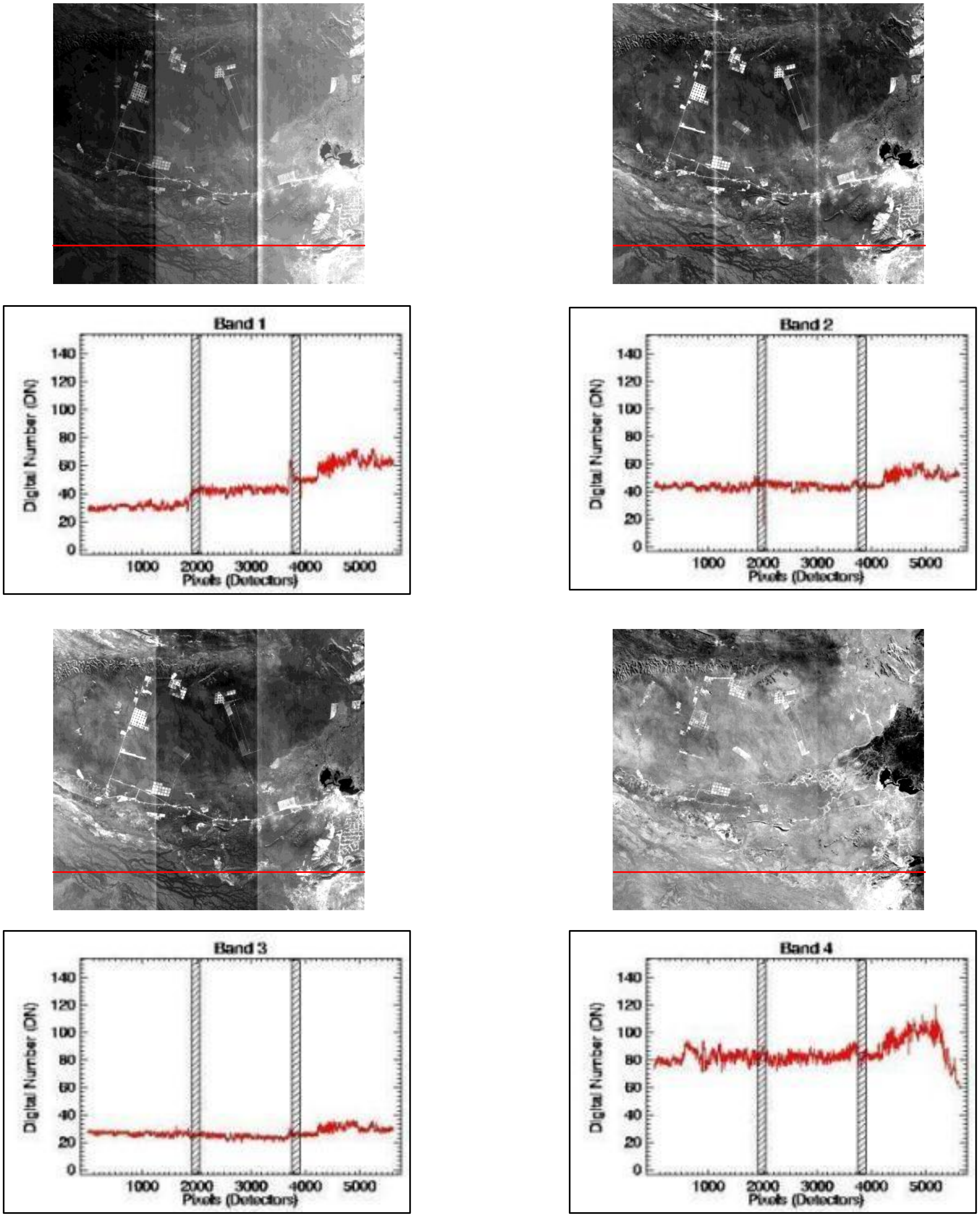


Figure 44. CBERS-2 scene and histograms illustrating systematic distortion. Horizontal bars indicate regions of overlap. Red lines on images indicate location of transect used to generate histograms.

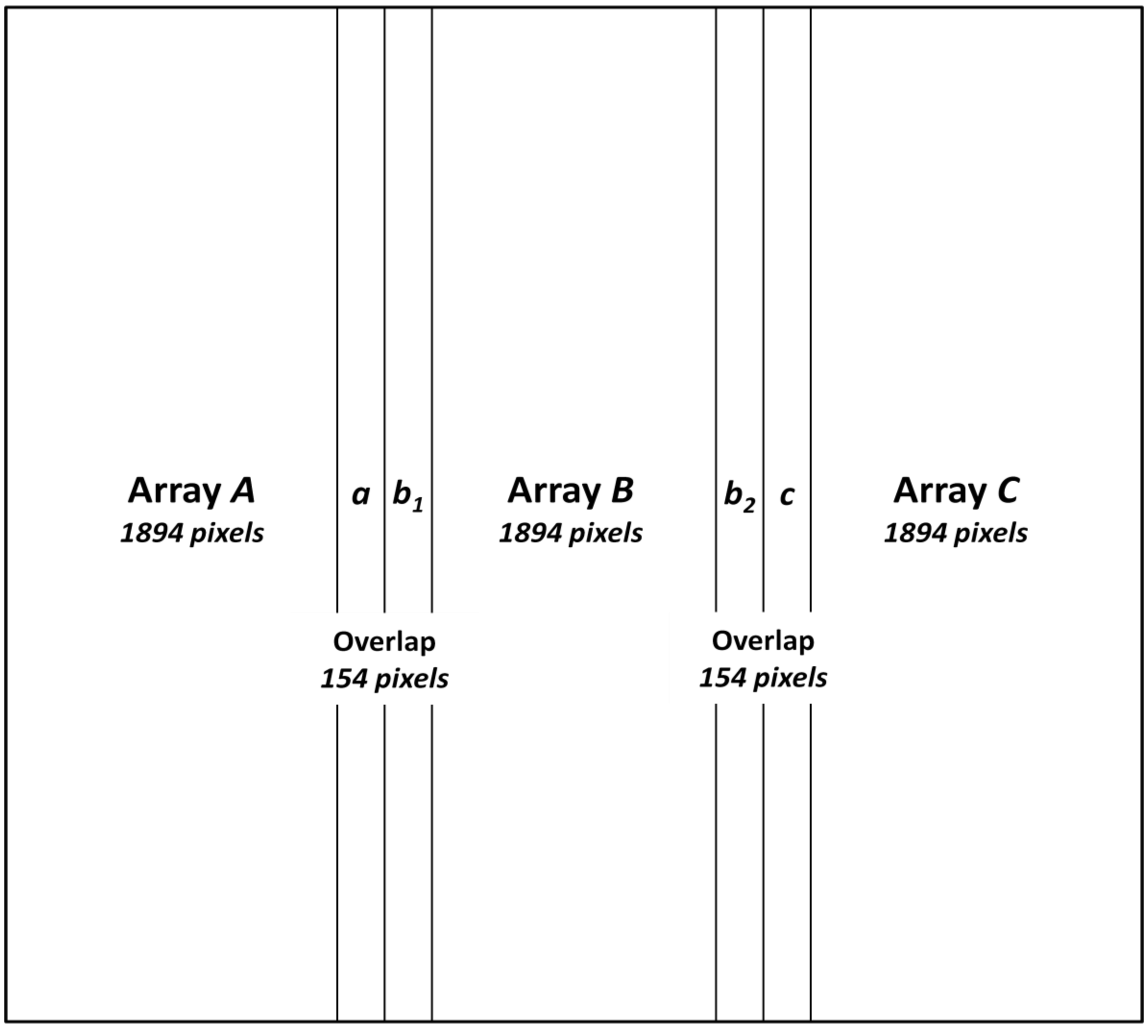


Figure 45. Diagram of a CBERS-2 CCD scene. It is partitioned into large sub-regions and smaller sub-regions based on the natural separation of each of the three, 9-km arrays. 6,130 pixels are received in each line for each band; 14 pixels in Array C are not received by the collecting station; 154 pixels are overlap between arrays Figure B and B-C and 8 pixels are dark. Thus, the final image contains 5,798 pixels (adapted from Jianning et al. 2005 and Fonseca et al. 2004).

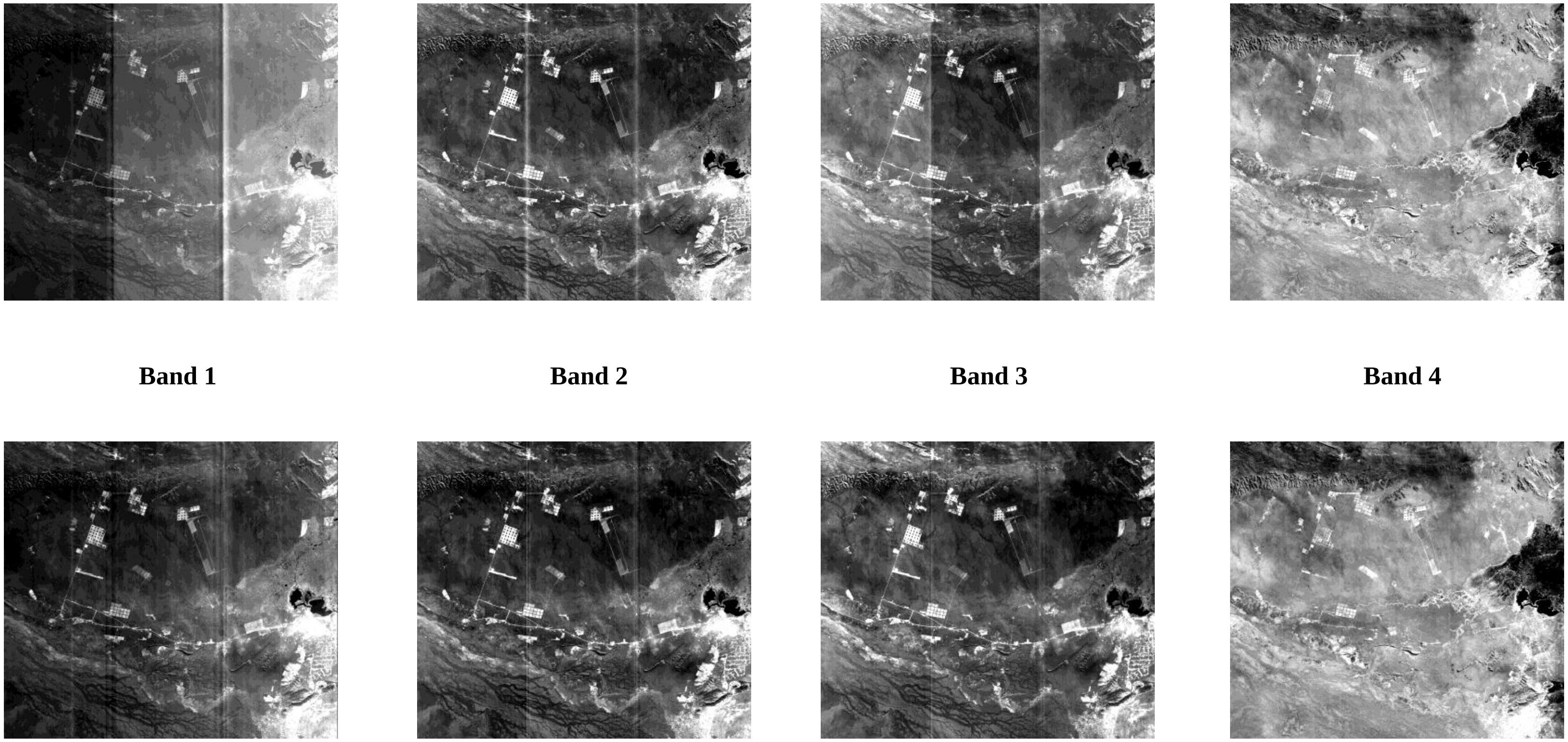


Figure 46. Comparison of uncorrected/corrected CBERS-2 scene by bands.

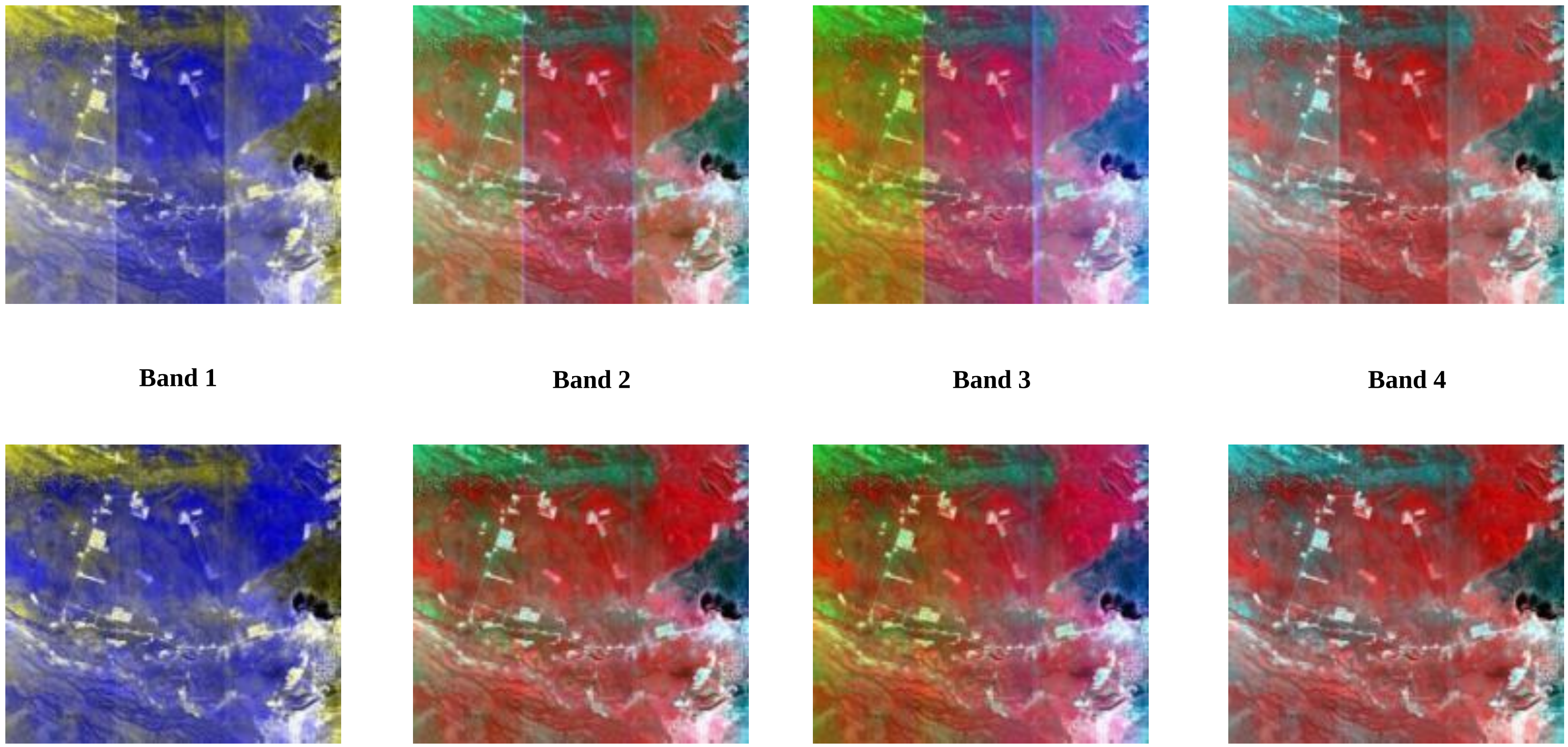


Figure 47. Comparison of uncorrected/corrected CBERS-2 scene by composites.

Table 27

2008 CBERS-2B accuracy assessment results.

Tierra Bajas [a]	*Producers Accuracy (%)*	*Users Accuracy (%)*	*Commission (%)*	*Omission (%)*
Forest	99.91	99.99	0.01	0.09
Non-Forest	99.94	99.45	0.55	0.06
Bare Ground/Savanna	100.00	98.98	1.02	0.00
Water Bodies	100.00	99.97	0.03	0.00
Infrastructure	100.00	99.88	0.12	0.00
Brazilian Shield [b]	*Producers Accuracy (%)*	*Users Accuracy (%)*	*Commission (%)*	*Omission (%)*
Forest	89.99	95.29	4.71	10.01
Non-Forest	91.34	89.04	10.96	8.66
Bare Ground/Savanna	87.02	63.95	36.05	12.98
Water Bodies	--	--	--	--
Infrastructure	96.20	99.58	0.42	3.80
Pantanal [c]	*Producers Accuracy (%)*	*Users Accuracy (%)*	*Commission (%)*	*Omission (%)*
Forest	94.47	99.63	0.37	5.53
Non-Forest	96.06	94.85	5.15	3.94
Bare Ground/Savanna	100.00	46.92	53.08	0.00
Water Bodies	100.00	100.00	0.00	0.00
Infrastructure	100.00	100.00	0.00	0.00

[a] Overall Accuracy = 99.2; Kappa Coefficient = 0.99
[b] Overall Accuracy = 90.5; Kappa Coefficient = 0.84
[c] Overall Accuracy = 97.5; Kappa Coefficient = 0.96

Table 28

Land-use and land-cover change (1975-2008) statistics.

	1975	1986-88			1993-94			2000			2006-2007			2008		
TIERRAS BAJAS CLASSES	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*
Forest	18,928.9	-5.5	-0.5	17,892.5	-13.8	-1.9	15,426.3	-34.6	-4.1	10,089.1	-6.2	-0.6	9,461.5	-6.5	-2.8	8,845.8
Non-forest	2,473.0	39.8	0.5	3,457.9	71.0	1.9	5,913.9	89.5	4.1	11,204.6	4.6	0.5	11,724.6	5.2	2.8	12,331.3
Bare/Open Ground	142.6	2.4	0.0	146.0	-35.2	0.0	94.6	30.4	0.0	123.3	-23.0	0.0	95.0	1.4	0.0	96.4
Water Bodies	159.6	-15.8	0.0	134.4	-5.4	0.0	127.1	-19.1	0.0	102.8	26.4	0.0	130.0	-0.5	0.0	129.3
Urban	48.0	124.2	0.0	107.6	49.9	0.0	161.4	49.0	0.1	240.4	50.1	0.1	361.0	2.3	0.0	369.4
TOTAL	**21,752.1**	--	--	**21,738.4**	--	--	**21,723.3**	--	--	**21,760.3**	--	--	**21,772.1**	--	--	**21,772.1**

	1975	1986-88			1992-93			2000-2001			2007			2008		
BRAZILIAN SHIELD CLASSES	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*
Forest	25,852.2	-0.4	0.0	25,744.3	-0.6	-0.1	25,596.8	1.9	0.3	26,088.3	-3.4	-0.6	25,206.9	-1.4	-1.2	24,865.8
Non-forest	45.7	238.3	0.0	154.6	72.2	0.1	266.2	104.4	0.2	544.2	89.5	0.3	1,031.0	21.0	0.8	1,247.3
Bare/Open Ground	2,319.1	-0.2	0.0	2,313.3	1.6	0.0	2,350.3	-33.5	-0.5	1,562.0	39.6	0.4	2,181.0	-5.0	-0.4	2,072.1
Water Bodies	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Urban	29.4	29.6	0.0	38.1	-3.4	0.0	36.8	51.0	0.0	55.5	33.2	0.0	73.9	-0.8	0.0	73.3
TOTAL	**28,246.3**	--	--	**28,250.2**	--	--	**28,250.0**	--	--	**28,250.0**	--	--	**28,492.8**	--	--	**28,258.4**

	1975	1986-89			1993-94			2001			2007			2008		
PANTANAL CLASSES	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*	*% Change*	*Ann. Rate*	*Area (Km^2)*
Forest	11,891.2	1.7	0.2	12,089.6	-0.6	-0.1	12,012.8	-2.2	-0.3	11,753.6	-4.2	-0.8	11,263.8	-1.1	-0.9	11,143.9
Non-forest	21.4	230.4	0.0	70.6	82.3	0.1	128.8	110.0	0.2	270.3	99.5	0.4	539.2	24.3	1.0	670.1
Bare/Open Ground	636.9	-48.9	-0.2	325.6	-9.4	0.0	294.9	53.7	0.2	453.2	36.8	0.3	620.1	-1.8	-0.1	609.2
Water Bodies	90.5	62.8	0.0	147.3	35.8	0.1	200.0	-23.0	-0.1	153.9	33.7	0.1	205.8	-0.1	0.0	205.6
Urban	15.6	14.9	0.0	17.9	10.1	0.0	19.7	82.9	0.0	36.0	17.4	0.0	42.3	0.0	0.0	42.3
TOTAL	**12,655.5**	--	--	**12,651.0**	--	--	**12,656.2**	--	--	**12,667.1**	--	--	**12,671.1**	--	--	**12,671.1**

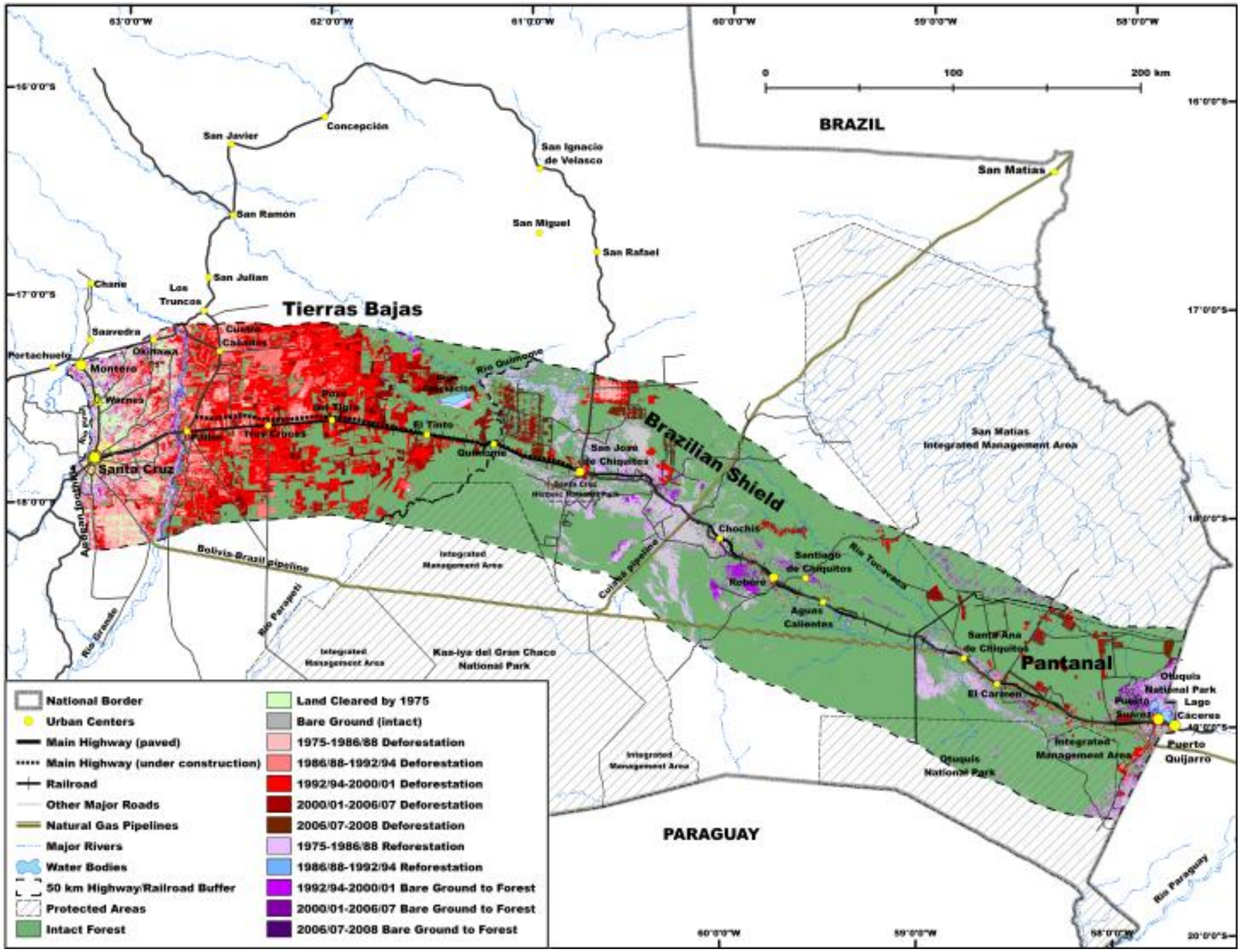


Figure 48. Land-use and land-cover change (1975-2008) map.

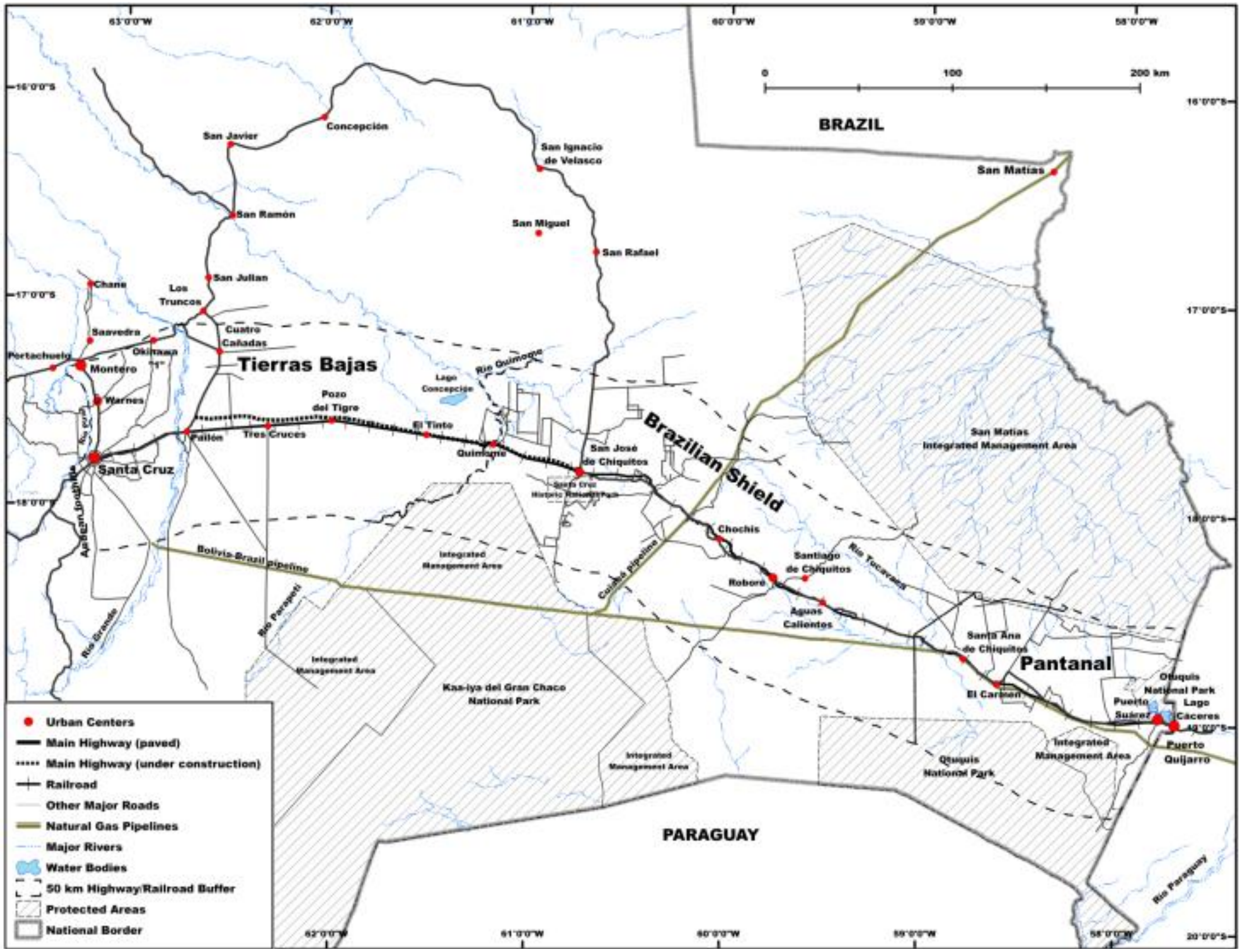


Figure 49. The Corredor Bioceánico of southeastern Bolivia. A 50-km buffer north and south of the main highway (dashed lines) has been used to demarcate the study area. Internal boundaries are defined by the Andean foothills and the Río Piraí to the west, Río Quimome and western ranges of the Brazilian Shield in the center and the Bolivia-Brazil border in the east (see text).

Table 29
Comparison of peer-reviewed LCLU change studies.

Author(s)	*Time Period*	*Area (km^2)*	*Sensors*	*Land-Cover Classes*[1]	*Land-Use Classes*[2]
Davies 1993	1975-1991	15,659	Landsat MSS/TM	Pf, Sf, F	A, P
Tucker & Townshend 2000	1992-1994	784,759	Landsat TM	F	Nf
Steininger et al. 2001a	1984-1994	700,000	Landsat MSS/TM	F	Nf
Steininger et al. 2001b	1975-1998	19,533	Landsat MSS/TM	F, Wa	Nf
Mertens et al. 2004	1989-1994	364,615	Landsat TM	F	Nf
Killeen et al. 2007	1976-2004	720,915	Landsat MSS-ETM+	F, Sc, Gr, We, Wa	--
Killeen et al. 2008	1975-2004	729,024	Landsat MSS-ETM+	F, Sc, Gr, We, Wa	--
Navarro & Ferreira 2007	1994	1,098,580	Landsat TM	F[†]	--

[1]**Land-Cover Classes:**
Pf = Primary Forest   Sc = Scrubland   Wa = Water
Sf = Secondary Forest   Gr = Grassland
F = Forest   We = Wetland

[2]**Land-Use Classes:**
Nf = Non-Forest
A = Agriculture
P = Pasture

[†]175 natural vegetation classes derived from Navarro and Ferreira (2007)

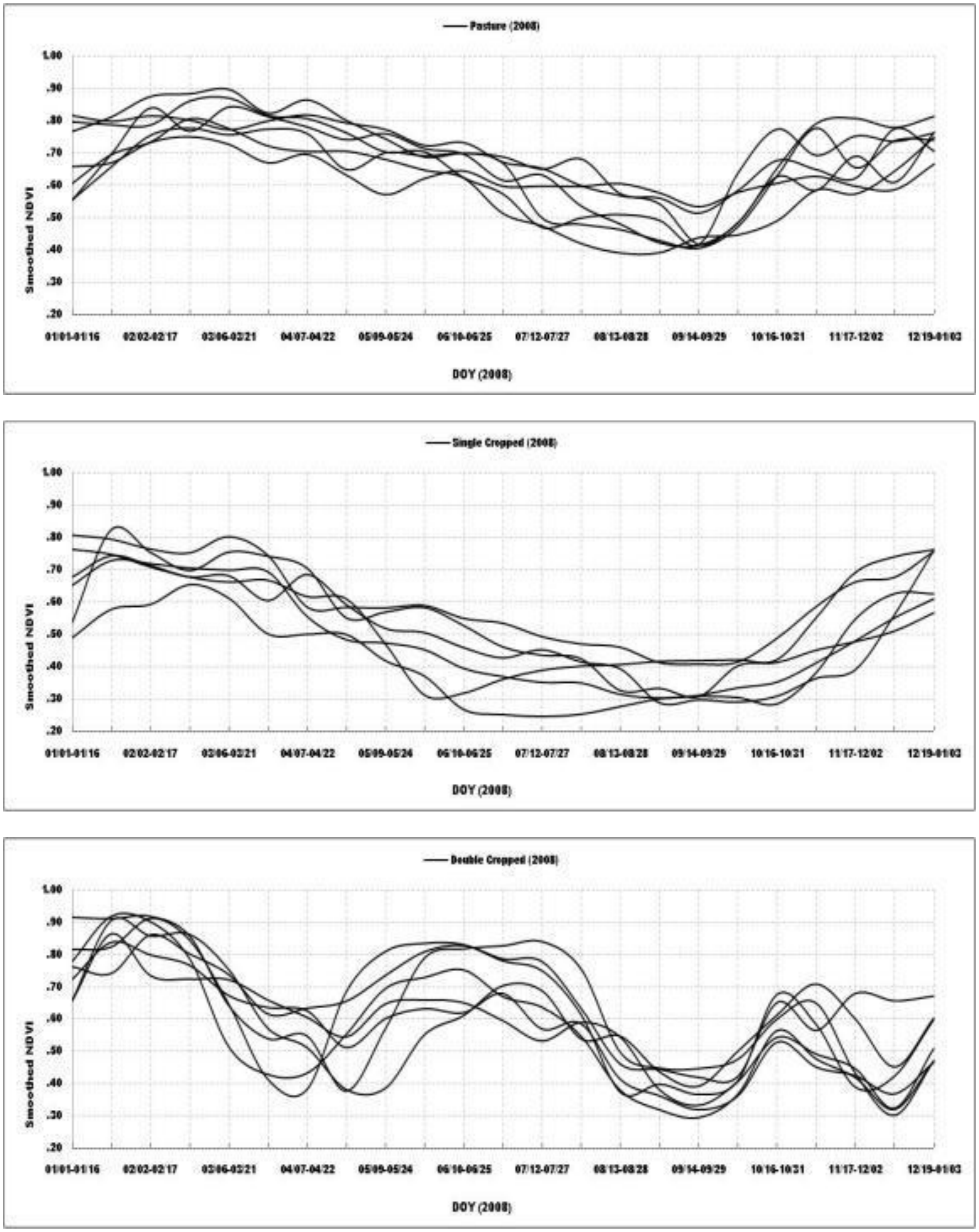


Figure 50. Phenology curves representing individual values. These curves are derived from seven test sites under pasture and double and single cropped fields for 2008.

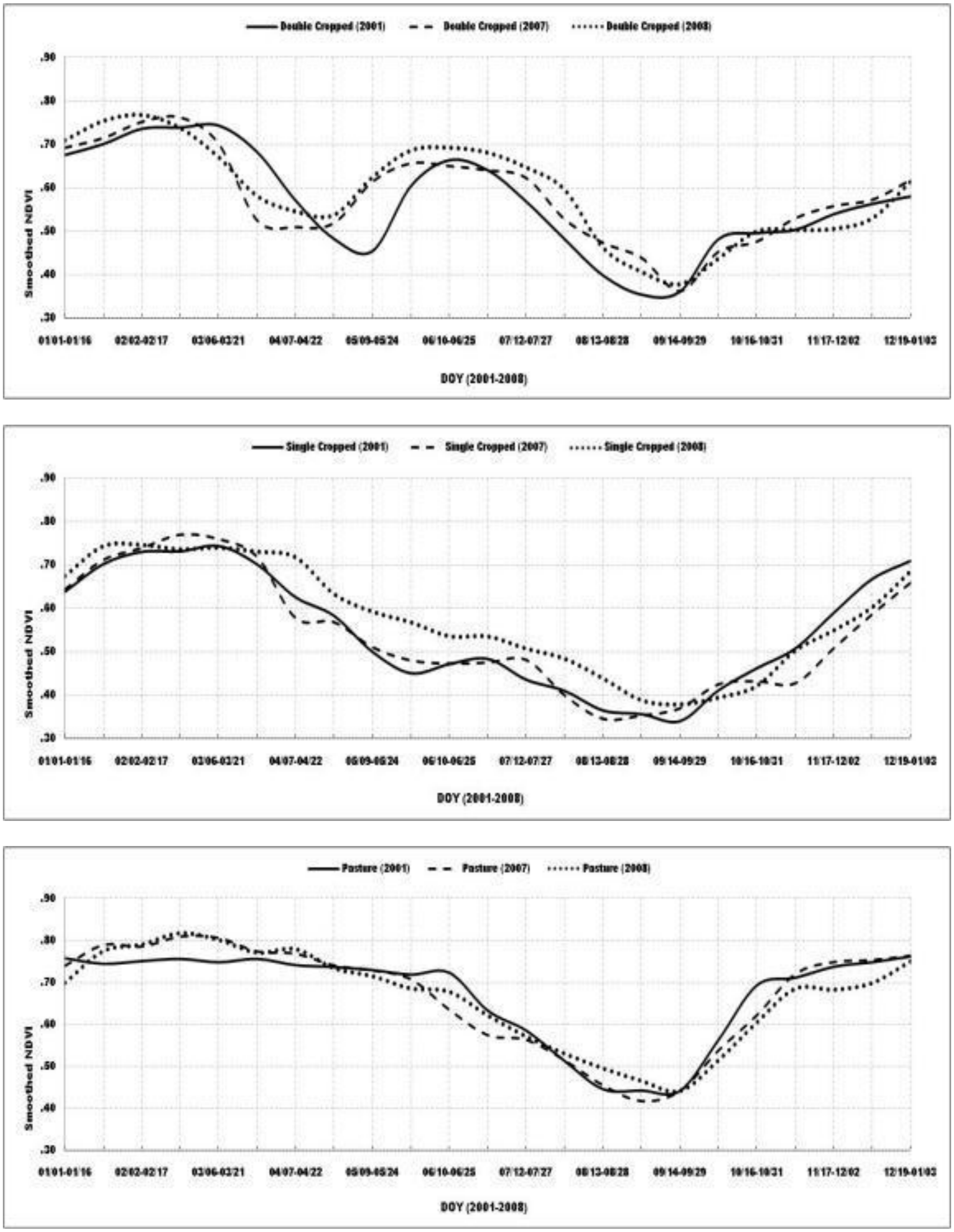


Figure 51. Phenology curves representing composited values. These curves are derived from all test sites under pasture and double and single cropped fields for 2001, 2007 and 2008.

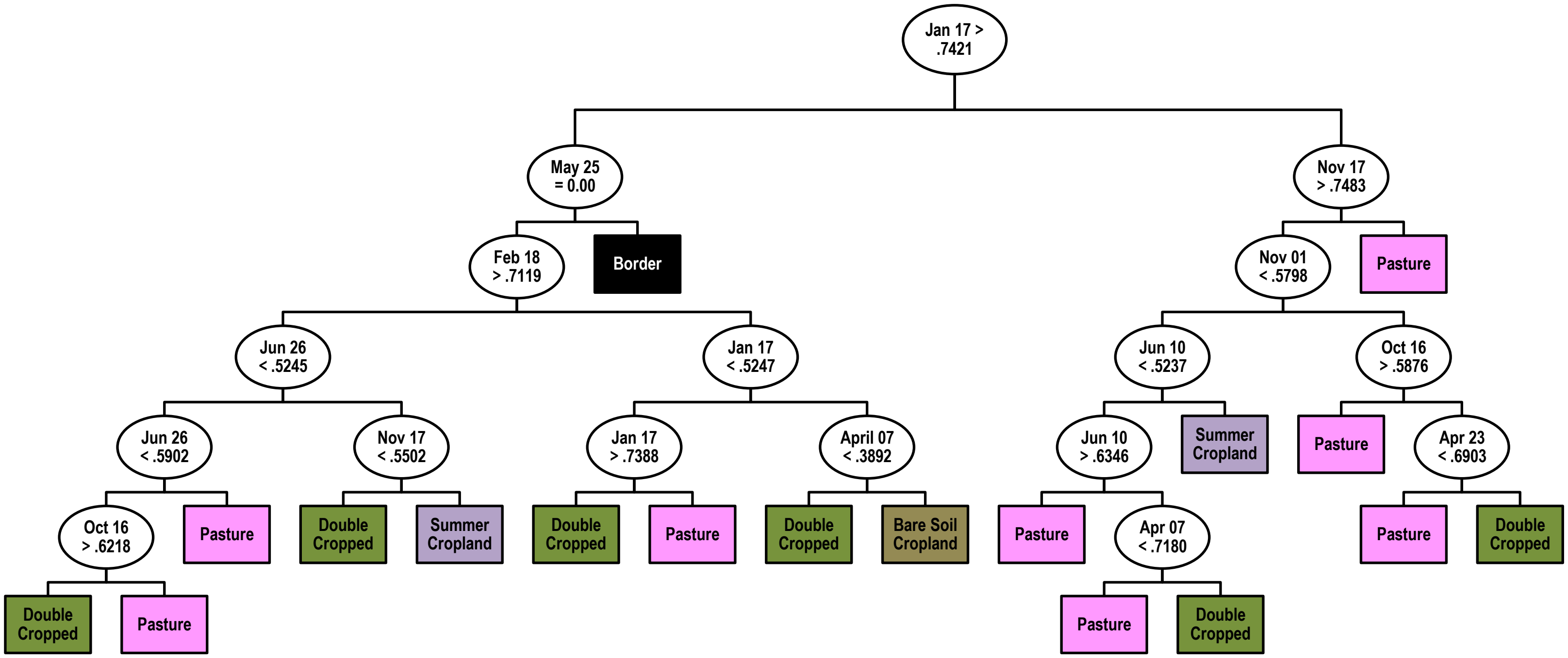


Figure 52. Final decision tree classifier for the year 2007. Circular boxes represent mathematical decisions while rectangular boxes represent final land-use classes.

Table 30
Land-use classification accuracy for 2001, 2007 and 2008.

2001 [a]	*Producer's Accuracy (%)*	*User's Accuracy (%)*	*Commission (%)*	*Omission (%)*
Pasture	98.03	95.13	4.87	1.97
Double Cropped	83.50	90.76	9.24	16.50
Single Crop, Summer	89.11	89.11	10.89	10.89
Annual Fallow	92.00	85.19	14.81	8.00
2007 [b]	*Producer's Accuracy (%)*	*User's Accuracy (%)*	*Commission (%)*	*Omission (%)*
Pasture	96.37	94.94	5.06	3.63
Double Cropped	87.63	90.91	9.09	12.37
Single Crop, Summer	79.31	74.19	25.81	20.69
Annual Fallow	93.33	93.33	6.67	6.67
2008 [c]	*Producer's Accuracy (%)*	*User's Accuracy (%)*	*Commission (%)*	*Omission (%)*
Pasture	96.61	93.44	6.56	3.39
Double Cropped	86.73	88.83	11.17	13.27
Single Crop, Summer	77.78	77.78	22.22	22.22
Annual Fallow	75.00	100.00	0.00	0.00

[a] Overall Accuracy = 92.98%; Kappa Coefficient = 0.8751
[b] Overall Accuracy = 92.44%; Kappa Coefficient = 0.8544
[c] Overall Accuracy = 91.64%; Kappa Coefficient = 0.8465

Table 31

Vegetation classes which experienced the most change (1994-2008)

Vegetation Class:	**Area (km^2) in 1994:**	**Vegetation Description:**	**Dominant Species or Variant:**	**Spatial Distribution:**
c1	1,070.87	Sub-humid semi-deciduous forests of Chiquitanía on well-drained soils; Forest group which is seasonally rainy and represents the natural potential vegetation zone of soils moderately deep, well-drained		
c13	687.75	Chiquitano-Chaco transitional forest on medium to poorly drained, clayey or silty soils		Chiquitanía-Chaco transition zone
c13a	1,678.29	Chiquitano-Chaco transitional forest on imperfectly drained soils of east-central Chiquitanía	*Diplokeleba floribunda-Acosmium cardenasii*	Wide distribution along the southern boundary of the Chiquitanía mountain ranges
c13b **c13b+d14a** **c13b+d14a+c14a**	6,350.06 417.02 721.87	Chiquitano-Chaco transitional forest on poorly drained soils of east Chiquitanía	*Schinopsis brasiliensis-Lonchocarpus nudiflorens*	Contact zone between the middle and lower basin of the Río Tucavaca
c17+c1e	111.84	Set of herbaceous pampas grasses, typical of oligotrophic soils temporarily flooded to varying degrees depending on the topography, mainly by water from depressions		Chiquitanía
c1a **c1a+d7an+d9a+d14**	119.82 713.07	Floodplain forest of south-central Chiquitanía on well-drained soils	*Machaerium scleroxylon-Acosmium cardenasii*	Southern boundary of the Chiquitanía toward the Chaco, in the central province of Chiquitos
c1b+c13a	278.89	Floodplain forest of east Chiquitanía on well-drained soils	*Machaerium scleroxylon-Acosmium cardenasii*	Alluvial plains of the watersheds of the Middle Rio Otuquis and Lower Tucavaca
c2 **c2+c9**	956.42 198.87	Lowland Chiquitano forest on rocky or sandy soils (Savannah, "Pampa-Monte"). Semi-deciduous forests with a canopy of 10-16 m developed on excessively drained, shallow soils		
c2b	1,709.38	Lowland forest on sandy soils of eastern Chiquitanía	*Pterodon emarginatum-Terminalia argentea*	Undulating low ridges with wind-blown, sandy tops between Roboré and San Jose de Chiquitos
c2d	271.47	Pampa, Cerrado, and lowland forest on shallow, sandy or rocky soils of east-central Chiquitanía	*Schinopsis brasiliensis-Aspidosperma tomentosum*	Chiquitanía mountain ranges
c2e	649.71	Lowland forest on sandy soils of southern Chiquitanía		Mountain ranges or rolling hills with wind-blown tops located south of San José de Chiquitos
c2e+c17	347.68	Pampa, Cerrado, and lowland forest on rocky, sandy soils of southern Chiquitanía / Sclerophyllous chaparral + Oligotrophic flooded grassy savannas of Chiquitanía		
c3b	319.94	Sub-humid, transitional Chiquitano-Chaco forest on well-drained soils.	*Athyana weinmannifolia-Schinopsis brasiliensis*	Chiquitano forest which transitions to Chaco forest in areas seasonally rainy south of the Chiquitos Province
c6	816.54	Sclerophyllous chaparral of Chiquitanía transitioning to the Chaco on sand (Abayoy). Lowland forests and scrublands, semi-dense, developed on low, rolling peneplains with wind-blown, sandy ridge tops		
c6a	2,045.76	Abayoy Chaparral on sandstone substrates	*Tabebuia selachidentata-Terminalia argentea*	Sandy soils on rocks of Paleozoic sandstone
c6c	1,852.69	Abayoy Chaparral on the sloping, sandstone outer edges of the Chochis Plateau	*Copaifera langsdorfii-Terminalia fagifolia*	Plateaus of the foothills of Chochís and Ipiás, between the mountain ranges of San José and Santiago
c9e & c9ee **c9e+d9**	717.39 44.52	Mesophytic-phreatophytic floodplain forests of the wind-blown alluvial plains of Santa Cruz	*Albizia niopoides-Gallesia integrifolia*	Potential climax forest of central and southern plains of Santa Cruz on well-drained deep soils

Table 31. Continued

Vegetation Class:	Area (km^2) in 1994:	Vegetation Description:	Dominant Species or Variant:	Spatial Distribution:
ca	1,640.52	Human-influenced vegetation complex: Vegetation heavily influenced or transformed by human action, including extensive cropland, pasture, fallow land, and deforested areas		
ca+ c1e+c9e	382.15	Human influenced vegetation + Chiquitano forest on the wind-blown, sandy alluvial soils of Santa Cruz	*Erythrina dominguezii-Astronium urundeuva*	Ancient alluvial floodplains of the Río Piraí, to the west
ca+(c9e+d7as+d9i+c1e) **ca+c9e**	491.34 278.96	Human influenced vegetation + Mesophytic-phreatophytic floodplain of the wind-blown alluvial plains of Santa Cruz	*Albizia niopoides-Gallesia integrifolia*	Potential climax forest of central and southern plains of Santa Cruz on well-drained deep soils
d12c	308.67	Carandá palm forest of medium-high flooding in the Chaco-Pantanal-Chiquitanía transition	*Triplaris gardneriana-Copernicia alba*	Palms flooded six months or more a year by river overflow from water, interrupted and partly mineralized
d14a	565.85	Forest in seasonal streams and flooded depressions in the northern Chaco	*Coccoloba guaranitica-Geoffroea spinosa*	Represents the type of hydrophytic Chaco forest most widespread in Bolivia and northern Paraguay
d14b+d15a+d18	39.34	Seasonally flooded forests of the Chaco-Chiquitanía-Pantanal transition. Vegetation series homologous to the previous series	*Zygia pithecollobioides-Geoffroea spinosa*	Located within ecological and biogeographical transition belt between the northeastern Chaco and southern Pantanal
d14c	211.57	Forest in seasonal streams and flooded depressions in the Chaco-Chiquitanía transition. Semi-deciduous forest with an irregular canopy 15-18 m in height, emerging 20-22 m	*Lonchocarpus pluvialis-Ruprechtia exploratricis*	
d7a+d7aa **d7a+d9a**	917.31 778.00	Transitional Chaco forest on floodplain soils medium to imperfectly drained	*Diplokeleba floribunda-Phyllostylon rhamnoides*	Most widespread transitional Chaco vegetation
d7aa+d7an	311.13	Transitional Chaco forest on floodplain soils medium to imperfectly drained + Transitional Chaco forest on floodplain soils medium to imperfectly drained	Variant of some sandy soils	
d7an	1,772.00	Transitional Chaco forest on floodplain soils medium to imperfectly drained	*Diplokeleba floribunda-Phyllostylon rhamnoides*	Most widespread transitional Chaco vegetation
d7an/d9a	255.41	Transitional Chaco forest on floodplain soils medium to imperfectly drained / Forest on soils poorly drained with Saó palms	d7an = Variant with phreatic influence; d9a = *Diplokeleba floribunda-Trithrinax schizophylla*	
d7an+d9a+d14a **d7an+d9a+d14b**	2,939.45 519.02	Transitional Chaco forest on floodplain soils medium to imperfectly drained + Forest on soils poorly drained with Palma Saó	d7an = Variant influenced with water that collects on an impermeable surface; d9a = *Diplokeleba floribunda-Trithrinax schizophylla*	
d7c **d7c+d9h**	353.38 814.19	Transitional Chaco forest on floodplains of the Río Quimome. Transitional Chaco forest with a restricted range extending to the ancient floodplains of the Río Quimome, east to Lake Concepción	*Ceiba samauma-Phyllostyllon rhamnoides*	
d9a	3,097.13	Forest on soils poorly drained with Palma Saó. Forest on clay or poorly drained, silty clay soils of the northern Bolivian Chaco	*Diplokeleba floribunda-Trithrinax schizophylla*	
d9h	468.62	Palocruzal vegetation on ancient floodplains of the Otuquis and Quimome rivers	*Tabebuia nodosa-Lonchocarpus nudiflorens*	Distributed in the large, semi-closed drainage basin created by Quimome River east of Lake Concepción

Table 32

Area (% of total) of vegetation class lost in the Tierras Bajas.

	1994-2001				*1994-2007*				*1994-2008*			
Vegetation Class	Pasture	Double Cropped	Single Cropped	Fallow	Pasture	Double Cropped	Single Cropped	Fallow	Pasture	Double Cropped	Single Cropped	Fallow
d9a	17.02%	22.00%	17.63%	22.66%	13.31%	20.89%	15.18%	28.95%	13.67%	21.11%	19.85%	17.70%
d7an+d9a+d14a	11.98%	17.52%	43.54%	29.65%	17.53%	16.44%	21.65%	15.26%	19.79%	16.00%	23.37%	14.25%
d7an	10.77%	9.20%	10.90%	3.37%	9.60%	10.71%	6.79%	18.44%	9.39%	11.05%	9.17%	21.21%
d7a+d7aa	6.86%	6.70%	5.46%	22.08%	4.89%	6.65%	4.36%	3.91%	4.78%	7.52%	2.87%	1.58%
c1a+d7an+d9a+d14	4.32%	8.72%	3.70%	10.31%	5.94%	7.22%	4.28%	3.66%	6.30%	6.45%	6.27%	3.31%
ca+(c9e+d7as+d9i+c1e)	6.90%	3.28%	0.25%	0.36%	4.64%	4.34%	13.42%	0.84%	3.97%	4.64%	8.08%	2.22%
ca+c1e+c9e	5.00%	2.75%	0.51%	--	3.61%	2.82%	8.81%	0.58%	2.92%	3.10%	4.65%	1.16%
d7an/d9a	2.82%	2.36%	2.56%	1.09%	1.40%	2.74%	0.65%	7.16%	0.95%	2.92%	1.74%	1.07%
d7an+d9a+d14b	1.56%	4.53%	3.39%	1.45%	2.82%	3.31%	1.46%	1.00%	2.99%	2.84%	2.31%	1.48%
c9ee	3.47%	3.13%	0.76%	2.88%	3.73%	2.82%	1.58%	1.75%	3.10%	2.76%	3.03%	2.81%
ca+c9e	2.97%	3.06%	4.02%	1.32%	1.98%	2.71%	4.51%	7.77%	1.72%	2.73%	2.62%	17.06%
c9e	4.46%	1.58%	0.16%	--	3.98%	2.27%	1.25%	0.06%	3.19%	2.31%	1.29%	--
d7aa+d7an	3.66%	1.18%	--	--	3.07%	1.52%	0.97%	0.26%	3.01%	1.77%	0.79%	0.25%
d7a+d9a	1.99%	1.08%	0.52%	--	2.50%	1.41%	0.02%	--	2.63%	1.26%	0.06%	--
d7an+d9e+d14b	0.69%	1.56%	0.12%	--	1.26%	1.18%	0.97%	0.17%	1.58%	1.07%	1.30%	0.25%
c17+c1e	1.42%	0.66%	1.10%	--	0.78%	0.99%	1.19%	--	0.60%	1.02%	0.72%	--
d7af	2.33%	0.83%	0.10%	1.09%	1.53%	0.97%	0.24%	1.14%	1.28%	0.94%	0.41%	4.17%
d7an+a	0.71%	0.55%	--	--	0.67%	0.47%	3.41%	--	0.73%	0.46%	2.67%	--
c9e+d9	0.54%	0.34%	0.09%	--	0.48%	0.44%	0.07%	--	0.40%	0.42%	0.10%	--
c1a	0.05%	0.08%	--	--	0.56%	0.24%	0.14%	--	1.19%	0.23%	0.16%	--
d7c+d9h	0.02%	0.04%	--	--	0.89%	0.32%	0.28%	--	0.86%	0.23%	0.54%	--
ca+c1e+c17+c18	0.57%	0.31%	0.29%	--	0.59%	0.16%	0.13%	--	0.48%	0.16%	0.33%	--
d14b+d15a+d18	0.10%	0.34%	--	--	0.44%	0.17%	0.40%	--	0.47%	0.11%	0.52%	--
TOTAL (%)†	**90.21%**	**91.80%**	**95.10%**	**96.25%**	**86.20%**	**90.79%**	**91.76%**	**90.95%**	**86.00%**	**91.10%**	**92.85%**	**88.52%**
TOTAL (km^2)	**3,691.85**	**3,427.34**	**298.83**	**16.63**	**2,533.64**	**4,966.55**	**257.19**	**65.28**	**3,006.0**	**5,143.27**	**192.22**	**22.46**

†Note: Class totals do not add up to 100% because classes with very low percentage losses were omitted (see paper).

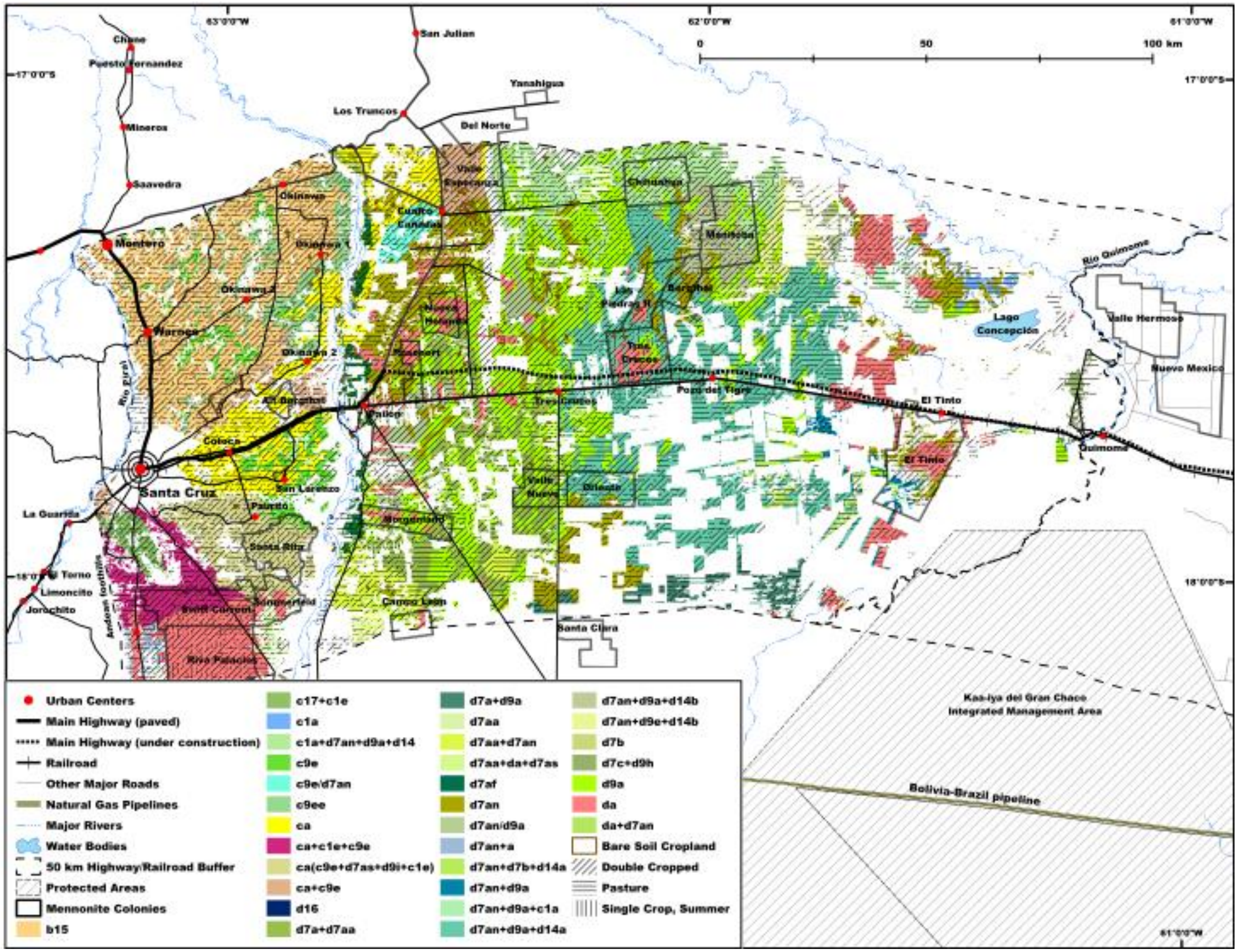


Figure 53. Dominant vegetation classes lost in the Tierras Bajas. For a description of vegetation classes see Table 31.

Table 33

Area (% of total) of vegetation class lost in the Brazilian Shield.

	1994-2001				*1994-2007*				*1994-2008*			
Vegetation Class	Pasture	Double Cropped	Single Cropped	*Fallow*	Pasture	Double Cropped	Single Cropped	*Fallow*	Pasture	Double Cropped	Single Cropped	*Fallow*
d7c+d9h	1.38%	2.99%	--	--	9.95%	19.34%	2.95%	--	16.46%	22.96%	13.95%	--
c13b	2.52%	0.09%	--	--	12.40%	1.35%	1.48%	--	8.60%	0.38%	--	--
d7c	2.73%	5.97%	--	--	8.39%	14.77%	3.88%	--	7.88%	23.97%	4.54%	--
c3b	13.64%	14.37%	--	--	7.66%	7.21%	9.07%	--	6.74%	2.83%	5.07%	--
d9h	1.46%	1.44%	--	--	2.68%	4.47%	2.60%	--	5.43%	5.60%	4.92%	--
c2b	14.47%	6.86%	--	--	7.05%	2.76%	0.98%	--	4.84%	0.91%	3.80%	--
d14c	4.66%	10.93%	18.70%	--	1.45%	6.85%	4.59%	1.93%	4.35%	6.38%	24.94%	--
c2e	6.48%	4.33%	--	--	4.86%	2.87%	19.19%	--	4.29%	1.64%	10.95%	100.00%
c6	1.64%	1.41%	--	--	3.60%	1.47%	10.94%	--	4.25%	2.16%	4.25%	--
d14a	2.86%	5.13%	--	--	1.52%	3.18%	5.65%	98.07%	3.52%	5.17%	9.83%	--
c13a	1.48%	0.21%	--	--	4.82%	0.45%	1.94%	--	3.40%	0.32%	1.37%	--
c6c	4.17%	12.14%	65.14%	--	3.64%	5.60%	1.84%	--	3.05%	4.56%	0.95%	--
c1i+c9+c16	6.01%	5.48%	10.24%	--	3.38%	4.75%	4.52%	--	2.96%	4.45%	3.63%	--
c1	5.98%	5.98%	5.92%	--	3.92%	3.06%	5.13%	--	2.85%	1.95%	4.44%	--
c2e+c17	8.90%	1.15%	--	--	4.06%	2.67%	7.76%	--	2.83%	0.28%	3.17%	--
c13	1.23%	0.71%	--	--	3.04%	7.24%	6.44%	--	2.70%	7.32%	--	--
c1b+c13a	2.92%	0.90%	--	--	2.84%	1.34%	0.93%	--	2.29%	--	--	--
c2+c9	1.49%	6.73%	--	--	1.84%	2.22%	4.99%	--	2.06%	1.82%	1.27%	--
c9b+d14	1.90%	0.60%	--	--	1.57%	0.31%	0.04%	--	1.09%	--	--	--
c2d	0.51%	1.10%	--	--	0.77%	0.83%	0.18%	--	0.46%	0.05%	1.27%	--
TOTAL(%)†	**86.43%**	**88.52%**	**100.00%**	**0.00%**	**89.44%**	**92.74%**	**95.10%**	**100.00%**	**90.05%**	**92.75%**	**98.35%**	**100.00%**
TOTAL (km^2)	**170.40**	**42.20**	**1.06**	**0.00**	**444.98**	**154.88**	**18.27**	**0.06**	**693.74**	**122.91**	**9.70**	**0.06**

† Note: Class totals do not add up to 100% because classes with very low percentage losses were omitted (see paper).

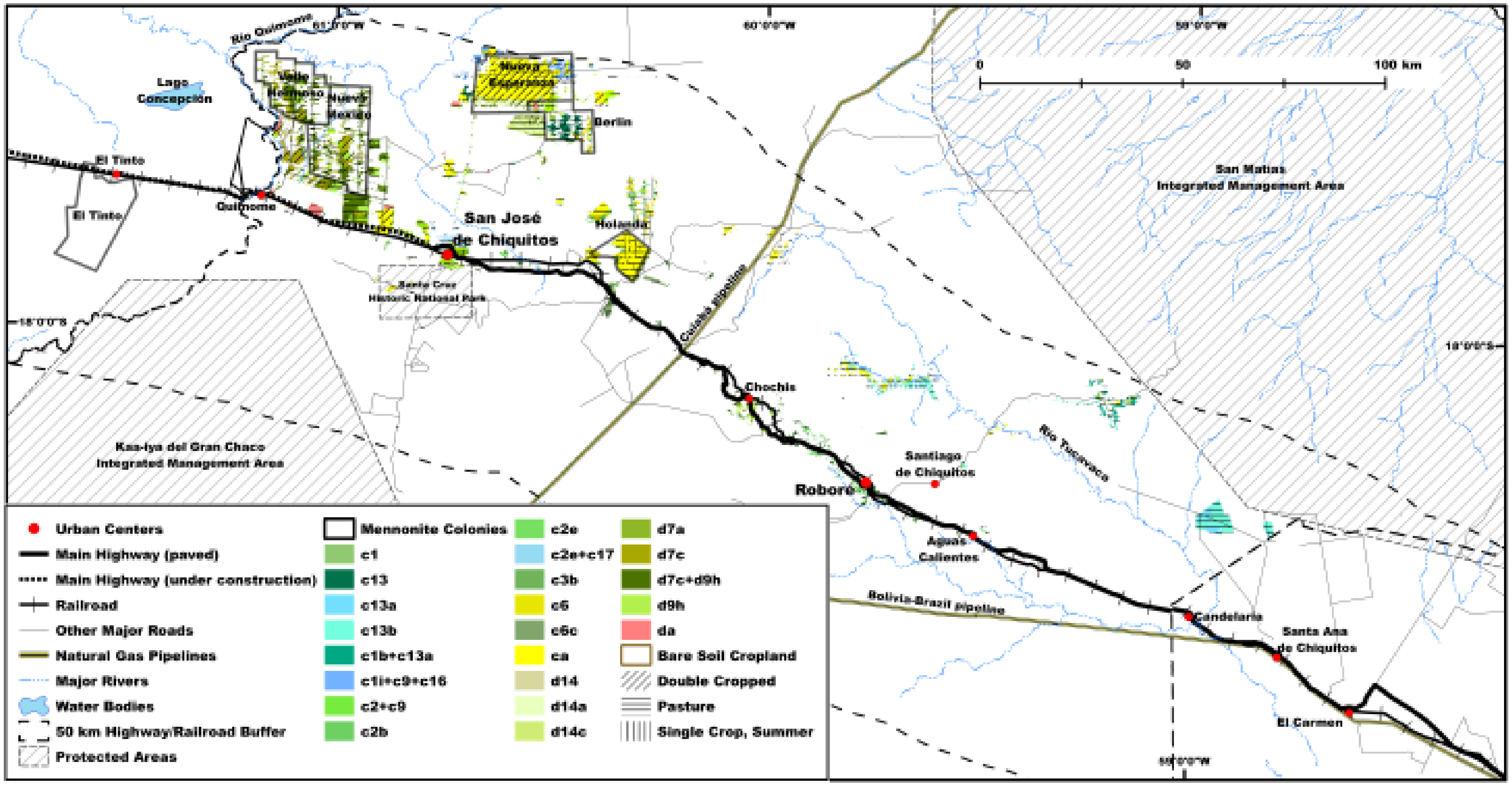


Figure 54. Dominant vegetation classes lost in the Brazilian Shield. For a description of vegetation classes see Table 31.

Table 34

Area (% of total) of vegetation class lost in the Pantanal.

	1994-2001				*1994-2007*				*1994-2008*			
Vegetation Class	Pasture	Double Cropped	Single Cropped	*Fallow*	Pasture	Double Cropped	Single Cropped	*Fallow*	Pasture	Double Cropped	Single Cropped	*Fallow*
c13b	22.44%	47.40%	--	--	46.23%	41.95%	40.28%	--	52.49%	44.66%	26.92%	--
c13a	22.28%	12.77%	--	--	15.57%	17.49%	22.09%	--	15.50%	19.78%	20.37%	--
c13b+d14a+c14a	17.17%	9.80%	--	--	16.64%	13.14%	20.80%	--	12.26%	15.12%	34.69%	--
c13b+d14a	8.99%	0.43%	--	--	3.64%	5.73%	--	--	3.10%	3.55%	1.12%	--
d12c	2.03%	0.87%	--	--	1.62%	8.03%	--	--	1.81%	4.33%	--	--
c1i	3.82%	2.66%	--	--	1.71%	2.26%	--	--	1.58%	0.88%	0.06%	--
c1h+c13a+a	3.75%	0.87%	--	--	1.34%	0.01%	--	--	1.48%	0.52%	--	--
c6a	2.67%	7.37%	--	--	1.26%	1.39%	7.39%	--	1.36%	2.27%	6.73%	--
c2	1.07%	7.54%	--	--	1.10%	0.69%	--	--	0.87%	0.58%	--	--
c14a+d14a	1.21%	3.89%	--	--	0.97%	0.90%	7.10%	--	0.61%	1.00%	7.69%	--
TOTAL(%)†	**85.43%**	**93.60%**	**0.00%**	**0.00%**	**90.08%**	**91.59%**	**97.66%**	**0.00%**	**91.06%**	**92.69%**	**97.58%**	**0.00%**
TOTAL (km^2)	**109.13**	**13.51**	**0.00**	**0.00**	**323.61**	**67.02**	**5.28**	**0.00**	**411.30**	**88.86**	**5.44**	**0.00**

† Note: Class totals do not add up to 100% because classes with very low percentage losses were omitted (see paper).

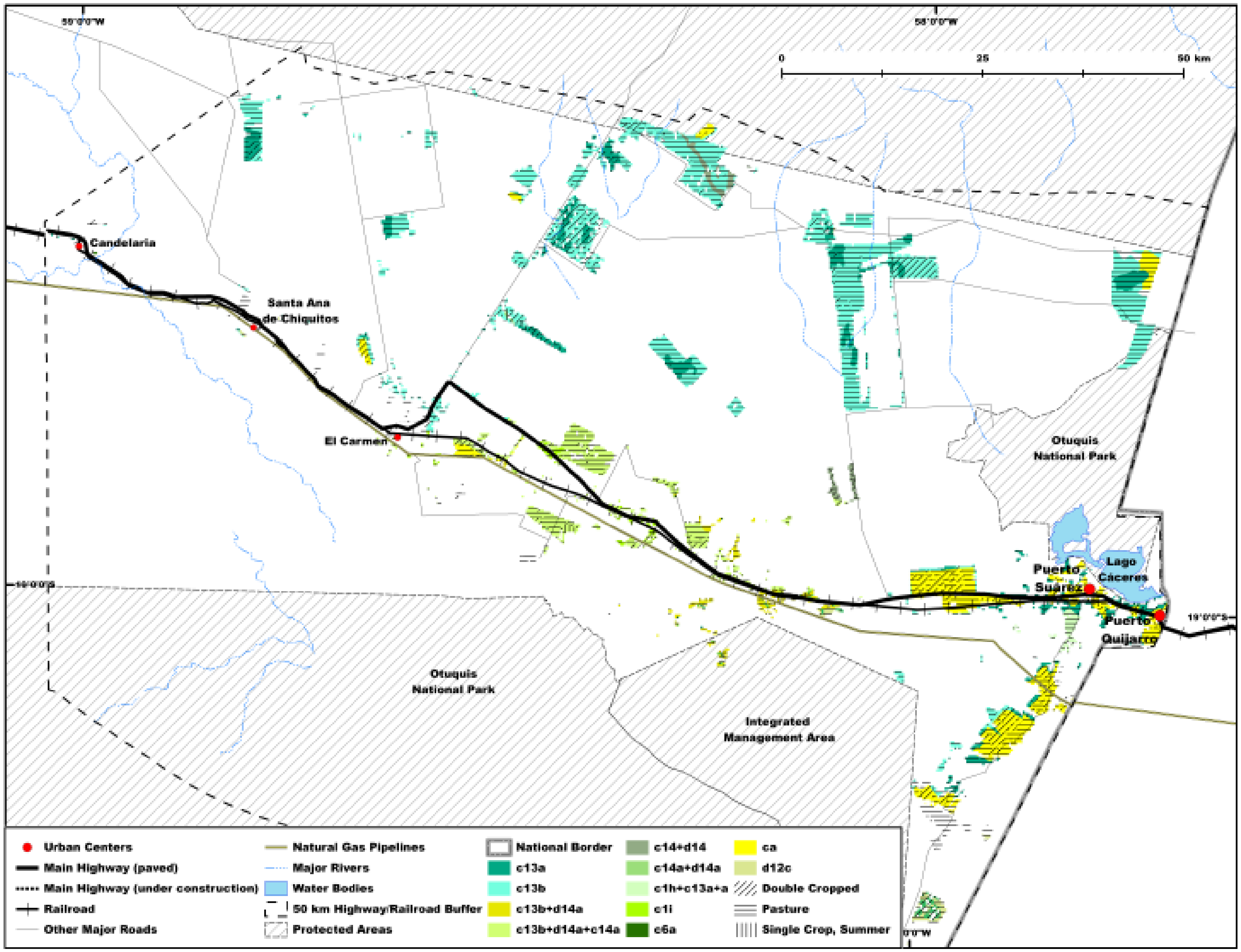


Figure 55. Dominant vegetation classes lost in the Pantanal. For a description of vegetation classes see Table 31.

Table 35

Change in pasture and cropland classes from 2001 to 2008.

	2001		*2001-2007*			*2007-2008*		
Tierra Bajas	*Area (%)*	*Area (km^2)*	*Area (%)*	*Area (km^2)*	*Change (%)*	*Area (%)*	*Area (km^2)*	*Change (%)*
Pasture	52.06%	5,973.94	42.82%	5,112.50	-14.42	37.83%	4,776.56	+16.15
Double Cropping	44.35%	5,089.19	52.24%	6,237.25	+22.56	59.26%	7,483.13	+3.40
Single Crop (Summer)	3.42%	392.19	4.21%	502.81	+28.21	2.66%	335.75	-33.23
Bare Soil Cropland	0.17%	20.06	0.73%	87.19	+334.58	0.25%	32.13	-63.15
TOTAL	**100.00%**	**11,475.38**	**100.00%**	**11,939.75**		**100.00%**	**12,627.56**	
	2001		*2001-2007*			*2007-2008*		
Brazilian Shield	*Area (%)*	*Area (km^2)*	*Area (%)*	*Area (km^2)*	*Change (%)*	*Area (%)*	*Area (km^2)*	*Change (%)*
Pasture	62.97%	353.06	62.63%	652.88	+84.92	74.19%	945.06	+44.75
Double Cropping	33.65%	188.69	32.56%	339.44	+79.89	23.18%	295.31	-13.00
Single Crop (Summer)	3.38%	18.94	4.80%	50.00	+164.03	2.58%	32.81	-34.38
Bare Soil Cropland	0.00%	0.00	0.01%	0.06	0.00	0.05%	0.63	+900.00
TOTAL	**100.00%**	**560.69**	**100.00%**	**1,042.38**		**100.00%**	**1,273.81**	
	2001		*2001-2007*			*2007-2008*		
Pantanal	*Area (%)*	*Area (km^2)*	*Area (%)*	*Area (km^2)*	*Change (%)*	*Area (%)*	*Area (km^2)*	*Change (%)*
Pasture	83.45%	226.88	79.12%	438.94	+93.47	78.58%	534.50	+21.77
Double Cropping	16.30%	44.31	19.69%	109.25	+146.54	20.37%	138.56	+26.83
Single Crop (Summer)	0.25%	0.69	1.18%	6.56	+854.55	1.05%	7.13	+8.57
Bare Soil Cropland	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00
TOTAL	**100.00%**	**271.88**	**100.00%**	**554.75**		**100.00%**	**680.19**	

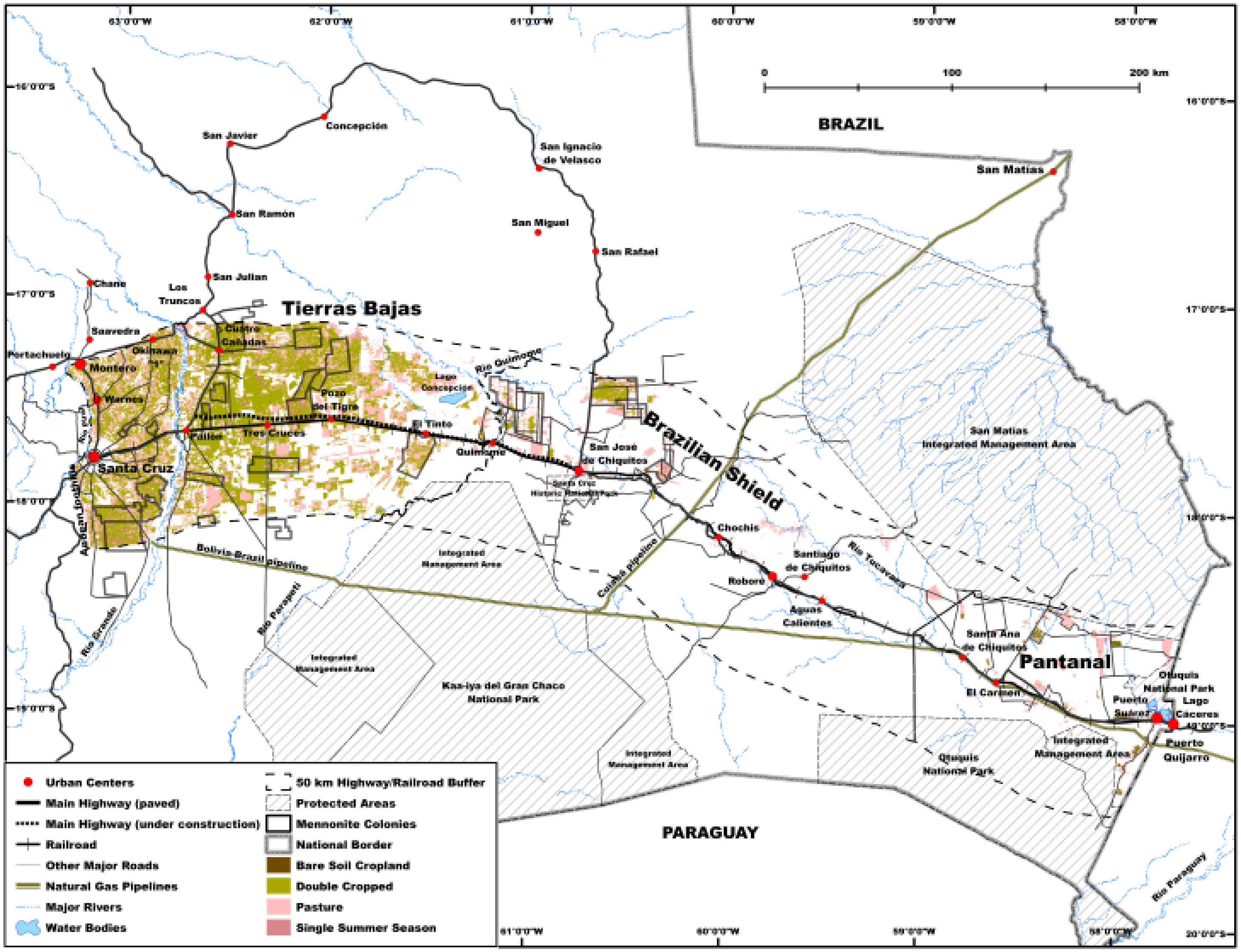


Figure 56. Pasture and cropland regimes classified for 2008.

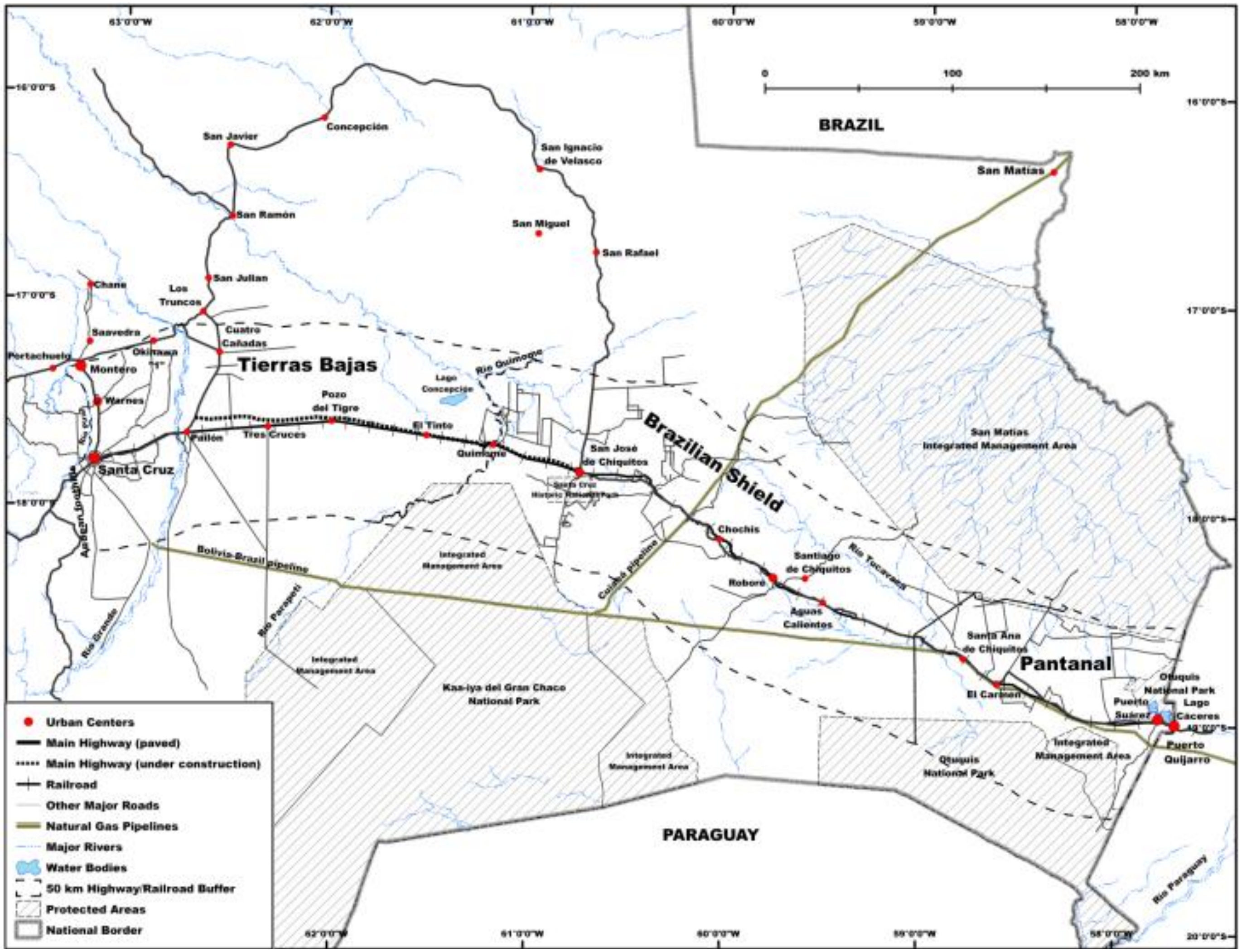


Figure 57. The Corredor Bioceánico of southeastern Bolivia. A 50-km buffer north and south of the main highway (dashed lines) has been used to demarcate the study area. Internal boundaries are defined by the Andean foothills and the Río Piraí to the west, Río Quimome and western ranges of the Brazilian Shield in the center and the Bolivia-Brazil border in the east (see text).

Table 36

Age, nationality and farm locations of respondents interviewed (from May to June, 2009).

Farm Size and Type	**Area/#**	**Nationality**	**%**	**Age**	**%**	**Property Location**[1]	**%**
Small farms (<50 ha)		*(Bolivia)*	(56.1%)	*High*	76	*Tierras Bajas Integrated Zone*	
Total size (ha)	107	Beni	3.1%	*Low*	35	Humid Northeast	9.1%
Average (ha)	27	Cochabamba	6.3%	*Average*	51.2	Intermediate Northeast	6.1%
Crop-only producers (#)	4	La Paz	3.1%	*30-44*	21.9%	Intermediate Central	18.2%
Animal-only producers (#)	0	Potosí	3.1%	*45-59*	56.2%	Dry South	18.2%
Hybrid producers (#)	0	Santa Cruz	40.5%	*60-79*	9.4%	*Tierras Bajas Expansion Zone*	
Medium farms (51-500 ha)		*Argentina*	3.1%	*Not Available*	12.5%	Humid North	6.1%
Total size (ha)	3,061	*Belize*	6.3%	**TOTAL (%)**	**100.0%**	Intermediate North	21.1%
Average (ha)	235	*Brazil*	3.1%	**TOTAL (#)**	**32**	Pailón-Tunás	9.1%
Crop-only producers (#)	5	*Canada*	3.1%			South Pailón	3.0%
Animal-only producers (#)	5	*Mexico*	9.4%			*Brazilian Shield*	6.1%
Hybrid producers (#)	3	*United Kingdom*	3.1%			*Pantanal*	3.0%
Agri-business (>501 ha)		*United States*	3.1%			**TOTAL (%)**	**100.00%**
Total size (ha)	61,350	*Not Available*	12.5%			**TOTAL (#)**[2]	**33**
Average (ha)	3,834	**TOTAL (%)**	**100.0%**				
Crop-only producers	6	**TOTAL (#)**	**32**				
Animal-only producers	4						
Hybrid producers	6						

[1] Locational categories are based on classification scheme used by CAO

[2] One respondent discussed two separate properties

Table 37

Rationale for Crop/animal and/or type (% of total responses).

	Minimize Risks	Price/ Market	Precipitation	Requires Less Input[3]	Soil Tillage/ Rotation[4]	Government Policy[5]	Production (Quantity)	Beneficial to Other Crops	Animal Feed	Prevent Vegetation	Tradition	Subsistence
Soybeans	0.6%	6.3%	1.7%	1.1%	2.3%	0.6%	--	--	--	0.6%	0.6%	--
Sunflower	--	0.6%	--	--	2.3%	0.6%	--	--	--	--	0.6%	--
Wheat	--	1.1%	1.7%	--	2.3%	--	--	--	--	--	0.6%	--
Sorghum	--	1.7%	0.6%	0.6%	4.0%	0.6%	1.1%	--	2.3%	--	1.7%	--
Maize	--	2.8%	1.1%	0.6%	2.8%	1.1%	--	1.1%	2.3%	--	2.3%	0.6%
Sugar	--	0.6%	0.6%	0.6%	--	--	--	--	--	--	1.7%	--
Cotton	--	0.6%	--	0.6%	1.1%	--	--	--	--	--	0.6%	--
Sesame	--	1.1%	--	--	0.6%	--	--	--	--	--	--	--
Rice	--	2.8%	2.3%	--	1.1%	0.6%	--	--	--	0.6%	0.6%	0.6%
Peanuts	--	1.1%	--	--	--	0.6%	--	--	--	--	0.6%	0.6%
Other Crops[1]	--	2.3%	1.7%	--	1.1%	0.6%	--	--	--	--	1.7%	0.6%
Dairy Cattle	--	1.1%	--	1.1%	--	--	--	--	--	--	2.3%	--
Meat Cattle	3.4%	2.3%	2.3%	0.6%	--	--	--	--	--	--	4.0%	--
Chick		0.6%	--	--	--	--	--	--	--	--	--	--
Other Animals[2]	1.7%	0.6%	0.6%	--	--	--	--	--	--	--	1.1%	0.6%
TOTAL (%)	5.7%	25.6%	12.5%	5.1%	17.6%	4.5%	1.1%	1.1%	4.5%	1.1%	18.2%	2.8%
TOTAL (#)	10	45	22	11	31	8	2	8	8	2	32	5

[1] Other Crops: Chia Seeds, Citrus, Tomatoes, Watermelon, Beans

[2] Other Animals: Sheep, Pigs & Buffalo

[3] Requires less input of labor, time, and chemicals (fertilizer, herbicide, pesticide)

[4] Soil Tillage/Rotation: Maintain soil fertility, moisture, composition & keeps pests/disease to a minimum; zero tillage system

[5] Government Policy includes support through funding & training as well as export limitation

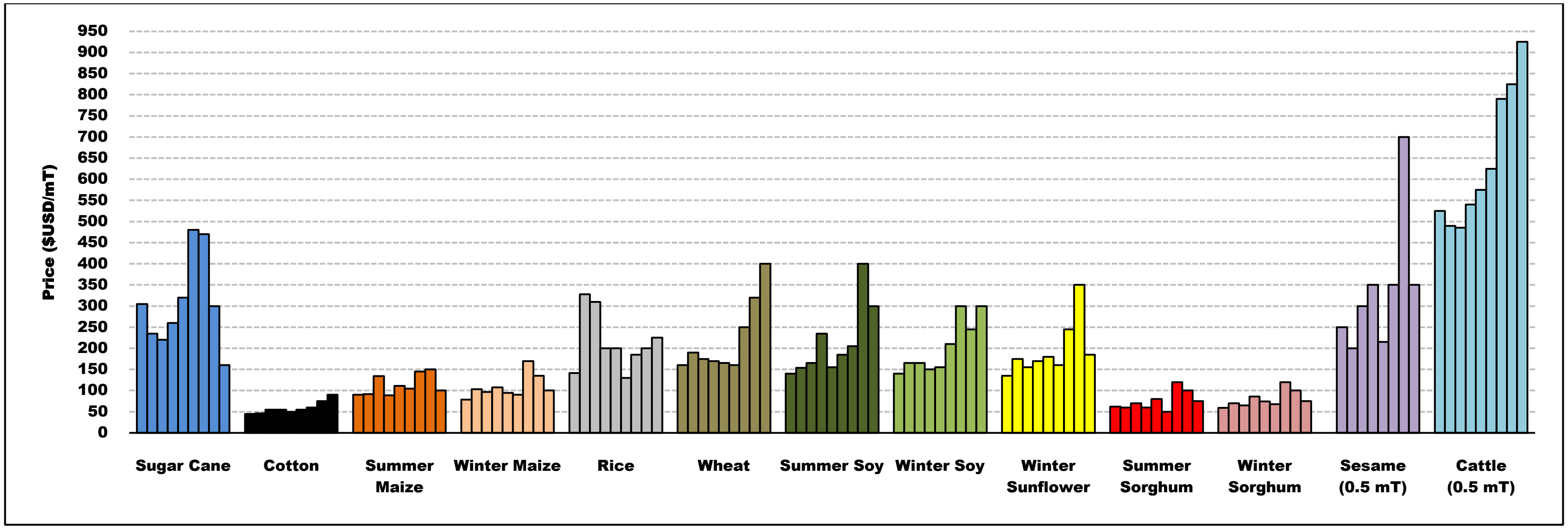


Figure 58. Price of major crops and cattle in Santa Cruz. Each bar for each crop represents a single year (2000-2009). The price of sesame and cattle are scaled at 0.5 metric tons to provide better comparison to other land-use types.

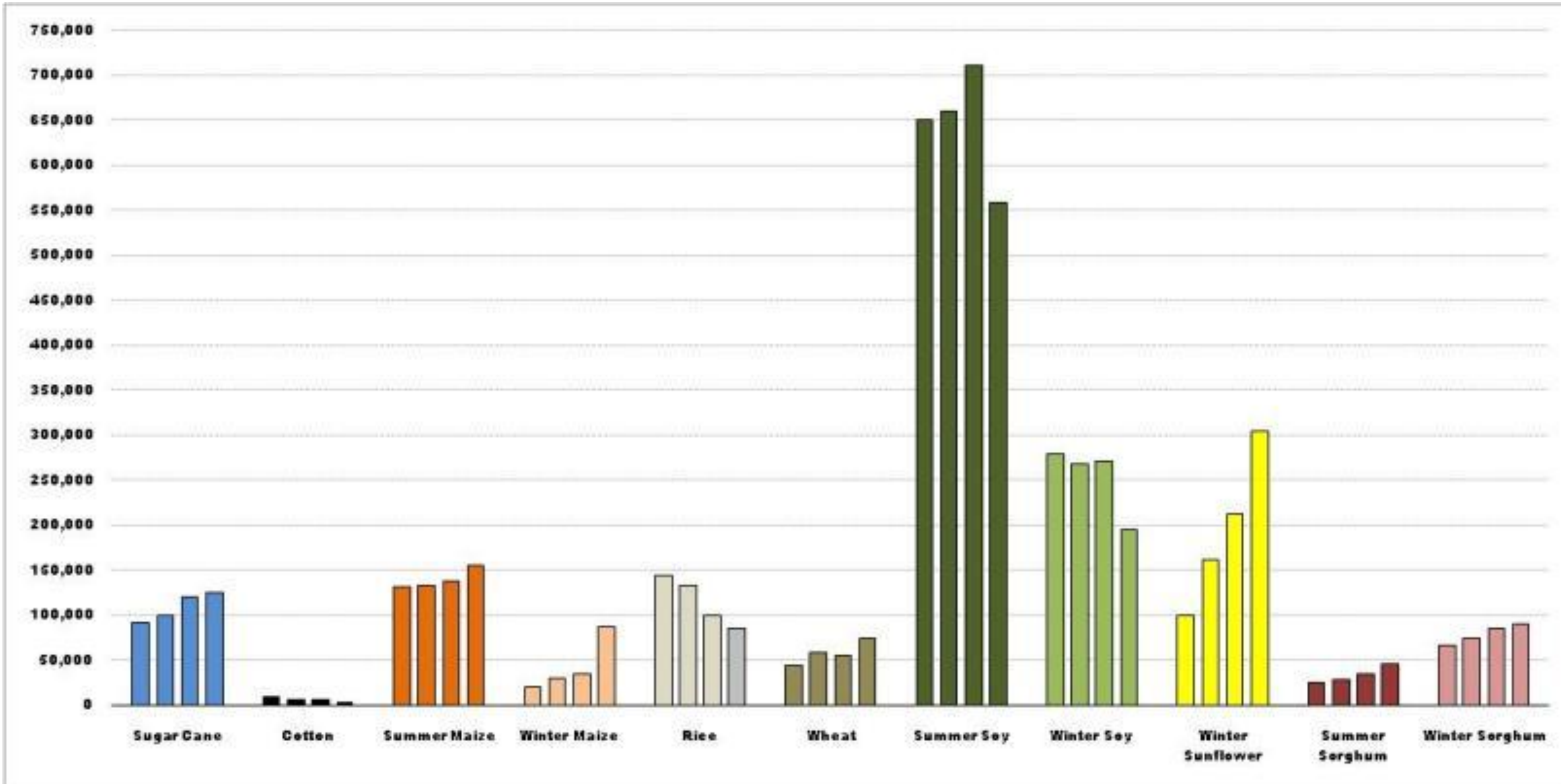


Figure 59. Bar graph showing the major commercial crop areas. Each bar for each crop type represents a year between 2000 and 2009 (ANAPO 2008; CAO 2008).

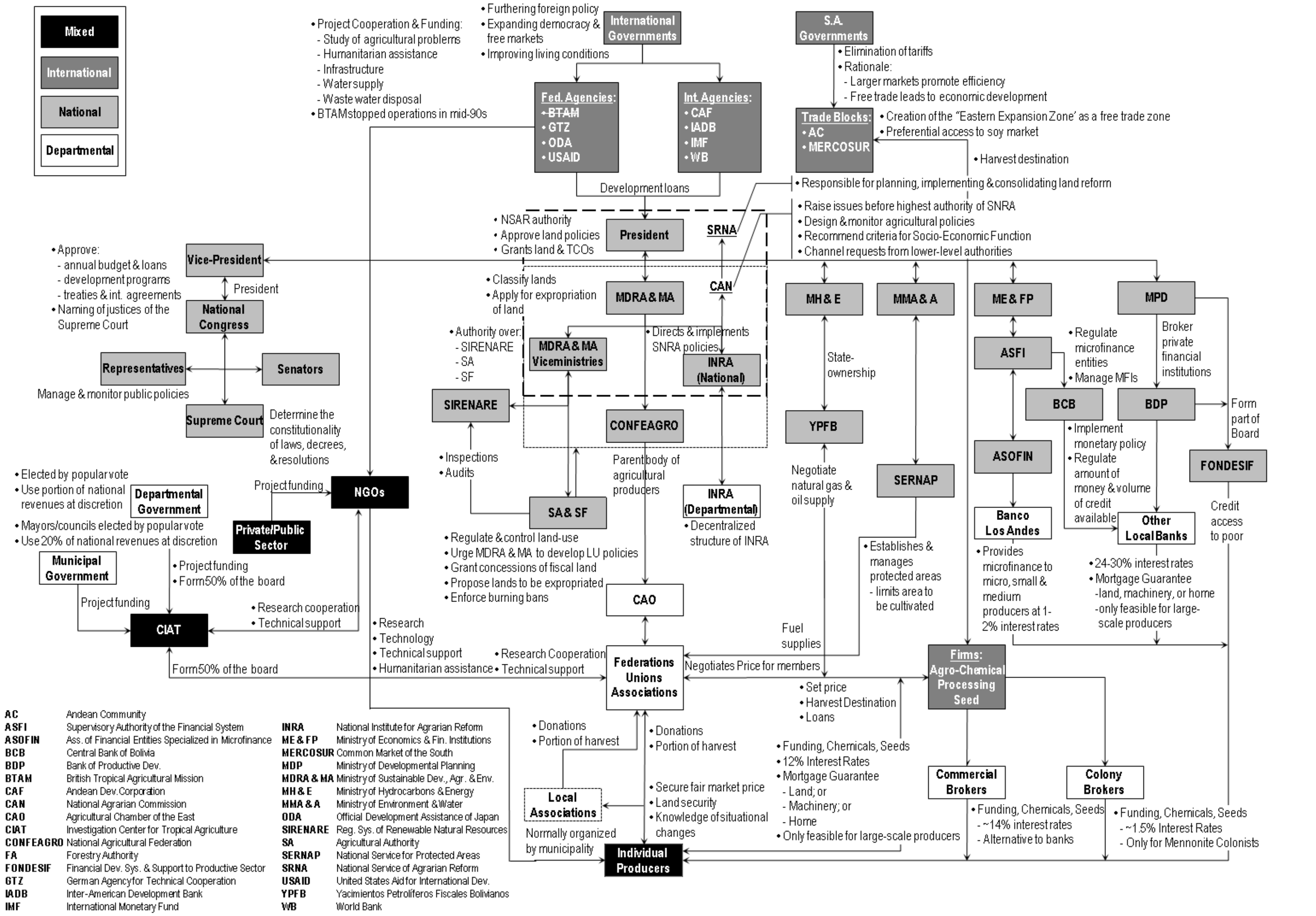


Figure 60. Organizational structure of actors.

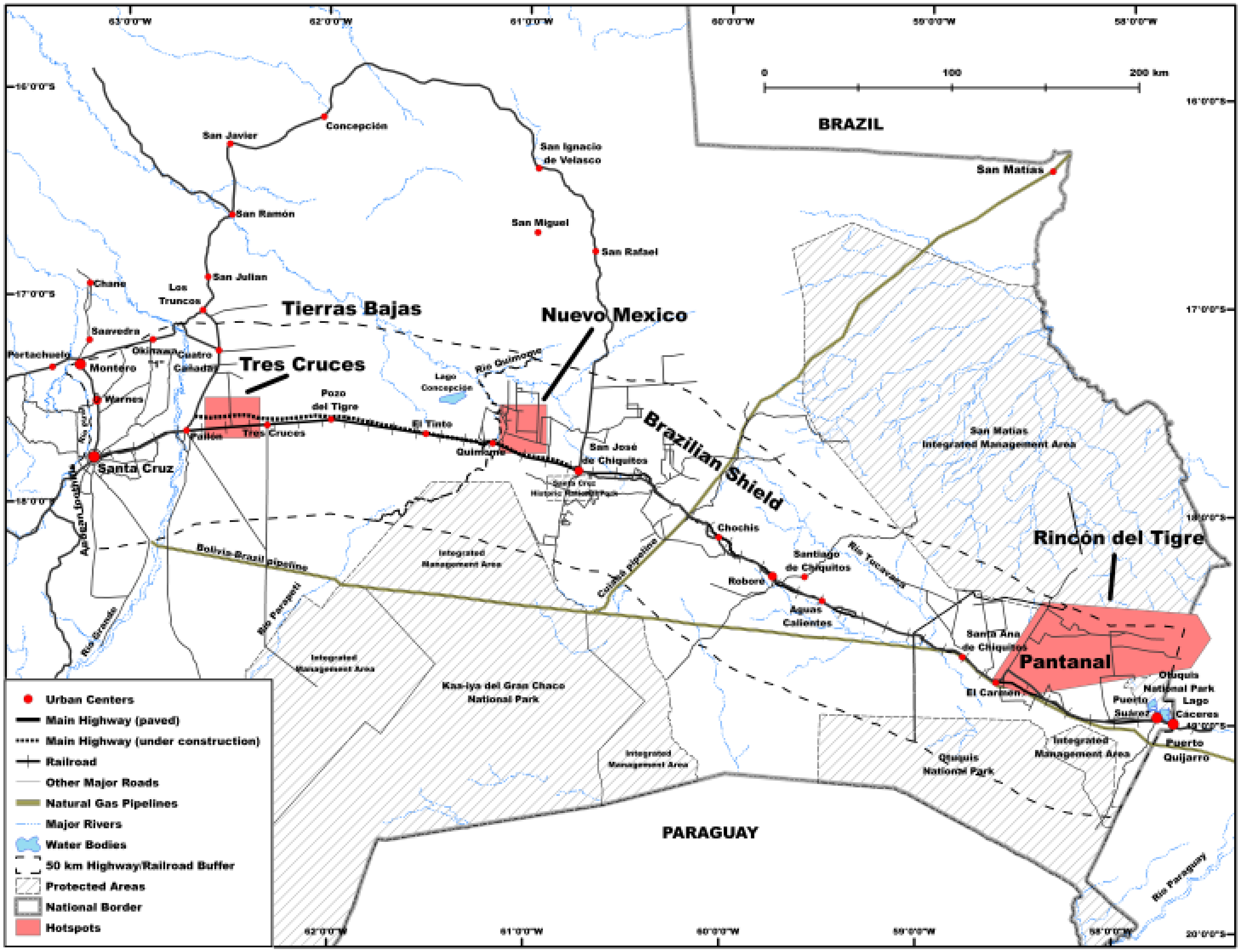


Figure 61. Locational map of the Corredor Bioceánico and three 'hotspots.'

Table 38
Description of satellite imagery used in classification.

	Tierras Bajas[i]				**Tres Cruces**[iv]			
	Landsat TM	Landsat TM	Landsat ETM+		CBERS-2	CBERS-2	CBERS-2B	CBERS-2B
Path/Row	1986-88	1992-94	2000-01	Path/Row	2005	2006	2007	2008
231/72	25-July-86	09-July-92	11-Aug-01	172/120	10-Oct-05	09-Oct-06	31-May-07	20-Oct-08
231/73	25-July-86	29-Aug-93	11-Aug-01					
230/72	26-May-87	19-June-93	07-Dec-00					
230/73	02-July-86	10-July-92	01-Aug-00					
229/72	16-July-88	17-July-94	25-July-00					
	Brazilian Shield[ii]				**Nuevo México**[v]			
	Landsat TM	Landsat TM	Landsat ETM+		CBERS-2	CBERS-2	CBERS-2B	CBERS-2B
Path/Row	1986-88	1992-94	2000-01	Path/Row	2005	2006	2007	2008
229/72	16-July-88	17-July-94	25-July-00	170/120	30-July-05	03-July-06	06-June-07	21-Nov-08
229/73	27-July-86	17-July-94	25-July-00	171/120	17-Sept-05	30-June-06	29-June07	27-Sept-08
228/72	24-Oct-86	21-June-93	07-Sept-01					
228/73	24-Oct-86	21-June-93	31-Mar-01					
227/73	10-May-89	17-June-94	12-June-01					
	Pantanal[iii]				**Rincón El Tigre**[vi]			
	Landsat TM	Landsat TM	Landsat ETM+		CBERS-2	CBERS-2	CBERS-2B	CBERS-2B
Path/Row	1986-88	1992-94	2000-01	Path/Row	2005	2006	2007	2008
228/73	24-Oct-86	21-June-93	31-Mar-01	167/121	13-July-05	07-Aug-06	15-June-07	18-Aug-08
227/73	10-May-89	17-June-94	12-June-01	168/121	05-Aug-05	04-Aug-06	12-June-07	19-July-08

[i] For the purposes of this study, the Tierras Bajas is defined by the Andean foothills to the west and western ranges of the Brazilian Shield to the east.
[ii] The Brazilian Shield is defined by the three ranges of the Brazilian Shield which extend into Bolivia.
[iii] The Pantanal is limited to the wetlands which define the region and the Bolivia-Brazil border.
[Iii] The Tres Cruces subset is contained within the Tierras Bajas study area and centered west of the city of Tres Cruces
[iv] The Nuevo México subset is contained within the Brazilian Shield study area and centered on the newly formed Mennonite community of Nuevo Mexico
[v] The Rincón El Tigre subset is partially contained within the Pantanal study region and covers the town of El Carmen illegal colonization along the Brazilian border.

Table 39

Agrarian reforms implemented in Bolivia (1953-2009).

Year(month)	Reforms	Administration	Key Elements
1953 (August)	Law Nº 3464	Víctor Paz Estenssoro (1952-56)	• Attempted to dissolve *latifundias* and give peasants small plots of cultivable land (*minifundia*) • Promoted migration to the eastern lowlands • Expropriation was largely confined to the Altiplano as cronyism and lack of institutions to enforce regulation permitted the coalescence of large plots in the lowlands • Compensation was given to landowners, payable in the form of government bonds
1996 (October)	Law Nº 1715	Gonzalo Sánchez de Lozada (1993-97)	• Distributed state-owned lands and land obtained through corruption to peasants • Provided for the recognition of indigenous communal lands (TCOs) • Provided only minimal benefits for peasants • Allowed the continued existence of large estates in the lowlands • TCO creation was only moderately effective as the succeeding Banzer administration reorganized key institutions and/or fired key staff members
2006 (November)	Law Nº 3545	Evo Morales (2006-present)	• Modifies and attempts to effectively implement Law 1715 • Grants State the right to expropriate and redistribute land in non-compliance of the SEF
2009 (January)	Constitutional Amendment	Evo Morales (2006-present)	• *Existing land holdings grandfathered in* • *Caps future landed estates at 5,000 hectares* • Requires that land meet the SEF at all times

Sources: adapted from Klein (2003); Sanjines (2005); Pacheco (2006); Köppen (2008)

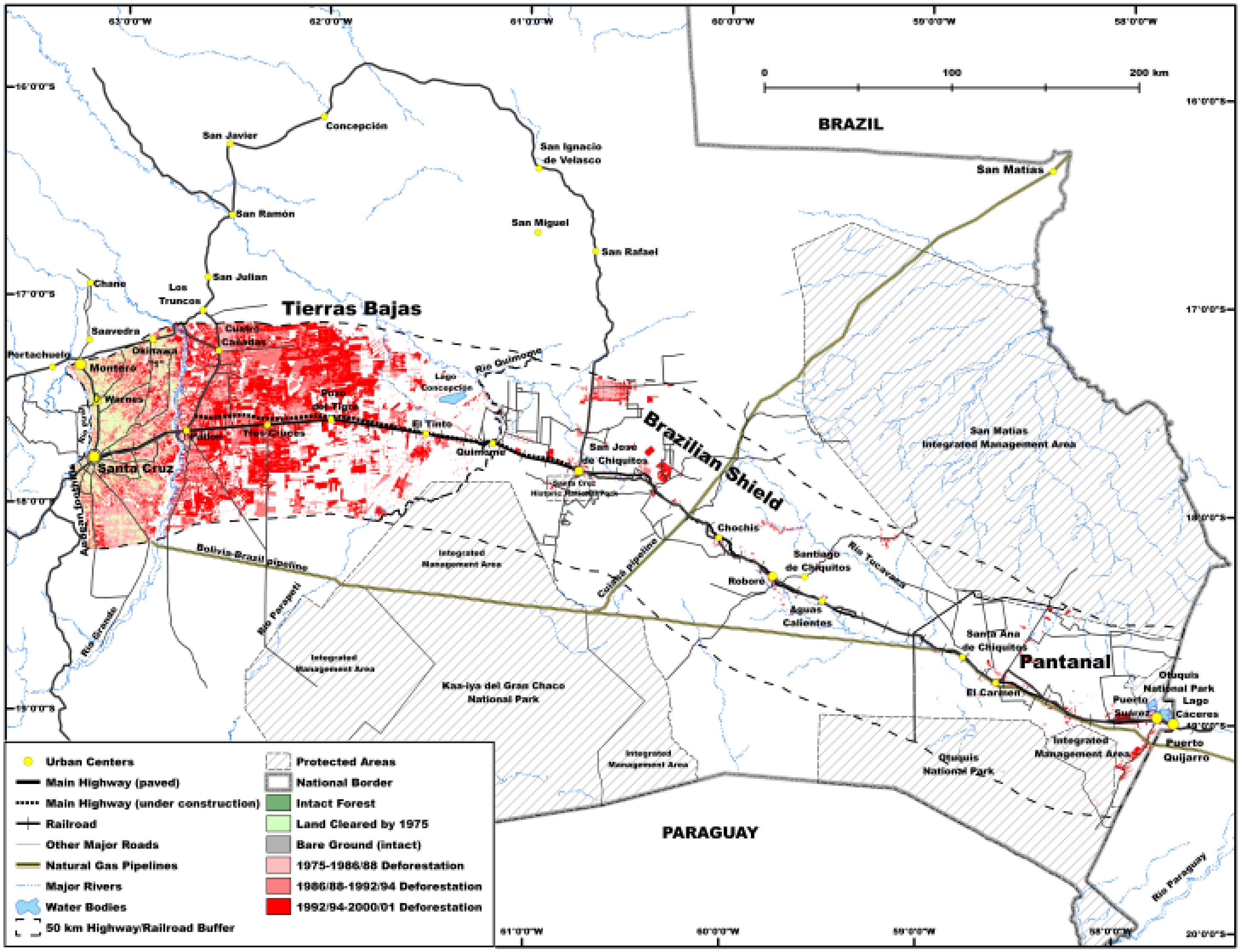


Figure 62. Forest clearance (1986-2001) during the neoliberal period.

Table 40

Deforestation for neoliberal period (1986-2001).

Tierra Bajas	**1986-88**	**1992-94**		**2000**	
Classes	Area (km^2)	Area (km^2)	% Change (Area)	Area (km^2)	% Change (Area)
Forest	17,892.5	15,426.3	-13.8	10,089.1	-34.6
Agriculture	3,457.9	5,913.9	+71.0	11,204.6	+89.5
Bare Ground	146.0	94.6	-35.2	123.3	+30.4
Water Bodies	134.4	127.1	-5.4	102.8	-19.1
Urban/Infrastructure	107.6	161.4	+49.9	240.4	+49.0
TOTAL	**21,738.4**	**21,723.3**	**--**	**21,760.3**	**--**
Brazilian Shield	**1986-88**	**1992-93**		**2000-01**	
Classes	Area (km^2)	Area (km^2)	% Change (Area)	Area (km^2)	% Change (Area)
Forest	25,744.3	25,596.8	-0.6	26,088.3	+1.9
Agriculture	154.6	266.2	+72.2	544.2	+104.4
Bare Ground	2,313.3	2,350.3	+1.6	1,562.0	-33.5
Water Bodies	0.0	0.0	0	0.0	0
Urban/Infrastructure	38.1	36.8	-3.5	55.5	+51.0
TOTAL	**28,250.2**	**28,250.0**	--	**28,250.0**	**--**
Pantanal	**1986-89**	**1993-94**		**2001**	
Classes	Area (km^2)	Area (km^2)	% Change (Area)	Area (km^2)	% Change (Area)
Forest	12,089.6	12,012.8	-0.6	11,753.6	-2.2
Agriculture	70.6	128.8	+82.3	270.3	+110.0
Bare Ground	325.6	294.9	-9.4	453.2	+53.7
Water Bodies	147.3	200.0	+35.8	153.9	-23.0
Urban/Infrastructure	17.9	19.7	+10.1	36.0	+82.9
TOTAL	**12,651.0**	**12,656.2**	**--**	**12,667.1**	--

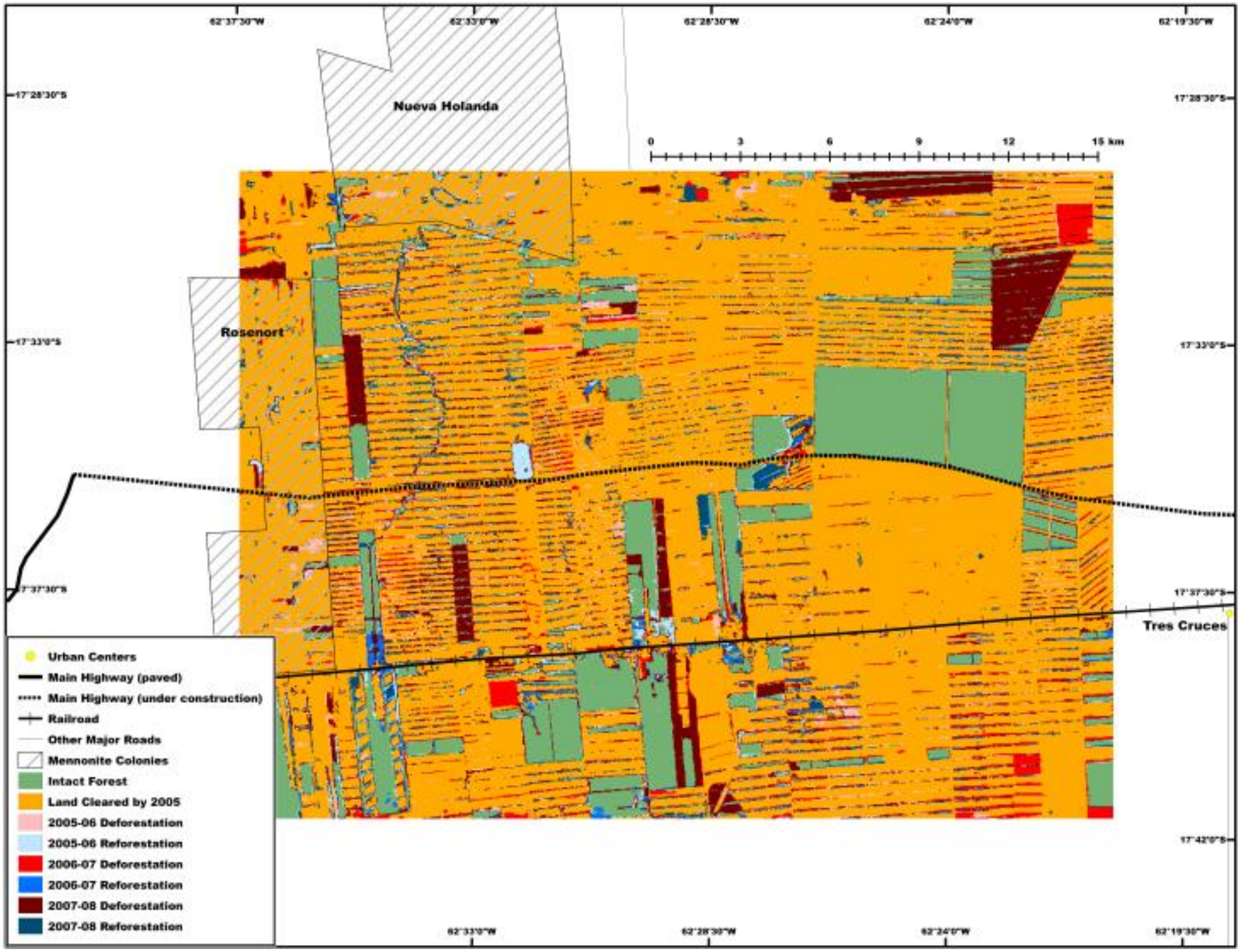


Figure 63. Forest clearance (2005-2008) near Tres Cruces.

Table 41

Deforestation for the post-neoliberal period (2005-2008).

Tres Cruces	**2005**	**2006**		**2007**		**2008**	
Classes	Area (km^2)	Area (km^2)	% Change (Area)	Area (km^2)	% Change (Area)	Area (km^2)	% Change (Area)
Forest	144.7	154.5	+6.8	150.4	-2.7	121.9	-18.9
Agriculture	492.3	482.5	-2.0	486.6	+0.8	515.1	+5.9
TOTAL	**637.0**	**637.0**	**--**	**637.0**	**--**	**637.0**	**--**
Nuevo México	**2005**	**2006**		**2007**		**2008**	
Classes	Area (km^2)	Area (km^2)	% Change (Area)	Area (km^2)	% Change (Area)	Area (km^2)	% Change (Area)
Forest	613.0	594.4	-3.0	566.7	-4.7	451.2	-20.4
Agriculture	37.0	55.6	+50.3	83.7	+50.5	198.8	+137.5
TOTAL	**650.0**	**650.0**	**--**	**650.4**	**--**	**650.0**	**--**
Rincón del Tigre	**2005**	**2006**		**2007**		**2008**	
Classes	Area (km^2)	Area (km^2)	% Change (Area)	Area (km^2)	% Change (Area)	Area (km^2)	% Change (Area)
Forest	3,425.7	3,379.8	-1.3	3,353.1	-0.8	3,224.5	-3.8
Agriculture	174.3	220.2	+26.6	246.9	+12.1	375.5	+52.1
TOTAL	**3,600.0**	**3,600.0**	**--**	**3,600.0**	**--**	**3,600.0**	**--**

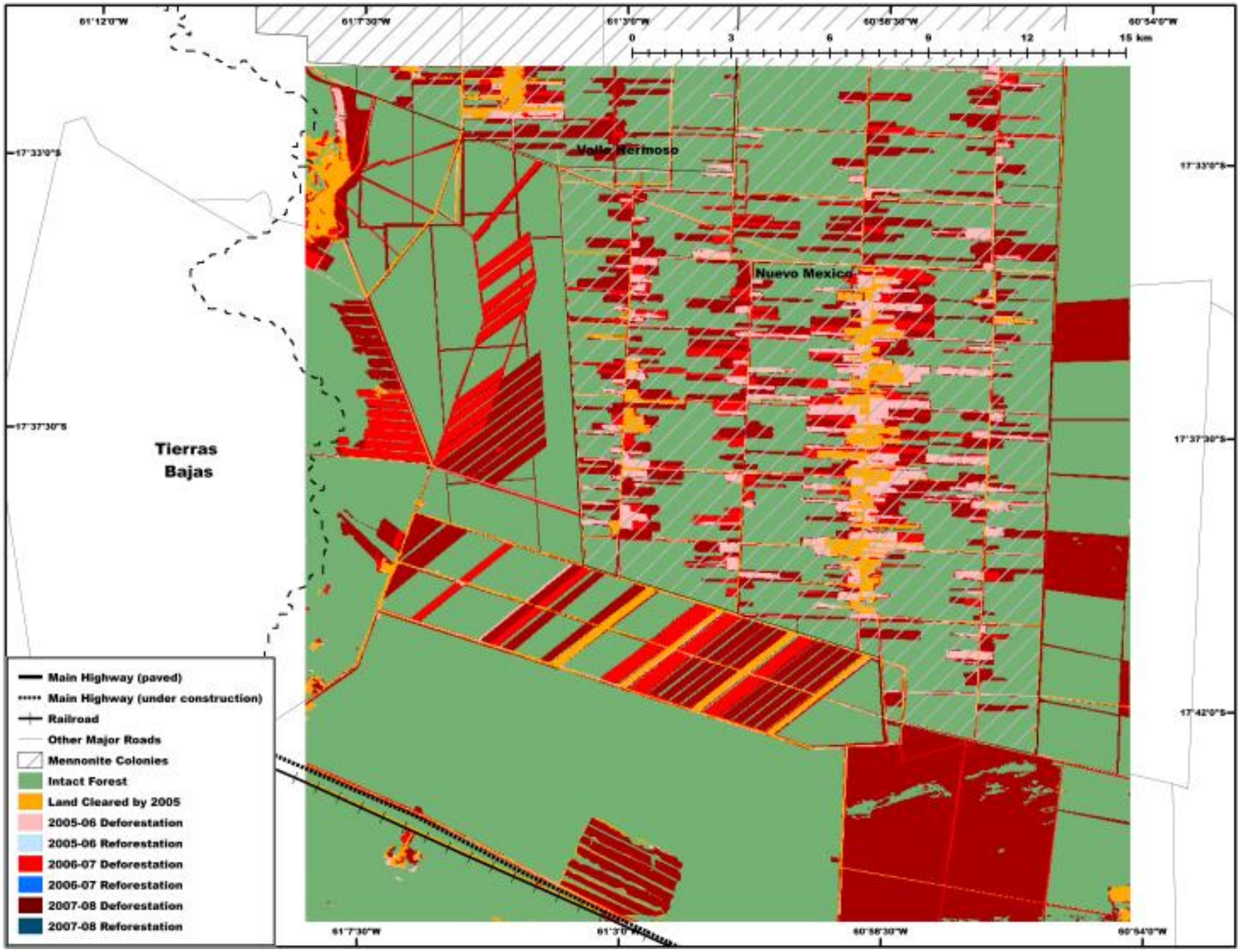


Figure 64. Forest clearance (2005-2008) in Nuevo México.

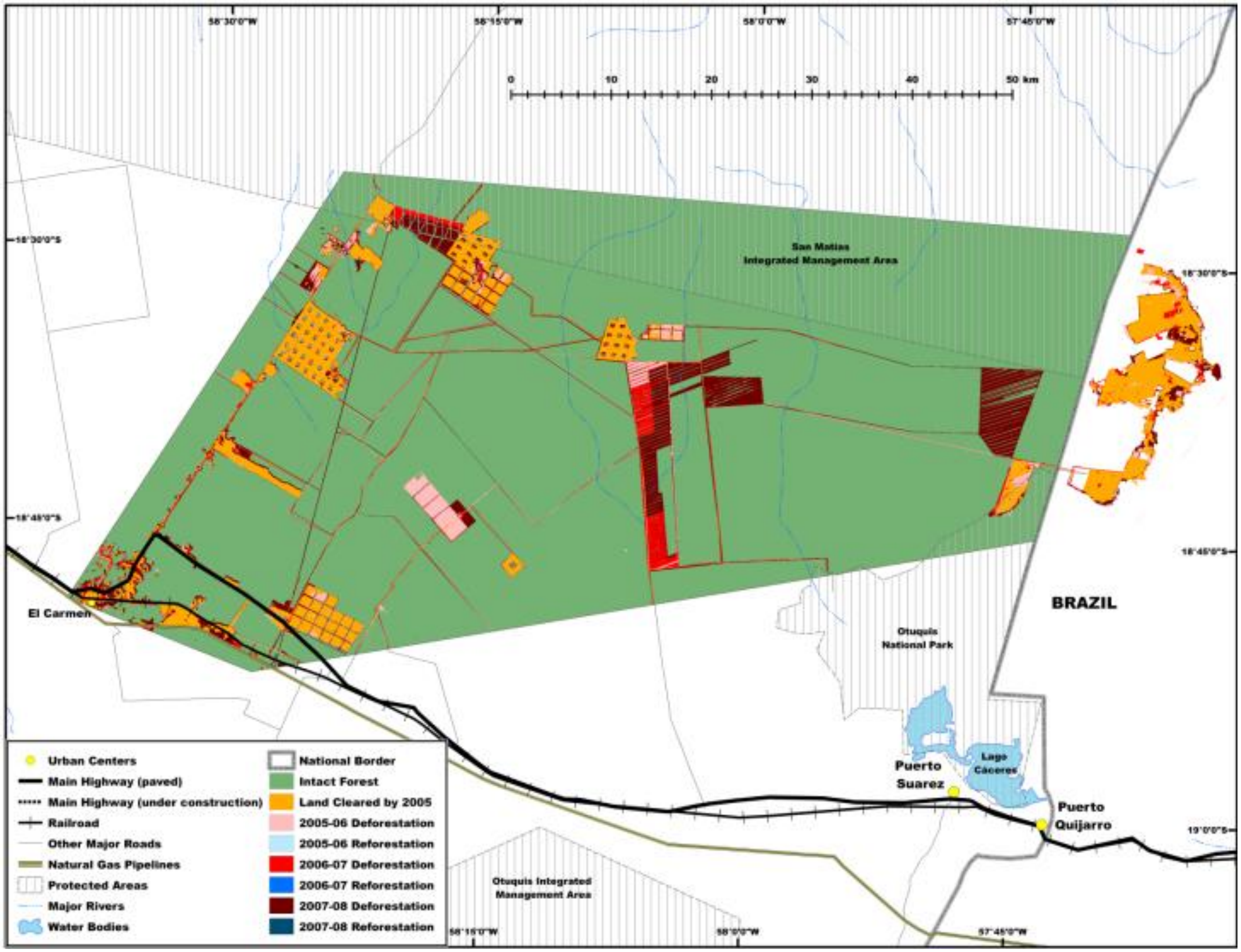


Figure 65. Forest clearance (2005-2008) in Rincón del Tigre. Pasture lands located in Brazil are intended to illustrate the close proximity of legal Brazilian settlement to Bolivia and have been eliminated from statistical analysis.

Table 42

Lands expropriated under Law N° 3545.

Status	Charge/Reason	Department	Province	Size (km^2)
Redistributed	Illegal settlements	Santa Cruz	Guarayos	160.0
Redistributed	Child labor; Slavery conditions	Santa Cruz	Cordillera	37.9
Redistributed	Child labor; Slavery conditions	Santa Cruz	Cordillera	19.3
Redistributed	Child labor; Slavery conditions	Santa Cruz	Cordillera	109.6
Redistributed	Child labor; Slavery conditions	Santa Cruz	Cordillera	44.7
Redistributed	Child labor; Slavery conditions	Santa Cruz	Cordillera	152.6
In Process	Lands illegally acquired; Slavery conditions	Chuquisaca	Luis Calvo/Hernando Siles	1,800.0
In process	Non-compliance with the SEF	La Paz	Nor Yungas	4.5
In process	Promote mining in Mutún	Santa Cruz	German Busch	1.1
In process	Promote mining in Mutún	Santa Cruz	German Busch	1.3
In process	Slavery conditions	Santa Cruz	Guarayos	125.8

Source: *Instituto Nacional de Reforma Agraria* (http://www.inra.gob.bo/)

Table 43
Fire hotspots and fire permits issued in Bolivia (2000-2007).

	Fire Hotspots					**Fire Permits Issued**	
Year	No.	% Annual Change	Area (km^2)	% in Santa Cruz[i]	% in Beni[i]	No.	Area (km^2)
2000	643	--	10,332	--	--	--	--
2001	2,079	+223.3	5,396	--	--	--	--
2002	3,035	+45.9	9,202	--	--	--	--
2003	20,298	+568.7	28,620	--	--	68	995
2004	50,464	+148.6	61,061	12.6	11.6	136	2,424
2005	29,743	-41.0	35,989	3.4	24.7	195	100
2006	21,827	-26.6	28,562	13.0	15.9	0[ii]	0
2007	21,667	-0.7	--	20.0	12.4	0[iii]	0

[i] Aggregated % from top 3 municipalities containing greatest number of fires in the Department of Santa Cruz and Beni.
[ii] No permits granted; application either did not meet requirements or fell outside the area permitted for fires.
[iii] No permit requests made.

Sources: *Superintendencia Agraria*; *Agencia Boliviana de Información* (2008)

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