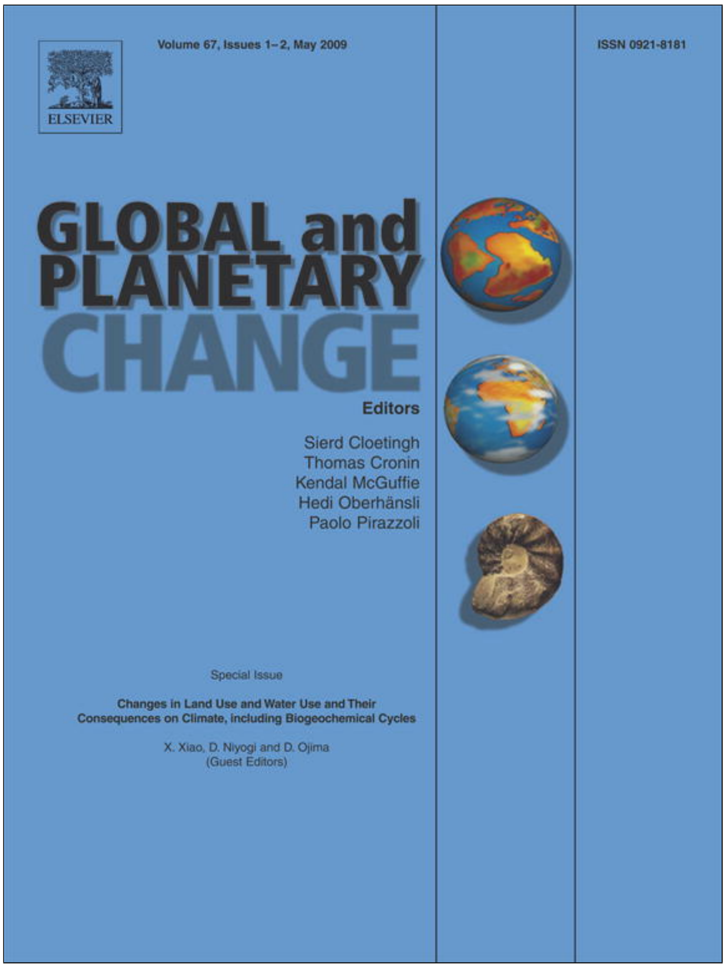
Volume 67, Issues 1–2, May 2009
ISSN 0921-8181
ELSEVIER
GLOBAL and PLANETARY CHANGE
Editors
Sierd Cloetingh
Thomas Cronin
Kendal McGuffie
Hedi Oberhänsli
Paolo Pirazzoli
Special Issue
Changes in Land Use and Water Use and Their Consequences on Climate, including Biogeochemical Cycles
X. Xiao, D. Niyogi and D. Ojima
(Guest Editors)

Global and Planetary Change 67 (2009) 1–12

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Assessment of Paraguay's forest cover change using Landsat observations

Chengquan Huang [a,*], Sunghee Kim [b,1], Kuan Song [a,b], John R.G. Townshend [a], Paul Davis [a,b], Alice Altstatt [a], Oscar Rodas [c], Alberto Yanosky [c], Rob Clay [c], Compton J. Tucker [a,d], John Musinsky [e]

[a] Department of Geography, University of Maryland, College Park, MD 20742, USA
[b] Institute for Advanced Computer Studies, University of Maryland, College Park, MD 20742, USA
[c] Coronel Rafael Franco 381, P.O. Box 1132, Asunción, Paraguay
[d] NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[e] Conservation International, 1919 M Street, NW Suite 600, Washington, DC 20036, USA

ARTICLE INFO

Article history:
Accepted 8 February 2008
Available online 3 January 2009

Keywords:
Atlantic forest
Chaco Woodland
forest loss
protected area
Landsat
Paraguay

ABSTRACT

Comprehensive assessments of Paraguay's forest cover (FC) change from the 1970s to the 2000s using Landsat observations were conducted, including a wall-to-wall mapping of changes across the whole country between the 1990s and 2000s, and an assessment of forest area in the Atlantic Forest ecoregion in the 1970s using a systematic sampling approach. The derived wall-to-wall FC change map was evaluated using available high resolution satellite images and aerial photos. The overall accuracy values were 92% or higher in the areas covered by those high resolution data sets. The results revealed that the Atlantic Forest ecoregion experienced the most forest loss, with the 73.4% forest cover in the 1970s decreasing precipitously down to 40.7% by the 1990s and further down to 24.9% by the 2000s. The rapid loss of Atlantic forests was driven by complex social economic forces, including widespread land disputes arising from long time inequalities and profits from exporting agricultural products. Forest changes in the Humid Chaco and the Chaco ecoregions were relatively moderate. However, extensive forests were converted to non-forest land use near a major population center. The results also revealed that so far the established protected areas were effective in protecting forest within their border. However, most of the forests surrounding the protected areas were lost by the 2000s. Loss of Atlantic forest is a major threat to the rich biodiversity found in this region. The alarming deforestation rates over the last three decades and the low percentage of Atlantic forest left by the 2000s call for immediate actions to halt the trends of forest loss.

1. Introduction

Paraguay is an ecologically unique country located at the confluence of five ecoregions: the Atlantic Forest, the Humid Chaco, the Chaco Woodland, the Pantanal, and the Cerrado. The Rio Paraguay River bisects the country into distinctive ecological regions. To the east of the river are the remnants of the humid Interior Atlantic Forest, an ecological region containing many endemic subtropical tree species as well as some tropical and Cerrado species. It is one of the biologically most diverse ecoregions and home to many rare Atlantic vertebrates (Gauto, 1989). To the west of the river are vast alluvial plains supporting the Chaco Woodland, a habitat for many species rarely seen in other ecoregions and home to many endangered species. For instance, a reportedly extinct mammal, *Catagonus*, which is a third species of peccary, was found to be living in the Chaco Woodland of western Paraguay (Wetzel et al., 1975), as was the Black-bodied Woodpecker *Dryocopus schulzi* (Nieto and Pearman, 1992). Between the Atlantic Forest and the Chaco Woodland is the Humid Chaco. Due to the heterogeneity of the habitat in this ecoregion, the fauna is considerably diversified (WWF, 2001). The richness and distinctiveness of Paraguay's biodiversity was recognized as early as in the late 19th century. The country was described as a paradise of animal life (Levi, 1874) and Morong (1889) stated that few countries the size of Paraguay could have such a diverse and prolific flora.

A major threat to Paraguay's rich biodiversity is rapid forest loss. The country has experienced massive changes in forest cover over the last several decades. High rates of forest loss have been reported by international organizations such as the Food and Agriculture Organization (FAO) of the United Nations, the World Wildlife Fund (WWF) (FAO, 2003; Dros, 2004), and the United States Agency for International Development (USAID) (Catterson et al., 2004). The massive forest loss was observable even at the 8-km spatial resolution using Advanced Very High Resolution Radiometer (AVHRR) data acquired between 1982 and 1999 (Hansen and DeFries, 2004). In eastern Paraguay, rapid increase in mechanized farming of soybeans, cotton, and sugar caused massive and uncontrolled forest clearance (Nickson, 1981; Rios and Zardini, 1989). Even protected areas such as the San Rafael Reserve and Mbaracayu

* Corresponding author. 2181 LeFrak Hall, Department of Geography, University of Maryland, College Park, MD 20742, USA. Tel.: +1 301 314 2585; fax: +1 301 314 9299.
E-mail addresses: cqhuang@umd.edu (C. Huang), sunghee@wam.umd.edu (S. Kim).
[1] Present address: Water Resources PhD Program, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742, USA.

0921-8181/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2008.12.009

Nature Reserve were threatened by cash crops, hunting, and illegal logging (Hill et al., 1997; Quintana and Morse, 2005). In western Paraguay, increasing human encroachment due to overgrazing, timber harvesting, and the expansion of cash crop plantations brought negative impacts on biodiversity and natural resources (Bucherm and Huszar, 1999). For instance, the development of the Trans-Chaco road allowed increased accessibility, which increased forest clearance (Wetzel et al., 1975; Taber, 1989; Bucherm and Huszar, 1999). Not only such rapid forest loss threatens the uniquely rich biodiversity (Sánchez-Azofeifa et al., 1999), but also the unsustainable agricultural practices that follow deforestation often result in severe soil erosion and loss of fertility (Lal, 1996). The wide spread deforestation is a major source of carbon emission in the tropical and subtropical forest region (DeFries et al., 2002; Hirsch et al., 2004).

Analyzing the consequences of forest change requires the change to be quantified systematically and reliably. Understanding the magnitude of forest cover (hereafter FC) change for the entirety of a country is essential to conservation efforts from all levels to help prevent further forest loss. While there have been reports on deforestation in Paraguay, as discussed before, there has not been a systematic analysis of forest change. According to an assessment of Paraguay's forestry and biodiversity conservation reported by USAID, inconsistent data sets from different studies impeded collaborative framework for natural resources management (Catterson and Fragano, 2004). Knowledge of land cover and change in the Chaco region is especially poor, although the area is as ecologically diverse and fragile as the Atlantic forest (Spichiger and Ramella, 1989; Keel et al., 1993; Eriksson et al., 2001; Catterson and Fragano, 2004).

This paper presents a comprehensive assessment of Paraguay's FC change using Landsat Multi-Spectral Scanner (MSS) images acquired in the1970s, Thematic Mapper (TM) images acquired in the 1990s, and Enhanced Thematic Mapper Plus (ETM+) images acquired in 2000s. Among all existing or previous satellite systems, the Landsat series provide the most comprehensive coverage, both spatially and temporally, of the Earth's land surface with spatial resolutions finer than 100 m. The three data sets used in this study were the best available Landsat data sets for Paraguay, with the 1970s data set being the earliest available. Because of different spectral and spatial characteristics between the MSS and TM images, a sampling based method was used to assess FC change between the 1970s and 1990s. For the 1990s–2000s period, however, the almost identical spatial and spectral characteristics of TM and ETM+ images allowed a wall-to-wall mapping of the whole country.

2. Data collection

2.1. Landsat images and preprocessing

The major data sets used in this study consisted of Landsat images acquired in the 1970s, 1990s, and 2000s. For the 1970s and 1990s epochs, the GeoCover Landsat images acquired through NASA's Science Data Buy program were used (Tucker et al., 2004). The 1970s' GeoCover data set consists of MSS images with a spatial resolution of 57-meter, whereas the 1990s' GeoCover data set consists of Landsat TM images with a spatial resolution of 28.5-meter. The GeoCover images have been orthorectified to achieve very high geolocation accuracy. While there is also a GeoCover 2000 data set, this data set was not available at the beginning of this study. Instead, Landsat 7 ETM+ images obtained from the U.S. Geological Survey (USGS) were utilized. These images were co-registered to the GeoCover 1990 images using manually selected ground control points (GCPs). For each image to be co-registered, a minimum of 25 GCPs scattered across the entire image were selected. The maximum allowed residual error measured by the root mean square of the difference between corrected coordinates and reference coordinates was 0.5 TM pixel.

Table 1
Acquisition dates of images used in this study.

(a). Landsat TM and ETM+ images for the 1990s and the 2000s epochs, respectively

Image (WRS2 scheme)		TM	ETM+
Path	Row		
224	77	5/24/1990	3/03/2001
224	78	4/19/1989	8/05/1999
224	79	5/13/1989	3/03/2001
225	76	11/25/1988	8/01/2001
225	77	11/18/1991	9/18/2001
225	78	3/22/1988	8/30/2000
225	79	1/10/1988	8/01/2001
226	75	7/06/1989	8/08/2001
226	76	7/06/1989	3/01/2001
226	77	6/23/1987	3/14/2000
226	78	3/03/1987	10/11/2001
226	79	3/03/1987	6/21/2001
227	74	5/10/1989	6/12/2001
227	75	4/24/1986	8/31/2001
227	76	3/15/1989	5/24/2000
227	77	3/15/1989	7/30/2001
228	73	10/24/1986	3/31/2001
228	74	10/24/1986	6/03/2001
228	75	5/14/1985	6/03/2001
228	76	1/26/1992	8/17/1999
228	77	1/26/1992	4/16/2001
229	73	7/27/1986	7/25/2000
229	74	7/27/1986	6/26/2001
229	75	1/17/1992	6/26/2001
229	76	1/17/1992	8/29/2001

(b). MSS images in the Atlantic Forest ecoregion for the 1970s epoch

Image (WRS1 scheme)		MSS
Path	Path	
240	77	5/23/1975
240	78	2/23/1973
240	79	3/231973
241	76	3/14/1973
241	77	9/15/1972
241	78	2/24/1973
241	79	9/15/1972
242	76	3/15/1973
242	77	3/15/1973

The GeoCover Landsat TM images in the 1990s for earlier dates (T1) and the Landsat ETM+ images in the 2000s for later dates (T2) were used to develop a FC change product for the whole of Paraguay and to identify the type of land use conversions leading to forest loss in the Atlantic Forest region. The GeoCover Landsat MSS images were used to evaluate the areal extent of FC in the Atlantic Forest region in the 1970s. Table 1 lists the Landsat images used in this study and their acquisition dates.

2.2. Other geospatial data sets

In addition to the Landsat images, boundaries of geographic entities were defined using various geospatial data sets. Paraguay's administrative boundaries were defined based on a data set obtained from the International Potato Center (CIP) website (CIP, 2004). Because administrative boundaries were sometimes defined along rivers or other terrain features, we considered the matching of some administrative boundaries delineated in the CIP data set with terrain features shown in the Landsat images as evidence of the reliability of the CIP data set. For the analysis of protected areas, two data sources were used. Boundaries of protected areas in eastern Paraguay were provided by local collaborators (Guyra Paraguay), while the World Database on Protected Areas (WDPA, 2004) created by the World Conservation Union (IUCN) and the United Nations Environment Programme (UNEP) was used for protected areas in western Paraguay. Ecoregion boundaries were obtained from the Global 200, a global ecoregion data set developed by the World Wildlife

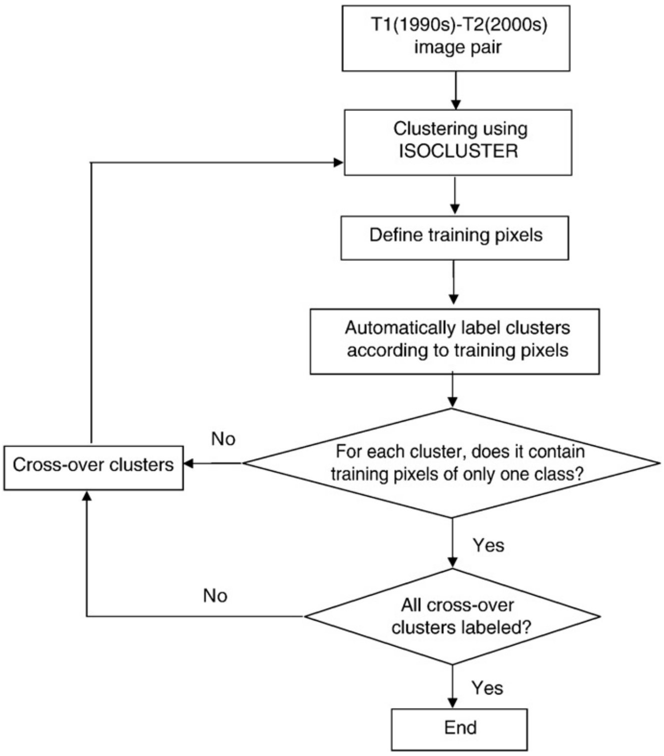

Fig. 1. A flow chart of the iterative clustering-supervised labeling change mapping method.

Fund (Olson and Dinerstein, 1998). Global 200, in a vector format, was downloaded from the World Wild Foundation (WWF) website.

3. Forest change assessment methods

3.1. Literature review

The use of remotely sensed data to map land cover changes started as early as land remote sensing imagery was made available in the 1970s. Since then numerous land cover change detection techniques have been developed. Comprehensive reviews of those techniques have been provided by a number of authors (Singh, 1989; Cohen et al., 1996; Coppin and Bauer, 1996; Coppin et al., 2004; Lu et al., 2004). While image differencing, principal component analysis (PCA), and post-classification comparison are among the most commonly used methods, Lu et al. (2004) concluded that different change assessment algorithms have their own merits and no single approach is optimal for all applications. Coppin and Bauer (1994) used image differencing algorithms and PCA to detect FC changes based on Landsat TM imagery. The study claimed that the relationship between reflective TM data and forest canopy change is explicit enough that these methods can be used in a FC change stratification phase prior to a more detailed assessment. Mas (1999) compared six change assessment methods such as image differencing, vegetation index differencing, selective-PCA, post-classification change differencing, direct multi-date unsupervised classification, and a combination of image enhancement with post-classification comparison. Based on Kappa coefficient calculations, post-classification comparison was the most accurate technique among the methods tested.

It should be noted that most studies of land cover change detection techniques have been conducted for relatively small areas (Collins and Woodcock, 1994; Lyon et al., 1998; Ridd and Liu, 1998). For change studies over very large areas that consist of diverse landscapes, intensive human inputs have typically been required in order to achieve acceptable results (Skole and Tucker, 1993; Townshend et al., 1995; Loveland et al., 2002).

3.2. Wall-to-wall mapping method

Wall-to-wall mapping of FC change for the entire Paraguay was achieved through the following steps using the 1990s (T1) and 2000s (T2) Landsat images described in Section 2.1. For each World Reference System2 (WRS2) path and row, the T1 and T2 images were stacked to make an image pair. Then the image pair was analyzed using an iterative clustering-supervised labeling method to produce a FC change map. Finally, the change maps for individual WRS2 path/row were mosaicked to produce a wall-to-wall map for the entire country.

The iterative clustering-supervised labeling method consisted of two major processes: unsupervised isodata clustering and supervised labeling of clusters based on defined training pixels (Fig. 1). The initial clustering classified an image pair into groups of up to 250 clusters. Training pixels were then delineated for all clusters by visual interpretation of the Landsat images with local experts' assistance. Paraguay's forests were categorized into two broad types, Atlantic Forest and Chaco Woodland. According to the Vegetation Continuous Field (VCF) of tree cover derived from the Moderate Resolution Imaging Spectroradiometer data (Hansen et al., 2002), most Chaco Woodland forests have VCF values below 55% while the Atlantic forests have VCF values above 55% (Fig. 2). Therefore, we used the 55% forest cover threshold value to separate Chaco Woodland from Atlantic Forest. Forest loss was defined as the conversion of either type of forest in the 1990s to non-forest surfaces in the 2000s. Non-forest and water also were identified (Table 2). After the delineation of training data sets, an in-house program was employed to count the

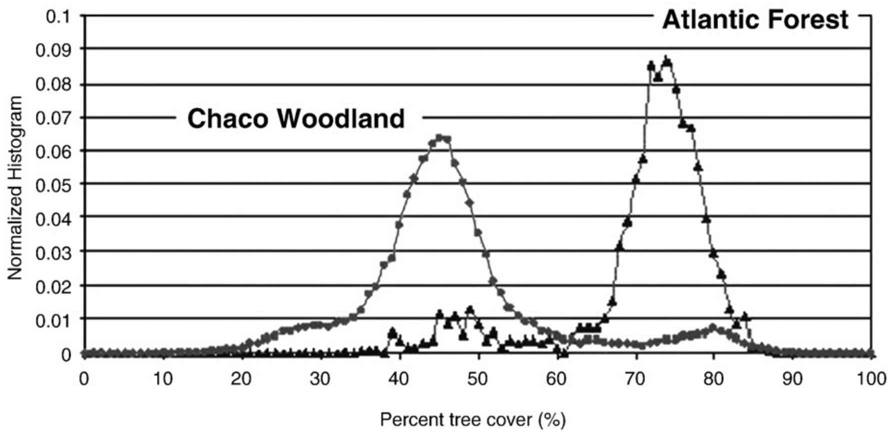

Fig. 2. Distribution of percent tree cover of Paraguay's Chaco Woodland and Atlantic Forest according to the MODIS Vegetation Continuous Field of tree cover data set (Hansen and DeFries, 2004).

Table 2
Definition of land cover and change classes used in this study.

Class	Definition
Atlantic forest	Moist, subtropical, predominantly evergreen forest with height > 10 m and forest cover > 55%, remained forested in the 1990s and 2000s
Chaco woodland	Xerophytic, semi-deciduous woodland with height > 3 m and 35% < forest cover < 55%, remained forested in the 1990s and 2000s
Non-forest	Areas being non-forest land in the 1990s and 2000s
Water	Areas covered by water body in the 1990s and 2000s
Forest loss	Areas covered by Atlantic Forest (mostly in eastern Paraguay) or Chaco Woodland (mostly in western Paraguay) in the 1990s and converted to non-forest land in the 2000s

training pixels within each cluster. For clusters containing training data of only one class, the program automatically assigned that class to the concerned clusters. Clusters containing training data of multiple classes were called "cross-over" clusters and were subjected to another isodata clustering-supervised labeling process. This clustering–labeling process was repeated until there were no more "cross-over" clusters and all pixels were classified appropriately.

In order to reduce "pepper and salt" classes commonly resulting from classifying spectral data, the developed FC change map for each WRS2 path/row was filtered by merging class polygons smaller than 4 TM pixels with the largest neighboring polygon. Such FC change maps for individual WRS2 path/rows were mosaicked to produce a wall-to-wall map for the entire country according to the following rules. For the overlap-area between adjacent WRS2-based maps, the following decision rules were applied in determining the class-precedence. If class-discrepancies occurred primarily due to significant differences in acquisition dates between two adjacent WRS2-based image pairs, classes from the FC map based on an image-pair acquired later than the other took precedence. If the acquisition dates of images for two neighboring WRS2-based maps were not significantly different, change classes had precedence over static classes. Among static classes, the non-forest class had precedence over forest classes in a given overlap-area. Once class-precedence was determined, the class with the highest precedence was assigned to a concerned pixel in an overlap-area.

3.3. Sampling-based assessment method

Due to the different spatial and spectral resolutions between the Landsat MSS images of GeoCover 1970s data set and the Landsat TM images of GeoCover 1990s data set, the wall-to-wall mapping method described in Section 3.2 was not applied in order to produce FC change map during 1970s–1990s. Instead, a systematic sampling approach was used to estimate the percentage of FC in the 1970s (Fig. 3). For this analysis, we focused on the Atlantic Forest region because in spite of its unique ecological value, the wall-to-wall mapping analysis revealed that this ecoregion experienced the most forest loss during 1990s–2000s.

In order to produce an estimate of FC with a confidence interval of 95% or higher, a minimum of 300 samples were required (EPA, 2002). Sampling the Atlantic Forest ecoregion at a spatial interval of 0.15° in both the latitude and longitude directions yielded 342 samples. Each sample contained 9 MSS pixels within a 3 by 3 window. Each pixel of a given sample was classified as either "forest", "non-forest", or "partially-forested" based on visual interpretation of the MSS images to determine if the sample was forested or not. The "partially-forested" class was assigned when a confident call of forest or non-forest could not be made on a pixel based on visual interpretations. Forest percentages of 100 and 0 were assigned to pixels labeled with "forest" and "non-forest", respectively. The appropriate forest percentage for "partially-forested" pixels was determined such that this sampling approach yielded a FC estimate at the ecoregion level

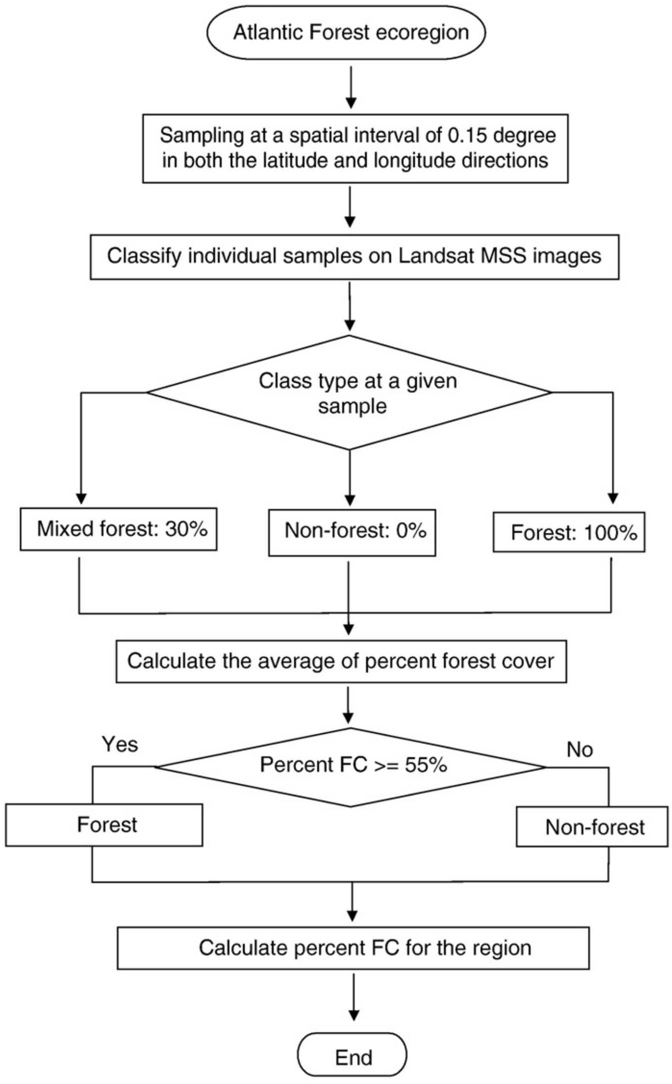

Fig. 3. A flow chart of the sampling approach for estimating FC in the 1970s.

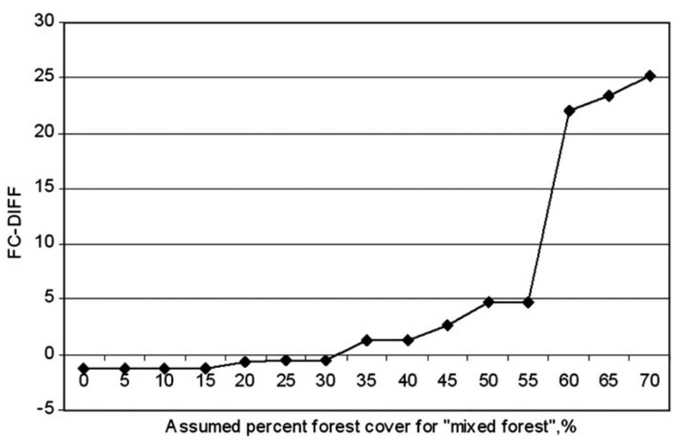

Fig. 4. Difference between the overall 1990s FC value in the Atlantic Forest ecoregion estimated using the sampling approach and the wall-to-wall mapping approach (FC-DIFF) as a function of FC value assigned to the "partially-forested" pixels. The FC-DIFF was closest to 0 when 30% of forest cover was assigned to the "partially-forested" pixels.

that was equivalent to a FC estimate derived from the wall-to-wall mapping approach. Fig. 4 shows that the sampling approach-based FC estimate was closest to that derived from the wall-to-wall mapping approach when the forest percentage of 30% was assigned to "partially-forested" pixels.

Once the FC for all 9 pixels of a given sample was known, the FC for that sample was calculated as the average of those values. According to the definition of the Atlantic forest class (Table 2), samples having at least 55% of FC were classified as "forest" and those having less than 55% of FC were classified as "non-forest". The percentage of FC in the Atlantic Forest ecoregions in the 1970s was estimated as the proportion of the FC estimate based on the 342-sample statistics. It should be noted that although some partially forested pixels having FC values less than 55% were classified as "non-forest" according to our definition, Fig. 2 shows that such pixels only accounted for a small portion in the Atlantic Forest ecoregion.

4. Validation of the wall-to-wall FC change map

The developed wall-to-wall FC change map for Paraguay was validated using available high spatial resolution images, including 1 IKONOS images, 4 QuickBird images, and 211 aerial photographs. The

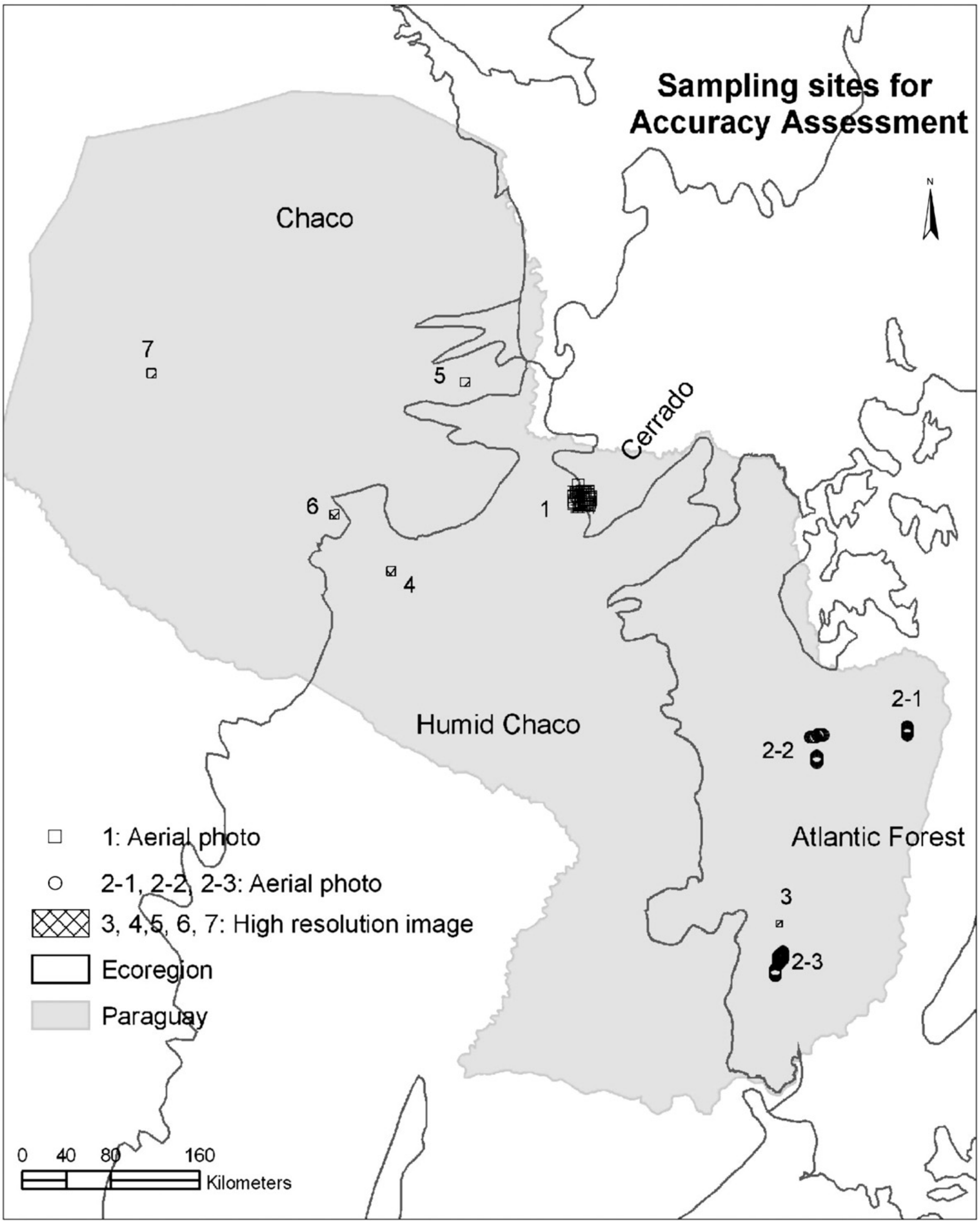

Fig. 5. Location of the 211 aerial photos, 1 IKONOS images and 4 QuickBird images used in the accuracy assessment.

Table 3
Accuracy values of the FC map for the 2000s epoch for areas covered by available high resolution data sets.

Data type	Area name (No.) (See Fig. 5 for their location)	Overall accuracy	95% confidence interval	User's accuracy		Producer's accuracy	
				Forest	Non-forest	Forest	Non-forest
Aerial photo	Cerrado (1)	0.967	±0.019	0.993	0.953	0.924	0.996
	Atlantic forest (2–1, 2–2, 2–3)	0.939	±0.025	0.968	0.818	0.956	0.863
IKONOS	Atlantic forest (3)	0.975	±0.0184	0.992	0.921	0.976	0.972
QuickBird	Humid chaco (4)	0.935	±0.029	0.966	0.894	0.924	0.952
	Chaco (5)	0.934	±0.029	0.910	0.961	0.962	0.907
	Chaco (6)	0.950	±0.025	0.985	0.896	0.936	0.974
	Chaco (7)	0.921	±0.031	0.926	0.894	0.980	0.677

spatial resolutions of these three types of data sets were 4 m, 2.8 m, and 0.5 to 2 m, respectively. The IKONOS and QuickBird images were georeferenced by the data vendors and were found adequately co-registered with the Landsat images. For the aerial photos an in-house program was developed to automatically co-register them to the Landsat images. Because all reference data were acquired around 2000s, they were used to validate the 2000s FC map derived from the 1990s–2000s FC change product by converting the forest loss class to non-forest.

The limited availability of high resolution data did not allow a designed based accuracy assessment for the entire country of Paraguay (Stehman, 1999). Instead, the high resolution data sets were grouped into 7 area groups (Fig. 5). A designed based accuracy assessment was conducted for the area covered by each group of high resolution data sets. For each area or area group, approximately 300 TM pixels were randomly selected. The reference cover type for each sample pixel was determined by visually interpreting the high resolution images.

Accuracy estimates including overall accuracy and its confidence interval, and class specific user's and producer's accuracies were calculated according to Congalton and Green (1999). Table 3 lists the accuracy values for the 7 groups of reference data locations. The overall accuracy values for the areas covered by available high resolution data

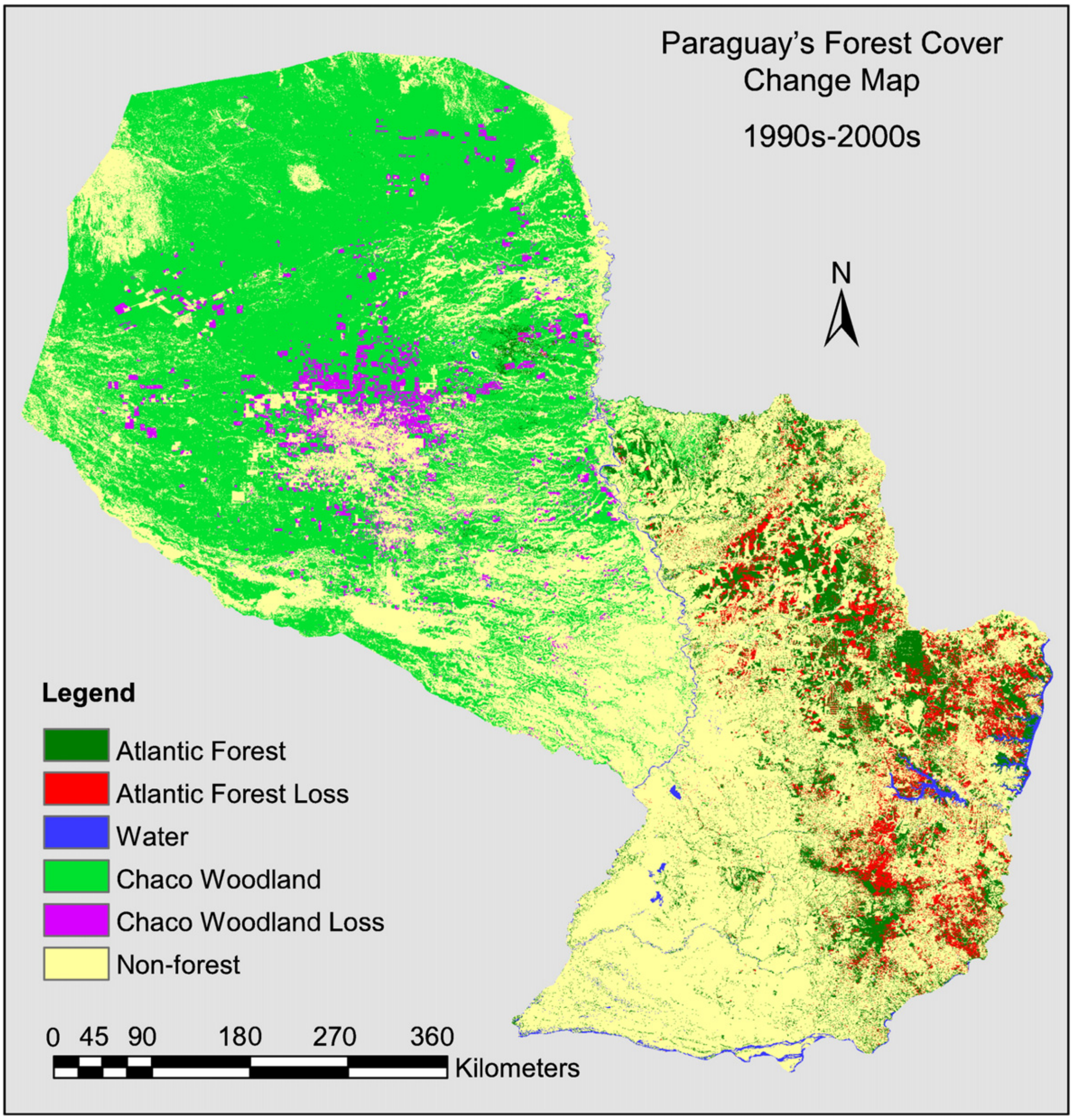

Fig. 6. Paraguay's forest cover change map derived using Landsat images acquired in the 1990s and 2000s.

ranged between 92% and 97.5%. As to the class specific user's and producer's accuracy values, most of them were above or near 90%, with only two in the low- to mid-80%. Considering the very different seasonality of the images used as represented by the acquisition month and day shown in Table 1(a), the consistently high accuracy values not only demonstrate the reliability of the 2000 FC map for the entire country, but also the robustness of the change mapping method to produce consistent results with temporally inconsistent inputs. The only accuracy value below 80% is the 67.7% producer's accuracy for the non-forest class in the Chaco (7) test area (Table 3). This low producer's accuracy value is probably due to the difficulty of mapping forest change using one image acquired in summer (January 17, 1992) and the other in winter (June 26, 2001, see Table 1(a)). This could be further complicated by the extremely high forest-to-nonforest ratio (about 6:1) in this particular area. With such a small portion of the land area being non-forest, misclassifying a small amount of non-forest area to the forest class would cause the producer's accuracy of this class to go down dramatically without much impact on the other user's and producer's accuracy values (Table 3).

5. Results and discussion

A wall-to-wall map depicting the spatial distribution of FC change at the 28.5-meter spatial resolution was developed for the entire country of Paraguay (Fig. 6). It was demonstrated to be highly reliable based on high resolution data sets (see Section 4). According to the FC change map, Paraguay had 202,202 km^2 of forest in the 1990s. By the 2000s, the extent of forest decreased to 176,741 km^2. The FC values for the 5 ecoregions and 17 administrative departments in Paraguay are summarized in Tables 4 and 5. The departments in eastern Paraguay where strong growth of soy crop between 1984 and 2001 was reported (Dros, 2004), including Caaguazu, Canindeyu, Caazapa and Alto Parana, generally experienced higher rate of changes than those in other regions.

5.1. Paraguay's forest loss

Among the five ecoregions in Paraguay, the Atlantic Forest ecoregion experienced the highest deforestation rate (Table 4). Based on the 342 samples selected across the Atlantic Forest ecoregion, the area had 73.4 ± 4.9% forest cover in the 1970s. However, the FC value dropped to 40.7% by the 1990s and further down to 24.9% by 2000s.

The rapid loss of Atlantic forest can be attributed to many complex social economic processes (Macedo and Cartes, 2003). Paraguay was long plagued by widespread land disputes resulting from inequalities in land tenure (Nagel, 1999). In 1981, 5.8% of the farmers in eastern Paraguay controlled 79% of the land in this region (Weisskoff, 1992). The construction of the Itaipú Dam between 1973 and 1982 may have had long lasting contributions to forest loss. On the one hand, the construction of the dam prompted a tidal wave of Brazilian migration (in the order of hundreds of thousands) in the eastern border region of Paraguay.[2] On the other hand, the economic downturn following the completion of the construction in 1982 left thousands of Paraguayans who worked on the construction of the dam landless. With the perception prevalent in Paraguay that forest land was unproductive or “unused”, landless settlers often “invaded” or expropriated forested areas by clearing small patches of forests, often in the order of tens of hectares (Fig. 7(a)) (Sanjurjo and Gauto, 1996; Nagel, 1999; Cartes, 2003). In the mean time, large private land owners converted extensive forest areas to very large patches of agricultural fields (Fig. 7(b)), driven in part by the fear that their forest land could be expropriated if left forested but more likely by the profits from agricultural products (Sanjurjo and Gauto, 1996), including soybean, corn, and cotton (Weisskoff, 1992). Because the areas cleared by the settlers and the large private land owners had very different sizes, they were distinguishable in the Landsat images (Fig. 7(c) and (d)). A systematic analysis of the two types of deforestation processes revealed that the ratio of areas cleared by the large land owners and the settlers was 6:4 between the 1970s and 1990s and 8:2 between the 1990s and 2000 (Huang et al., 2006), indicating that the large land owners were responsible for the majority of forest loss.

The deforestation rates between the 1990s and 2000 in the Humid Chaco and Chaco ecoregions were 9.8% and 6.4% respectively. While region-wise these rates were relatively moderate as compared with that in the Atlantic Forest ecoregion, significant changes were found near Filadelfia, the population center in the Chaco ecoregion (Fig. 8). These changes were most likely driven by the Mennonite community dominating this region. With the first settlers arriving in the early 20th century, the Mennonite settlement led to the development of a major agricultural research and extension infrastructure, which covered most aspects of crop, grassland and livestock production.[3] The emphasis on cash crops, extension of transportation network by the Trans-Chaco Highway, and the needs to export goods led to intensification of agriculture through heavy investment in machinery, fertilizers, and agro-chemicals (Weisskoff, 1992). However, the Chaco region consists mostly of marginal land that may not be suitable for large scale farming. While the deforested areas may generate short

Table 4
FC and change in Paraguay's 5 ecoregions. Percent change (last column) was calculated as the percentage of forest in the 1990s that was lost by the 2000s.

Ecoregion	Total area (km^2)	Forest in1990s (km^2)	Forest in 2000s (km^2)	Percent change (%)
Pantanal	1938.32	325.63	323.77	0.57
Atlantic forest	85,502.37	34,766.61	21,254.63	38.86
Humid Chaco	128,050.59	29,499.75	26,606.18	9.81
Cerrado	8167.95	3233.15	2802.87	13.31
Chaco	174,289.12	134,376.51	125,753.79	6.42

Table 5
FC and change in Paraguay's administrative departments. Percent change (last column) was calculated as the percentage of forest in the 1990s that was lost by the 2000s.

Paraguay	Department	Total area (km^2)	Forest in 1990s (km^2)	Forest in 2000s (km^2)	Percent change (%)
Western	Alto Paraguay	77,624.58	62,196.73	59,325.88	4.62
	Boqueron	88,639.43	67,081.66	62,045.64	7.51
	Presidente Hayes	73,035.14	28,282.31	25,653.42	9.30
Eastern	Amambay	12,585.16	4557.47	3354.24	26.40
	San Pedro	20,879.70	6306.59	4353.67	30.97
	Paraguari	8687.44	777.87	720.83	7.33
	Caaguazu	12,895.32	3812.78	2261.59	40.68
	Caazapa	9538.62	3216.80	1933.11	39.91
	Canindeyu	14,835.82	8262.97	4903.05	40.66
	Central	2488.47	89.27	80.79	9.49
	Cordillera	4786.66	310.82	250.95	19.26
	Guaira	3821.72	941.72	654.31	30.52
	Neembucu	11,057.22	442.23	436.21	1.36
	Misiones	8232.42	240.01	230.71	3.87
	Itapua	16,389.06	4192.13	2577.98	54.51
	Alto Parana	13,692.88	5043.96	2599.79	48.46
	Concepcion	18,756.14	6446.00	5358.89	16.86

[2] http://workmall.com/wfb2001/paraguay/paraguay_history_international_factors_and_the_economy.html. Last accessed in June 2007.

[3] http://www.fao.org/ag/aGp/agpc/doc/Bulletin/Granchaco.htm, last accessed in June 2007.

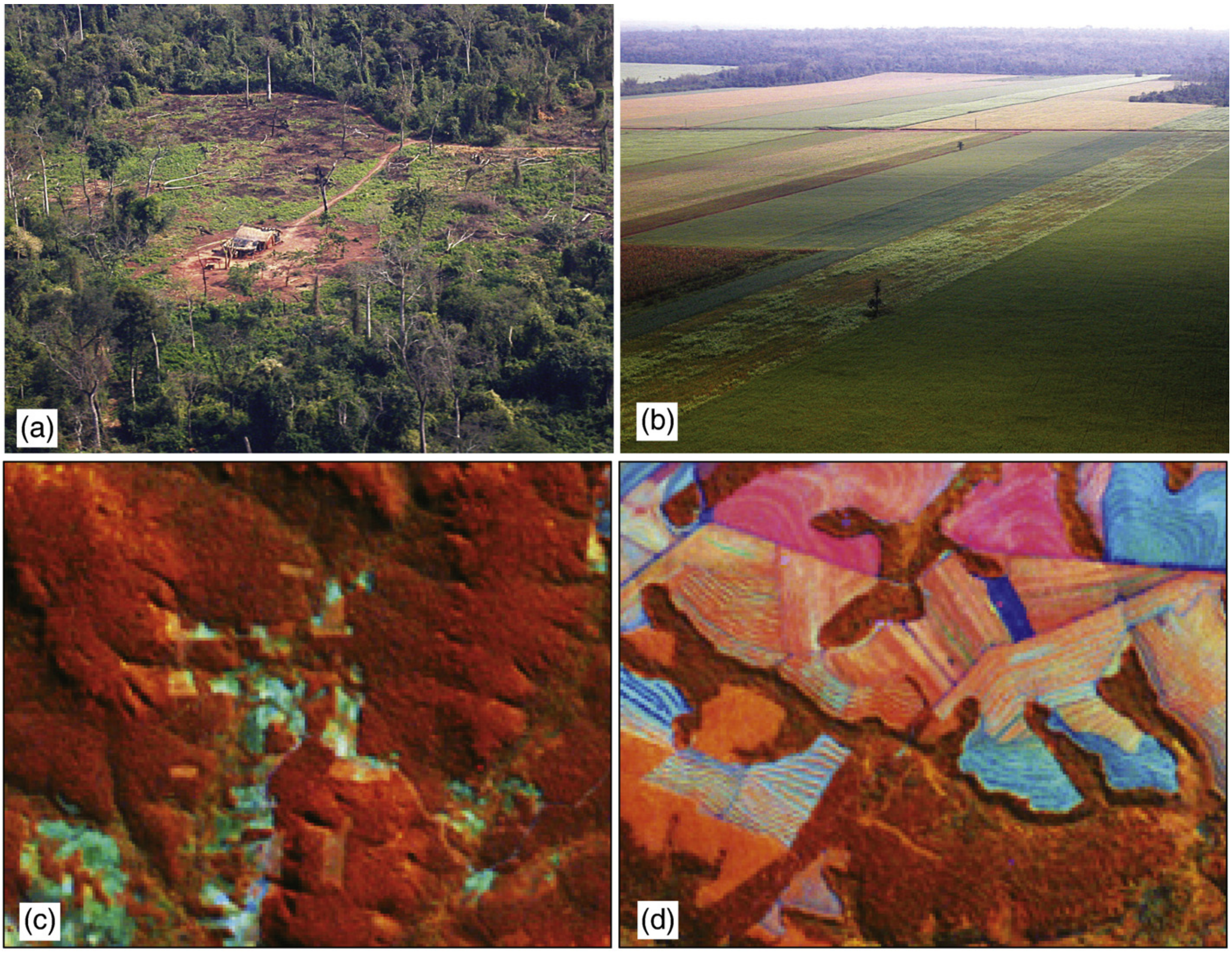

Fig. 7. Field photos showing a small patch of forest cleared by a settler (a) and extensive forests cleared and converted to large agriculture fields by private land owners (b). In the Landsat images, the small patches cleared by settlers appear in small polygons consisting of a few pixels (c), while the land cleared by private land owners forms large polygons having relatively homogeneous colors or regular patterns (d). With bands 4, 5, and 3 shown in red, green, and blue in the two Landsat images, forest generally appears dark red or dark orange while deforested areas appear in other colors.

term economic benefits, the resultant agricultural systems may not be ecologically sustainable. Therefore, even moderate rates of forest loss in this region should be alarming.

5.2. Forest loss within and near protected areas

With growing concerns on the conservation of forest and biodiversity in Paraguay (Fragano and Clay, 2003), the country established many protected areas. In fact, Paraguay was reported to have higher percentage of land allocated to parks and reserves than South America and the United States (Yahnke et al., 1998). The wall-to-wall map allowed detailed analyses of FC change within and around Paraguay's protected areas. Table 6 lists the 1990s and 2000s FC within each protected areas. The percentage of FC change was calculated as the ratio of forest loss between the 1990s and 2000s to forest area in the 1990s epoch. FC change in 1–5 km, 5–10 km, and 10–15 km buffer zones from the protected areas are summarized in Table 7. Table 6 reveals that most protected areas in Paraguay experienced minimal forest loss within their boundaries. Thirteen out of the twenty protected areas in eastern Paraguay had less than 10% of FC change within their borders during 1990s–2000s. In addition, all three protected areas in western Paraguay experienced less than 2% of FC change. The protected areas that experienced substantially high forest loss are either very small or primarily non-forested. The Salto del Guaira that had 30% forest loss is only 8 km^2. While suffering a 54% forest loss, Kuriy had only 13% FC in the 1990s.

As to the surrounding regions of the protected areas, however, even well-managed protected areas experienced substantial changes just outside of their boundaries. Table 7 shows that many protected areas experienced 30% or more forest loss within their buffer zones. Fig. 9 shows the location of protected areas listed in Tables 6 and 7 and the 1990s–2000s FC change map for three protected areas in western Paraguay and three in eastern Paraguay. While very little changes occurred within or near the three protected areas in western Paraguay, the areas surrounding the three protected areas in eastern Paraguay experienced massive forest loss. Very few forest remnants existed in the buffer zones of the three areas by the 2000s. The high rates of forest loss in the areas surrounding the protected areas can adversely impact the protected areas. Forests surrounding a protected area can serve both as wildlife corridors and as a buffer zone shielding the protected area from being exploited (Cooperrider et al., 1999). Massive forest loss in the surrounding areas not only left the protected areas highly isolated as ecological “island”, it may also be

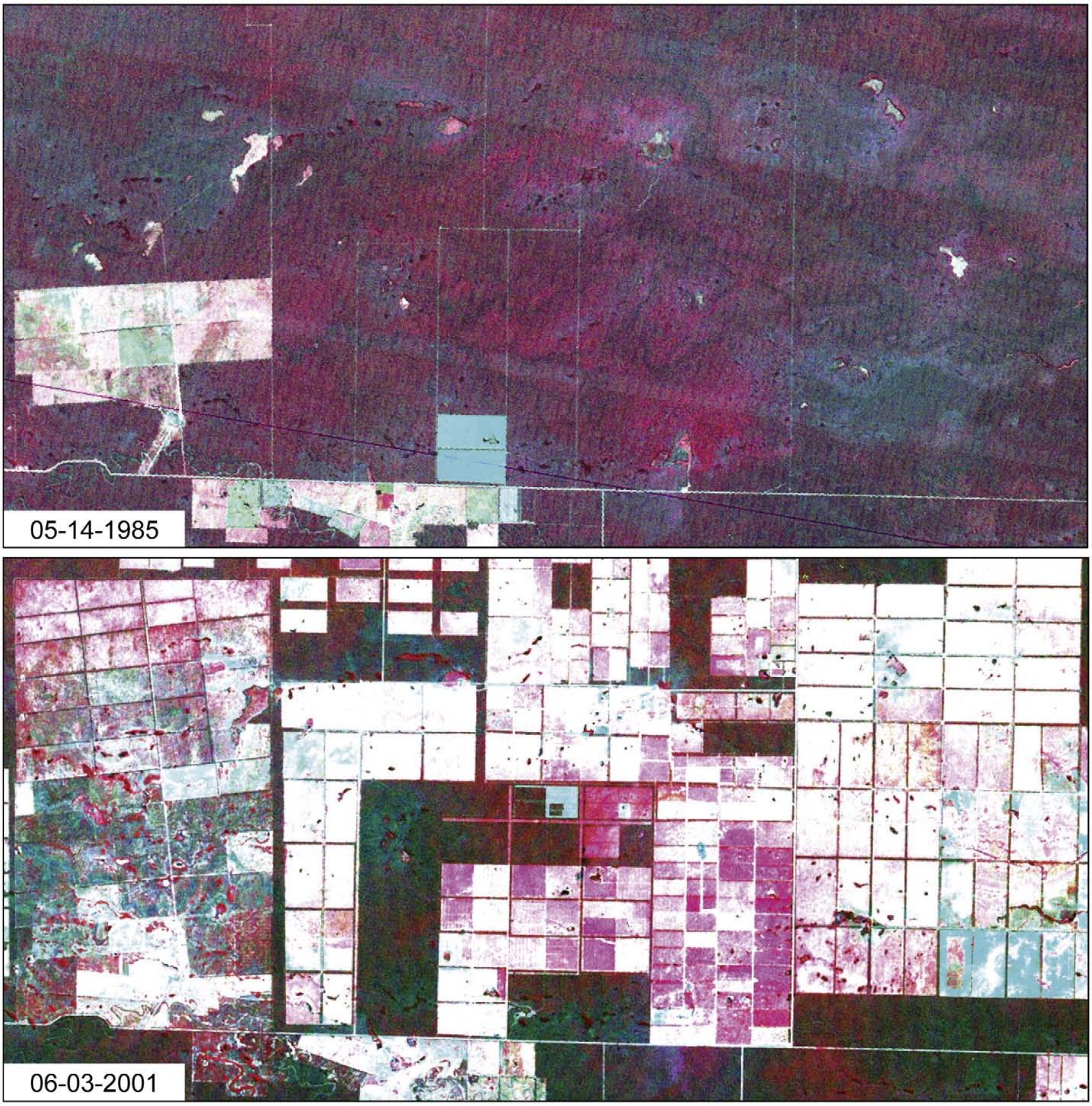

Fig. 8. Landsat images acquired in 1985 (top) and 2001 (bottom) showing massive clearing of Chaco forests in a 34.2 km × 17.1 km area near Filadelfia, the largest population center in the Chaco Woodland ecoregion. With bands 4, 3, and 2 shown in red, green, and blue, Chaco forests appear red or dark red while the mostly rectangular fields in other colors are deforested areas. Notice roads (linear features in the 1985 image) were constructed prior to forest clearing.

a precursor to rapid forest loss within the protected areas. An analysis of forest change in Indonesia's protected areas revealed that some protected areas experienced rapid forest loss within their boundaries after massive deforestation occurred in their surrounding areas (Curran et al., 2004). Therefore, Paraguay's protected areas may face imminent threats that can cause severe forest loss within their boundaries. These protected areas should be continuously monitored using recent and future satellite observations, as they are critical for the conservation of many species endemic or limited to this region (Fragano and Clay, 2003).

6. Summaries and conclusions

Comprehensive assessments of Paraguay's FC change from the 1970s to 2000s were carried out using Landsat observations. The assessments consisted of a wall-to-wall mapping of FC change during 1990s–2000s for the entire country and an estimation of forested area in the Atlantic Forest ecoregion in the 1970s.

The wall-to-wall FC change map was developed using an iterative clustering-supervised labeling method. The supervised labeling module of this method substantially reduced the need for human

Table 6
FC and change in Paraguay's protected areas. Percent change (last column) was calculated as the percentage of forest in the 1990s that was lost by the 2000s.

Region	Name of protected area	Total area (km^2)	Forest in 1990 (km^2)	Forest in 2000 (km^2)	Percent change (%)
Eastern	Cerro Corra	120.70	56.92	49.48	13.07
	Mbaracayu	634.26	584.25	571.83	2.13
	Salto del Guaira	8.93	0.93	0.60	35.93
	Limoy	133.92	125.04	124.37	0.54
	Itabo	113.11	103.32	97.02	6.10
	Tati Yupi	16.84	11.99	11.92	0.57
	Monument Moises Be	1.42	1.25	1.23	1.24
	Kuriy	20.06	3.23	1.49	53.75
	Ybytyruzu	248.56	165.84	147.16	11.26
	Caaguazu (1)	58.31	58.07	57.37	1.21
	Ybycui	54.95	38.55	37.31	3.20
	Nacunday	21.91	18.46	17.64	4.44
	Caaguazu (2)	74.96	69.39	65.63	5.42
	San Rafael	777.32	620.87	557.80	10.16
	Cerro Sarambi	82.75	59.15	56.25	4.90
	Carapa	13.07	11.82	5.52	53.30
	Ypoa	700.59	10.12	9.72	3.98
	Serrannia San Luis	96.45	51.01	50.82	0.36
	Ypacarai	142.58	4.30	3.23	24.80
	Acahay	30.98	3.44	3.22	6.49
Western	Rio Negro	2973.50	1957.14	1920.31	1.88
	Defenseores del chaco	7325.82	6647.76	6607.87	0.60
	Tinfunque	2246.99	1376.67	1372.47	0.30

intervention, while its iterative nature ensured high accuracy of the developed products. Accuracy assessments using high resolution data sets showed that the derived FC change map was highly reliable, with overall accuracy values of 92% or higher in the areas covered by the high resolution data sets. It demonstrated the effectiveness of the change mapping method in dealing with multi-temporal satellite data over large areas and the reliability of the developed FC change product.

The results show that among the 5 ecoregions in Paraguay, the Atlantic Forest ecoregion experienced the most forest loss. The forest cover in this ecoregion was 73.4% in the 1970s. It dropped to 40.7% by the 1990s and further down to 24.9% by the 2000s. With such a low forest cover by the 2000s, any further loss of Atlantic forest can be a major threat to the rich biodiversity found in this ecoregion. The rapid loss of Atlantic forests was likely driven by complex social economic forces, including widespread land disputes arising from long time inequalities and profits from exporting agricultural products. Major constructions including the Itaipú Dam and the Trans-Chaco highway also had long lasting effects. The alarming deforestation rates over the last three decades call for immediate actions to halt the trends of forest loss in this region.

Forest loss was relatively moderate in the Humid Chaco and Chaco ecoregions, with percent forest loss being 9.8% and 6.4% for the two ecoregions, respectively. However, extensive Chaco forests were converted to fields for diary farming or cash crops near the major population center – Filadelfia. Because this region consists mostly of marginal land that may not be suitable for large scale farming, the agricultural systems converted from Chaco forests may not be ecologically sustainable. Therefore, even moderate rates of forest loss in this region should be alarming.

The developed FC change map revealed that most protected areas in Paraguay experienced minimal forest loss within their boundaries. However, deforestation in the areas surrounding the protected areas was as severe as anywhere else in the country, if not worse. Massive forest loss in the surrounding areas not only left the protected areas highly isolated as ecological "island", it may also be a precursor to rapid forest loss within the protected areas. Therefore, Paraguay's protected areas may face imminent threats that can cause severe forest loss within their boundaries. These protected areas should be continuously monitored using recent and future satellite observations.

Results from this study highlighted Paraguay's environmental changes over the last three decades. Because the satellite data sets and the derived products likely will be useful for many conservation and ecological studies, they will be made available through the internet at the Global Land Cover Facility (http://landcover.org). With NASA's GeoCover data sets providing global coverage of Landsat data (Tucker et al., 2004), the techniques developed in this study can be used to assess forest change between the 1970s and 2000s for any land area.

Table 7
FC change in the buffer zones of Paraguay's protected areas (0–5, 5–10, 10–15 km from boundary). Percent change was calculated as the percentage of forest in the 1990s that was lost by the 2000s.

Region	Name of protected area	Percent change (%)		
		0–5 km	5–10 km	10–15 km
Eastern	Cerro Corra	10.68	16.63	20.26
	Mbaracayu	39.25	44.59	40.40
	Salto del Guaira	32.60	46.59	49.43
	Limoy	49.36	52.67	56.88
	Itabo	38.08	46.05	49.24
	Tati Yupi	28.40	17.67	35.87
	Monument Moises Be	42.41	24.21	51.13
	Kuriy	66.74	59.71	50.69
	Ybytyruzu	27.23	32.59	36.18
	Caaguazu (1)	58.86	53.05	53.71
	Ybycui	10.26	8.38	11.17
	Nacunday	15.23	19.89	41.35
	Caaguazu (2)	53.33	49.25	48.11
	San Rafael	35.23	31.83	38.92
	Cerro Sarambi	21.04	15.28	22.95
	Carapa	63.58	56.19	44.23
	Ypoa	1.75	3.26	3.43
	Serrannia San Luis	1.59	1.48	1.33
	Ypacarai	19.86	27.82	25.63
	Acahay	8.89	10.76	4.90
Western	Rio Negro	3.03	6.00	10.47
	Defenseores del chaco	2.01	2.02	2.05
	Tinfunque	1.45	2.11	6.16

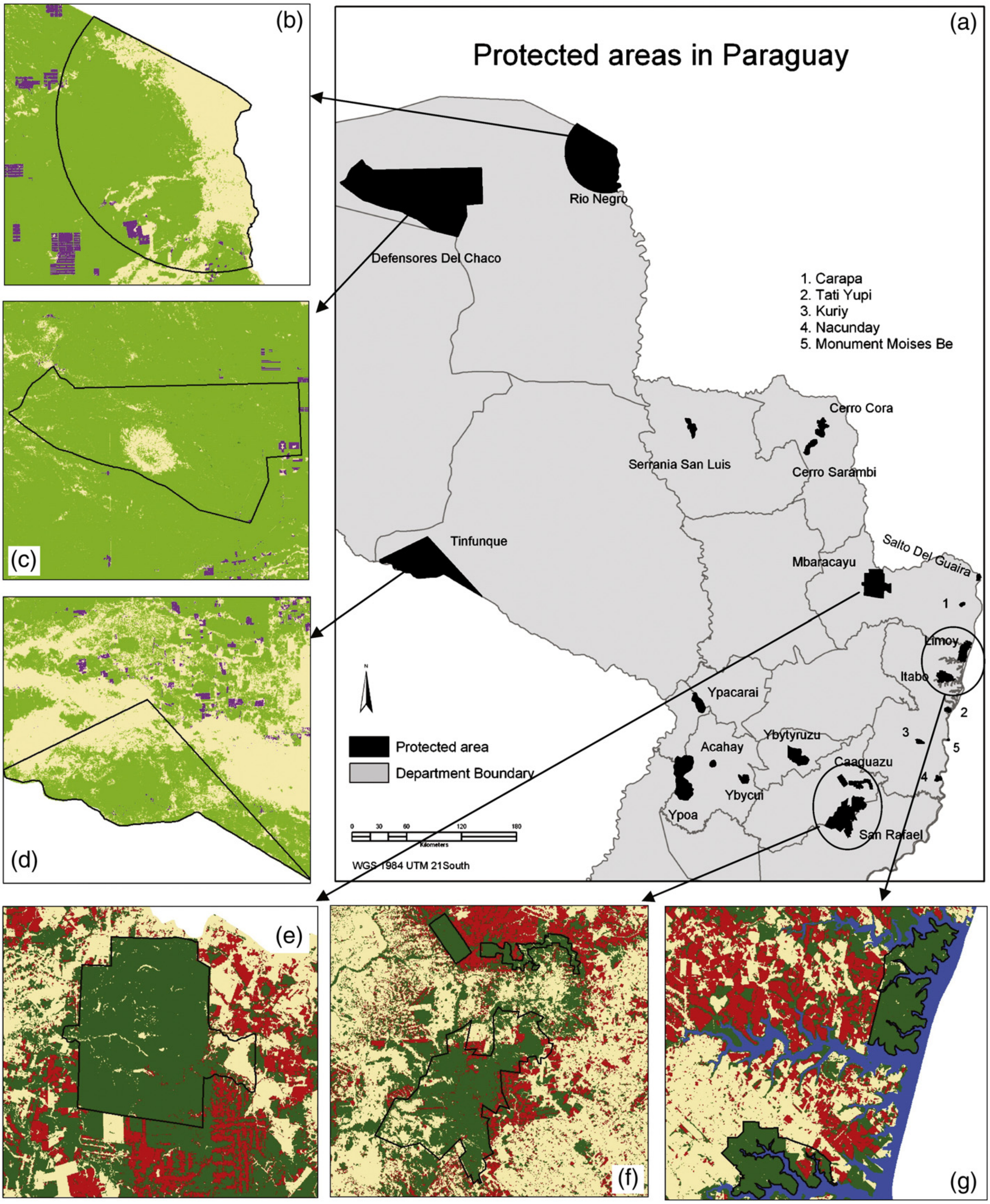

Fig. 9. Location of Paraguay's protected areas (PAs) listed in Tables 6 and 7 (a) and the 1990s–2000s FC change map for three PAs in western Paraguay (b)–(d) and three in Eastern Paraguay (e)–(g). In (b)–(d), non-forest, Chaco Woodland, and Chaco Woodland loss are shown in yellow, bright green, and purple, respectively. In (e)–(g), non-forest, water, Atlantic forest, and Atlantic forest loss are shown in yellow, blue, dark green, and red, respectively.

Such assessments likely will be especially valuable for conservation studies in remote areas where data availability often constitutes a major constraint.

Acknowledgements

This study was funded under NASA's REASoN Program (NNG 04GC53A) and NASA's Land Cover Land Use Change Program (NAG5-9337). We are grateful to our colleague Saurabh Channan for his technical support and the anonymous reviewers for their comments.

References

Bucherm, E.H., Huszar, P.C., 1999. Sustainable management of the Gran Chaco of South America: ecological promises and economic constraints. Journal of Environmental Management 57, 99–108.

Cartes, J.L., 2003. Brief history of conservation in the interior Atlantic forest. In: Galindo-Leal, C., Camara, I.d.G. (Eds.), The Atlantic Forest of South America: Biodiversity Status, Threats, and Outlook. Island Press, Washington, DC, pp. 269–287.

Catterson, T.M., Fragano, F.V., 2004. Tropical Forestry and Biodiversity Conservation in Paraguay: Final Report of a Section 118/119 Assessment EPIQ II Task Order No.1. USAID/ Paraguay, Asuncion, Paraguay.

CIP, 2004. PRY Administrative Boundaries. Available at http://www.cipotato.org. Accessed in 2004.

Cohen, W., Kushla, John, Ripple, William, Garman, Steven, 1996. An introduction to digital methods in remote sensing of forested ecosystems: focus on the Pacific Northwest, USA. Environmental Management 20 (3), 421–435.

Collins, J.B., Woodcock, C.E., 1994. Change detection using the Gramm–Schmidt transformation applied to mapping forest mortality. Remote Sensing of Environment 50, 267–279.

Congalton, R., Green, K., 1999. Assessing the Accuracy of Remotely Sensed Data. Lewis Publisher, New York.

Cooperrider, A.Y., Day, S., Jacoby, C., 1999. The bioreserve strategy for conserving biodiversity. In: Baydack, R.K., Campa, H.I., Haufler, J.B. (Eds.), Practical Approaches to the Conservation of Biological Diversity. Island Press, Washington, DC, pp. 35–53.

Coppin, P.R., Bauer, M.E., 1994. Processing of multitemporal Landsat TM imagery to optimize extraction of forest cover change features. IEEE Transactions on Geoscience and Remote Sensing 32 (4), 918–927.

Coppin, P.R., Bauer, M.E., 1996. Digital change detection in forest ecosystems with remote sensing imagery. Remote Sensing Reviews 13, 207–234.

Coppin, P., Jonchheere, I., Nackaerts, K., Muys, B., 2004. Review article: digital change detection methods in ecosystem monitoring: a review. International Journal of Remote Sensing 25 (9), 1565–1596.

Curran, L.M., Trigg, S.N., McDonald, A.K., Astiani, D., Hardiono, Y.M., Siregar, P., Caniago, I., Kasischke, E., 2004. Lowland forest loss in protected areas of Indonesian Borneo. Science 303, 1000.

DeFries, R.S., Houghton, R.A., Hansen, M.C., Field, C.B., Skole, D., Townshend, J., 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. International Journal of Remote Sensing 99 (22), 14256–14261.

Dros, J.M., 2004. Managing the Soy Boom: Two Scenarios of Soy Production Expansion in South America. AIDEnvironment, Amsterdam.

EPA, 2002. Guidance on Choosing a Sampling Design for Environmental Data Collection. Available at http://www.epa.gov/quality/qs-docs/g5s-final.pdf. Accessed in 2004.

Eriksson, L.M., Edenius, L., Areskoug, V., Meritt Jr., D.A., 2001. Nest-predation at the edge: an experimental study contrasting to types of edges in the dry Chaco, Paraguay. Ecography 24, 742–750.

FAO, 2003. Forest Resources Assessment 2001. FAO Forestry Paper 140. Food and Agricultural Organization of the United Nations, Rome.

Fragano, F., Clay, R., 2003. Biodiversity status of the interior Atlantic forest of Paraguay. In: Galindo-Leal, C., Camara, I.d.G. (Eds.), The Atlantic Forest of South America: Biodiversity Status, Threats, and Outlook. Island Press, Washington, pp. 288–309.

Gauto, R., 1989. Private conservation programs in Paraguay. Conservation Biology 3 (2), 120.

Hansen, M., DeFries, R., 2004. Detecting long-term global forest change using continuous fields of tree-cover maps from 8-km Advanced Very High Resolution Radiometer (AVHRR) data for the years 1982–99. Ecosystems 7 (7), 695–716.

Hansen, M., DeFries, R., Townshend, J., Sohlberg, R., Dimiceli, C., Carroll, M., 2002. Towards an operational MODIS continuous field of percent tree cover algorithm: examples using AVHRR and MODIS data. Remote Sensing of Environment 83, 303–319.

Hill, K., Padwe, J., Bejyvagi, C., Bepurangi, A., Jakugi, F., Tykuarangi, R., Tykuarangi, T., 1997. Impact of hunting on large vertebrates in the Mbaracayu Reserve, Paraguay. Conservation Biology 11 (6), 1339–1353.

Hirsch, Adam, Little, W.S., Houghton, R.A., Scott, N.A., White, J.D., 2004. The net carbon flux due to deforestation and forest re-growth in the Brazilian Amazon: analysis using a process-based model. Global Change Biology 10 (5), 908.

Huang, C., Kim, S., Altstatt, A., Townshend, J.R.G., Davis, P., Song, K., Tucker, C.J., Rodas, O., Yanosky, A., Clay, R., Musinsky, J., 2006. Rapid loss of Paraguay's Atlantic forest and the status of protected areas – a Landsat assessment. Remote Sensing of Environment 106, 460–466.

Keel, S., Gentry, A.H., Spinzi, L., 1993. Using vegetation analysis to facilitate the selection of conservation sites in eastern Paraguay. Conservation Biology 7 (1), 66–75.

Lal, R., 1996. Deforestation and land-use effects on soil degradation and rehabilitation in Western Nigeria. III. Runoff, soil erosion and nutrient loss. Land Degradation & Development 7, 99–119.

Levi, Leone, 1874. On the geography and resources of Paraguay. Proceedings of the Royal Geographical Society of London 18 (2), 117–129.

Loveland, T.R., Sohl, T.L., Stehman, S.V., Gallant, A.L., Sayler, K.L., Napton, D.E., 2002. A strategy for estimating the rates of recent United States land-cover changes. Photogrammetric Engineering & Remote Sensing 68 (10), 1091–1099.

Lu, D., Mausel, P., Brondizio, E., Moran, E., 2004. Change detection techniques. International Journal of Remote sensing 25 (12), 2365–2407.

Lyon, J.G., Yuan, D., Lunetta, R.S., Elvidge, C.D., 1998. A change detection experiment using vegetation indices. Photogrammetric Engineering & Remote Sensing 64 (2), 143–150.

Macedo, A.M., Cartes, J.L., 2003. Socioeconomic drivers in the Interior Atlantic Forest. In: Galindo-Leal, C., Camara, I.d.G. (Eds.), The Atlantic Forest of South America: Biodiversity Status, Threats, and Outlook. Island Press, Washington, pp. 310–324.

Mas, J.-F., 1999. Monitoring land-cover changes: a comparison of change detection techniques. International Journal of Remote Sensing 20 (1), 139–152.

Morong, Thomas, 1889. Paraguay and its flora II. Botanical Gazette 14 (10), 246–253.

Nagel, B.Y., 1999. “Unleashing the Fury”: the cultural discourse of rural violence and land rights in Paraguay. Comparative Studies in Society and History 41, 148–181.

Nickson, R.A., 1981. Brazilian colonization of the eastern border region of Paraguay. Journal of Latin American Studies 13 (1), 111–131.

Nieto, A., Pearman, M., 1992. Distribution, status and taxonomy of the near-threatened black-bodied woodpecker *Dryocopus schulzi*. Bird Conservation international 2 (4), 253–271.

Olson, D.M., Dinerstein, E., 1998. The Global 200: a representation approach to conserving the Earth's the most biologically valuable ecoregions. Conservation Biology 12 (3), 502–515.

Quintana, J., Morse, S., 2005. Social interactions and resource ownership in two private protected areas of Paraguay. Journal of Environmental management 77, 64–78.

Ridd, M.K., Liu, J., 1998. A comparison of four algorithms for change detection in an urban environment. Remote Sensing of Environment 63, 95–100.

Rios, E., Zardini, E., 1989. Conservation of biological diversity in Paraguay. Conservation Biology 3 (2), 118–120.

Sánchez-Azofeifa, G.A., Quesada-Mateo, C., Gonzalez-Quesada, P., Dayanandan, S., Bawa, K.S., 1999. Protected areas and conservation of biodiversity in the tropics. Conservation Biology 13, 407–411.

Sanjurjo, M., Gauto, R., 1996. Paraguay. In: Harcourt, C.S., Sayer, J.A. (Eds.), The Conservation Atlas of Tropical Forests: The Americas. Simon & Schuster, New York, pp. 286–293.

Singh, A., 1989. Digital change detection techniques using remotely-sensed data. International Journal of Remote Sensing 10 (6), 989–1003.

Skole, D., Tucker, C., 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. Science 260, 1905–1910.

Spichiger, R., Ramella, L., 1989. The Forests of the Paraguayan Chaco. Academic Press, London, pp. 259–270.

Stehman, S.V., 1999. Basic probability sampling designs for thematic map accuracy assessment. International Journal of Remote Sensing 20 (12), 2423–2441.

Taber, A.B., 1989. Pig from green hell. Animal Kingdom 92 (4), 20–27.

Townshend, J.R.G., Bell, V., Desch, A.C., Havlicek, C., Justice, C.O., Lawrence, W.E., Skole, D., Chomentowski, W.W., 1995. The NASA Landsat pathfinder humid tropical deforestation project. Land Satellite Information in the Next Decade. Tyson's Corner, Virginia, pp. 76–87.

Tucker, C.J., Grant, D.M., Dykstra, J.D., 2004. NASA's global orthorectified Landsat data set. Photogrammetric Engineering & Remote Sensing 70 (3), 313–322.

WDPA Consortium, 2004. World Database on Protected Areas. World Conservation Union (IUCN) and UNEP-World Conservation Monitoring Centre (UNEP-WCMC). Source for this dataset was available at the Global Land Cover Facility (www.landcover.org).

Weisskoff, R., 1992. The Paraguayan agro-export model of development. World Development 20, 1531–1540.

Wetzel, R.M., Robert, E.D., Robert, L.M., Myers, P., 1975. Catagonus, an “extinct” peccary, alive in Paraguay. Science 189 (4200), 379–381.

WWF, 2001. World Wildlife Fund Scientific Report. Available at http://worldwildlife.org/wildworld/profiles/terrestrial_nt.html. Accessed in 2006.

Yahnke, C.M., Fox, I.G., Colman, F., 1998. Mammalian species richness in Paraguay: the effectiveness of national parks in preserving biodiversity. Biological Conservation 84 (3), 263–268.