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Rapid loss of Paraguay's Atlantic forest and the status of protected areas — A Landsat assessment

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Abstract

Using Landsat images acquired since early 1970s, we have mapped the forest cover and change between 1989 and 2000, and estimated forest area in 1973 in Paraguay's Atlantic Forest Ecoregion (PAFE). The results revealed that as of 1973, 73.4% of the PAFE region was covered by forest. Since then, the proportion of forested area was quickly reduced to 40.7% by 1989 and further down to 24.9% by 2000. Two competing deforestation processes contributed to this rapid forest loss, with the first being driven by settlers and the second by large private land owners. During the 1989–2000 period, 80% of deforested areas were cleared by private land owners and 20% by the settlers. Protected areas slowed down forest loss within their boundaries, but not in their surrounding areas. The average percent forest loss in the area within 5 km from the boundary of Paraguay's major forested protected areas was 39% during the 1989–2000 period, which was essentially the same as that for the entire PAFE region during the same period. The high rates of forest loss in the areas surrounding the protected areas not only left the protected areas highly isolated as ecological "islands", they may also be precursors to rapid forest loss within the protected areas. These protected areas are critical to the conservation of many species endemic or limited to the PAFE region and surrounding areas, and should be continuously monitored using recent and future satellite observations.

Keywords: Atlantic forest; Deforestation; Paraguay; Protected area

1. Introduction

The Atlantic forest in South America has been identified as one of the top priority ecosystems for global biological conservation (Myers, 1988; Olson & Dinerstein, 2002). The forest has extremely high levels of biodiversity, hosting an estimated 20,000 plant species and over 1300 non-fish vertebrate species (Mittermeier et al., 1999). The level of endemism is generally high. More than 6000 plant species, 60% mammal species, 30% reptiles, and 90% forest amphibians are thought to be endemic, with many found nowhere else on the Earth (Mittermeier et al., 1999; Myers et al., 2000).

Much of the original Atlantic forest was in Brazil, spanning along the Atlantic coast from the northeast in the state of Rio Grande do Norte to the southernmost border, and extending inland to Argentina and Paraguay in the south. The vast majority of the original Atlantic forest in Brazil has disappeared. Estimates of remaining Atlantic forest in Brazil ranged from 1% to 12% (Saatchi et al., 2001). While the Atlantic forest in eastern Paraguay only accounts for a small portion of the geographic area of the Atlantic Forest ecoregion, it has an improportionately high level of species diversity. The number of vascular

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plant species in eastern Paraguay was estimated at the order of 10,000 (Zardini, 1993), while the number of invertebrate species in Paraguay was around 100,000 (Catterson & Fragano, 2004). Many species endemic or limited to the Atlantic Forest have been documented in Paraguay, including 5 species of social wasps, 7 amphibian species, 11 reptile species, and 11 mammal species, with some found in Paraguay only (Fragano & Clay, 2003). Much of Paraguay's Atlantic forest remained "intact" before 1940, with the main form of deforestation being selective logging (Cartes, 2003). Since then, however, forest clearance became the major form of deforestation. Massive loss of Paraguay's forest resources has been reported since the 1970s, especially in eastern Paraguay (FAO, 1993, 2001; Sanjurjo & Gauto, 1996).

Using images acquired by the Landsat satellite series, we have systematically mapped the spatial extent of forest cover in 1989 and 2000 and the change between the two epochs for the entire country of Paraguay (Kim et al., submitted for publication), and estimated the total forest area within Paraguay's Atlantic Forest Ecoregion in the early 1970s using a systematic sampling approach. In this communication, we report on the status of Paraguay's Atlantic forest and its change since 1970s based on analysis of satellite observations, provide insight into the driving forces of the changes through analyzing the spatial patterns of mapped changes, and discuss the status of the protected areas in this region.

2. Data and methods

The study area was defined by intersecting Paraguay's country boundary with the Atlantic Forest Ecoregion developed by the World Wildlife Foundation (WWF) through the Global 200 project (Olson & Dinerstein, 2002). The resultant area of 85,502 km^2 will be referred to as Paraguay's Atlantic Forest Ecoregion (PAFE) hereafter. Nine spatially neighboring Landsat images were required to make a wall-to-wall coverage of the PAFE region. Three sets of Landsat images were used in this analysis. The first set consisted of Multi-Spectral Scanner (MSS) images having a nominal acquisition year of 1973. The second set consisted of Thematic Mapper (TM) images having a nominal acquisition year of 1989. The third set consisted of Enhanced Thematic Mapper Plus (ETM+) images having a nominal acquisition year of 2000. The pixel size of the MSS images was 57 m and that for TM and ETM+ images was 28.5 m. Table 1 lists the images used in this study.

Table 1
Landsat images used in this study and their acquisition dates

MSS images (1973)			TM (1989) and ETM+ (2000) images			
WRS1		Acquisition date	WRS2		Acquisition date	
Path	Row		Path	Row	1989	2000
240	77	05/23/1975	224	77	05/24/1990	03/03/2001
240	78	02/23/1973	224	78	04/19/1989	08/05/1999
240	79	03/231973	224	79	05/13/1989	03/03/2001
241	76	03/14/1973	225	76	11/25/1988	08/01/2001
241	77	09/15/1972	225	77	11/18/1991	09/18/2001
241	78	02/24/1973	225	78	03/22/1988	08/30/2000
241	79	09/15/1972	225	79	01/10/1988	08/01/2001
242	76	03/15/1973	226	76	07/06/1989	03/01/2001
242	77	03/15/1973	226	77	06/23/1987	03/14/2000

The Worldwide Reference System (WRS) used to index the MSS images (WRS1) is different from that used to index the TM and ETM+ images (WRS2). The format of the acquisition date is mm/dd/yyyy.

The Landsat images were geometrically and radiometrically corrected using standard image preprocessing methods (Irish, 2000). Furthermore, the MSS and TM images were orthorectified to achieve high geolocation accuracy (Tucker et al., 2004). The ETM+ images were coregistered to TM images using manually collected ground control points. The residual coregistration error between the two sets of images was less than 0.5 pixel.

2.1. 1989–2000 forest cover change mapping and validation

The TM and ETM+ images were used to develop a wall-to-wall forest cover change map using an iterative clustering-supervised labeling (ICSL) method. This method was used to analyze one pair of TM–ETM+ images at a time. It consisted of unsupervised clustering using the isodata algorithm (Tou & Gonzalez, 1974) and supervised labeling of clusters using training pixels, and was applied iteratively to resolve spectral confusions among the concerned classes. Requiring intensive human inputs, this method could produce highly reliable results even when the input images were acquired in different seasons of the year (e.g. Steininger et al., 2001). It was previously used to produce forest cover change products for pan-Amazon countries including Bolivia, Peru, Columbia, and Ecuador (Townshend et al., 1995). More details on the ICSL method were provided by Kim et al. (submitted for publication). The produced map had four major classes: forest, non-forest, water, and deforestation. The first three classes refer to pixels that remained the same class in both nominal years 1989 and 2000. The deforestation class refers to pixels being forest in 1989 and non-forest in 2000. Bad data such as cloud and shadow in either or both dates were labeled appropriately.

The developed forest cover change map was validated at three levels. First, because the ICSL method required intensive human interventions, the change map was consistently inspected against the input images as the map was developed. Any misclassification errors identified at this stage were fixed. Second, the change map was carefully evaluated by all authors of this paper and by some local experts who had extensive knowledge on Paraguay's land cover. Finally, some high spatial resolution data were available to this study, including a QuickBird image covering a single area of 64 km^2 and 136 aerial photos clustered at five locations covering a total area of 91.8 km^2. With the QuickBird image acquired in 2002 and the aerial photos acquired between 1999 and 2003, these high resolution images were used as reference data to assess the accuracy of the mapped forest cover in the 2000 epoch for the areas covered by them. We first split the forest cover change map into a 1989 forest cover map and a 2000 forest cover map. We then randomly selected 325 samples within the area covered by the QuickBird image and 392 samples within the area covered by the 136 aerial photos. Here each sample was a 28.5 m TM pixel. The actual cover type at each sample location was determined by visually interpreting the high resolution images. Overall accuracy as well as user's and producer's accuracies for the two areas was calculated according to Stehman (1997).

2.2. Forest cover estimation for 1973

Because the MSS images had different spatial resolutions and spectral characteristics than the TM images, forest cover change between nominal year 1973 and 1989 was not mapped using the wall-to-wall approach. In order to estimate the total forest area in nominal year 1973, we visually interpreted samples systematically selected across the entire PAFE region. Specifically, samples were selected at an interval of 0.15° in both latitudinal and longitudinal directions. This yielded 342 samples for the entire study area. For each sample location, a window of 3 by 3 MSS pixels (2.9 ha) centered at the sample location was visually interpreted to determine if the sample location was forest or non-forest. To ensure that forest areas estimated using this sampling approach and that calculated based on the wall-to-wall mapping approach were comparable, we also applied the sampling approach to the 1989 TM images and obtained almost the same estimate of total forest area as that derived using the wall-to-wall mapping approach. The total forest area estimated using the two approaches only differed by 0.4%.

2.3. Change pattern analysis

In order to understand the social economic driving forces of forest change, we analyzed the spatial patterns of mapped changes. While many social economic forces may have contributed to forest loss in this region (Macedo & Cartes, 2003), two of them stood out in eastern Paraguay. One was the country's long time perception of forest as unproductive land. Forest was viewed as "an obstacle to agricultural production and a land of wild animals and vermin" (Cartes, 2003). The other factor was widespread land disputes caused by long time inequalities in land tenure. Due to lack of public land to be offered under settlement plans, private lands were often "invaded" and expropriated by settlers, resulting in two competing deforestation processes. On the one hand, the land expropriated by squatters was converted to small patches of farmland, typically 10 ha per plot (Nagel, 1999). On the other hand, large landowners converted extensive forest areas to agricultural uses, often out of the fear that their land, if left forested, would be considered "unused" and therefore be expropriated (Sanjurjo & Gauto, 1996). These two deforestation processes resulted in agricultural areas of distinctively different sizes with spatial patterns discernable in the Landsat images (Fig. 1). We used a systematic sampling approach to quantify the proportion of forest loss due to the two deforestation processes. First, based on the developed forest cover change map, 338 samples were selected at the interval of 0.125° in both latitudinal and longitudinal directions from areas where deforestation occurred between 1989 and 2000. For the 1 km by 1 km area centered at each sample location, the 1989 and 2000 Landsat images were visually inspected to determine the proportion of forest lost to small farmlands and the proportion cleared by large land owners. The derived proportion estimates for each sample location were adjusted using the percentage of change area within the 1 km by 1 km window as a weighting factor and then averaged across all 338 samples to calculate the overall proportion of forest loss caused by the two deforestation processes.

2.4. Assessment of protected areas

The wall-to-wall forest cover change map developed in Section 2.1 allowed a comprehensive assessment of the forests at the protected areas. Paraguay's protected areas include national parks, biological reserves, biological refuges, and national monuments. We assessed the ones that were mostly forested, were larger than 50 km^2, and were located within the PAFE region. For each selected protected area, we examined the forest cover and change within its boundary as well as the surrounding area within 5 km from the boundary.

3. Results

3.1. Forest cover and change analysis

Fig. 2(A) shows the developed forest cover change map depicting the spatial distribution of forest within Paraguay's Atlantic Forest Ecoregion (PAFE) in the nominal years 1989 and 2000 and the forest loss during this period. As described in

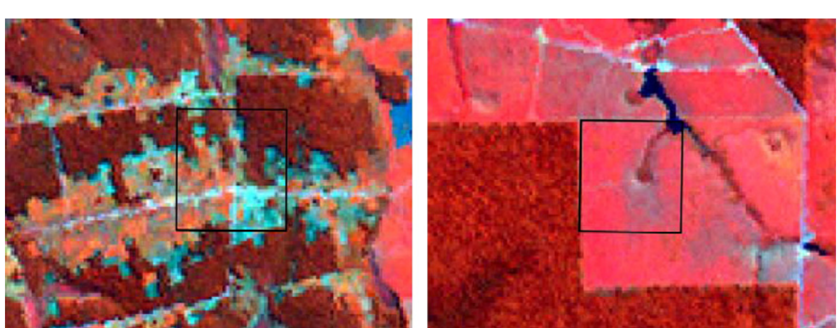

Fig. 1. Agriculture patterns resulting from deforestation processes initiated by settlers (left) and large private land owners (right) as seen on Landsat ETM+ images. The ETM+ images are shown with the near infrared, red, and green bands in red, green and blue colors. Forest appears dark red. Deforested areas appear in other colors. The black box shown in each image is a 1-km^2 sample unit used during the systematic analysis of agriculture patterns.

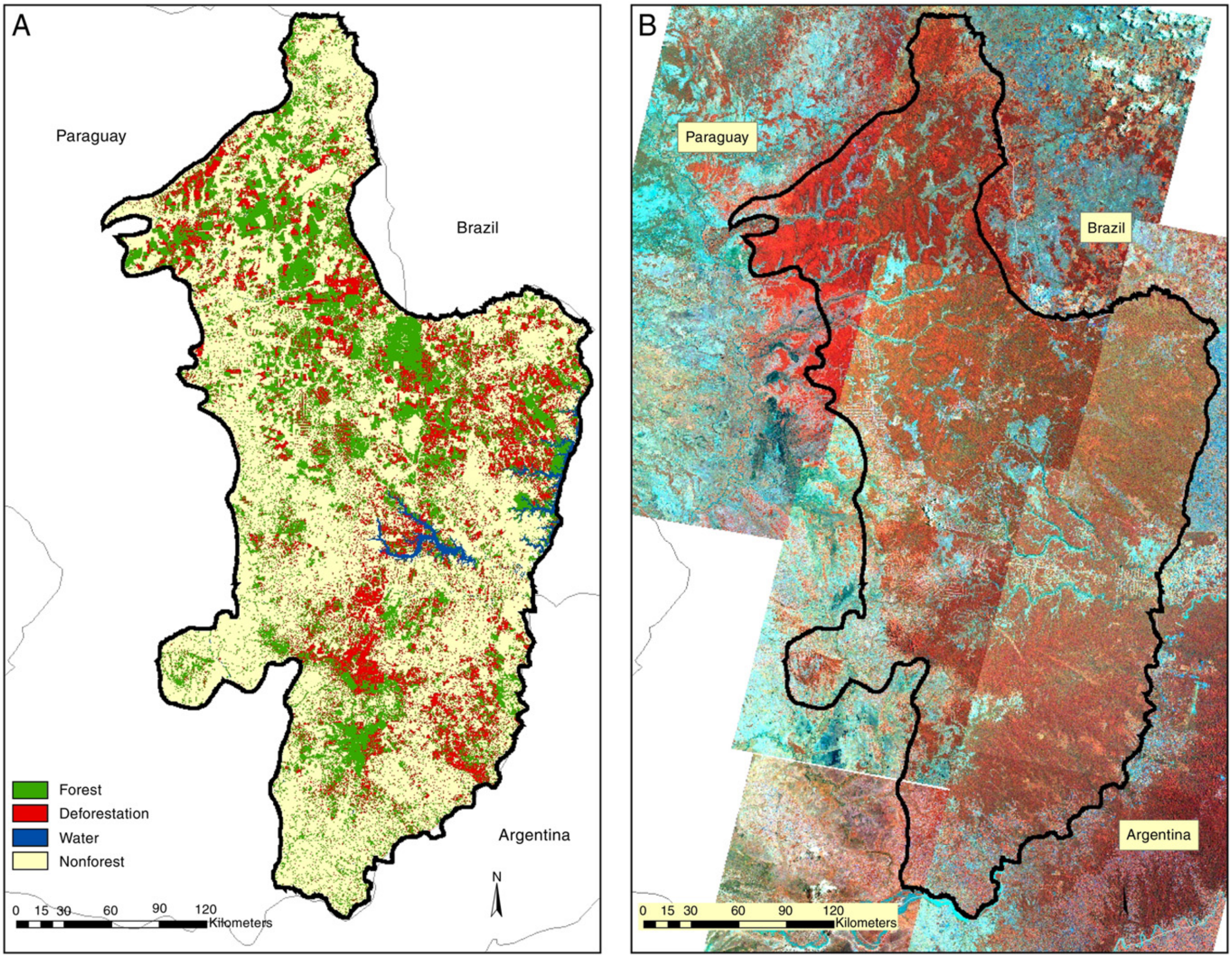

Fig. 2. (A). Forest cover and change in Paraguay's Atlantic Forest Ecoregion (PAFE) between 1989 and 2000. (B). MSS image mosaic showing the spatial extent of forest in Paraguay's Atlantic Forest Ecoregion (PAFE) in 1973. MSS near infrared, red and green bands are shown in red, green and blue colors. Forest generally appears dark red or red in the image mosaic.

Section 2.1, this map was extensively evaluated first by the image analysts during its development and then by the rest of the coauthors and some local land cover experts after it was developed. Such evaluations revealed that the developed map was highly reliable. For the two areas where the high resolution QuickBird image and aerial photos were available, the accuracies of the derived forest cover map for the 2000 epoch as evaluated using the high resolution data are listed in Table 2. Except for the non-forest class in the area covered by the aerial photos, which had user's accuracy of 81.8% and producer's accuracy of 86.3%, all other accuracy values listed in Table 2 were well above 90%. Due to limited area coverage of the high resolution data, these accuracy values likely will not be the same as those for the entire PAFE region. Nevertheless, they confirmed the evaluation results conducted by the coauthors and

Table 2
Accuracy values (%) of mapped forest cover for the 2000 epoch evaluated over the areas covered by available high resolution data

Type of high resolution data	Overall accuracy	User's accuracy		Producer's accuracy	
		Forest	Non-forest	Forest	Non-forest
Aerial photos	93.9	96.8	81.8	95.6	86.3
QuickBird image	97.5	99.2	92.1	97.6	97.2

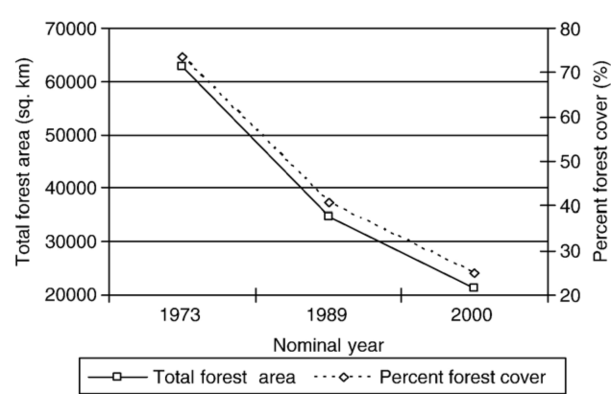

Fig. 3. Landsat derived forest cover in Paraguay's Atlantic Forest Ecoregion in nominal years 1973, 1989 and 2000.

Table 3
Forest cover and change within Paraguay's major forested protected areas

Name of protected areas	Total area (km^2)	Forest in 1989 (km^2)	Forest in 2000 (km^2)	Percent forest loss (%)	Is it public?[a]
Parque Nacional Cerro Cora	**120.70**	**56.92**	**49.48**	**13.07**	**Yes**
Reserva Natural Bosque Mbaracayu	634.26	584.25	571.83	2.13	No
Reserva Biologica Limoy	133.92	125.04	124.37	0.54	No
Reserva Biologica Itabo	113.11	103.32	97.02	6.10	No
Parque Nacional Ybytyruzu	**248.56**	**165.84**	**147.16**	**11.26**	**Yes**
Parque Nacional Caaguazu	133.27	127.46	123.00	3.3	Yes
Parque Nacional Ybycui	54.95	38.55	37.31	3.20	Yes
Parque Nacional San Rafael	**777.32**	**620.87**	**557.80**	**10.16**	**Yes**
Parque Nacional Cerro Sarambi	82.75	59.15	56.25	4.90	No

Areas that experienced more than 10% forest loss during the 1989–2000 period were highlighted in bold face.
[a] Note: According to Catterson and Fragano (2004).

local experts. Although no reference data was available to evaluate the mapped forest cover for the 1989 epoch, we expect it to have similar accuracy values because the TM images of 1989 and ETM+ images of 2000 had very similar spatial and spectral characteristics, and the forest cover for the two epochs was mapped simultaneously using the same method.

Fig. 3 shows the total forest area and percent forest cover for the PAFE region in the three nominal years: 1973, 1989 and 2000. The areas for 1989 and 2000 were calculated based on the developed forest cover change map, and that for the 1973 was based on the 342 samples systematically selected across the entire region. Fig. 3 reveals that the PAFE region had extensive forest cover up to the early 1970s, with over 70% of the area being forested. The spatial distribution of those forests is shown in Fig. 2(B) using the MSS images, where forest pixels appear dark red or red. Within less than 30 years from the early 1970s, the forest cover in the PAFE region was reduced to 40.7% by 1989 and further to less than 25% by 2000. The average deforestation rate in this region was 1749.97 km^2/year between 1973 and 1989 and 1228.21 km^2/year between 1989 and 2000.

The spatial pattern of mapped forest change within the PAFE region revealed that the deforestation process by the large land owners as described in Section 2.3 was far more devastating than that by the settlers. Of the forest areas cleared between 1989 and 2000, nearly 80% was converted to large tracts of agricultural fields by private land owners and 20% to small farmland patches by settlers.

3.2. Status of protected areas

Nine of Paraguay's protected areas were mostly forested, were larger than 50 km^2, and were located within the PAFE region. Table 3 lists their forest cover in nominal years 1989 and 2000 according to the developed 1989–2000 forest cover change map. Percent forest loss (PFL) was defined as the proportion of forest that existed in 1989 that was lost by 2000. The following can be observed according to Table 3:

– The protected areas slowed down the loss of forest within the boundary of the protected areas. While for the entire PAFE area nearly 40% of the forest that existed in 1989 was cleared by 2000, most protected areas lost only a few percent of their forests during the same period, with the maximum PFL being 13.1%. Fig. 4 shows the developed forest cover change maps for the two largest protected areas, Reserva Natural Bosque Mbaracayu and Parque Nacional San Rafael, and their surrounding areas.
– Some public protected areas experienced substantially higher rates of forest loss than non-public ones. All three protected

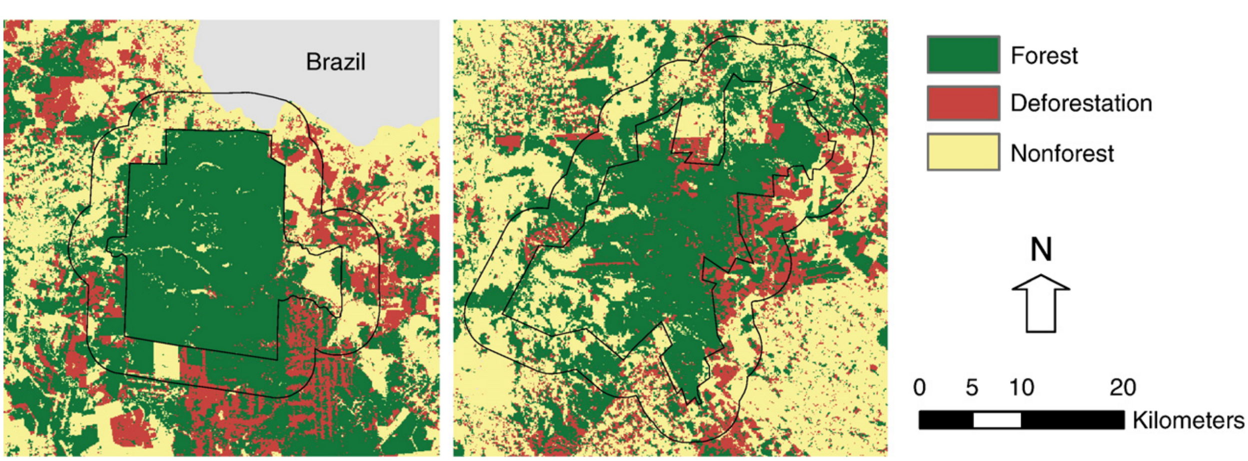

Fig. 4. Forest cover and change within the Reserva Natural Bosque Mbaracayu (left) and the Parque Nacional San Rafael (right) and the 5-km buffer zones (black lines) surrounding them.

Table 4
Forest cover and change in the buffer zone area within 5 km from the boundary of forested protected areas

Name of protected areas	Total area (km^2)	Forest in 1989 (km^2)	Forest in 2000 (km^2)	Percent forest loss (%)
Parque Nacional Cerro Cora	397.10	94.27	84.20	10.68
Reserva Natural Bosque Mbaracayu	632.50	394.47	239.65	39.25
Reserva Biologica Limoy	311.31	125.90	63.76	49.36
Reserva Biologica Itabo	364.33	87.91	54.44	38.08
Parque Nacional Ybytyruzu	443.49	107.61	78.31	27.23
Parque Nacional Caaguazu	713.42	547.55	245.47	56.10
Parque Nacional Ybycui	259.22	69.54	62.41	10.26
Parque Nacional San Rafael	919.07	519.48	336.48	35.23
Parque Nacional Cerro Sarambi	316.61	120.08	94.81	21.04

areas that lost more than 10% of their forests during the 1989–2000 period, including the Parque Nacional Cerro Cora, Parque Nacional Ybytyruzu, and Parque Nacional San Rafael, are public protected areas, revealing that the public protected areas were not as well protected as the non-public ones. This may have been caused by at least two reasons. The first was lack of adequate funding for Paraguay's protected areas (Catterson & Fragano, 2004). The second was mixed land ownerships in many public protected areas. For example, the government only owned 40% of the land of the Parque Nacional Cerro Cora and 30% of that of Parque Nacional Ybycui while all land of the Parque Nacional Ybytyruzu and Parque Nacional San Rafael was privately owned (Yanosky & Cabrera, 2003). Disputes with land owners over land and land use caused serious implementation problems for the public protected areas (Cartes, 2003).

Analysis of forest change in areas surrounding the protected areas revealed that the protected areas did not slow down the forest loss in their surrounding areas. Table 4 lists the PFL within a 5-km buffer zone from the boundary of the 9 protected areas. With an average PFL value of 39%, the deforestation rate in the areas surrounding the protected areas was essentially the same as that for the entire PAFE region between 1989 and 2000.

4. Discussions and conclusions

Using satellite images obtained since 1970s, we have mapped the spatial extent of Paraguay's Atlantic forests in nominal years 1989 and 2000 and their change between the two epochs, and estimated the total forest area within the PAFE region in the nominal year 1973. Mapped forest cover for the 2000 epoch was found highly reliable, with overall accuracy values being 93.9% and 97.5% in the two areas where a high resolution satellite image and aerial photos were available. The developed forest cover change map is publicly available from the Global Land Cover Facility at www.landcover.org. With wall-to-wall coverage and a high spatial resolution of 28.5 m, this product can be used in a wide range of conservation studies and applications in eastern Paraguay and the surrounding areas, including developing strategies for restoring biodiversity, identifying conservation hotspots and establishing wildlife corridors (Baydack et al., 1999).

Our results revealed that as of the early 1970s, 73.4% of the PAFE region was covered by forest. Since then, the proportion of forested area was quickly reduced to 40.7% by 1989 and further down to 24.9% by 2000. Paraguay lost nearly two thirds of its Atlantic forest between 1973 and 2000, a result mainly of two competing deforestation processes, one by the settlers and the other by the large land owners, with the latter being far more devastating. The developed forest cover change map for the 1989–2000 period revealed the status of protected areas. In general, the protected areas slowed down forest loss within their boundaries. While nearly 40% of Paraguay's Atlantic forests that existed in 1989 were lost by 2000, most protected areas, especially the non-public ones, only lost small proportions of their forest during the same period. The protected areas, however, did not slow down forest loss in their surrounding areas. The average percent forest loss between 1989 and 2000 in the area within 5 km from the boundary of the protected areas was 39%, which was essentially the same as that for the entire PAFE region during the same period.

The high rates of forest loss in the areas surrounding the protected areas can adversely impact the protected areas. Forests surrounding a protected area 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 a precursor to rapid forest loss within the protected areas. Fig. 4 shows that the massive forest loss in the surrounding areas has penetrated into the Parque Nacional San Rafael. An analysis of forest change in Indonesia's protected areas revealed that some protected areas experienced rapid forest loss within their boundaries after massive forest loss within 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 to the conservation of many species endemic or limited to the PAFE region and surrounding areas (Fragano & Clay, 2003).

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