Forest Carbon Sequestration from Avoided Deforestation and Reforestation in Mata Atlântica (Atlantic Forest), Sul da Bahia, Brazil

Patrick Gonzalez

The Nature Conservancy, 4245 North Fairfax Dr., Arlington, VA 22203-1606 USA

Alessandro Marques

Instituto de Estudos Sócio-Ambientais do Sul da Bahia, Ilhéus, Bahia, Brazil

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Disclaimer

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Abstract

Deforestation for agriculture, livestock, and timber harvesting has reduced Mata Atlântica (Atlantic Forest), a unique type of tropical forest, to a fraction of its historical extent. Deforestation of Mata Atlântica has decreased the species richness of a region of globally unique biodiversity and contributed to global climate change by releasing substantial amounts of greenhouse gases from high-biomass forest areas. Here, we determine patterns and rates of historical forest cover change in an 1100 km^2 area of Mata Atlântica tropical rainforest in northeast Brazil through spatial analyses of remote sensing data. We also quantify the carbon sequestration potential of forest conservation and reforestation and the uncertainty of the sequestration estimates through Monte Carlo analyses of forest carbon data. Analyses of Landsat data reveal a partial recovery of Mata Atlântica in the last decade, with net reforestation in the period 1986-2001 in the Parque Estadual da Serra do Conduru, the Reserva Biológica de Una, and the buffer zones of the two areas. In Serra do Conduru, a gross rate of reforestation of 0.035 y^{-1} exceeded the gross rate of deforestation of 0.009 y^{-1}. Likewise, in Una, a gross rate of reforestation of 0.023 y^{-1} exceeded the gross rate of deforestation of 0.012 y^{-1}. Even though the total area of forest is increasing at a net rate of 0.002 y^{-1}, the gains are occurring in secondary forest while the area of primary forest continues to contract. The results suggest that a 1993 Brazil Federal Decree that banned logging in Mata Atlântica, a substantial reduction in the area of cabruca (shade-grown *Theobroma cacao* (cocoa)) following an outbreak of *Crinipellis perniciosa* (Witches' Broom fungus), and a decrease in the local human population have contributed to a partial recovery of Mata Atlântica. Forest conservation in the buffer zones and in 11 private reserves could prevent deforestation of 180 km^2 in 30 years, averting emissions of 2.9 million ± 170 000 t carbon. Reforestation of 52 km^2 of non-forest land eligible under the United Nations Clean Development Mechanism could, in 30 years, sequester 140 000 ± 3200 t carbon above the baseline carbon sequestration of natural regeneration. Forest conservation and reforestation could help conserve the globally unique biodiversity of southern Bahia tropical forests and reduce climate change through carbon sequestration.

Introduction

Mata Atlântica (Atlantic Forest) encompasses humid evergreen tropical rainforests and semi-deciduous moist forests that stretch along the Atlantic coast of Brazil from 6º to 30º S latitude and extend 50 to 700 km inland (SOS Mata Atlântica and INPE 2002). The rich and diverse flora and fauna of these forests, including over 20 000 plant species and 1300 vertebrate species and a 40% level of endemism, mark them as a global biodiversity hotspot (Myers et al. 2000). Mata Atlântica hosts 2500 tree and shrub species that represent 500 genera and 100 botanical families (Oliveira-Filho and Fontes 2000).

Deforestation for agriculture, livestock, and timber harvesting has reduced Mata Atlântica to a fraction of its historical extent. From European colonization in 1500 A.D. to 2000 A.D., the original 1.3 million km^2 extent of Mata Atlântica has decreased to 8 to 12% of its original area (SOS Mata Atlântica et al. 1998, SOS Mata Atlântica and INPE 2002). Forest remnants are fragmented and surrounded by urban and agricultural areas. Edge effects render tropical forest fragments susceptible to drought, invasive species, and physical disturbance (Laurance et al. 2006). In Mata Atlântica, fragmentation may threaten one-third of tree species with extirpation due to the loss of birds that disperse fruits, necessary for tree propagation (da Silva and Tabarelli 2000).

The federal and state governments of Brazil have established a network of parks and management areas that protect important forest remnants. Recognizing that the existing protected areas system may be insufficient to conserve the biodiversity of Mata Atlântica (Tabarelli et al. 2005), government agencies and non-governmental organizations have identified priority areas for further protection (Brasil MMA 2000). Government policies have sought to offer protection to the vast areas of privately-owned forest land. The Brazil Forest Code (1965) requires that rural landowners manage 20% of the area of any private forest land property as a legal forest reserve. Brazil Federal Decree 98.914 (1990) created a special type of protected area on private land, the Reserva Particulares do Patrimônio Natural (RPPN) (Natural Heritage Private Reserve). Brazil Federal Decree 750 (1993) delimited the boundaries of the Mata Atlântica domain and banned the cutting of any primary or advanced secondary forest.

In addition to local impacts on ecosystems, deforestation causes global impacts by emitting carbon dioxide and other greenhouse gases that cause climate change. Greenhouse gas emissions from human activities have increased to 9 billion t carbon y^{-1}, entering the atmosphere at twice the rate at which vegetation and oceans can naturally sequester carbon (IPCC 2007a). The increase in atmospheric carbon dioxide has raised global mean surface temperature 0.7 ± 0.2 ºC in the 20th Century, while continued emissions at current rates could raise global temperatures 1.8–4ºC in the 21st Century (IPCC 2007a). Climate change is damaging ecosystems and human well-being by shifting vegetation, increasing wildfire, raising sea level, and intensifying storms (IPCC 2007b). Fossil fuel power plants, vehicles, and cement plants produce approximately 80% of global carbon emissions while deforestation produces the remainder (IPCC 2007a). At the same time, deforestation reduces the provision of ecosystem services, including watershed protection and biodiversity conservation. In response, natural resource management agencies and conservation organizations are implementing forest conservation and reforestation projects to conserve ecosystem functions and to reduce climate change through carbon sequestration. The Instituto de Estudos Sócio-Ambientais do Sul da Bahia (IESB), a non-governmental organization (NGO), is collaborating with government agencies and other NGOs to develop forest carbon projects.

Here, we conduct spatial analyses of remote sensing and forest carbon data to determine patterns and rates of historical forest cover change in an 1100 km^2 area of Mata Atlântica tropical rainforest in northeast Brazil. We also quantify the carbon sequestration potential of forest conservation and reforestation and the uncertainty of the sequestration estimates through Monte Carlo analyses of forest carbon data.

Methods

Research Area

The research area includes proposed buffer zones around two government protected areas and proposed expansion areas of 11 private reserves, covering a combined land area of 1100 km^2 of Mata Atlântica tropical rainforest (Figure 1) and agricultural land between 14º18' and 15º20' S latitude and 39º and 39º36' W longitude in northeast Brazil (Figures 2, 3). The two protected areas are the Parque Estadual da Serra do Conduru (Serra do Conduru State Park), established by the State Government of Bahia on February 21, 1997, and the Reserva Biológica de Una (Una Biological Reserve), established by the Federal Government of Brazil on December 10, 1980. The private reserves include nine Reservas Particulares do Patrimônio Natural (RPPNs, Natural Heritage Private Reserves) – Ararauna, Arte Verde, Ecoparque de Una, Mae da Mata, Paraíso, Pedra do Sabía, Salto Apepique, Serra Bonita, Teimoso – and two privately managed areas under consideration for RPPN status – Fazenda Capitão and Fazenda Nova Angelica. All areas are in the State of Bahia, with the majority of land in the municipalities of Ilhéus, Itacaré, Una, and Uruçuca, except for two RPPNs in the municipalities of Canacan, Jussari, and Pau Brasil.

The climate is humid throughout the year, with mean annual temperature of 24 ± 0.4º C (1901-2002), mean precipitation of 1700 ± 300 mm y^{-1} (1901-2002), and no pronounced dry season (Mitchell and Jones 2005). This climate has created the conditions for the rainforest that dominates the research area.

The rainforest is humid evergreen tropical forest stratified into several layers of trees and shrubs that support an abundance of epiphytes, ferns, and lianas. Forest areas include mature primary forest and secondary forest in various stages of regeneration from agriculture or timber harvesting. Botanical surveys in the Conduru area and in the Reserva Biológica de Una (Thomas et al. 1998) identified over 600 species representing 60 families (Table 1). The species richness per unit area is one of the highest in any neotropical rainforest (Martini et al 2007). One-quarter of the species in southern Bahia are endemic (Thomas et al. 1998). Species in the families *Myrtaceae, Melastomataceae, Rubiaceae*, and *Fabaceae* are the most abundant in Mata Atlântica tropical rainforest (Oliveira-Filho and Fontes 2000). Two notable endangered species in southern Bahia include *Caesalpinia echinata* (pau-brasil), valued for its wood for violin bows and other specialized uses, and *Leontopithecus chrysomelas* (Golden-headed Lion Tamarin), a unique species of monkey.

From European colonization in 1500 A.D. to 2000 A.D., the original 200 000 km^2 extent of Mata Atlântica in the State of Bahia has diminished to 6 to 13% of its original area (SOS Mata Atlântica et al. 1998, SOS Mata Atlântica and INPE 2002). In the municipalities of Ilhéus, Itacaré, Una, and Uruçuca, original forest cover has decreased to 70% of its original area (SOS Mata Atlântica and INPE 2002).

Cocoa cultivation dominates the agricultural lands of the research area. The majority of cocoa plantations are cabrucas, shade-grown stands of the native tree *Theobroma cacao* (cocoa) that farmers establish by thinning the forest understory and planting cocoa trees. The Reserva Biológica de Una protects one of the largest remaining areas of primary forest in northeast Brazil, with cabrucas covering less than 10% of the surrounding area (Faria et al. 2007). In contrast, the forests around Serra do Conduru are fragmented and surrounded by extensive cabrucas (Faria et al. 2007). In both areas, ranchers clear forest to establish pastures for cattle.

Figure 1. Mata Atlântica tropical rainforest in the Serra do Conduru area (photo ©2003 P. Gonzalez).

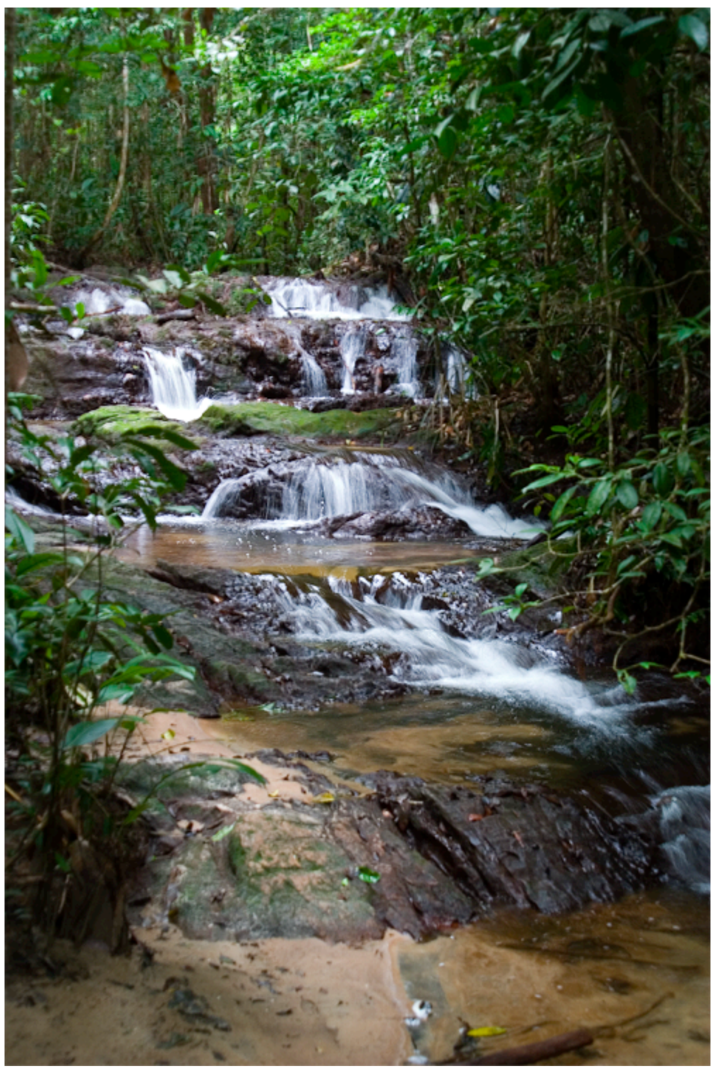


Figure 2. Location of the research area in South America
(remote sensing data National Aeronautics and Space Administration (NASA).

Table 1. Species and family richness of the flora of the research area
(P. Gonzalez analysis of data from Thomas et al. 1998).

	Parque Estadual da Serra do Conduru	Reserva Biológica de Una
plant species	830	950
tree species	600	600
plant families	90	130
tree families	60	50

The two government protected areas and 11 private reserves of the research area form the nuclei of potential forest carbon projects under consideration by IESB and its partners. The project components include:

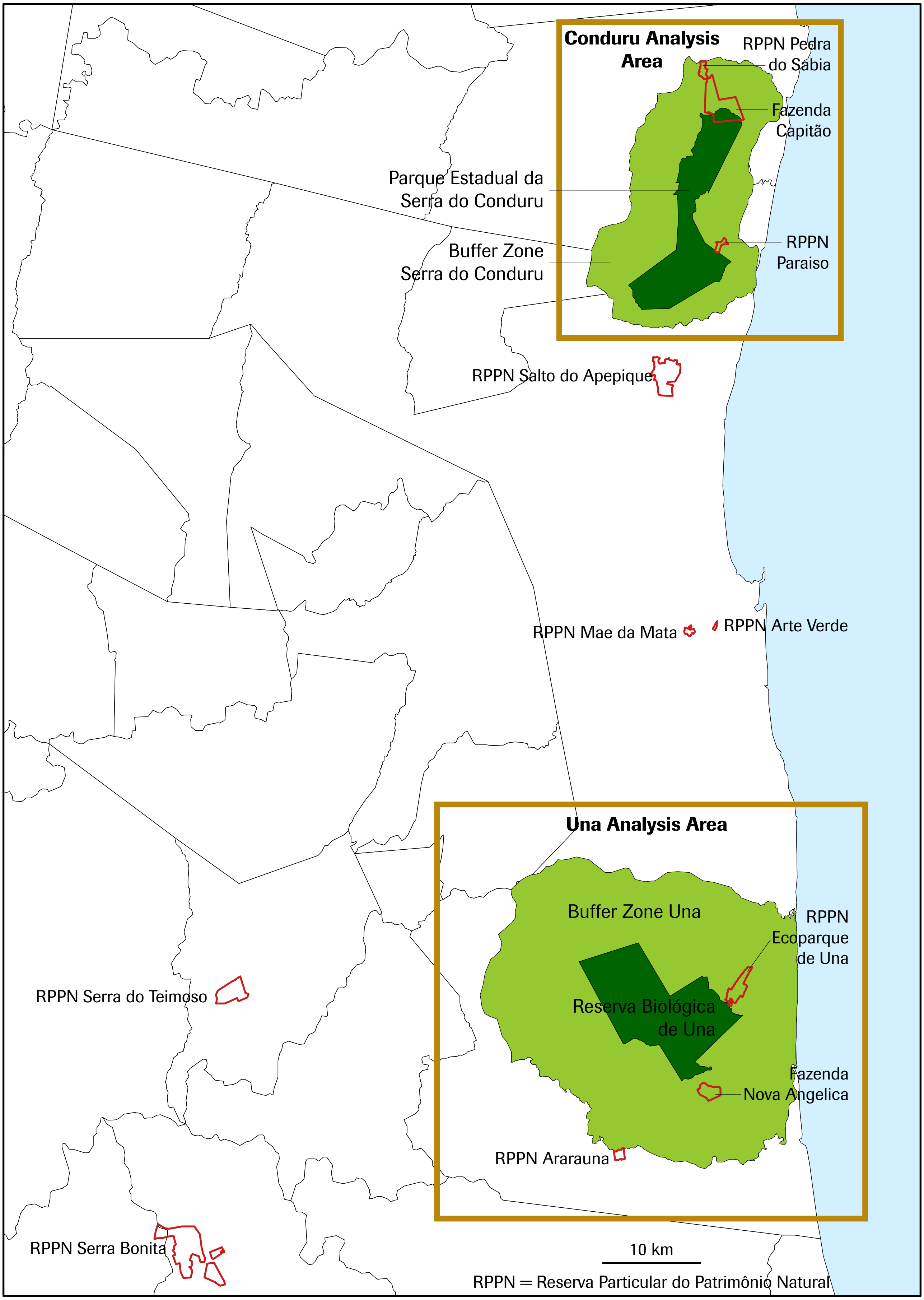
(1) Forest conservation in buffer zones around Serra do Conduru and Una

(2) Reforestation in buffer zones around Serra do Conduru and Una

(3) Forest conservation in new areas to be added to nine existing RPPNs and in two reserves that would be designated as RPPNs

(4) Reforestation in new areas to be added to nine existing RPPNs and in two reserves that would be designated as RPPNs

Figure 3. Research Area.



We delineated the Serra do Conduru and Una buffer zones as areas of approximately 5 km and 10 km width, respectively, around each protected area. We set the exact boundaries along streams and ridge tops so that the buffer zones correspond to local ecological features. The Una buffer zone is similar to a zone identified in the government management plan for the reserve. Both buffer zones represent areas where local NGOs plan activities to reduce deforestation. We calculate carbon sequestration only in the buffer zones and in potential additions to the RPPN network because these are the only areas where future carbon sequestration would be additional to carbon sequestration from activities that were already planned.

Remote Sensing Analyses

To determine spatial patterns and rates of historical forest cover change, we conducted spatial analyses on remote sensing data from the U.S. Geological Survey Landsat satellites. We used four 28.5 m spatial resolution multispectral Landsat scenes, acquired September 11, 1986 and May 23, 2001 in path 215, row 070 and path 215, row 071. We selected these years as the scenes with the lowest cloud cover close to the United Nations (U.N.) 1990 base year for Clean Development Mechanism forest project activities and to the present year. We geographically registered the 1986 scenes to the 2001 scenes in the UTM projection, zone 18 S, horizontal datum WGS-84.

We conducted a supervised classification of forest cover for each Landsat scene, using land cover maps for 1997 (Una) and 2002 (Conduru) derived by IESB through manual interpretation of aerial photos at 2 m spatial resolution. The IESB land cover maps covered only a portion of the research area. We classified the Landsat data into four classes: forest, non-forest land, clouds, and water. Due to the similar spectral characteristics of primary forest, secondary forest, and cabruca (Saatchi et al. 2001), the forest class includes all forest types. The difference between forest cover in 1986 and 2001 showed areas of deforestation, reforestation, and no change.

The gross rates of deforestation and reforestation for any part of the research area equal the quotients of the areas of deforestation or reforestation to the 1986 forest area and the 15-year time period:

Equation 1:

$$r_{change} = \frac{A_{forest}(2001) - A_{forest}(1986)}{A_{forest}(1986) \times (2001 - 1986)}$$

A_{forest} (year) = area of forest in a specified year (ha)

r_{change} = rate of deforestation or reforestation (y^{-1})

Because the private reserves were relatively small in surface area, a rate calculated only for the reserve area could fail to reflect the deforestation or reforestation factors of the surrounding area that influence forest cover change within the reserve. Therefore, we delineated a buffer zone for each area with a width equivalent to the radius of the longest dimension of the private reserve and calculated the rates of change for the reserve and its buffer zone.

Forest Carbon Analyses

If historical rates of deforestation and reforestation continue into the future, then the rates of change and the forest areas derived from remote sensing provide key data to calculate potential carbon sequestration from avoided deforestation and reforestation. We calculated potential avoided emissions from forest conservation by calculating, in turn, cumulative area, biomass, and carbon (Gonzalez and Marques 2006):

Equation 2: $$A_{\text{forest type}}(t_{\text{final}}) = A_{\text{forest type}}(t_{\text{start}}) \times (1 - (1 - r_{\text{deforestation}})^{t_{\text{final}} - t_{\text{start}}})$$

Equation 3: $$S_{\text{forest type}}(t_{\text{final}}) = A_{\text{forest type}}(t_{\text{final}}) \times (B_{\text{forest type}} - B_{\text{cut land class}})$$

Equation 4: $$C_{\text{emissions}} = f_C \times \sum^{\text{all forest types}} S_{\text{forest type}}(t_{\text{final}})$$

$A_{\text{forest type}}(t)$	= cumulative area of avoided deforestation from t_{start} to t (ha)
$B_{\text{cut land class}}$	= biomass density of the land class after the forest is cut (t biomass ha^{-1})
$B_{\text{forest type}}$	= biomass density of the existing forest type (t biomass ha^{-1})
$C_{\text{emissions}}$	= total baseline carbon emissions to the atmosphere (t carbon)
f_C	= carbon fraction of biomass (kg carbon (kg biomass)$^{-1}$)
$r_{\text{deforestation}}$	= rate of deforestation (y^{-1})
$S_{\text{forest type}}(t)$	= biomass stock in a single forest type in a specified year (t biomass)
t	= year
t_{final}	= final year of the project
t_{start}	= starting year of the project

Due to a lack of detailed forest inventories in the research area, we calculated emissions based on the 335 ± 11 t ha^{-1} biomass density of Mata Atlântica measured in permanent plots at Vale do Rio Doce Reserve, 300 km south of the research area (Rolim et al. 2005). Because the forest of Vale do Rio Doce is semi-deciduous, the biomass density of that forest is probably lower than the biomass density in our research area. To represent the biomass of deforested areas, we used the 1.15 ± 0.35 t ha^{-1} biomass density measured in pastures on former forest land 100 km south of our research area (de P Rezende et al. 1999). To convert biomass to carbon, we used the global average carbon fraction of 0.47 kg carbon (kg biomass)$^{-1}$ (McGroddy et al. 2004). We calculated estimates for a 30-year project operating from 2010 to 2039.

To quantify the uncertainty of the estimate of carbon emissions from avoided deforestation, we used Monte Carlo analysis (IPCC 2006), a statistical technique that calculates the error of an estimate based on probability distribution functions of individual parameters. Monte Carlo analysis quantifies how the errors of field measurements, wood density, allometric equations, and forest area estimates propagate to a level of inaccuracy in the final estimate. We conducted a Monte Carlo analysis of 1000 iterations using the standard deviation of the biomass density (Rolim et al. 2005) and an assumed 10% error in remote sensing estimates of forest area.

We calculated potential net sequestration from reforestation by calculating baseline biomass and carbon accumulation from reforestation that would occur naturally (Gonzalez et al. 2006):

Equation 6: $$B_{\text{baseline}}(t) = \sum_{\text{age}=1}^{t - t_{\text{end}} + 1} r_{\text{reforestation}} \times A_{\text{project}} \times [B(\text{age}) - B(\text{age}-1)] \times 1 \text{ y}$$

Equation 7: $$C_{\text{baseline}} = f_C \times \sum_{t_{\text{start}}}^{t_{\text{end}}} B_{\text{baseline}}(t)$$

Equation 8: $$C_{\text{net}} = C_{\text{potential}} - C_{\text{baseline}} - L_{\text{leakage}}$$

age	= age of a reforestation area (y)
$A_{project}$	= total area of proposed reforestation project activity (ha)
B(age)	= biomass density of regenerating forest at a specified age (t biomass ha^{-1})
$B_{baseline}(t)$	= biomass accumulation in baseline reforestation during year t (t biomass)
$C_{baseline}$	= baseline net carbon removal by reforestation (t carbon)
C_{net}	= net anthropogenic carbon sequestration by reforestation (t carbon)
$C_{potential}$	= total carbon removal by reforestation (t carbon)
f_C	= carbon fraction of biomass (kg C (kg biomass)$^{-1}$)
$L_{leakage}$	= leakage (t carbon)
$r_{reforestation}$	= projected rate of baseline reforestation (y^{-1})
t	= calendar year, range of values t_{start} to t_{end} (y)
t_{end}	= year of the end of the operational lifetime of a project activity (y)
t_{start}	= year of the starting date of the project activity (y)

For these calculations, we used the Mata Atlântica biomass density of 335 ± 11 t ha^{-1} (Rolim et al. 2005) and a linear biomass accumulation rate that would achieve that biomass density in 100 years. To estimate leakage, the unintended displacement of carbon emissions to land outside the research area, we reduced final net sequestration estimate by 5% (Gonzalez et al. 2006). To convert biomass to carbon, we used the global average carbon fraction of 0.47 kg carbon (kg biomass)$^{-1}$ (McGroddy et al. 2004). We calculated estimates for a 30-year project operating from 2010 to 2039. We estimated the uncertainty of the final carbon sequestration estimate by using the standard deviation of the biomass density as upper and lower bounds.

Results

The spatial analyses of Landsat data showed net reforestation at rates near 0.002 y^{-1} in Serra do Conduru (Table 2), Una (Table 3), and three of the private reserves (Table 4). In Serra do Conduru, a gross rate of reforestation of 0.035 y^{-1} exceeded the gross rate of deforestation of 0.009 y^{-1}. Likewise, in Una, a gross rate of reforestation of 0.023 y^{-1} exceeded the gross rate of deforestation of 0.012 y^{-1}. Some deforestation has occurred in the two government protected areas, but deforestation rates are twice as high in the buffer zones. Areas of reforestation are ubiquitous, but rates are higher within the two government protected areas. Figure 4 through Figure 9 show the Landsat real-color images for 1986 and 2001 and forest cover changes for Serra do Conduru and Una.

Forest carbon analyses show that forest conservation in the buffer zones and in 11 private reserves could prevent deforestation of 180 km^2 and avert emissions of 2.9 million ± 170 000 t carbon. Monte Carlo analysis reduced the uncertainty of that estimate to approximately 6%. Reforestation of 52 km^2 of non-forest land eligible under the U.N. Clean Development Mechanism could sequester an additional 140 000 ± 3200 t carbon above baseline sequestration of natural regeneration. So, the potential sequestration from forest conservation exceeds the potential sequestration of reforestation by an order of magnitude. In total, a combined forest conservation and reforestation project could sequester 3 million ± 180 000 t carbon in 30 years.

Table 2. Forest cover change, 1986-2001, Parque Estadual Serra do Conduru.

	Park	Buffer Zone	Total area
forest cover (ha)			
1986	6 000	15 400	21 400
2001	6 200	16 300	22 500
forest change (ha)			
forest	5 500	13 000	18 500
reforestation	600	3 400	4 000
deforestation	500	2 500	2 900
no forest	400	3 200	3 600
clouds	1 200	3 800	5 000
total	8 000	26 000	34 000
rates of change (y^{-1})			
gross deforestation	0.005	0.011	0.009
gross reforestation	0.039	0.034	0.035
net change	0.002	0.003	0.002

Table 3. Forest cover change, 1986-2001, Reserva Biológica de Una.

	Park	Buffer Zone	Total area
forest cover (ha)			
1986	8 200	35 300	43 500
2001	8 600	37 200	45 800
forest change (ha)			
forest	7 500	28 100	35 700
reforestation	1 000	9 000	10 100
deforestation	700	7 100	7 800
no forest	1 200	17 600	18 700
clouds	100	3 300	3 500
total	11 000	65 000	76 000
rates of change (y^{-1})			
gross deforestation	0.006	0.013	0.012
gross reforestation	0.030	0.023	0.023
net change	0.002	0.002	0.002

Table 4. Forest cover change, 1986-2001, Reservas Particulares do Patrimônio Natural (RPPN), Sul da Bahia.

RPPN	Esta-blished	Existing area (ha)	Proposed area (ha)	Gross deforestation (y^{-1})	Gross reforestation (y^{-1})	Net change (y^{-1})
Ararauna	2003	39	96	0.017	0.027	0.003
Arte Verde	1998	10	17	0.021	0.015	-0.009
Capitão	NA	0	971	0.007	0.042	0.002
Ecoparque de Una	1999	384	384	0.011	0.025	-0.004
Mae da Mata	2004	13	65	0.025	0.020	-0.008
Nova Angelica	NA	0	261	0.008	0.021	-0.003
Paraíso	2000	26	77	0.011	0.028	-0.003
Pedra do Sabía	2001	22	114	0.007	0.047	0.010
Salto Apepique	1997	118	742	0.006	0.038	-0.001
Serra Bonita	2004	1200	1641	0.013	0.029	-0.007
Teimoso	1997	200	522	0.025	0.011	-0.014

Table 5. Potential forest carbon sequestration from avoided deforestation and reforestation in Sul da Bahia, 2010-2039. The standard deviation of the avoided deforestation carbon estimate comes from a 1000-iteration Monte Carlo analysis. The uncertainty of the reforestation carbon estimate derives from maximum and minimum estimates of biomass density.

	Existing conser-vation (ha)	Proposed forest conser-vation (ha)	Avoided deforesta-tion (ha)	Avoided deforestation (t)	Avoided deforestation standard deviation (t)	CDM eligible area (ha)	CDM reforesta-tion project (ha)	Gross reforestation (t)	Baseline reforestation (t)	Net reforestation (t)	Net reforesta-tion uncertainty (t)	Avoided deforestation and reforestation (t)	Total uncertainty (t)
Private Reserves													
Ararauna	39	96	12	1 800	110	21	15	690	300	390	9	2 200	120
Arte Verde	10	17	1	180	10	4	3.8	180	40	130	3	310	10
Capitão	0	971	178	28 000	1 700	1	0				0	28 000	1 700
Ecoparque de Una	384	384	0	0	0	10	0				0	0	0
Mae da Mata	13	65	19	2 900	180	11	5.3	240	80	170	4	3 100	180
Nova Angelica	0	261	58	9 000	540	6	0				0	9 000	540
Paraíso	26	77	13	2 000	120	1	7.2	330	150	180	4	2 200	130
Pedra do Sabía	22	114	17	2 600	160	5	2.2	100	80	30	1	2 700	160
Salto Apepique	118	742	98	15 000	930	3	0				0	15 000	930
Serra Bonita	1200	1641	113	18 000	1 100	149	102	4 700	2 200	2 500	53	20 000	1 100
Teimoso	200	522	59	9 200	560	32	40	1 800	300	1 500	39	11 000	600
total	**2000**	**4900**	**570**	**88 000**	**5 400**	**240**	**180**	**8 100**	**3 100**	**4 900**	**110**	**93 000**	**5 500**
Park Buffer Zones													
Serra do Conduru		26 000	4 500	700 000	41 000	3200	1000	46 000	25 000	21 000	400	720 000	42 000
Una		65 000	12 000	2 100 000	130 000	18 000	4000	180 000	66 000	120 000	2 700	2 200 000	130 000
total		**91 000**	**17 000**	**2 800 000**	**170 000**	**21 000**	**5 000**	**230 000**	**92 000**	**140 000**	**3 100**	**2 900 000**	**170 000**
Total		**96 000**	**17 000**	**2 900 000**	**170 000**	**21 000**	**5 200**	**240 000**	**95 000**	**140 000**	**3 200**	**3 000 000**	**180 000**

Figure 4. Parque Estadual do Serra do Conduru, 1986, real-color Landsat.

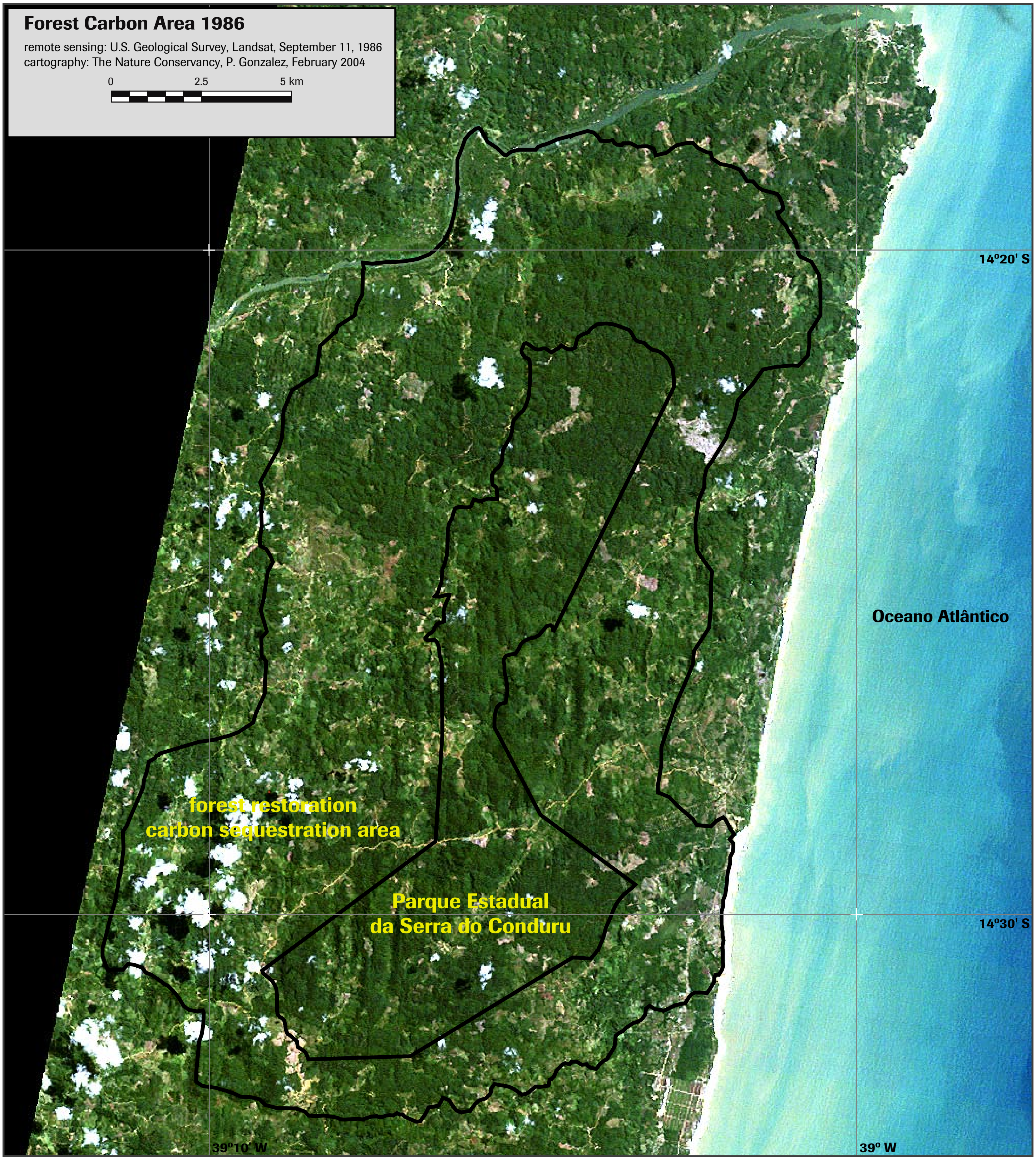


Figure 5. Parque Estadual do Serra do Conduru, 2001, real-color Landsat.

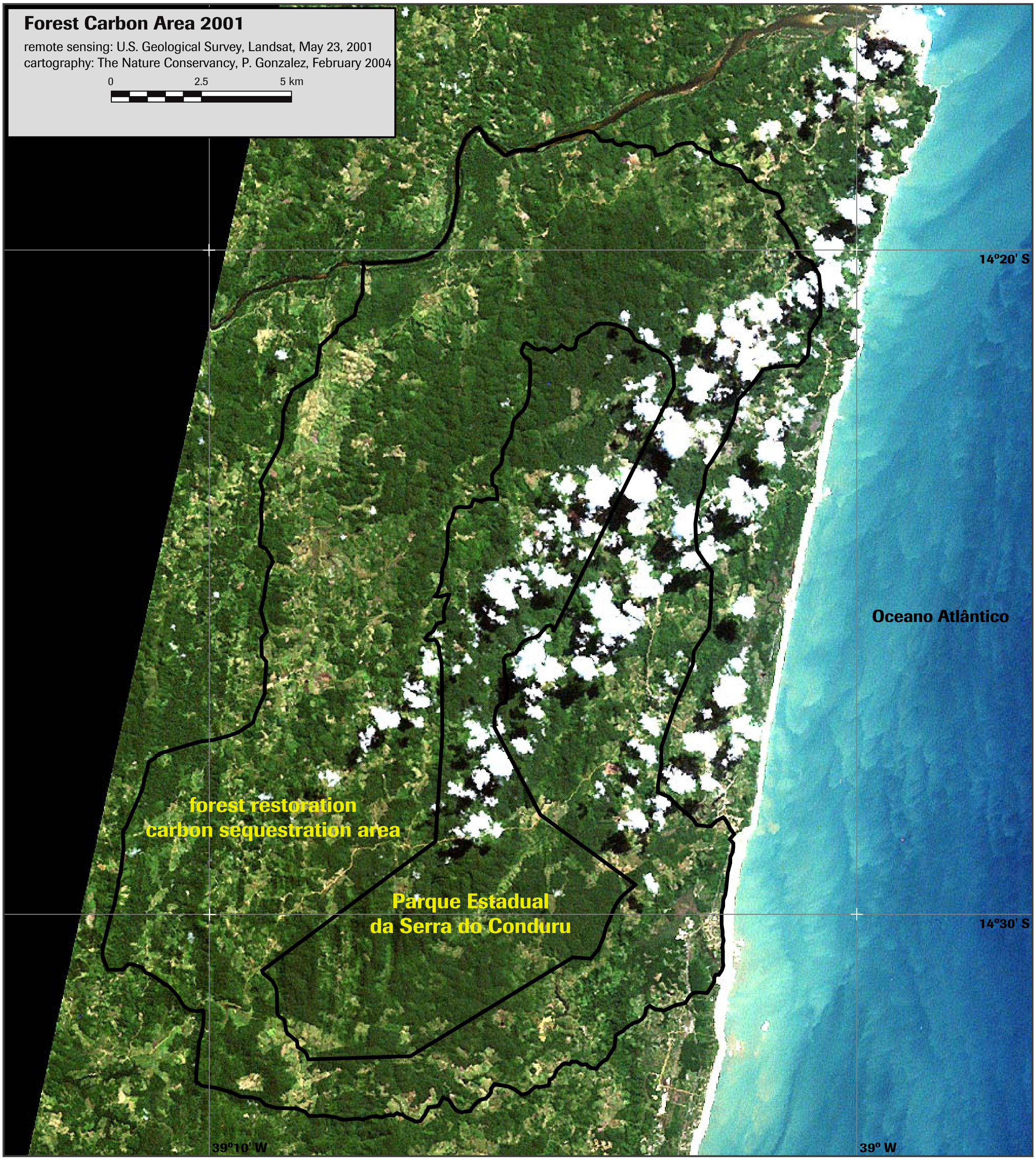


Figure 6. Parque Estadual do Serra do Conduru, 1986-2001, Forest Cover Change.

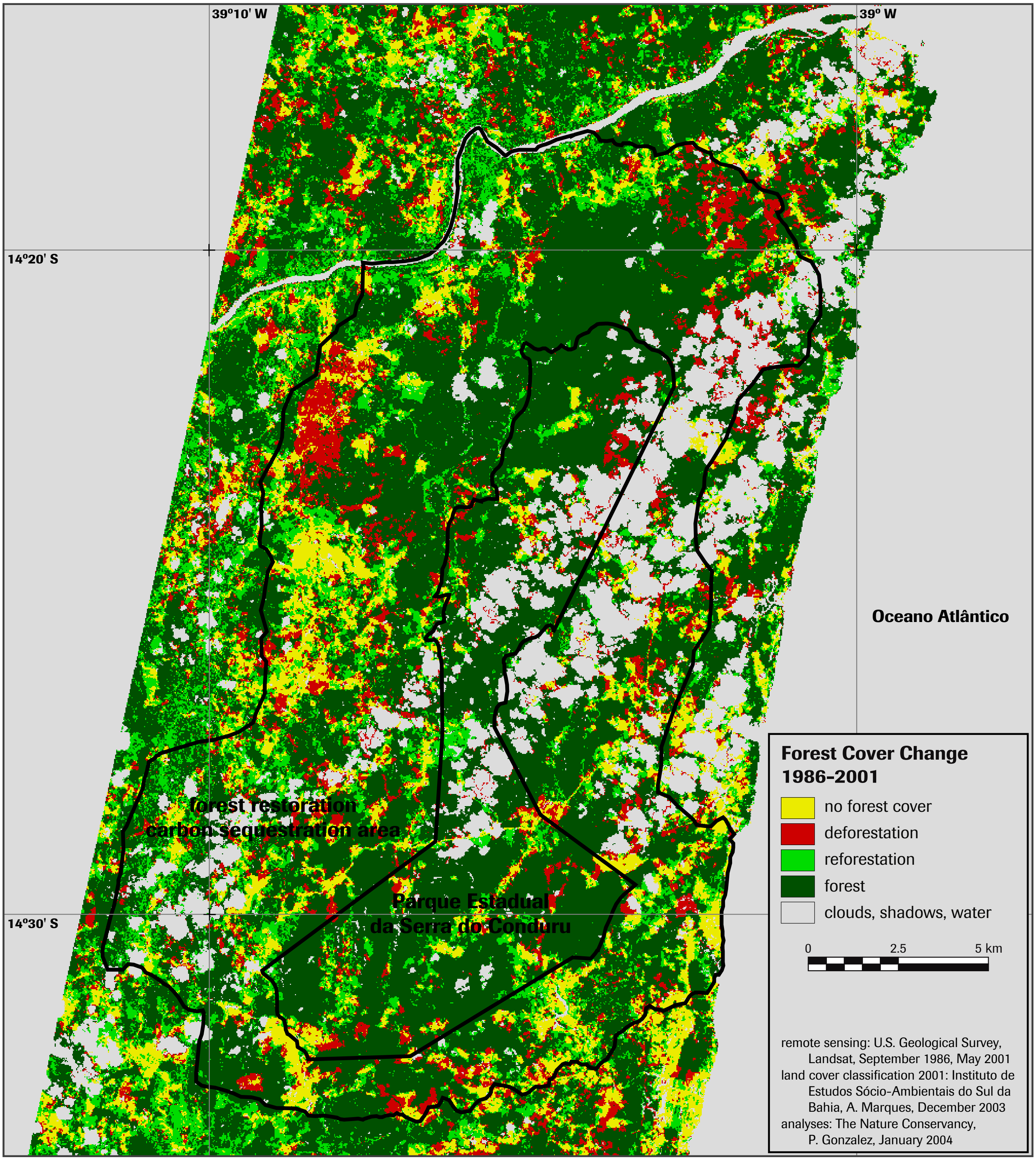


Figure 7. Reserva Biológica de Una, 1986, real-color Landsat.

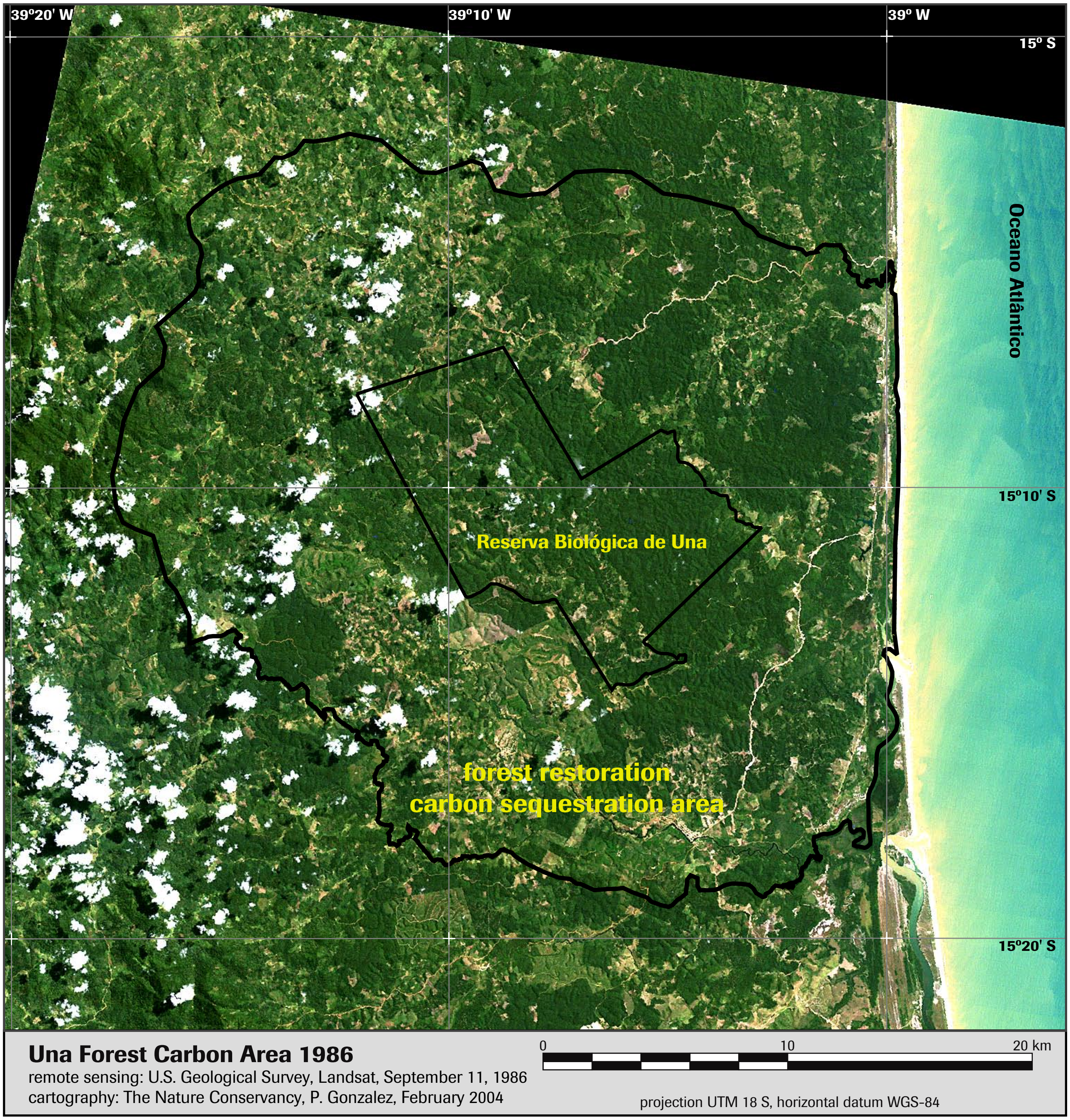


Figure 8. Reserva Biológica de Una, 2001, real-color Landsat.

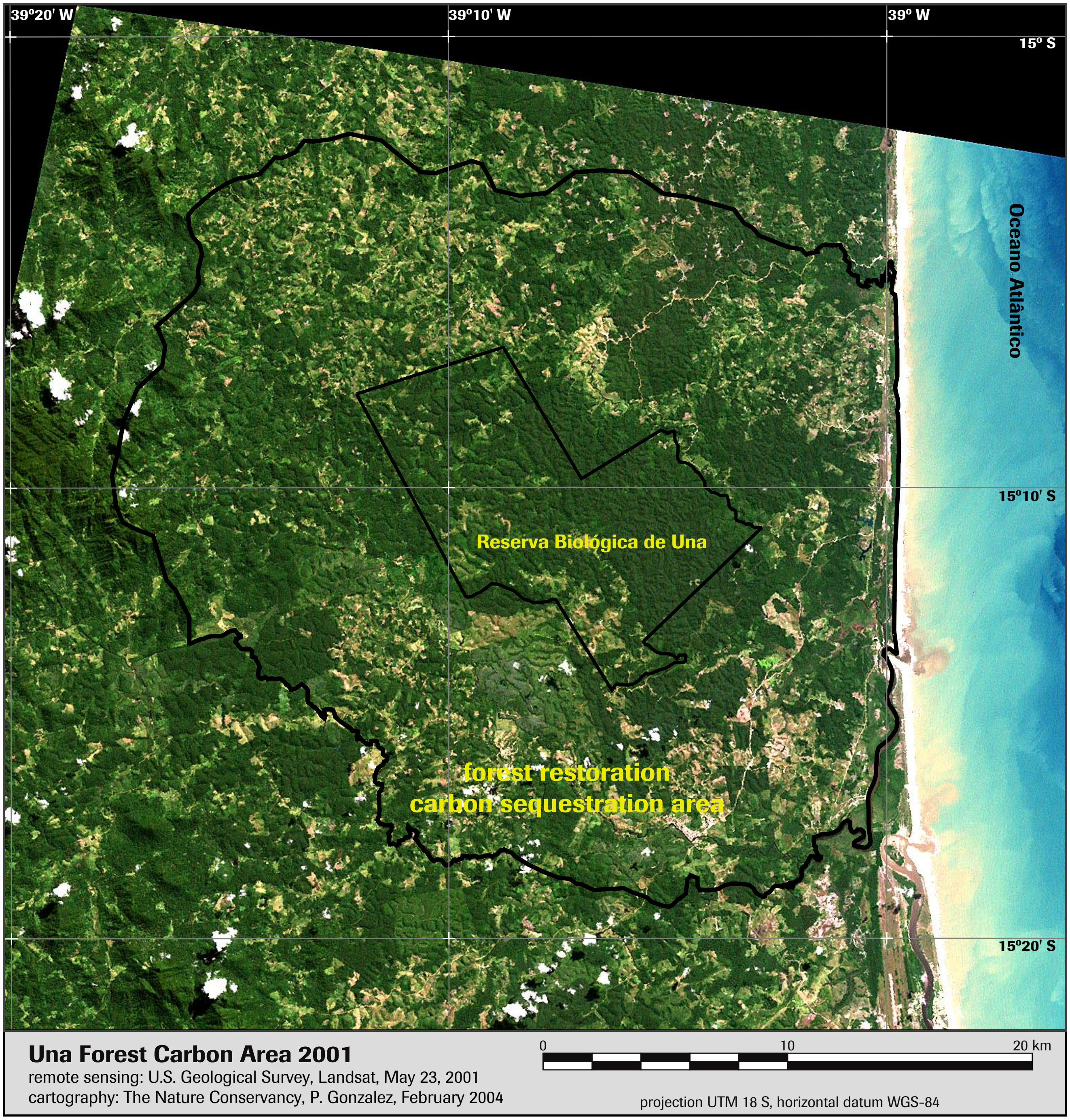
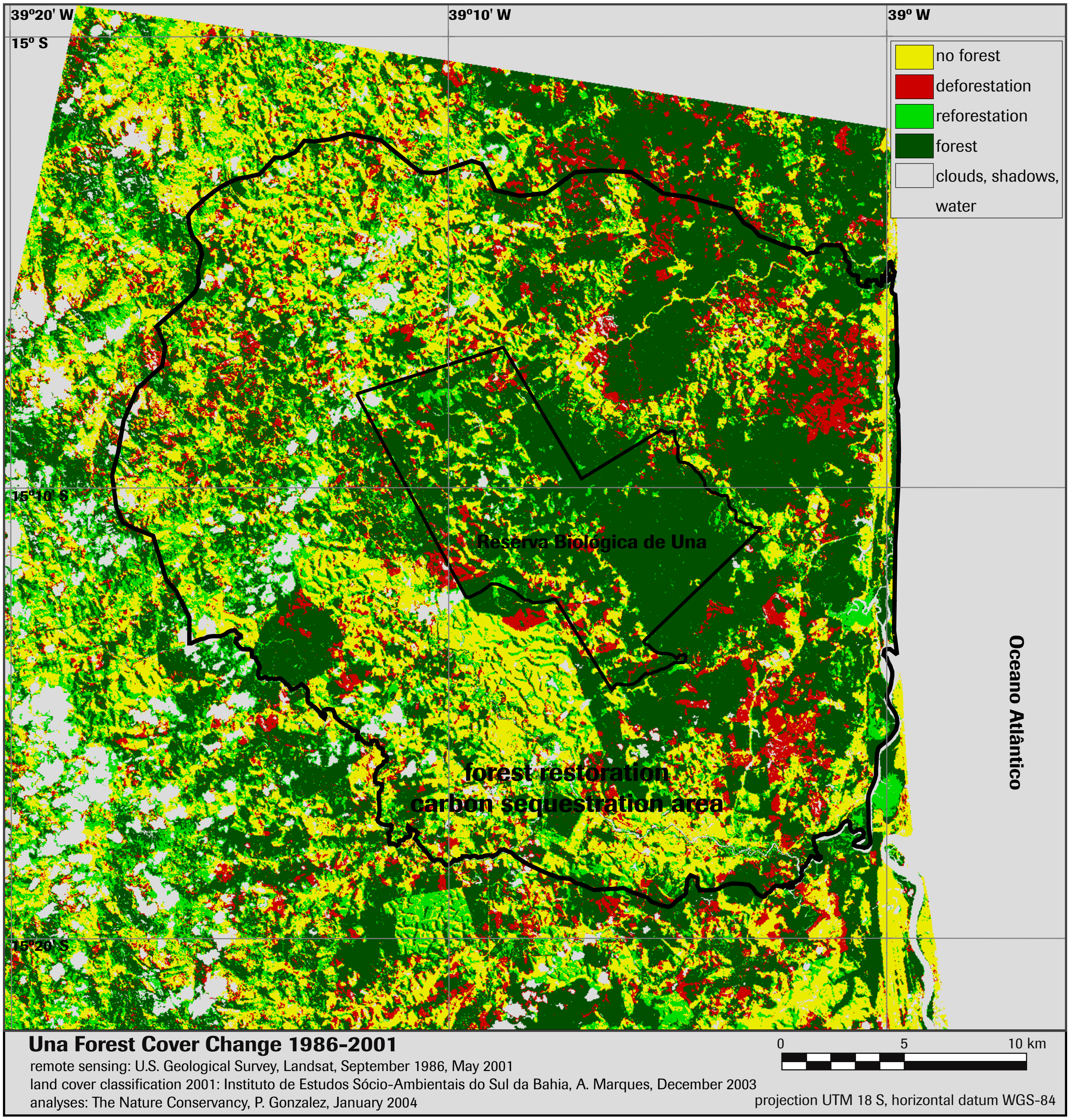


Figure 9. Reserva Biológica de Una, 1986-2001, Forest Cover Change.



Discussion and Conclusion

The Landsat analyses reveal a partial recovery of Mata Atlântica in the last decade. Three factors have contributed to the partial recovery of Mata Atlântica:

(1) Reduced timber harvesting due to the 1993 Brazil Federal Decree that banned logging in Mata Atlântica
(2) Substantial reduction in the area of cabruca (shade-grown *Theobroma cacao* (cocoa)) following an outbreak of *Crinipellis perniciosa* (Witches' Broom fungus)
(3) Decrease in the local human population.

Brazil Federal Decree 750 (1993) delimited the boundaries of the Mata Atlântica domain and banned the cutting of any primary or advanced secondary forest. Since then, federal and state government agencies and NGOs have monitored primary forest remnants for illegal timber harvesting and agricultural clearing (Brasil MMA 2000, Cullen et al. 2005).

Theobroma cacao (cocoa) is a tree native to the Amazon. Brazilians began to cultivate the tree in Bahia in the early 19th Century and the region eventually became the primary producer of cocoa in Brazil. In its native habitat, cocoa is an understory species. Because of the adaptation of the species to shade, farmers in Bahia primarily cultivate cocoa by thinning the understory of a native forest stand and planting cocoa trees to form a shade-grown cocoa plantation called a cabruca. The cabruca agroforestry system provides ecological benefits, including natural control of insect pests and weeds, microclimatic stability, and maintenance of soil fertility (Johns 1999). Cabrucas resemble advanced secondary forest (Saatchi et al. 2001) and can harbor old-growth tree species that readily reestablish through natural regeneration (Sambuichi and Haridasan 2007). On the other hand, removal of understory trees and shrubs and thinning of the canopy encourages the establishment of early successional species (Rolim and Chiarello 2004) and produces low quality habitat for forest-dependent species of birds, amphibians, and mammals (Faria et al. 2007).

In May 1989, *Crinipellis perniciosa* (Witches' Broom fungus), a pathogen endemic to the Amazon, appeared for the first time in Bahia (Pereira et al. 1989). The fungus causes Witches' Broom disease, which causes hypertrophic growth of infected buds into thin, elongated structures. Abnormal growth of the buds, combined with direct infection and destruction of seed pods, causes a nearly complete loss of cocoa seed production. Control efforts failed to contain the outbreak (Pereira et al. 1996). Consequently, cocoa cultivation and seed production fell from 550 000 ha and 300 000 tons in 1990 to 490 000 ha and 110 000 tons in 2003 (data Instituto Brasileiro de Geografia e Estatística). Many farmers abandoned cabrucas, which have regenerated into secondary forest.

The Witches' Broom fungus caused a collapse of the cocoa sector, increased unemployment, and diminished economic opportunities in southern Bahia. Many of the people that had depended on work in the cocoa sector migrated to other regions of Brazil. Consequently, the population of the Municipalities of Ilhéus, Itacaré, Una, and Uruçuca declined from 297 000 in 1991 to 292 000 in 2000, a rate of decrease of -0.002 y^{-1} (data Instituto Brasileiro de Geografia e Estatística). In addition, many people departed from rural areas to live in the cities, decreasing the rural fraction of the population from 0.45 in 1991 to 0.32 in 2000. The thinning of the rural population may have reduced deforestation pressures.

Recognizing the need to improve certain aspects of this research, we are conducting further analyses, including estimation of biomass densities from three local forest inventories, discrimination of primary and secondary forest classes in Landsat data, and validation of Landsat-derived forest classes with the aerial photo-derived forest classes.

In conclusion, our results indicate a partial recovery of Mata Atlântica and a potential for substantial carbon sequestration by reducing future deforestation. Continued forest recovery could increase the total area of Mata Atlântica, reduce forest fragmentation by filling large gaps between remnants of primary forest, and improve biodiversity conservation, forest carbon sequestration, water supplies for local communities, and other ecosystem services. Forest conservation and reforestation could help conserve the globally unique biodiversity of Mata Atlântica tropical rainforest and reduce global climate change through a potentially significant amount of carbon sequestration.

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