Forest Restoration Carbon Analysis of Baseline Carbon Emissions and Removal in Tropical Rainforest at La Selva Central, Perú

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January 10, 2006

Topical Report
Award DE-FC-26-01NT41151
U.S. Department of Energy, National Energy Technology Laboratory, Morgantown, WV USA

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Abstract

Conversion of tropical forest to agricultural land and pasture has reduced forest extent and the provision of ecosystem services, including watershed protection, biodiversity conservation, and carbon sequestration. Forest conservation and reforestation can restore those ecosystem services. We have assessed forest species patterns, quantified deforestation and reforestation rates, and projected future baseline carbon emissions and removal in Amazon tropical rainforest at La Selva Central, Peru. The research area is a 4800 km^2 buffer zone around the *Parque Nacional Yanachaga-Chemillén, Bosque de Protección San Matías-San Carlos,* and the *Reserva Comunal Yanesha.* A planned project for the period 2006-2035 would conserve 4000 ha of forest in a proposed 7000 ha *Área de Conservación Municipale de Chontabamba* and establish 5600 ha of natural regeneration and 1400 ha of native species plantations, laid out in *fajas de enriquecimiento* (contour plantings), to reforest 7000 ha of agricultural land. Forest inventories of seven sites covering 22.6 ha in primary forest and 17 sites covering 16.5 ha in secondary forest measured 17 073 trees of diameter ≥ 10 cm. The 24 sites host trees of 512 species, 267 genera, and 69 families. We could not identify the family of 7% of the trees or the scientific species of 21% of the trees. Species richness is 346 in primary forest and 257 in the secondary forest. In primary forest, 90% of aboveground biomass resides in old-growth species. Conversely, in secondary forest, 66% of aboveground biomass rests in successional species. The density of trees of diameter ≥ 10 cm is 366 trees ha^{-1} in primary forest and 533 trees ha^{-1} in secondary forest, although the average diameter is 24 ± 15 cm in primary forest and 17 ± 8 cm in secondary forest. Using Amazon forest biomass equations and wood densities for 117 species, aboveground biomass is 240 ± 30 t ha^{-1} in the primary sites and 90 ± 10 t ha^{-1} in the secondary sites. Aboveground carbon density is 120 ± 15 t ha^{-1} in primary forest and 40 ± 5 t ha^{-1} in secondary forest. Forest stands in the secondary forest sites range in age from 10 to 42 y. Growth in biomass (t ha^{-1}) as a function of time (y) follows the relation: biomass = 4.09 - 0.017 age^2 ($p < 0.001$). Aboveground biomass and forest species richness are positively correlated ($r^2 = 0.59$, $p < 0.001$). Analyses of Landsat data show that the land cover of the 3700 km^2 of non-cloud areas in 1999 was: closed forest 78%; open forest 12%, low vegetation cover 4%, sparse vegetation cover 6%. Deforestation from 1987 to 1999 claimed a net 200 km^2 of forest, proceeding at a rate of 0.005 y^{-1}. Of those areas of closed forest in 1987, only 89% remained closed forest in 1999. Consequently, closed forests experienced disruption in the time period at double the rate of net deforestation. The three protected areas experienced negligible deforestation or slight reforestation. Based on 1987 forest cover, 26 000 ha are eligible for forest carbon trading under the Clean Development Mechanism, established by the Kyoto Protocol to the United Nations Framework Convention on Climate Change. Principal components analysis showed that distance to non-forest was the factor that best explained observed patterns of deforestation while distance to forest best explained observed patterns of reforestation, more significant than elevation, distance to rivers, distance to roads, slope, and distance to towns of population > 400. Aboveground carbon in live vegetation in the project area decreased from 35 million ± 4 million t in 1987 to 34 million ± 4 million t in 1999. Projected aboveground carbon in live vegetation would fall to 33 million ± 4 million t in 2006, 32 million ± 4 million t in 2011, and 29 million ± 3 million t in 2035. Projected net deforestation in the research area would total 13 000 ± 3000 ha in the period 1999-2011, proceeding at a rate of 0.003 ± 0.0007 y^{-1}, and would total 33 000 ± 7000 ha in the period 2006-2035. The proposed 7000 ha of forest conservation could prevent gross baseline deforestation of 100 ha (min. 70 ha, max 150 ha) in the period 2006-2035, averting baseline carbon emissions of 10 000 t (min. 6 000 t, max. 18 000 t). Projected gross reforestation in the research area would total 8500 ± 1500 ha in the period 1999-2011, proceeding at a rate of 0.0012 y^{-1} (min. 0.01 y^{-1}, max. 0.014 y^{-1}), and would total 24 000 ± 4000 ha in the period 2006-2035. Gross baseline reforestation for the proposed 7000 ha of reforestation would total 2600 ± 400 ha in the period 2006-2035, representing a baseline removal from the atmosphere of 73 000 t carbon (min. 30 000 t, max. 120 000 t). The proposed reforestation project could sequester 230 000 t carbon (min. 140 000 t, max. 310 000 t) above baseline removal in the period 2006-2035. Through this applied research, we have developed a forest restoration carbon analysis method that quantifies measures of success for forest conservation and projects the future carbon benefit of the restoration of biologically significant forests.

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Introduction

Carbon emissions from human activities have grown to 8 billion t y^{-1}, entering the atmosphere at twice the rate at which vegetation and oceans can naturally sequester carbon (IPCC 2001a). The increased concentration of carbon dioxide in the atmosphere has raised global mean surface temperature 0.6 ± 0.2 ºC in the 20th Century and could raise global mean surface temperature by 1.4–5.8ºC in the 21st Century (IPCC 2001a). Climate change will cause significant global impacts, including extensive shifts in vegetation biomes, changes in wildfire regimes, increases in sea level, increases in storm intensities, changes in agricultural systems, increases in certain human diseases, and altered economic conditions (IPCC 2001b, USGCRP 2001).

Fossil fuel power plants, vehicles, and cement plants produce 65-90% of global carbon emissions while deforestation and other land cover changes contribute the remainder (IPCC 2001a). At the same time, deforestation decreases the provision of ecosystem services, including watershed protection, biodiversity conservation, and carbon sequestration. Tropical deforestation claimed 49 000 ± 13 000 km^2 y^{-1} in the period 1990-1997 (Achard et al. 2002), proceeding at a rate of 0.0043 y^{-1} and releasing at least 1.1 ± 0.3 billion t carbon y^{-1} (Achard et al. 2004).

Forest conservation and reforestation can restore ecosystem services and help reduce climate change through carbon sequestration. Forest conservation is the cessation of the clearing of forests. Reforestation is the establishment of forests on non-forest areas through plantation or natural regeneration. Forest restoration is the renewal of effective ecosystem functioning of a forest through forest conservation or reforestation.

The maximum amount of carbon that forest conservation could prevent from release to the atmosphere amounts to 80-170% of post-industrial global carbon emissions (IPCC 2001a). The maximum amount of carbon that reforestation could sequester amounts to 15-30% of post-industrial global carbon emissions (IPCC 2001a).

The Clean Development Mechanism, established by the Kyoto Protocol to the United Nations Framework Convention on Climate Change, the Voluntary Reporting of Greenhouse Gases Program, administered by the U.S. Department of Energy, and other policy initiatives offer programs in which forest conservation or reforestation projects can sell the rights to forest carbon to energy utilities and other private companies so that the companies can offset their greenhouse gas emissions.

For a forest conservation project, the amount of carbon sequestered equals the carbon contained in the projected area of forest that would be cut during the project period. That amount constitutes the baseline carbon emissions to the atmosphere. For a reforestation project, the amount of carbon sequestered equals the difference of the carbon produced in new forest growth and the carbon contained in new forest growth that would have occurred even if no project actively engaged in reforestation. The latter amount constitutes the baseline carbon removal from the atmosphere. Quantification of the potential carbon sequestration of forest conservation or reforestation activities requires projections of future baseline emissions of carbon to the atmosphere and future baseline removal of carbon from the atmosphere.

We have conducted applied research in tropical rainforest at Selva Central, Peru in order to support a proposed project to improve biodiversity conservation and forest carbon sequestration through conservation of a 7000 ha forest and reforestation of 7000 ha of agricultural lands. The research objectives are:

1. To assess forest species patterns and tree sizes
2. To estimate past and to project future rates of deforestation and reforestation
3. To project future carbon baseline emissions to the atmosphere by deforestation and future carbon baseline removal from the atmosphere by reforestation

Methods

Research Area

The research area is 4800 km^2 of tropical rainforest and agricultural land between 9º 50' 42" S and 10º 50' 26" S latitude and between 74º 59' 44" W and 75º 47' 13" W longitude in Selva Central, Peru, a region at the western edge of the Amazon Basin (Figure 1). The area forms a buffer zone of private land to the west of areas protected by the government: *Parque Nacional Yanachaga-Chemillén* (national park, established 1986), *Bosque de Protección San Matías-San Carlos* (protection forest, established 1987), and the *Reserva Comunal Yanesha* (communal reserve, established 1988).

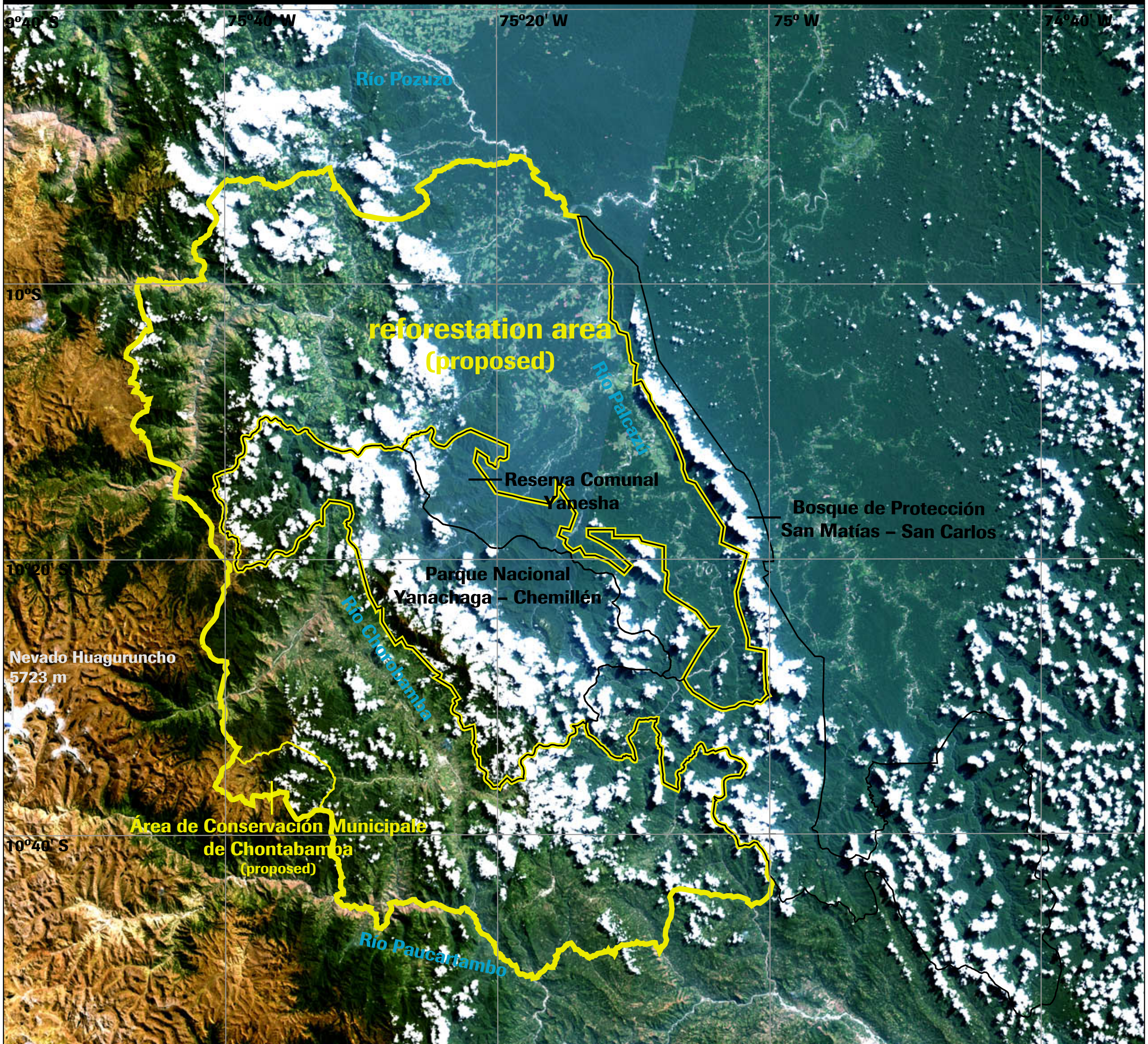
Selva Central hosts intact ecosystems that support globally unique plant and animal species, provide freshwater and hydroelectricity for local people, store high densities of forest carbon, and offer scenic river and mountain landscapes. Since 1991, the *Fundación Peruana para la Conservación de la Naturaleza* (ProNaturaleza), a Peru non-governmental organization, and the Nature Conservancy have worked together with local people to improve biodiversity conservation and socio-economic conditions.

Within the 4800 km^2 research area, ProNaturaleza and the Nature Conservancy have developed a plan to conserve a 7000 ha forested watershed and to reforest 7000 ha of agricultural land. The forest conservation project would protect a 4000 ha block of intact natural forest in the 7000 ha upper section of the watershed of the *Río Chontabamba,* the source of water for the town of Oxapampa, in a new *Área de Conservación Municipale de Chontabamba.* The reforestation project would establish *fajas de enriquecimiento* (contour plantings) on land formerly planted in crops or kept in pasture. The contour plantings would consist of 8 m wide strips of natural regeneration of existing small trees and seedlings of native species alternating with 2 m wide strips with a single line of planted trees of native species down the center. A spacing of 10 m between plantation lines and 3 m between trees would produce a plantation density of 333 trees ha^{-1}. The 7000 ha would be divided among non-contiguous parcels identified through this analysis as eligible under the Clean Development Mechanism. ProNaturaleza will provide technical assistance to each landowner.

The research area stretches across parts of the Southwest Amazon, Ucayali, and Yungas ecoregions (Olson et al. 2001). It encompasses the valleys of the *Ríos Chorobamba, Palcazú, Paucartambo,* and *Pozuzo,* rivers that lead to the Amazon River, and mountain areas up to 4400 m elevation on the eastern flank of the Andes Mountains.

Figure 1.

Selva Central, Perú



Selva Central Climate Action Project

The Nature Conservancy
Fundación Peruana para la Conservación de la Naturaleza (ProNaturaleza)

remote sensing: U.S. Geological Survey, Landsat, August 1999;
analyses: Gonzalez, P., B. Kroll, and C.R. Vargas. 2004. Forest restoration carbon analysis in moist tropical forest at La Selva Central, Perú. Ecological Society of America Annual Meeting Abstracts 89: 182.

- proposed reforestation area
- proposed forest conservation area
- government protected areas

0 12.5 25 km
scale 1:800 000

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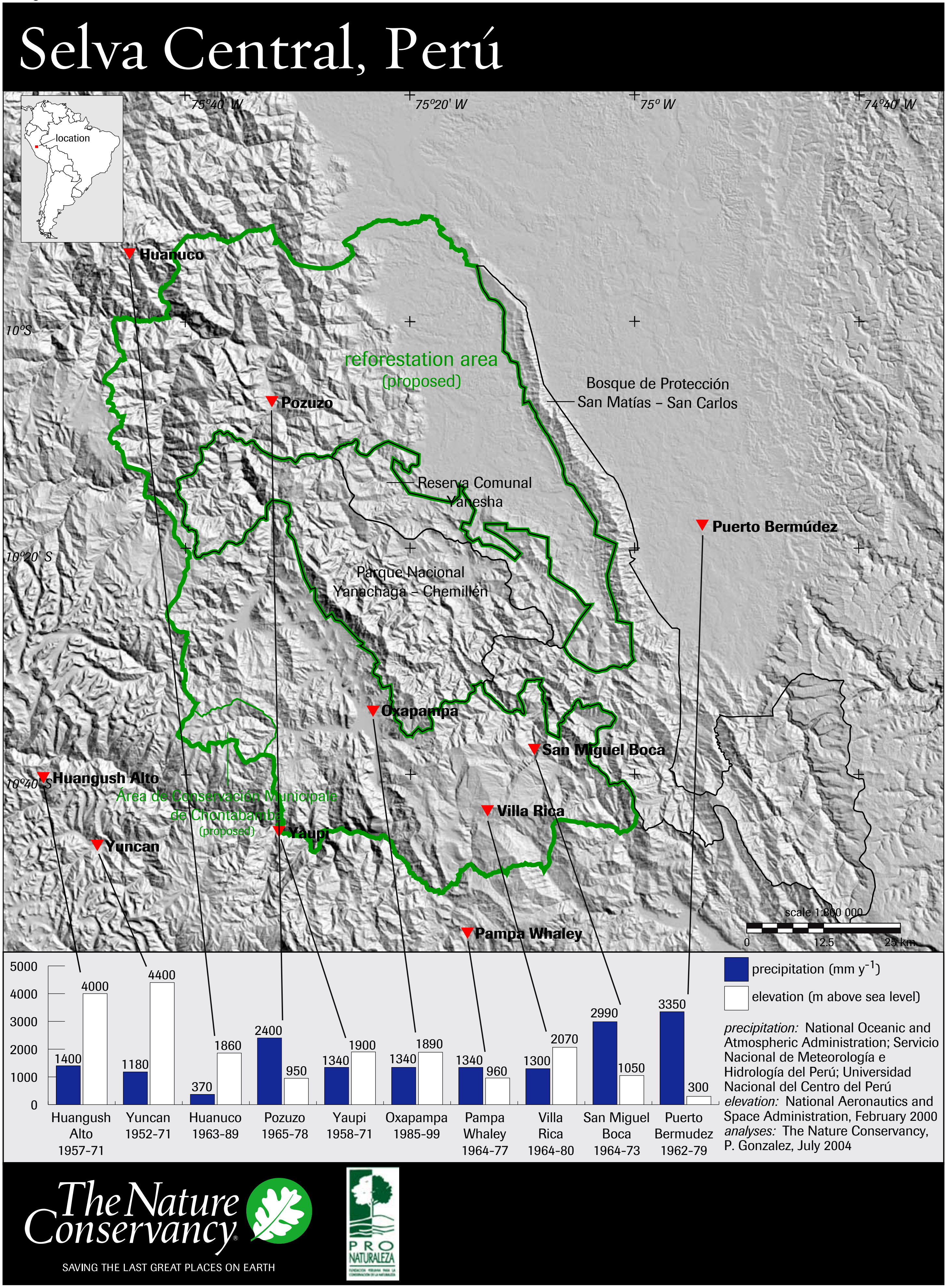
Figure 2.



Selva Central, Perú
75º40' W
75º20' W
75º W
74º40' W
10ºS
10º20' S
10º40' S
location
Huanuco
Pozuzo
reforestation area
(proposed)
Bosque de Protección
San Matías – San Carlos
Reserva Comunal
Yanesha
Puerto Bermúdez
Parque Nacional
Yanachaga – Chemillén
Oxapampa
San Miguel Boca
Huangush Alto
Área de Conservación Municipale
de Chontabamba
(proposed)
Villa Rica
Yaupi
Yuncan
Pampa Whaley
scale 1:800 000
0
12.5
25 km
5000
4000
3000
2000
1000
0
Huangush Alto 1957-71: 1400, 4000
Yuncan 1952-71: 1180, 4400
Huanuco 1963-89: 370, 1860
Pozuzo 1965-78: 2400, 950
Yaupi 1958-71: 1340, 1900
Oxapampa 1985-99: 1340, 1890
Pampa Whaley 1964-77: 1340, 960
Villa Rica 1964-80: 1300, 2070
San Miguel Boca 1964-73: 2990, 1050
Puerto Bermudez 1962-79: 3350, 300
precipitation (mm y-1)
elevation (m above sea level)
precipitation: National Oceanic and Atmospheric Administration; Servicio Nacional de Meteorología e Hidrología del Perú; Universidad Nacional del Centro del Perú
elevation: National Aeronautics and Space Administration, February 2000
analyses: The Nature Conservancy, P. Gonzalez, July 2004
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A warm, humid climate extends over most of the research area, with a rainy season that generally lasts from November to April. Measured mean annual precipitation in the region (Figure 2) ranges from 3400 mm y^{-1} in the lowlands (Puerto Bermúdez, 1962-1979) to 370 mm y^{-1} in the mountains (Huanuco, 1963-1989) (National Oceanic and Atmospheric Administration, *Servicio Nacional de Meteorología e Hidrología del Perú, Universidad Nacional del Centro del Perú)*. Mean maximum temperatures (1960-2000) range from 30ºC in the lowlands to 22ºC in the mountains, while mean minimum temperatures (1960-2000) range from 21ºC in the lowlands to 10ºC in the mountains *(Servicio Nacional de Meteorología e Hidrología del Perú).*

Altitude differentiates the flora of Selva Central into four principal vegetation types: *Selva Baja* (lowland Amazonian rainforest), *Yungas* (low altitude montane rainforest), *Ceja de la Montaña* (mid-altitude cloud forest), and *Puna* (high-altitude alpine grassland) (ONERN 1985, Brako and Zarucchi 1993, Gentry 1993, Richards 1996). The unique topography and ecology of the area has fostered a high level of plant endemism, with up to 30% of plant species native only to Peru (Brako and Zarucchi 1993). Selva Central hosts endemic plant species at a density of 13 per 1000 km^2 (van der Werff and Consiglio 2004). The restricted altitudinal range of many of the forest species renders them particularly susceptible to climate change (IPCC 2001b, Bush et al. 2004, Chambers and Silver 2004).

Selva Baja (lowland Amazonian rainforest) is closed-canopy tropical evergreen forest that occurs in the broad, flat valleys of Selva Central. These forests harbor over 1000 plant species, including over 300 species of trees and shrubs (Gentry 1993). The dominant plant families are *Fabaceae, Moraceae,* and Rubiaceae, with many species also representing the families *Annonaceae, Euphorbaceae, Lauraceae,* and *Melastomataceae* (Gentry 1993). *Selva Baja* provides important habitat for high numbers of butterflies, birds, and mammals.

Yungas (low altitude montane rainforest) is closed-canopy tropical evergreen forest that occurs in the hills and valleys on the east flank of the Andes Mountains, with an approximate elevation range of 500-2400 m. These montane rainforests exhibit a floristic composition and diversity similar to lowland rainforests. The dominant family is *Fabaceae,* followed by *Moraceae* and then by *Annonaceae, Arecaceae, Burseraceae, Euphorbiaceae, Lauraceae, Myrtaceae, Nyctaginaceae, Melastomataceae, Meliaceae,* and *Rubiaceae* (Gentry 1993). Many epiphytic and terrestrial orchids bloom in the *Yungas.*

Ceja de la Montaña (mid-altitude cloud forest) is tropical forest often shrouded in the clouds that ascend from the Amazon Basin up to the Andes Mountains. These forests occur in an approximate elevation range of 1500-3900 m (Gentry 1993, Richards 1996). The dominant plant families are *Araliaceae, Ericaceae, Lauraceae, Melastomataceae, Myrsinaceae, Myrtaceae, Rubiaceae,* and *Solanaceae,* with many species possessing small sclerophyllous leaves (Gentry 1993, Richards 1996). Orchids become most prevalent and diverse in these montane cloud forests (Gentry 1993).

Puna (high-altitude alpine grassland) is perennial grassland occurring up to the crest of the Andes Mountains, with an approximate elevation range of 3500-4500 m (Gentry 1993, Richards 1996). This grassland is taxonomically and ecologically distinct from the forest vegetation types (Gentry 1993).

Three soil types predominate in the area (McClain and Cossío 2003): entisols in modern alluvial deposits, inceptisols in former alluvial deposits, and coarse ultisols on hillsides. Acidity generally increases and fertility generally decreases with increasing altitude.

Most of the research area is located administratively in the *Distritos* (districts) *de Chontabamba, Huancabamba, Oxapampa, Palcazu, Pozuzo,* and *Villa Rica* of the *Provincia de Oxapampa* in the *Departamento de Pasco.* The population of the six districts was 56 000 in 2001 (INEI 2001), although some of these people live outside the research area. Population grew at a rate of 0.014 y^{-1} in the period 1990-2001 (INEI 2001). The 2001 population density of the six districts was 7 people km^{-2} (INEI 1997, 2001). Three main ethnic groups live in the research area: populations of indigenous Yanesha and Quechua, descendants of German immigrants from the 19th and 20th Centuries, and mestizo immigrants from other parts of Peru.

People use fire to clear the land to farm corn, manioc, and coffee and to raise cattle, mainly in the *Selva Baja* and *Yungas.* The *Instituto Nacional de Áreas Naturales Protegidas* (INRENA) does not allow resource extraction in the national park, although it does permit companies to harvest timber in the protection forest. The Yanesha control natural resource management in the communal reserve and have effectively excluded resource extraction, although economic pressures are changing their traditional natural resource management practices (Hamlin and Salick 2003).

Forest Restoration Carbon Analysis (FRCA)

FRCA is an integrated spatial analysis of forest inventory, biodiversity, and remote sensing data (Gonzalez et al. 2004). The method assesses forest species patterns, quantifies deforestation and reforestation rates, and projects future baseline carbon emissions and removals for an ecologically-defined area of analysis.

FRCA employs principal components analysis, a multivariate statistical test, to calculate the weight of different factors in explaining observed reforestation and deforestation. It also uses bivariate statistical fitting of forest change observations to calculate future probabilities of deforestation and reforestation for each pixel in a Landsat image. In this way, FRCA extrapolates potential future conditions based solely on observations of past trends.

FRCA not only provides central estimates of final carbon amounts, but it also calculates high and low estimates of the carbon amounts by tracking major sources of measurement error and statistical variability (Phillips et al. 2002, Chave et al. 2004). In effect, FRCA calls for users to run all of the carbon calculations three times.

FRCA proceeds through the following 13 steps:

1. Definition of forest project area based on biological significance
2. Establishment of permanent forest inventory plots
3. Analyses of biodiversity, tree, and stand measures
4. Calculation of biomass using local tree allometric equations and species-specific wood densities
5. Derivation of growth functions
6. Change detection using forest inventories and Landsat images

7. Compilation of spatial data of major deforestation and reforestation factors
8. Principal components analysis to calculate weight of factors in explaining observed deforestation and reforestation
9. Derivation of deforestation and reforestation probability functions
10. Calculation of deforestation and reforestation probability for each pixel
11. Projection of future deforestation and reforestation
12. Projection of future baseline carbon emissions and removal
13. Estimation of future carbon sequestration due to the proposed forest project

Step 1 Definition of forest project area based on biological significance

Natural resource management agencies and conservation organizations engage in forest restoration projects to secure multiple benefits. Nevertheless, the primary objective of most forest restoration projects is to improve ecosystem function through conservation of biodiversity. In that case, carbon sequestration remains an important, yet secondary objective. Therefore, biological significance constitutes the primary criterion for defining the project area.

Biologically significant geographic features include vegetation types, climate zones, ecoregions, mountains or other distinct topography, watersheds, rivers, and declared natural resource management areas. These features will generally define areas with similar ecological characteristics or with broadly similar land management regimes. The relative homogeneity of such areas will facilitate statistical sampling and generalization of results. On the other hand, administrative boundaries or other arbitrary geometric shapes, like rectangles or circles, will generally cut across natural features and generate areas of conflicting environmental characteristics.

One practical criterion for defining the total size of a project area is the logistic capability of the organization that will implement the forest project.

The three protected areas in Selva Central present the clearest features of biologically significance on which to define the project area (research area). Moreover, the boundary between *Yungas* forest and *Puna* grassland delineates an upper elevation limit to the project area. Therefore, we have defined the project area as the *Selva Baja, Yungas,* and *Ceja de la Montaña* forest areas on the west side of the *Parque Nacional Yanachaga-Chemillén, Bosque de Protección San Matías-San Carlos,* and the *Reserva Comunal Yanesha*. We set the other borders of the project at natural boundaries: *Puna* grassland to the west, the *Río Pozuzo* and the *Río Huampumayo* in the north, the *Río Paucartambo* in the south, and mountain ridges to the northwest and the southwest. This project area consists of the private agricultural lands and forests that form a buffer zone for the three protected areas. Deforestation to clear land for agricultural crops and pastures and to harvest timber and firewood comprise the major local threats to ecosystem health.

As described in the previous section, ProNaturaleza and the Nature Conservancy have selected, within the

4800 km^2 project area, the 7000 ha upper watershed of the *Río Chontabamba* for a new *Área de Conservación Municipale de Chontabamba.* We have used the topography of that area to define its boundaries.

Step 2 Establishment of permanent forest inventory plots

ProNaturaleza staff established forest inventory plots on seven sites covering 22.6 ha in primary forest in 2001 and on 17 sites covering 16.5 ha in secondary forest in the period February-March 2003 (Table 1). We stratified our plots into two classes, primary forest and secondary forest, in order to match the classes that Landsat satellite data would later be able to detect in that area (Step 6). ProNaturaleza chose parcels dispersed throughout the research area that represented the general physiognomy and structure of the three forest vegetation types in the zone. The primary forest plots lie in areas that have not been harvested. The secondary forest plots include regeneration after both agricultural crops and pasture and span a range of stand age. The sample is not random. Instead, we chose parcels owned by farmers and ranchers with whom ProNaturaleza works because they are people that have already demonstrated an interest in forest conservation. We would not have been to establish permanent forest inventory plots on fields owned by strangers.

We aimed to establish square 1-hectare plots, but local conditions prevented establishment of exactly square plots at every site. ProNaturaleza divided each plot into 20 m x 20 m square sub-plots with corners marked with PVC pipes. For every tree with a diameter at a height of 1.3 m greater than or equal to 10 cm, ProNaturaleza staff identified the species of the tree to the lowest taxonomic level possible and measured the trunk diameter at a height of 1.3 m. Staff also measured the height of *Arecaceae* (palm trees) and *Cyathea spp.* (tree ferns). Qualitative evaluation of staff measurements indicated an approximate measurement error of ±1%.

ProNaturaleza staff secured agreements from landowners of five of the primary forest plots and 13 of the secondary forest plots to protect the plots as permanent monitoring sites. In 2005, ProNaturaleza fenced these plots and posted signs. For all trees whose diameter at a height of 1.3 m was greater than or equal to 10 cm, staff re-measured and tagged the tree with an aluminum tag at a height of 1.4 m.

Step 3 Analyses of biodiversity, tree, and stand measures

Forest inventories provide detailed information on species composition, tree sizes, and stand characteristics. Forest inventory data directly yield the following biodiversity measures: species richness; □-, □-, and □- species diversity (Whittaker 1960, 1972); and dominant families, genera, and species. The data also yield the following tree and stand measures: tree density, trunk diameter, basal area, biomass, and succession status.

Succession status is the development state of a stand. We have classified trees are either old-growth or successional. Old-growth forests are mature forests dominated by large trees of advanced age and characterized by a dense structure often differentiated into multiple canopies. Old-growth species are generally shade tolerant. Successional forests are young stands with trees of shorter stature and more open canopies that can allow sunlight to

Table 1. Selva Central forest inventory plots.

Plot	Latitude	Longitude	Distrito	Age (y)	Original land use	Area (ha)
Primary Forest						
Azulis	-10.45203	-75.07767	Palcazú		forest	1.8
Delfin	-10.13858	-75.58948	Pozuzo		forest	1.0
Loma Linda	-10.34148	-75.05693	Palcazú		forest	1.4
Nueva Esperanza	-10.24612	-75.265	Palcazú		forest	1.7
Palmira	-10.05775	-75.53401	Pozuzo		forest	2.0
Santa Rosa	-10.32003	-74.97217	Puerto Bermúdez		forest	13.4
Shiringamazú	-10.30469	-75.1466	Palcazú		forest	1.3
Secondary Forest						
HUPAP10	-10.48978	-75.44595	Huancabamba	10	pasture	1.0
HUPAP20	-10.47129	-75.44139	Huancabamba	20	pasture	1.0
HUPUA42	-10.45448	-75.54468	Huancabamba	42	agriculture	1.0
HUPUP40	-10.45503	-75.54611	Huancabamba	40	pasture	1.0
OXSAA15	-10.56928	-75.38048	Oxapampa	15	agriculture	1.0
PAEPA20	-10.31657	-75.10343	Palcazú	20	agriculture	1.0
PAEPP20	-10.31475	-75.10366	Palcazú	20	pasture	1.0
PAGAP10	-10.2455	-75.16481	Palcazú	10	pasture	1.0
PALLP30	-10.3298	-75.10466	Palcazú	30	pasture	1.0
PAPCA10	-10.29373	-75.23648	Palcazú	10	agriculture	1.0
PAPCA30	-10.29508	-75.23806	Palcazú	30	agriculture	1.0
POCHP10	-10.01794	-75.64679	Pozuzo	10	pasture	1.0
POHUA10	-10.09136	-75.52434	Pozuzo	10	agriculture	1.0
POLTP21	-10.04379	-75.52874	Pozuzo	21	pasture	1.0
POPAA20	-10.0625	-75.54526	Pozuzo	20	agriculture	0.9
POPAA30	-10.06134	-75.54181	Pozuzo	30	agriculture	1.0
POPPP30	-10.1325	-75.5348	Pozuzo	30	pasture	0.6

reach the ground. Successional species are generally shade intolerant. We used published surveys (Richards 1996, Terborgh et al. 1996, Nelson et al. 1999, Peña-Claros 2003, Laurance et al. 2004) of the succession status of many Amazonian tree species. For those species without published information, we evaluated succession status based on decades of observations in Selva Central by co-author B. Kroll and the observed prevalence in our primary and secondary forest inventory plots.

In Amazon rainforest, “primary forest” is generally forest that either has never been cut or was cut over 100 years ago (Richards 1996). “Secondary forest” is generally forest that is re-growing from a cut.

Almost all of the trees in a primary forest should be old-growth trees, although natural disturbances and mortality will open gaps for a relatively small number of successional trees. Conversely, a majority of the trees in a secondary forest will be successional trees. Therefore, the percentage of the biomass of a forest that resides in old-growth trees constitutes a measure of success of forest conservation that ProNaturaleza and the Nature Conservancy can track over time through the stages of the Conservation by Design planning process (Nature Conservancy 2001).

Step 4 Calculation of biomass using local tree allometric equations and species-specific wood densities

Allometric equations are empirical functions that give the biomass of a tree as a function of tree diameter and/or tree height. Foresters derive allometric equations by cutting down trees, measuring their physical dimensions, and weighing their components. Differences in the architecture, form, and physiognomy among tree species renders necessary the development of allometric equations specific to a taxon or to a functional group (King 1996, Ter-Mikaelian and Korzukhin 1997, Ketterings et al. 2001, Jenkins et al. 2004). We used six allometric equations developed in Amazon rainforest (Baker et al. 2004a, Chambers et al. 2001a, Nelson et al. 1999, Saldarriaga et al. 1988) (Table 2). We were not able to use a set of allometric equations developed in Peru (Barrena et al. 1986, Barrena 1988) because those were developed for the merchantable part of the trunk, not the entire tree.

In Amazon rainforest, basic wood density strongly influences the spatial patterns of forest biomass (Baker et al. 2004b). Therefore, we used published wood densities for 117 Amazon tree species (Aróstegui 1974, Nalvarte et al. 1993, Fearnside 1997) to accurately calculate biomass using the primary (Chambers et al. 2001a, Baker et al. 2004a) and secondary (Nelson et al. 1999) Amazon forest equations. Natural variation of wood density measured in Peruvian Amazon rainforest was approximately ±10% (Aróstegui 1974).

Measurements of the carbon content of biomass in Amazon rainforest trees and shrubs show a carbon fraction of 0.49 (Chambers et al. 2001b). Due to a lack of specific data on belowground biomass, dead wood, litter, and soil organic carbon in the research area, we have not calculated the carbon in those pools.

Carbon density of a forest area equals the sum of the carbon in individual trees:

♦ Equation 8:
$$C_{area} = f_C \times \frac{\sum^{\text{all trees}} \left(\frac{\rho_{tree}}{\rho_{sample}}\right) \times b_{tree}}{A} \times \left(\frac{1\ t}{10^3\ kg}\right)$$

A	= area of a forest (ha)
b_{tree}	= biomass of an individual tree (kg); data from Equations 1-7
C_{area}	= carbon density of a forest area (t ha^{-1})
f_C	= carbon fraction of biomass (kg C (kg biomass)$^{-1}$)
ρ_{sample}	= specific wood density of allometric sample (kg oven-dry biomass (kg field-dry biomass)$^{-1}$); Table 2 gives values of ρ_{sample} for Equations 1 and 2; ρ_{sample} / ρ_{tree} = 1 for Equations 3-7
ρ_{tree}	= specific wood density of tree (kg oven-dry biomass (kg field-dry biomass)$^{-1}$).

Step 5 Derivation of growth functions

In order to project future changes in carbon storage, we developed a function of growth in biomass over time. We used the calculated biomass of inventory plots in secondary forest sites that landowners estimated had grown for 10-42 years since cessation of farming or herding. We also used the calculated biomass of the primary forest sites, assuming that they were at least 100 years old (Richards 1996).

Table 2. Allometric equations for Amazon rainforest. Equation 6 was developed in Caribbean forest.

Eq. no.	Forest type or taxon	Equation	Specific wood density of sample	Source
1	primary *terra firme* Amazon forest	$\ln b_{tree} = 0.33 \ln d_{130} + 0.933 (\ln d_{130})^2 - 0.122 (\ln d_{130})^3 - 0.37]$	0.67	Baker et al. 2004a, Chambers et al. 2001a
2	secondary *terra firme* Amazon forest	$\ln b_{tree} = -1.9968 + 2.4128 \ln d_{130}$	0.54	Nelson et al. 1999
3	*Arecaceae*	$\ln b_{tree} = -6.3789 - 0.877 \ln (d_{130}^{-2}) + 2.151 \ln h$		Saldarriaga et al. 1988
4	*Bellucia spp*	$\ln b_{tree} = -1.8158 + 2.37 \ln d_{130}$		Nelson et al. 1999
5	*Cecropia sciadophylla*	$\ln b_{tree} = -2.5118 + 2.4257 \ln d_{130}$		Nelson et al. 1999
6	*Cyathea spp.*	$b_{tree} = 3.82 h - 3.62$		Weaver 2000
7	*Laetia procera*	$\ln b_{tree} = -2.2244 + 2.5105 \ln d_{130}$		Nelson et al. 1999

b_{tree} = tree aboveground biomass (kg)
d_{130} = diameter (cm) at h = 1.3 m
h = height (m)

Step 6 Change detection using forest inventories and Landsat images

Change detection is the analysis of spatial differences from two satellite scenes acquired over the same location at different times (Howarth and Wickware 1981, Lu et al. 2004). Scientists have used the Landsat series of satellites for detection of land cover change since the launch of the first satellite by the National Aeronautics and Space Administration (NASA) on July 23, 1972.

Landsat 7, launched by NASA on April 15, 1999 and managed by the U.S. Geological Survey (USGS), flies in a helio-synchronous orbit at an altitude of 705 km (USGS 2003). It maintains a constant angle between the Earth and the Sun with an equatorial crossing at approximately 10:00 AM local time. With an orbital period of 99 minutes, Landsat 7 completes a global orbital cycle of 233 orbits every 16 days, acquiring 248 scenes per orbit across a swath of 185 km. The Landsat Enhanced Thematic Mapping sensor captures visible and infrared frequencies in 6 bands at 30 m resolution, thermal data in two bands at 60 m resolution, and panchromatic data in one band at 15 m resolution. The research area lies at the intersection of three Landsat scenes.

We used two sets of Landsat scenes to generate difference images of forest change. The target date for the start of the forest change analysis period was December 31, 1989, because, in order to prevent opportunistic deforestation, the Clean Development Mechanism requires that eligible areas not contain forest from that date to the present. We searched the USGS archive for one set of scenes from 1989 and for a second set of scenes close to the present. The expanses of cloud forest in the research area, however, create cloudy conditions for most satellite passes. The two closest years to 1989 and the present with <20% cloud cover over the research area were 1987 and 1999. We used the following Landsat scenes for 1987: 5006067008715310 (June 6, 1987), 5007067008724010 (August 28, 1987), and 5006068008516310 (June 12, 1985, ~4% of project area). We used the following 1999 scenes: L71006067_06719990729 (July 29, 1999), L71007067_06719990805 (August 5, 1999), L71006068_06819990729 (July 29, 1999).

We used the software application ENVI/IDL 3.4 for remote sensing analyses and ArcGIS for vector analyses in this research.

We created a mosaic of the three 1999 scenes and used the mosaic as the base image to geographically register each of the 1987 scenes by Delauney triangulation on approximately 200 control points and by nearest neighbor value selection. After joining the 1987 scenes in a mosaic, we cropped each mosaic to a rectangle of 5099 x 4671 pixels bounded by 9º 39' 34" S and 10º 55' 39" S latitude and 75º 56' 22" W and 74º 32' 31" W longitude.

We had stratified our plots into two classes, primary forest and secondary forest (Step 2), in order to match the classes that Landsat satellite data would be able to detect in the research area. A few trial runs showed us that the spectral signatures of vegetation types in the research area are so similar that supervised classification could only reliably distinguish among the following land classes:

1. clouds, shadow, water
2. sparse vegetation – bare ground
3. low vegetation – agricultural fields and pastures
4. open forest – forest with a canopy cover of 10-40% (FAO 2001)
5. closed forest - forest with a canopy cover of >40% (FAO 2001).

Primary forest generally shows up in Landsat images as closed forest. Secondary forest generally shows up in Landsat images as open forest. Using the 24 forest inventory plots as ground-truth sites, we conducted a supervised classification employing the minimum distance algorithm to assign each pixel in both the 1987 and 1999 images to one of the five land classes.

As an intermediate step to generating a difference image, we condensed the non-forest classes and the forest classes into three forest classes:

0. clouds, shadow, water in either 1987 or 1999
1. non-forest (sparse and low vegetation)
2. forest (open and closed forest).

Comparing the forest images for 1987 and 1999, we produced a 1987-1999 difference image, the change detection image, with five classes:

0. water
1. non-forest
2. deforestation
3. reforestation
4. forest.

<u>Step 7 Compilation of spatial data of major deforestation and reforestation factors</u>

We examined six factors that could explain observed patterns of deforestation and reforestation and for which spatial data with continuous values is available:

1. distance to non-forest (for deforestation analysis) (meters) – We derived this distance from Landsat (Step 6). distance to forest (for reforestation analysis) – We derived this distance from Landsat (Step 6).
2. elevation (meters) – We downloaded data from the NASA Shuttle Radar Topography Mission, February 2000, at 90 m horizontal resolution. We re-projected the data from the Geographic Reference System to UTM by Delauney triangulation on approximately 200 control points and by nearest neighbor value selection. We split the data into 30 m resolution.
3. rivers (m) – We digitized rivers from Landsat images and verified with 1:100 000 scale paper maps *(Carta Nacional Topográfica, Instituto Geográfico Nacional* (IGN), Lima, Perú, sheets Bajo Pichananqui (1987), Codo del Pozuzo (1993), Iscozacín (1996), Oxapampa (1987), Panao (1990), Pozuzo (1984), Puerto Bermúdez (1999), Ulcumayo (1973), Yuyapichis (1996)).
4. roads (meters) – We digitized roads from Landsat images and verified with IGN paper maps.
5. slope (degrees) – We calculated slope from NASA elevation data.
6. towns of population > 400 (meters) – We digitized towns from Landsat images and verified with IGN maps and 1993 population data *(Instituto Nacional de Estadística e Informática).*

These factors act as indicators for the underlying deforestation threats of agricultural expansion and timber and firewood harvesting.

Step 8 Principal components analysis to calculate weight of factors in explaining observed deforestation and reforestation

A complex interaction of numerous environmental and socio-economic factors determines the amount and spatial pattern of deforestation. Multivariate statistical tests analyze this type of situation by linear algebra on matrices of statistical parameters of all possible combinations of a set of independent variables. For example, multivariate non-metric multidimensional scaling of ten different environmental and socio-economic variables across the 4 million km^2 of the Brazilian legal Amazon indicated that deforestation is most highly correlated to distance to highways and rural population density (Laurance et al. 2002).

Principal components analysis (Pearson 1901, Hotelling 1933) offers the exact statistical test required to determine the weight of different quantitative factors in explaining observed patterns of deforestation and reforestation. Principal components analysis determines the factors that account for most of the variability in a set of multivariate data and reveals any clustering of samples. In geometric terms, the principal components analysis algorithm reduces a projection of points, representing n samples, in multi-dimensional space into a centered and rotated set of points within n orthogonal axes, each axis defined by a linear combination of the standardized values of each variable.

We calculated the values of each of the six factors for each of the 241 842 deforestation pixels and each of the 94 641 reforestation pixels for the period 1987-1999. We conducted a principal components analysis, employing the correlation matrix, on the six deforestation data layers and, separately, on the six reforestation data layers.

Principal components analysis yields the following:

1. Six principal components, each a spatial data layer equal to a combination of the six original factors
2. Fraction of the variance in the data that each principal component explains
3. The eigenvalue loadings of each factor for each principal component
4. A 6 x 6 matrix of the correlation of each combination of two factors.

We used the scree test (Cattell 1966) to determine the number of explanatory principal components, then calculated the weights of each factor:

♦ Equation 8: $$W_n^{process} = \frac{V_m}{\sum_{m=1}^{i} V_m} \cdot \frac{L_{mn}}{\sum^{q} \sum_{n=1}^{j} \left| L_{mn} \right|}$$

i	= number of principal components
j	= number of factors
L_{mn}	= eigenvalue loading
m	= principal components
n	= factors explaining observed deforestation or, separately, observed reforestation
process	= either observed deforestation or observed reforestation
q	= number of explanatory principal components
V_m	= fraction of variance explained
$W_n^{process}$	= weight of each factor in explaining a process, range 0–1.

Step 9 Derivation of deforestation and reforestation probability functions

For each of the six factors, we derived equations of the probability of deforestation and, separately, the probability of reforestation, as a function of the value of the factor. First, we divided the continuous values of each factor layer (Step 7) into 500 m value classes for distance factors (non-forest, forest, rivers, roads, towns), 25 m value classes for elevation, and 0.5 degree value classes for slope. For each factor value class, we calculated the fraction deforested and, separately, the fraction reforested, in the period 1987-1999. The fraction deforested is equivalent to the probability, ranging from 0 to 1, that an individual 1987 forest pixel in a factor value class would be cut by 1999:

♦ Equation 9: $$p_{factor}^{deforestation} = f_{factor}^{deforestation} = \frac{A_{factor}^{deforestation}}{A_{factor}^{1987\ forest}}$$

$A_{factor}^{1987\ forest}$	= area in a factor value class that was forest in 1987 (ha)

$A_{factor}^{deforestation}$ = area in a factor value class deforested in the period 1987-1999 (ha)

$f_{factor}^{deforestation}$ = fraction of 1987 forest in a factor value class lost by 1999, range 0–1

$p_{factor}^{deforestation}$ = probability of deforestation in a specific factor value class in the period 1987-1999, range 0–1.

Separately, the fraction reforested is equivalent to the probability, ranging from 0 to 1, that an individual 1987 non-forest pixel in a factor value class would become forest by 1999:

♦ Equation 10: $$p_{factor}^{reforestation} = f_{factor}^{reforestation} = \frac{A_{factor}^{reforestation}}{A_{factor}^{1987\ non\text{-}forest}}$$

$A_{factor}^{1987\ non\text{-}forest}$ = area in a factor value class that was non-forest land in 1987 (ha)

$A_{factor}^{reforestation}$ = area in a factor value class reforested in the period 1987-1999 (ha)

$f_{factor}^{reforestation}$ = fraction of 1987 non-forest land in a factor value class that became forest by 1999, range 0–1

$p_{factor}^{reforestation}$ = probability of reforestation in a specific factor value class in the period 1987-1999, range 0–1.

We used the software application Systat TableCurve2D to fit empirical bivariate probability functions of probability vs. factor value. We derived probability functions for the upper and lower confidence intervals at p = 0.05.

<u>Step 10 Calculation of deforestation and reforestation probability for each pixel</u>

To estimate future deforestation and reforestation, we projected into the future only as many years as we possessed observations of the past. Therefore, we projected deforestation and reforestation probabilities for the 12-year period 1999-2011.

Using the continuous value spatial data layers for each factor (Step 7), we calculated the central, high, and low probabilities of deforestation by 2011 for each of the 3 429 276 forest pixels in 1999. The sum of the probabilities of the six factors, weighted by the principal component-derived weights, yields a value for each 1999 forest pixel of the probability, ranging from 0 to 1, that it will be cut by 2011. Separately, the sum of the probabilities of the six factors, weighted by the principal component-derived weights, yields a value for each of the 642 736 non-forest pixels in 1999 of the probability, ranging from 0 to 1, that it will become forest by 2011:

♦ Equation 11: $$p_{pixel}^{process} = \sum_{n=1}^{j} W_n^{process} \cdot p_n^{process}$$

j = number of factors.

n = factors explaining observed process

$p_n^{process}$ = probability of a process from a specific factor in the period 1999-2011, range 0–1

$p_{pixel}^{process}$ = total probability for an individual pixel of a process in the period 1999-2011, range 0–1

process = either <u>observed deforestation</u> or <u>observed reforestation</u>

$W_n^{process}$ = weight of each factor in explaining a process, range 0–1 (Step 8)

Step 11 Projection of future deforestation and reforestation

The fraction of 1999 forest that we project would be cut by 2011 equals the sum of the deforestation probabilities of all 1999 forest pixels. Likewise, the fraction of 1999 non-forest land that we project will become forest by 2011 equals the sum of the reforestation probabilities of all 1999 non-forest pixels:

♦ Equation 12: $$f^{process} = \sum^{\text{all pixels}} p_{pixel}^{process}$$

$f^{process}$ = fraction of 1999 land class undergoing a process by 2011, range 0–1

$p_{pixel}^{process}$ = total probability for an individual pixel of a process occurring in the period 1999-2011, range 0–1.

We projected deforestation and reforestation rates by dividing that fraction by the years elapsed:

♦ Equation 13: $$r_{process} = \frac{f^{process}}{t_{end} - t_{beginning}}$$

$f^{process}$ = fraction of 1999 land class undergoing a process by 2011, range 0–1

process = either observed deforestation or observed reforestation

$r_{process}$ = projected rate of a process (y^{-1})

$t_{beginning}$ = beginning year of forest change projection; $t_{beginning}$ = 1999 for the Selva Central projection

t_{end} = ending year of forest change projection; t_{end} = 2011 for the Selva Central projection.

We also used the pixel-by-pixel deforestation and reforestation probabilities to develop spatial data layers or maps of projected future land cover and future forest cover change. First, we determined the threshold deforestation probability–the probability at which the sum of the number of pixels above that probability equals the projected 1999-2011 deforestation. Separately, we determined the threshold reforestation probability–the probability at which the sum of the number of pixels above that probability equals the projected 1999-2011 reforestation.

We identified each 1999 forest pixel with a deforestation probability greater than the deforestation threshold, each 1999 non-forest pixel with a reforestation probability greater than the reforestation threshold, and each 1999 pixel that didn't change to produce a projected 1999-2011 forest change detection image with five classes used previously:

0. water
1. non-forest
2. deforestation

3. reforestation
4. forest.

Then, we applied the forest change detection image to the 1999 land cover layer to project a 2011 land cover data layer with the same land cover classes established previously:

0. clouds, shadow, water
1. sparse vegetation
2. low vegetation
3. open forest
4. closed forest.

We developed this data layer by changing 1999 forest pixels that were projected to undergo deforestation by 2011 to either sparse or low vegetation based on their probability and on the 1999 ratio of sparse to low vegetation observed among the pixels deforested in the period 1987-1999. We changed all 1999 non-forest pixels projected to undergo reforestation by 2011 to open forest.

The spatial data layers for 2011 directly give the projected land cover areas for that year. The projected areas of open and closed forest at the starting and final years of the proposed project, 2006 and 2035, equal values extrapolated with the 1999-2011 projected rates of change:

♦ Equation 14: $A_{\text{forest type}}(t_{\text{final}}) = A_{\text{forest type}}(t_{\text{start}}) + [(t_{\text{final}} - t_{\text{start}}) \times r_{\text{forest type change}} \times A_{\text{forest type}}(1999)]$

♦ Equation 15: $A_{\text{forest type}}(t_{\text{start}}) = A_{\text{forest type}}(1999) + [(t_{\text{start}} - 1999) \times r_{\text{forest type change}} \times A_{\text{forest type}}(1999)]$

$A_{\text{forest type}}(t)$	= area of one forest type in the conservation project area in a specified year (ha)
forest type	= either closed or open
$r_{\text{loss of forest type}}$	= projected rate of change of a forest type (y^{-1})
t_{final}	= final year of a project (y); t_{final} = 2035 for Selva Central
t_{start}	= starting year of the project (y); t_{start} = 2006 for Selva Central.

Step 12 Projection of future baseline carbon emissions and removal

Baseline carbon emissions to the atmosphere of a forest conservation project area equal the difference between the projected carbon stocks of the gross area of deforestation (without a project) at the start and end of the proposed project period:

♦ Equation 16: $C_{\text{emissions}} = f_C \times [S_{\text{forest}}(t_{\text{final}}) - S_{\text{forest}}(t_{\text{start}})]$

♦ Equation 17: $S_{\text{forest}}(t) = S_{\text{closed}}(t) + S_{\text{open}}(t)$

♦ Equation 18: $S_{\text{forest type}}(t) = A_{\text{forest type}}(t) \times (B_{\text{forest type}} - B_{\text{cut land class}})$

$A_{forest\ type}(t)$	= area of one forest type in the conservation project area in a specified year (ha)
$B_{cut\ land\ class}$	= biomass density of the land class after the forest is cut (t ha^{-1})
$B_{forest\ type}$	= biomass density of the existing forest type (t ha^{-1})
$C_{emissions}$	= total baseline carbon emissions to the atmosphere (t)
f_C	= carbon fraction of biomass (kg C (kg biomass)$^{-1}$); f_C = 0.49 kg C (kg biomass)$^{-1}$ for Amazon rainforest (Chambers et al. 2001b)
forest type	= either <u>closed</u> or <u>open</u>
$S_{forest}(t)$	= biomass stock in all forest types in a specified year (t)
t	= year
t_{final}	= final year of a project; t_{final} = 2035 for Selva Central
t_{start}	= starting year of the project; t_{start} = 2006 for Selva Central.

Baseline carbon removal from the atmosphere for a reforestation project equals the sum of baseline carbon accumulation each year in the gross area of reforestation without a project:

♦ Equation 19: $$C_{removal} = f_C \times \sum_{t_{start}}^{t_{final}} B_{reforestation}(t)$$

♦ Equation 20: $$B_{reforestation}(t) = \sum_{age=1}^{t - t_{start} + 1} R_{background}(age)$$

♦ Equation 21: $$R_{background}(age) = r_{reforestation} \times A_{project} \times [B(age) - B(age - 1)]$$

age	= age of a reforestation area (y)
$A_{project}$	= total area of proposed reforestation project (ha)
B(age)	= biomass density of regenerating forest at a specified age (t ha^{-1}); data from biomass growth curve (Step 5)
$B_{reforestation}(t)$	= baseline biomass accumulation in reforestation (without a project) during year t (t)
$C_{removal}$	= total baseline carbon removal from the atmosphere (t)
f_C	= carbon fraction of biomass (kg C (kg biomass)$^{-1}$); f_C = 0.49 kg C (kg biomass)$^{-1}$ for Amazon rainforest (Chambers et al. 2001b)
$R_{background}(age)$	= additional biomass accumulation (in one year) for an area of reforestation (without a project) of a specified age (t)
$r_{reforestation}$	= projected rate of a reforestation without a project (y^{-1})
t	= year
t_{final}	= final year of a project (y); t_{final} = 2035 for Selva Central

t_{start} = starting year of the project (y); t_{start} = 2006 for Selva Central.

Total carbon stocks in the 4800 km^2 research area for a specified year equal the sum of the product of carbon fraction, area, and biomass density for each land class in that year:

♦ Equation 22: $$C_{total}(t) = f_C \cdot \sum^{\text{all land classes}} A_{\text{land class}}(t) \cdot B_{\text{land class}}$$

♦ Equation 23: $$A_{\text{land class}}(2006) = A_{\text{land class}}(1999) + [(2006\text{-}1999) \times r_{\text{land class change}} \times A_{\text{land class}}(1999)]$$

♦ Equation 24: $$A_{\text{land class}}(2035) = A_{\text{land class}}(2006) + [(2035\text{-}2006) \times r_{\text{land class change}} \times A_{\text{land class}}(1999)]$$

$A_{\text{land class}}(t)$ = area of land class in specified year (ha); data for 1987, 1999, and 2011 from Steps 6 and 11

$B_{\text{land class}}$ = biomass density of a land class (t ha^{-1})

$C_{\text{land class}}(t)$ = carbon stock in one forest type in a specified year (t)

f_C = carbon fraction of biomass (kg C (kg biomass)$^{-1}$); f_C = 0.49 kg C (kg biomass)$^{-1}$ for Amazon rainforest (Chambers et al. 2001b)

land class = sparse vegetation or low vegetation or open forest or closed forest

$r_{\text{land class change}}$ = projected 1999-2011 rate of change of a land class (y^{-1})

t = year

Step 13 Estimation of future carbon sequestration due to the proposed forest project

For a forest conservation project, the amount of carbon sequestered equals the carbon contained in the projected area of forest that would be cut during the project period. Calculated in Equation 16, that amount equals the baseline carbon emissions to the atmosphere from the gross area of deforestation:

♦ Equation 25: $$C_{\text{forest conservation}} = C_{\text{emissions}}$$

$C_{\text{emissions}}$ = total baseline carbon emissions to the atmosphere (t)

$C_{\text{forest conservation}}$ = carbon sequestration of a forest conservation project (t).

For a reforestation project, the amount of carbon sequestered equals the difference of the carbon produced in new forest growth and the carbon contained in new forest growth that would have occurred even if no project organized reforestation efforts. Calculated in Equation 19, the latter amount constitutes the baseline carbon removal from the atmosphere for the gross area of reforestation without a project. The former amount, carbon to be produced in the proposed reforestation project, equals the sum of carbon accumulation each year of the different reforestation project stages:

♦ Equation 26: $$C_{\text{reforestation project total}} = f_C \cdot \sum_{t_{start}}^{t_{final}} B_{\text{reforestation project}}(t)$$

♦ Equation 27: $$B_{\text{reforestation project}}(t) = \sum^{\text{all stages of age>0}} R_{\text{nat.reg.}}(\text{age}) + R_{\text{plant}}(\text{age})$$

♦ Equation 28: $$R_{\text{nat.reg.}}(\text{age}) = A_{\text{nat.reg.}}(\text{stage}) \times [B(\text{age}) - B(\text{age} - 1)]$$

♦ Equation 29: $$R_{\text{plant}}(\text{age}) = A_{\text{plant}}(\text{stage}) \times \frac{D_{\text{plant}}}{D_{\text{secondary forest}}} \times [B(\text{age}) - B(\text{age} - 1)]$$

♦ Equation 30: $$\text{age} = t - t_{\text{start}} + G(\text{stage})$$

$A_{\text{nat.reg.}}$(stage)	= area of proposed natural regeneration for a specified stage (ha); Table 3 gives stage areas for Selva Central
A_{plant}(stage)	= area of proposed plantation for a specified stage (ha); Table 3 gives stage areas for Selva Central
age	= age of a reforestation area (y)
B(age)	= biomass density of regenerating forest at a specified age (t ha^{-1}); data from biomass growth curve (Step 5)
$B_{\text{reforestation project}}$(t)	= biomass accumulation in a reforestation project during year t (t)
$C_{\text{reforestation project total}}$	= total reforestation project carbon production (t)
C_{removal}	= total baseline carbon removal from the atmosphere (t)
D_{plant}	= tree density of a plantation (trees ha^{-1})
$D_{\text{secondary forest}}$	= tree density of natural secondary forest (trees ha^{-1})
f_C	= carbon fraction of biomass (kg C (kg biomass)$^{-1}$); f_C = 0.49 kg C (kg biomass)$^{-1}$ for Amazon rainforest (Chambers et al. 2001b)
G(stage)	= calculation coefficient (y); G(stage) = 1, 0, -1, -2, -3 …. for stage = 1, 2, 3, 4, 5…
R_{plant}(age)	= additional carbon accumulation (in one year) for a plantation of a specified age (t)
stage	= serial number of annual reforestation campaigns or stages; Table 3 gives stage numbers for the proposed Selva Central project
t	= year.

Table 3. Implementation stages for proposed Selva Central reforestation project. The natural regeneration and plantations are combined in *fajas de enriquecimiento* (contour plantings).

stage	year	natural regeneration (ha)	plantation (ha)	total (ha)
1	2006	160	40	200
2	2007	640	160	800
3	2008	1200	300	1500
4	2009	1200	300	1500
5	2010	1200	300	1500
6	2011	1200	300	1500
total	2006-2011	5600	1400	7000

For a reforestation project, the amount of carbon sequestered equals the difference of the carbon produced in new forest growth and the baseline carbon removal:

♦ Equation 31: $C_{\text{reforestation additional}} = C_{\text{reforestation project total}} - C_{\text{removal}}$

$C_{\text{reforestation additional}}$ = additional carbon sequestration by a reforestation project (t)

$C_{\text{reforestation project total}}$ = total reforestation project carbon production (t)

C_{removal} = total baseline carbon removal from the atmosphere (t)

The major sources of measurement error and statistical variability for the carbon calculations include:

1. diameter measurements ±1%
2. height measurements ±1%
3. wood density estimates density ±10%
4. bivariate deforestation probability curves ± confidence interval of curve fit at $p = 0.05$
5. bivariate reforestation probability curves ± confidence interval of curve fit at $p = 0.05$

In order to produce conservative carbon estimates, we used the lower values of (1), (2), (3), and (4) and the upper value of (5) to calculate the lower estimates of baseline carbon emissions and upper estimates of baseline carbon removal. Conversely, the opposite values yield upper estimates baseline carbon emissions and lower estimates of baseline carbon removal.

Results and Discussion

Step 1 Definition of forest project area based on biological significance

The project area is 4800 km^2 of tropical rainforest and agricultural land between 9º 50' 42" S and 10º 50' 26" S latitude and between 74º 59' 44" W and 75º 47' 13" W longitude in Selva Central, Peru. The “Research Area” and “FRCA, Step 1” subsections describe the area and its selection in detail. Within the 4800 km^2 area, ProNaturaleza and the Nature Conservancy have developed a plan to conserve a 7000 ha forested watershed and to reforest 7000 ha of agricultural land. The forest conservation project area is the 7000 ha upper section of the watershed of the *Río Chontabamba*. The 7000 ha reforestation project area would be divided among non-contiguous parcels identified in Step 6 as eligible under the Clean Development Mechanism.

Step 2 Establishment of permanent forest inventory plots

ProNaturaleza staff measured and identified 17 073 trees of diameter >= 10 cm in the 24 forest inventory plots. Table 1 gives the coordinates and characteristics of the plots.

Step 3 Analyses of biodiversity, tree, and stand measures

The sites host trees of 512 species, 267 genera, and 69 families (Tables 4, 5). We could not identify the family of 7% of the trees or the scientific species of 21% of the trees. The sites are as rich as other Amazon rainforest sites (Terborgh and Andresen 1998, Pitman et al. 2002, Laurance et al. 2004).

The species richness of the primary forest sites is 346; the species richness of the secondary sites is 257 (Table 5). The different inventory site sizes prevent statistical comparison of the two samples, but the data indicate that primary sites are richer and more diverse than the secondary sites.

The α-diversity ranges from 23 to 166 species. As measured by fraction of total species shared between primary and secondary forest, β-diversity is 0.18. The γ-diversity is 512 species. These diversity values fall in the range of diversity values for other Peruvian Amazon rainforests (Condit et al. 2002, ter Steege et al. 2003), although α-diversity is lower than for inundated forests in Southeast Peru (Pitman et al. 1999).

The families with the most trees in the primary sites are *Moraceae* (Mulberry family) and *Myristicaceae* (Nutmeg family); in the secondary sites, *Melastomataceae* (Melastome family) and *Mimosaceae* (Mimosa family) have the most trees. The dominant species, by biomass, are *Eschweilera sp. (palo misho,* Family *Lecythidaceae)* in primary forest and *Jacaranda copaia (charapach,* Family *Bignonaceae)* in secondary forest.

In the primary forest sites, 90% of aboveground biomass resides in old-growth (primary) species and 10% of in successional (secondary) species. Conversely, in the secondary forest sites, 66% of the biomass rests in successional (secondary) species and 34% in old-growth (primary) species. ProNaturaleza and the Nature Conservancy are tracking this indicator as a measure of success of forest conservation and restoration.

The density of trees of diameter ≥ 10 cm is 366 trees ha^{-1} in primary forest and 533 trees ha^{-1} in secondary forest. The average diameter is 24 ± 15 cm in primary forest and 17 ± 8 cm in secondary forest (Table 5), resulting from a more even and large size class distribution in primary forest (Figure 3). Basal area in primary forest is 24 m^3 ha^{-1} (18-40 m^3 ha^{-1}) and 15 m^3 ha^{-1} (8-26 m^3 ha^{-1}) in secondary forest. The forest inventory plots exhibit tree and stand dimensions similar to other networks of forest inventory plots throughout Amazon rainforest (ter Steege et al. 2003, Lewis et al. 2004, Rice et al. 2004, Chazdon et al. 2005).

Step 4 Calculation of biomass using local tree allometric equations and species-specific wood densities

Aboveground biomass is 240 t ha^{-1} ± 30 t ha^{-1} in the primary sites and 90 t ha^{-1} ±10 t ha^{-1} in the secondary sites. Aboveground carbon in live vegetation is 120 t ha^{-1} ± 15 t ha^{-1} in the primary sites and 40 t ha^{-1} ± 5 t ha^{-1} in the secondary sites. The carbon densities fall in the range of measured values for Amazon rainforest (Cummings et al. 2002, DeWalt and Chave 2004, Fearnside and Laurance 2004, Feldpausch et al. 2004, Rice et al. 2004), which possess the highest carbon densities in the Tropics (Olson et al. 1983, Matthews et al. 2000).

Aboveground biomass and forest species richness are positively correlated (significant at $p<0.001$) (Figure 4). Sites with higher numbers of species also tend to have higher amounts of biomass for the same area of

Table 4. Selva Central forest species.

Genus	*species*	local name	Family
Agonandra	*sp.*		*Opiliaceae*
Alchornea	*sp.*	*palo paloma*	*Euphorbiaceae*
Alchornea	*triplinervia*		*Euphorbiaceae*
Alibertia	*sp.*		*Rubiaceae*
Allophylus	*sp.*	*huacapulillo*	*Sapindaceae*
Amburana	*cearensis*		*Fabaceae*
Anacardium	*sp.*		*Anacardiaceae*
Aniba	*guianensis*	*moena amarilla*	*Lauraceae*
Aniba	*megaphylla*	*moena*	*Lauraceae*
Aniba	*panurensis*	*alcanfor amarillo*	*Lauraceae*
Aniba	*sp.*	*moena rosada*	*Lauraceae*
Annona	*sp.*	*anona*	*Annonaceae*
Annona	*sp.*	*anonilla*	*Annonaceae*
Annona	*sp.*	*anonilla canela*	*Annonaceae*
Annona	*sp.*	*anonilla negra*	*Annonaceae*
Annona	*sp.*	*anonilla verdadera*	*Annonaceae*
Annona	*sp.*	*huangana huasca*	*Annonaceae*
Apeiba	*membranacea*	*peine de mono*	*Tiliaceae*
Aptandra	*tubicina*		*Olacaceae*
Artocarpus	*altilis*	*pan de árbol*	*Moraceae*
Aspidosperma	*rigidum*		*Apocynaceae*
Aspidosperma	*sp.*		*Apocynaceae*
Aspidosperma	*vargasii*		*Apocynaceae*
Astrocaryum	*sp.*	*masanque*	*Arecaceae*
Banara	*nitida*		*Flacourtiaceae*
Batocarpus	*amazonicus*		*Moraceae*
Batocarpus	*orinocencis*		*Moraceae*
Batocarpus	*sp.*		*Moraceae*
Bellucia	*aequiloba*		*Melastomataceae*
Bellucia	*pentamera*	*estrella*	*Melastomataceae*
Bixa	*arborea*		*Bixaceae*
Bixa	*orellana*	*achiote*	*Bixaceae*
Bixa	*platycarpa*		*Bixaceae*
Bixa	*sp.*	*achotillo*	*Bixaceae*
Bonafousia	*sananho*		*Apocynaceae*
Borojoa	*claviflora*		*Rubiaceae*
Brosimum	*alicastrum*	*congona*	*Moraceae*
Brosimum	*lactescens*	*pan de árbol de monte*	*Moraceae*
Brosimum	*sp.*		*Moraceae*
Brosimum	*utile*		*Moraceae*
Buchenavia	*sp.*		*Combretaceae*
Byrsonima	*arthropoda*		*Malpighiaceae*
Cabralea	*cangerana*		*Meliaceae*
Cabralea	*sp.*	*cedro macho*	*Meliaceae*
Calatola	*sp.*		*Icacinaceae*
Calatola	*venezuelana*		*Icacinaceae*
Calliandra	*calothyrsus*	*cañopistola*	*Mimosaceae*
Calocarpum	*sp.*		*Sapotaceae*
Calophyllum	*brasiliense*	*lagarto caspi*	*Clusiaceae*
Calycophyllum	*spruceanum*	*capirona*	*Rubiaceae*
Calyptranthes	*sp.*		*Myrtaceae*
Campomanesia	*lineatifolia*	*palillo*	*Myrtaceae*
Cariniana	*decandra*	*cachimba rosada*	*Lecythidaceae*

Table 4. Selva Central forest species.

Genus	*species*	local name	Family
Cariniana	*sp.*		*Lecythidaceae*
Caryocar	*coccineum*	*almendro*	*Caryocaraceae*
Caryocar	*glabrum*		*Caryocaraceae*
Caryocar	*sp.*		*Caryocaraceae*
Casearia	*arborea*	*limón de monte*	*Flacourtiaceae*
Casearia	*megacarpa*		*Flacourtiaceae*
Casearia	*sp.*	*barba de leon, garahuasca*	*Flacourtiaceae*
Castilloa	*ulei*		*Moraceae*
Cavanillesia	*hylogeiton*		*Bombacaceae*
Cecropia	*engleriana*		*Cecropiaceae*
Cecropia	*sciadophylla*		*Cecropiaceae*
Cecropia	*sp.*	*cetico, tacona*	*Cecropiaceae*
Cedrela	*odorata*	*cedro*	*Meliaceae*
Cedrela	*sp.*	*cedro rojo*	*Meliaceae*
Cedrelinga	*catenaeformis*	*tornillo*	*Mimosaceae*
Ceiba	*insignis*		*Bombacaceae*
Ceiba	*pentandra*		*Bombacaceae*
Ceiba	*sp.*	*palo algodón*	*Bombacaceae*
Celtis	*schippii*	*huamansamana*	*Ulmaceae*
Ceroxylum	*sp.*	*palma real*	*Arecaceae*
Cestrum	*auriculatum*	*hierba santa*	*Solanaceae*
Cestrum	*sp.*		*Solanaceae*
Cheiloclinium	*cognatum*		*Hippocrateaceae*
Chimarrhis	*sp.*	*palo agua*	*Rubiaceae*
Chimarrhis	*williamsii*		*Rubiaceae*
Chlorophora	*tinctoria*	*turcash*	*Moraceae*
Chrysochlamys	*weberbaueri*	*colorado*	*Clusiaceae*
Chrysophyllum	*amazonicum*		*Sapotaceae*
Chrysophyllum	*sp.*		*Sapotaceae*
Cinchona	*grandiflora*		*Rubiaceae*
Cinchona	*micrantha*		*Rubiaceae*
Cinchona	*officinalis*	*cascarilla*	*Rubiaceae*
Cinchona	*sp.*	*cascarilla colorada*	*Rubiaceae*
Cinnamomum	*camphora*	*alcanfor*	*Lauraceae*
Citrus	*sp.*	*limon dulce*	*Rutaceae*
Citrus	*sp.*	*naranja*	*Rutaceae*
Clarisia	*biflora*	*pan de fruta*	*Moraceae*
Clarisia	*racemosa*	*machonaste, turpay*	*Moraceae*
Clarisia	*sp.*	*turpay hoja delgada*	*Moraceae*
Clethra	*sp.*	*paco paco*	*Clethraceae*
Copaifera	*reticulata*		*Caesalpiniaceae*
Cordia	*alliodora*		*Boraginaceae*
Cordia	*lomatoloba*		*Boraginaceae*
Cordia	*nodosa*		*Boraginaceae*
Cordia	*sp.*	*lucumbilla*	*Boraginaceae*
Cordia	*sp.*	*yanagara*	*Boraginaceae*
Couma	*macrocarpa*	*leche caspi*	*Apocynaceae*
Couratari	*sp.*		*Lecythidaceae*
Coussapoa	*sp.*		*Cecropiaceae*
Croton	*draconoides*	*rampa rampa, sangre de grado*	*Euphorbiaceae*
Croton	*sp.*		*Euphorbiaceae*

Table 4. Selva Central forest species.

Genus	*species*	local name	Family
Croton	*tessmannii*		*Euphorbiaceae*
Cupania	*sp.*	*misho pacay*	*Sapindaceae*
Cupania	*sp.*	*requia barbasco*	*Sapindaceae*
Cyathea	*sp.*	*helecho arboreo, auquish*	*Cyatheaceae*
Cyathea	*sp.*	*San Juan*	*Cyatheaceae*
Cyphomandra	*sp.*	*tomate de monte*	*Solanaceae*
Dacryodes	*kukachkana*		*Burseraceae*
Dacryodes	*roraimensis*	*copalillo blanco*	*Burseraceae*
Dacryodes	*sp.*		*Burseraceae*
Dendropanax	*sp.*		*Araliaceae*
Dendropanax	*tessmannii*		*Araliaceae*
Didymopanax	*morototoni*		*Araliaceae*
Didymopanax	*sp.*	*palo pinsha*	*Araliaceae*
Didymopanax	*sp.*	*tacona de monterreal*	*Araliaceae*
Diospyros	*sp.*		*Ebenaceae*
Diplotropis	*martiusii*	*chontaquiro*	*Fabaceae*
Duguetia	*sp.*		*Annonaceae*
Dyctocaryum	*sp.*	*basanco*	*Arecaceae*
Ecclinusa	*lanceolata*		*Sapotaceae*
Endlicheria	*dysodantha*		*Lauraceae*
Enterolobium	*sp.*		*Mimosaceae*
Eriotheca	*globosa*		*Bombacaceae*
Erythrina	*sp.*	*oropel*	*Fabaceae*
Erythrina	*sp.*	*pajuro, pashullo, pucherin*	*Fabaceae*
Eschweilera	*sp.*	*mashi mango, palo misho*	*Lecythidaceae*
Euterpe	*precatoria*	*huasaí, chonta*	*Arecaceae*
Ficus	*anthelmintica*	*ojé*	*Moraceae*
Ficus	*killipii*		*Moraceae*
Ficus	*maxima*		*Moraceae*
Ficus	*sp.*	*loro micuna*	*Moraceae*
Ficus	*sp.*	*matapalo*	*Moraceae*
Ficus	*sp.*	*matapalo amarillo*	*Moraceae*
Ficus	*sp.*	*matapalo blanco*	*Moraceae*
Ficus	*sp.*	*matapalo caspi*	*Moraceae*
Ficus	*sp.*	*matapalo colorado*	*Moraceae*
Ficus	*sp.*	*matapalo yuca*	*Moraceae*
Garcinia	*acuminata*		*Clusiaceae*
Garcinia	*sp.*		*Clusiaceae*
Gavarretia	*terminalis*	*palo paloma de monte*	*Euphorbiaceae*
Genipa	*americana*		*Rubiaceae*
Gordonia	*sp.*		*Theaceae*
Guarea	*kunthiana*		*Meliaceae*
Guarea	*pterorhachis*		*Meliaceae*
Guarea	*pubescens*		*Meliaceae*
Guarea	*sp.*	*cedro de agua*	*Meliaceae*
Guarea	*sp.*	*requia rojo*	*Meliaceae*
Guarea	*trichiliodes*	*requia*	*Meliaceae*
Guatteria	*elata*		*Annonaceae*
Guatteria	*sp.*	*sampama*	*Annonaceae*

Table 4. Selva Central forest species.

Genus	*species*	local name	Family
Guazuma	*sp.*	*bolaina amarilla*	*Sterculiaceae*
Hasseltia	*floribunda*		*Flacourtiaceae*
Hedyosmum	*sp.*	*aitacopa*	*Chloranthaceae*
Heisteria	*nitida*		*Olacaceae*
Heisteria	*sp.*		*Olacaceae*
Helicostylis	*sp.*		*Moraceae*
Heliocarpus	*popayanensis*	*huampo*	*Tiliaceae*
Heliocarpus	*sp.*	*huampo blanco*	*Tiliaceae*
Herrania	*sp.*		*Sterculiaceae*
Hevea	*brasiliensis*	*shiringa blanca*	*Euphorbiaceae*
Hevea	*guianensis*	*shiringa amarilla*	*Euphorbiaceae*
Hevea	*sp.*		*Euphorbiaceae*
Himatanthus	*sp.*		*Apocynaceae*
Himatanthus	*sucuuba*	*bellaco caspi*	*Apocynaceae*
Hirtella	*sp.*		*Chryso-balanaceae*
Huberodendron	*swietenioides*	*aguano masha*	*Bombacaceae*
Huertea	*glandulosa*		*Anacardiaceae*
Humiriastrum	*excelsum*		*Staphyleaceae*
Hyeronima	*alchorneoides*		*Euphorbiaceae*
Hymenaea	*oblongifolia*		*Caesalpiniaceae*
Hymenolobium	*elatum*		*Fabaceae*
Hymenolobium	*sp.*	*roble rosado*	*Fabaceae*
Inga	*capitata*		*Mimosaceae*
Inga	*edulis*		*Mimosaceae*
Inga	*jenmanii*		*Mimosaceae*
Inga	*marginata*	*pacay maní*	*Mimosaceae*
Inga	*pavoniana*	*pacaycillo*	*Mimosaceae*
Inga	*quaternata*		*Mimosaceae*
Inga	*semialata*		*Mimosaceae*
Inga	*sp.*	*pacay*	*Mimosaceae*
Inga	*sp.*	*pacay ácido*	*Mimosaceae*
Inga	*sp.*	*pacay blanco*	*Mimosaceae*
Inga	*sp.*	*pacay colorado*	*Mimosaceae*
Inga	*sp.*	*pacay de altura*	*Mimosaceae*
Inga	*sp.*	*pacay de monte*	*Mimosaceae*
Inga	*sp.*	*pacay loro*	*Mimosaceae*
Inga	*sp.*	*pacay negro*	*Mimosaceae*
Inga	*sp.*	*pacay peludo*	*Mimosaceae*
Inga	*sp.*	*pacay playa*	*Mimosaceae*
Inga	*sp.*	*pacay rojo*	*Mimosaceae*
Inga	*sp.*	*pacay sachavaca*	*Mimosaceae*
Inga	*sp.*	*pacaycillo amarillo*	*Mimosaceae*
Inga	*sp.*	*pacaycillo blanco*	*Mimosaceae*
Inga	*sp.*	*pacaycillo colorado*	*Mimosaceae*
Inga	*striata*		*Mimosaceae*
Inga	*umbellifera*		*Mimosaceae*
Iriartea	*deltoidea*	*camona sin patas, pona*	*Arecaceae*
Iriartea	*sp.*	*camona*	*Arecaceae*
Iriartea	*sp.*	*camonilla*	*Arecaceae*
Iryanthera	*juruensis*		*Myristicaceae*
Iryanthera	*sp.*		*Myristicaceae*

Table 4. Selva Central forest species.

Genus	*species*	local name	Family
Iryanthera	*tessmannii*	*cumalilla*	*Myristicaceae*
Jacaranda	*copaia*	*charapach, huamanzamana*	*Bignoniaceae*
Jacaratia	*digitata*	*papayita de monte*	*Caricaceae*
Jacaratia	*spinosa*		*Caricaceae*
Juglans	*neotropica*	*nogal*	*Juglandaceae*
Lacmellea	*arborescens*		*Apocynaceae*
Lacmellea	*peruviana*	*chochoque*	*Apocynaceae*
Lacmellea	*sp.*		*Apocynaceae*
Laetia	*procera*	*quillabordon blanco*	*Flacourtiaceae*
Laplacea	*sp.*		*Theaceae*
Lecointea	*peruviana*	*come cebo*	*Caesalpiniaceae*
Leonia	*crassa*		*Violaceae*
Leonia	*glycycarpa*		*Violaceae*
Leonia	*sp.*		*Violaceae*
Licania	*sp.*		*Chrysobalanaceae*
Licaria	*sp.*		*Lauraceae*
Loretoa	*peruviana*		*Rubiaceae*
Lunania	*parviflora*		*Rubiaceae*
Mabea	*maynensis*	*boquilla*	*Euphorbiaceae*
Mabea	*sp.*		*Euphorbiaceae*
Macrocnemum	*roseum*		*Rubiaceae*
Macrolobium	*limbatum*	*palo cal colorado*	*Fabaceae*
Macrolobium	*sp.*	*palo cal*	*Fabaceae*
Macrolobium	*sp.*	*palo cal hoja fina*	*Fabaceae*
Mangifera	*indica*	*mango*	*Anacardiaceae*
Manilkara	*sp.*		*Sapotaceae*
Maquira	*calophylla*		*Moraceae*
Maquira	*sp.*	*pan de árbol blanco*	*Moraceae*
Marila	*laxiflora*		*Clusiaceae*
Marila	*sp.*		*Clusiaceae*
Matayba	*sp.*		*Sapindaceae*
Matisia	*bicolor*		*Bombacaceae*
Matisia	*cordata*	*sapote*	*Bombacaceae*
Maytenus	*krukovii*		*Celastraceae*
Maytenus	*macrocarpa*		*Celastraceae*
Maytenus	*sp.*		*Celastraceae*
Meliosma	*bogotana*		*Sabiaceae*
Meliosma	*sp.*		*Sabiaceae*
Mezilaurus	*sp.*		*Lauraceae*
Miconia	*calvescens*	*palo gusano*	*Melastomataceae*
Miconia	*sp.*	*chilca*	*Melastomataceae*
Miconia	*sp.*	*chilca amarilla*	*Melastomataceae*
Miconia	*sp.*	*chilca blanca*	*Melastomataceae*
Miconia	*sp.*	*moronque*	*Melastomataceae*
Miconia	*sp.*	*tiri amarillo*	*Melastomataceae*
Miconia	*sp.*	*tiri blanco*	*Melastomataceae*
Miconia	*sp.*	*tiri lanudo*	*Melastomataceae*
Miconia	*sp.*	*tiri naranja*	*Melastomataceae*
Miconia	*sp.*	*tiri tiri*	*Melastomataceae*
Micropholis	*guyanensis*	*caimito rupino*	*Sapotaceae*
Micropholis	*sp.*		*Sapotaceae*
Micropholis	*venulosa*		*Sapotaceae*

Table 4. Selva Central forest species.

Genus	*species*	local name	Family
Minquartia	*guianensis*	*huacapú*	*Olacaceae*
Mouriri	*grandiflora*		*Melastomataceae*
Myrcia	*sp.*	*shacshapuyá hoja menuda*	*Myrtaceae*
Myriocarpa	*sp.*		*Urticaceae*
Myroxylon	*balsamum*	*estoraque*	*Fabaceae*
Myrsine	*sp.*	*lucma*	*Myrsinaceae*
Myrsine	*sp.*	*lucma hoja fina*	*Myrsinaceae*
Naucleopsis	*sp.*		*Moraceae*
Naucleopsis	*ternstroemiiflora*		*Moraceae*
Nealchornea	*yapurensis*		*Euphorbiaceae*
Nectandra	*matthewsii*		*Lauraceae*
Nectandra	*pulverulenta*		*Lauraceae*
Nectandra	*sp.*		*Lauraceae*
Nectandra	*turbacensis*		*Lauraceae*
Neea	*sp.*	*tuna de monte*	*Nyctaginaceae*
Ochroma	*pyramidale*	*huampo negro, topa*	*Bombacaceae*
Ocotea	*dielsiana*		*Lauraceae*
Ocotea	*gracilis*		*Lauraceae*
Ocotea	*javitensis*		*Lauraceae*
Ocotea	*obovata*		*Lauraceae*
Ocotea	*sp.*		*Lauraceae*
Oreopanax	*sp.*	*maqui maqui*	*Araliaceae*
Ormosia	*coccinea*	*huayruro amarillo*	*Fabaceae*
Ormosia	*schunkei*		*Fabaceae*
Ormosia	*sp.*	*huayruro*	*Fabaceae*
Osteophloeum	*platyspermum*		*Myristicaceae*
Otoba	*parvifolia*		*Myristicaceae*
Oxandra	*sp.*		*Annonaceae*
Pachira	*aquatica*		*Bombacaceae*
Pachira	*sp.*		*Bombacaceae*
Palicourea	*lasiantha*		*Rubiaceae*
Parahancornia	*sp.*		*Apocynaceae*
Parkia	*nitida*	*pashaco*	*Mimosaceae*
Parkia	*sp.*	*palo alberto*	*Mimosaceae*
Parkia	*velutina*	*pashaco vaina*	*Mimosaceae*
Peltogyne	*sp.*		*Caesalpiniaceae*
Pentagonia	*parvifolia*		*Rubiaceae*
Pentagonia	*sp.*		*Rubiaceae*
Pera	*ferruginea*		*Euphorbiaceae*
Perebea	*sp.*	*mallam*	*Moraceae*
Persea	*americana*	*palta*	*Lauraceae*
Persea	*sp.*	*palta plano*	*Lauraceae*
Piper	*sp.*	*matico*	*Piperaceae*
Piptadenia	*colubrina*	*vilco*	*Fabaceae*
Piptadenia	*sp.*	*vilco amarillo*	*Fabaceae*
Piptadenia	*sp.*	*vilco blanco*	*Fabaceae*
Piptadenia	*sp.*	*vilco calato*	*Fabaceae*
Piptadenia	*sp.*	*vilco colorado*	*Fabaceae*
Piptadenia	*sp.*	*vilco de altura*	*Fabaceae*
Piptadenia	*sp.*	*vilco espina larga*	*Fabaceae*
Piptadenia	*sp.*	*vilco espinoso*	*Fabaceae*
Pithecellobium	*pedicellare*	*pino blanco*	*Mimosaceae*

Table 4. Selva Central forest species.

Genus	*species*	local name	Family
Platymiscium	*ulei*		*Fabaceae*
Pleurothyrium	*nobile*		*Lauraceae*
Pleurothyrium	*sp.*		*Lauraceae*
Pollalesta	*sp.*	*rompe machete*	*Asteraceae*
Poulsenia	*armata*		*Moraceae*
Pourouma	*cecropiifolia*		*Cecropiaceae*
Pourouma	*guianensis*		*Cecropiaceae*
Pourouma	*minor*		*Cecropiaceae*
Pourouma	*mollis*		*Cecropiaceae*
Pourouma	*sp.*	*uvilla*	*Cecropiaceae*
Pouteria	*bilocularis*		*Sapotaceae*
Pouteria	*caimito*	*caimitillo amarillo*	*Sapotaceae*
Pouteria	*neglecta*	*caimito, caimito amarillo*	*Sapotaceae*
Pouteria	*reticulata*		*Sapotaceae*
Pouteria	*sp.*		*Sapotaceae*
Protium	*sp.*	*copal*	*Burseraceae*
Protium	*sp.*	*copal blanco*	*Burseraceae*
Prunus	*sp.*		*Rosaceae*
Pseudobombax	*septenatum*	*algodón botella*	*Bombacaceae*
Pseudolmedia	*laevis*		*Moraceae*
Pseudolmedia	*sp.*		*Moraceae*
Psidium	*guajava*	*guayaba*	*Myrtaceae*
Psidium	*sp.*		*Myrtaceae*
Pterocarpus	*sp.*		*Fabaceae*
Qualea	*impexa*		*Vochysiaceae*
Quararibea	*asterolepis*		*Bombacaceae*
Quararibea	*ochrocalyx*	*machin sapote*	*Bombacaceae*
Quararibea	*sp.*		*Bombacaceae*
Quiina	*sp.*		*Quiinaceae*
Rapanea	*sp.*	*gallguan, palo pesado*	*Myrsinaceae*
Rheedia	*sp.*		*Clusiaceae*
Rinorea	*sp.*		*Violaceae*
Rollinia	*sp.*		*Annonaceae*
Roucheria	*sp.*		*Linaceae*
Ruagea	*insignis*		*Meliaceae*
Rudgea	*sp.*		*Rubiaceae*
Rustia	*rubra*		*Rubiaceae*
Salacia	*sp.*		*Hippocrateaceae*
Sapium	*glandulosum*		*Euphorbiaceae*
Sapium	*laurifolium*		*Euphorbiaceae*
Sapium	*marmieri*		*Euphorbiaceae*
Sapium	*sp.*	*palo leche*	*Euphorbiaceae*
Sarcaulus	*brasiliensis*		*Sapotaceae*
Sclerolobium	*sp.*		*Caesalpiniaceae*
Sickingia	*tinctoria*		*Rubiaceae*
Simarouba	*amara*	*marupa*	*Simaroubaceae*
Simira	*sp.*		*Rubiaceae*
Siparuna	*sp.*	*achimosillo*	*Monimiaceae*
Sloanea	*latifolia*		*Elaeocarpaceae*
Sloanea	*sp.*	*achotillo pumaquiro*	*Elaeocarpaceae*
Socratea	*sp.*	*camona con patas*	*Arecaceae*

Table 4. Selva Central forest species.

Genus	*species*	local name	Family
Solanum	*sp.*	*anticristo*	*Solanaceae*
Sorocea	*hirtella*		*Moraceae*
Sorocea	*pileata*		*Moraceae*
Sorocea	*sp.*		*Moraceae*
Spondias	*mombin*		*Anacardiaceae*
Sterculia	*apetala*		*Anacardiaceae*
Sterculia	*pruriens*		*Anacardiaceae*
Sterculia	*sp.*	*huarmi caspi*	*Sterculiaceae*
Sterculia	*speciosa*		*Sterculiaceae*
Stylogyne	*cauliflora*		*Myrsinaceae*
Styrax	*guyanensis*		*Styracaceae*
Styrax	*sp.*		*Styracaceae*
Swartzia	*arborescens*	*palo ají*	*Caesalpiniaceae*
Swartzia	*sp.*	*aji de monte*	*Caesalpiniaceae*
Swietenia	*macrophylla*		*Meliaceae*
Symphonia	*globulifera*		*Clusiaceae*
Tabebuia	*serratifolia*	*chontaquiro amarillo*	*Bignoniaceae*
Tabebuia	*sp.*		*Bignoniaceae*
Tachigali	*sp.*	*chaira pacay*	*Caesalpiniaceae*
Tachigali	*sp.*	*chaira pacay colorado*	*Caesalpiniaceae*
Tachigalia	*sp.*		*Caesalpiniaceae*
Tapirira	*fanshawei*	*copal rosado*	*Anacardiaceae*
Tapirira	*guianensis*		*Anacardiaceae*
Tapirira	*sp.*		*Anacardiaceae*
Terminalia	*amazonica*	*tacho, yacushapana*	*Combretaceae*
Terminalia	*oblonga*	*facucho*	*Combretaceae*
Tetragastris	*sp.*	*copalillo*	*Burseraceae*
Tetrathylacium	*sp.*		*Flacourtiaceae*
Tetrorchidium	*rubrivenium*		*Euphorbiaceae*
Tetrorchidium	*sp.*	*col de monte*	*Euphorbiaceae*
Theobroma	*cacao*		*Sterculiaceae*
Theobroma	*obovatum*	*cacao de monte*	*Sterculiaceae*
Theobroma	*sp.*		*Sterculiaceae*
Thyrsodium	*sp.*		*Anacardiaceae*
Tovomita	*sp.*		*Clusiaceae*
Tovomitopsis	*sp.*	*lucmilla rosada*	*Clusiaceae*
Toxicodendron	*sp.*	*maico*	*Anacardiaceae*
Toxicodendron	*sp.*	*maico blanco*	*Anacardiaceae*
Toxicodendron	*sp.*	*maico rojo*	*Anacardiaceae*
Trema	*micrantha*	*atadijo, chicchilmay, pasalla*	*Ulmaceae*
Trichilia	*elegans*		*Meliaceae*
Trichilia	*pallida*		*Meliaceae*
Trichilia	*pleeana*		*Meliaceae*
Trichilia	*quadrijuga*		*Meliaceae*
Trichilia	*septentrionalis*	*requia amarilla*	*Meliaceae*
Trichilia	*sp.*	*requia colorada*	*Meliaceae*
Trichilia	*sp.*	*requia paujil*	*Meliaceae*
Triplaris	*americana*	*palo santo*	*Polygonaceae*
Triplaris	*peruviana*		*Polygonaceae*
Triplaris	*sp.*		*Polygonaceae*
Trophis	*caucana*		*Moraceae*

Table 4. Selva Central forest species.

Genus	*species*	local name	Family
Trophis	*sp.*		*Moraceae*
Turpinia	*occidentalis*		*Staphyleaceae*
Unonopsis	*sp.*		*Annonaceae*
Urera	*caracasana*	*ishanca, ishanga*	*Urticaceae*
Urera	*sp.*	*ishanca caliche*	*Urticaceae*
Urera	*sp.*	*ishanca de chancho*	*Urticaceae*
Vatairea	*sp.*	*chontaquiro negro*	*Fabaceae*
Vernonia	*sp.*	*ticsa micuna*	*Asteraceae*
Virola	*calophylla*	*cumala amarilla*	*Myristicaceae*
Virola	*elongata*	*cumala rosada*	*Myristicaceae*
Virola	*pavonis*	*cumala zancuda*	*Myristicaceae*
Virola	*peruviana*		*Myristicaceae*
Virola	*sebifera*		*Myristicaceae*
Virola	*sp.*	*banderilla*	*Myristicaceae*
Virola	*sp.*	*cumala*	*Myristicaceae*
Virola	*sp.*	*cumala amarilla zaranda*	*Myristicaceae*
Virola	*sp.*	*cumala blanca*	*Myristicaceae*
Vismia	*baccifera*	*café de monte, sogorapra*	*Clusiaceae*
Vismia	*sp.*	*café caspi*	*Clusiaceae*
Vismia	*sp.*	*café de monte hoja chica*	*Clusiaceae*
Vismia	*sp.*	*café de monte hoja grande*	*Clusiaceae*
Vismia	*sp.*	*palo café*	*Clusiaceae*
Vitex	*sp.*	*huacapú amarillo*	*Verbenaceae*
Vitex	*triflora*	*aceituna caspi*	*Verbenaceae*
Vochysia	*sp.*		*Vochysiaceae*
Weinmannia	*sp.*	*perejil*	*Cunoniaceae*
Williamodendron	*sp.*		*Lauraceae*
Xylopia	*sp.*	*pintana blanca*	*Annonaceae*
Xylosma	*benthamii*		*Flacourtiaceae*
Xylosma	*sp.*		*Flacourtiaceae*
Zanthoxylum	*sp.*	*chincho de monte*	*Rutaceae*
Genus	*sp.*	*bejuco*	*Bignoniaceae*
Genus	*sp.*	*caimitillo lanoso*	*Sapotaceae*
Genus	*sp.*	*caimito lanoso*	*Sapotaceae*
Genus	*sp.*	*capinurí*	*Moraceae*
Genus	*sp.*	*carhuania*	*Familia*
Genus	*sp.*	*chilizo*	*Familia*
Genus	*sp.*	*chirimoya de monte*	*Annonaceae*
Genus	*sp.*	*cien años*	*Myrtaceae*
Genus	*sp.*	*coquillo*	*Familia*
Genus	*sp.*	*cuñupa*	*Familia*
Genus	*sp.*	*gasacsiqui, tocra*	*Asteraceae*
Genus	*sp.*	*gavilancillo*	*Chrysobalanaceae*
Genus	*sp.*	*guayaquil*	*Arecaceae*
Genus	*sp.*	*huaya*	*Familia*
Genus	*sp.*	*huaychuiro*	*Familia*
Genus	*sp.*	*inciencio*	*Clusiaceae*
Genus	*sp.*	*llaulina*	*Familia*
Genus	*sp.*	*mancarron blanco*	*Solanaceae*
Genus	*sp.*	*mano del diablo*	*Araliaceae*

Table 4. Selva Central forest species.

Genus	*species*	local name	Family
Genus	*sp.*	*palo culebra*	*Rubiaceae*
Genus	*sp.*	*palo hueso*	*Myrtaceae*
Genus	*sp.*	*pama*	*Moraceae*
Genus	*sp.*	*papaya de monte*	*Caricaceae*
Genus	*sp.*	*pega pega*	*Familia*
Genus	*sp.*	*roble*	*Lauraceae*
Genus	*sp.*	*roble amarillo*	*Lauraceae*
Genus	*sp.*	*roble blanco*	*Lauraceae*
Genus	*sp.*	*roble canela*	*Lauraceae*
Genus	*sp.*	*roble hueso*	*Lauraceae*
Genus	*sp.*	*roble manzana*	*Lauraceae*
Genus	*sp.*	*roble negro*	*Lauraceae*
Genus	*sp.*	*roble playa*	*Lauraceae*
Genus	*sp.*	*roble zapallo*	*Lauraceae*
Genus	*sp.*	*roblecillo*	*Lauraceae*
Genus	*sp.*	*roblecillo amarillo*	*Lauraceae*
Genus	*sp.*	*sara*	*Meliaceae*
Genus	*sp.*	*suda sangre*	*Myristicaceae*
Genus	*sp.*		*Anacardiaceae*
Genus	*sp.*		*Apocynaceae*
Genus	*sp.*		*Araliaceae*
Genus	*sp.*		*Arecaceae*
Genus	*sp.*		*Bignoniaceae*
Genus	*sp.*		*Bombacaceae*
Genus	*sp.*		*Boraginaceae*
Genus	*sp.*		*Burseraceae*
Genus	*sp.*		*Caesalpiniaceae*
Genus	*sp.*		*Chrysobalanaceae*
Genus	*sp.*		*Clusiaceae*
Genus	*sp.*		*Combretaceae*
Genus	*sp.*		*Euphorbiaceae*
Genus	*sp.*		*Fabaceae*
Genus	*sp.*		*Flacourtiaceae*
Genus	*sp.*		*Lacistemataceae*
Genus	*sp.*		*Lauraceae*
Genus	*sp.*		*Lecythidaceae*
Genus	*sp.*		*Melastomataceae*
Genus	*sp.*		*Meliaceae*
Genus	*sp.*		*Mimosaceae*
Genus	*sp.*		*Moraceae*
Genus	*sp.*		*Myristicaceae*
Genus	*sp.*		*Myrtaceae*
Genus	*sp.*		*Nyctaginaceae*
Genus	*sp.*		*Rubiaceae*
Genus	*sp.*		*Sapindaceae*
Genus	*sp.*		*Sapotaceae*
Genus	*sp.*		*Solanaceae*
Genus	*sp.*		*Sterculiaceae*
Genus	*sp.*		*Tiliaceae*
Genus	*sp.*		*Urticaceae*
Genus	*sp.*		*primary forest*
Genus	*sp.*		*secondary forest*

Table 5. Forest inventory results.

	primary	secondary	total
plots	7	17	24
area (ha)	22.6	16.5	39.1
trees (d ≥ 10 cm at h = 1.3 m)	8267	8806	17073
biodiversity			
families	63	53	69
genera	232	141	267
species	346	257	512
unique species	255	166	
shared species	91	91	
trees of unknown family	588	639	1227
most abundant families	*Moraceae*	*Melastomataceae*	
	Myristicaceae	*Mimosaceae*	
stand characteristics			
density (trees ha^{-1})	366	533	
average diameter (cm)	24 ± 15	17 ± 8	
old growth trees	7079	2093	
old growth fraction	0.86	0.24	
successional trees	1188	6713	
successional fraction	0.14	0.76	
basal area (m^3 ha^{-1})	24 (18-40)	15 (8-26)	
old growth fraction	0.87	0.31	
successional fraction	0.13	0.69	
aboveground biomass (t ha^{-1})	240 ± 30	90 ± 10	
old growth fraction	0.9	0.34	
successional fraction	0.1	0.66	
aboveground live carbon (t ha^{-1})	120 ± 15	40 ± 5	

land. Indeed carbon storage is a function of species composition in another Neotropical forest (Bunker et al. 2005). Therefore, forest conservation and restoration can improve both carbon sequestration and biodiversity conservation.

Step 5 Derivation of growth functions

Biomass growth proceeds rapidly in the early years of re-growth, then slows over time, according to the statistically significant empirical function (Figure 5) derived from our forest inventory sites:

♦ Equation 32: $B(age) = 4.0887076 - 0.0174009\ age^2$ $(p < 0.001)$

age = age of a forest stand (y)

B(age) = biomass density (t ha^{-1}).

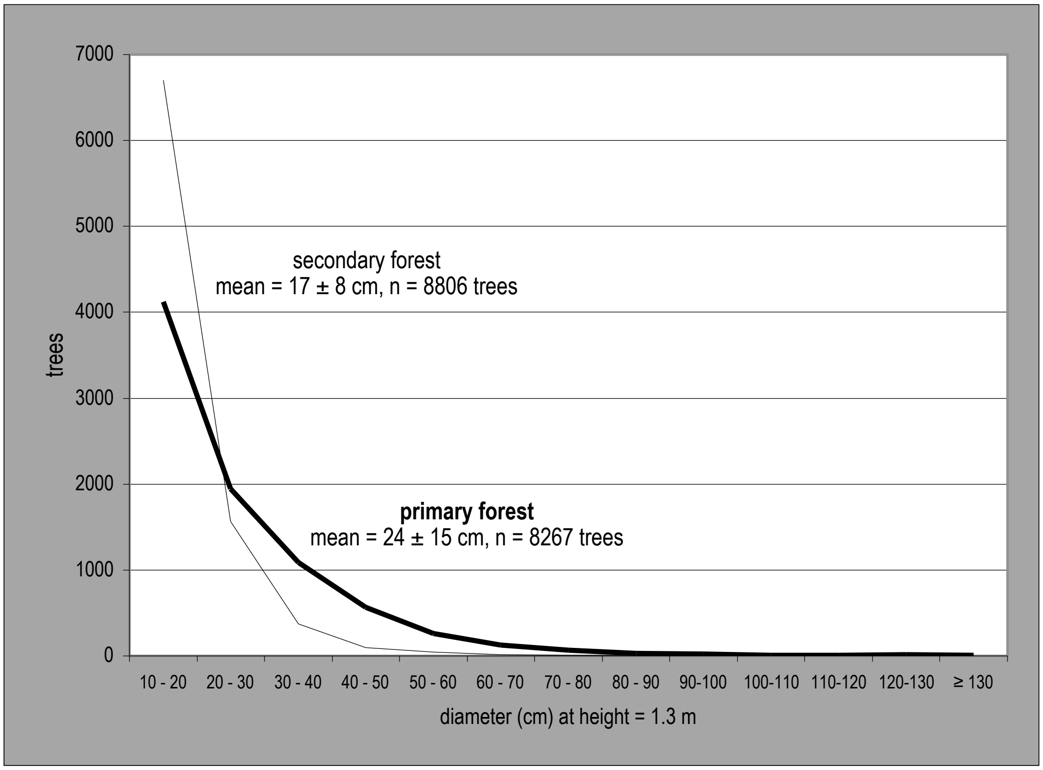


Figure 3. Size distribution of inventory trees.

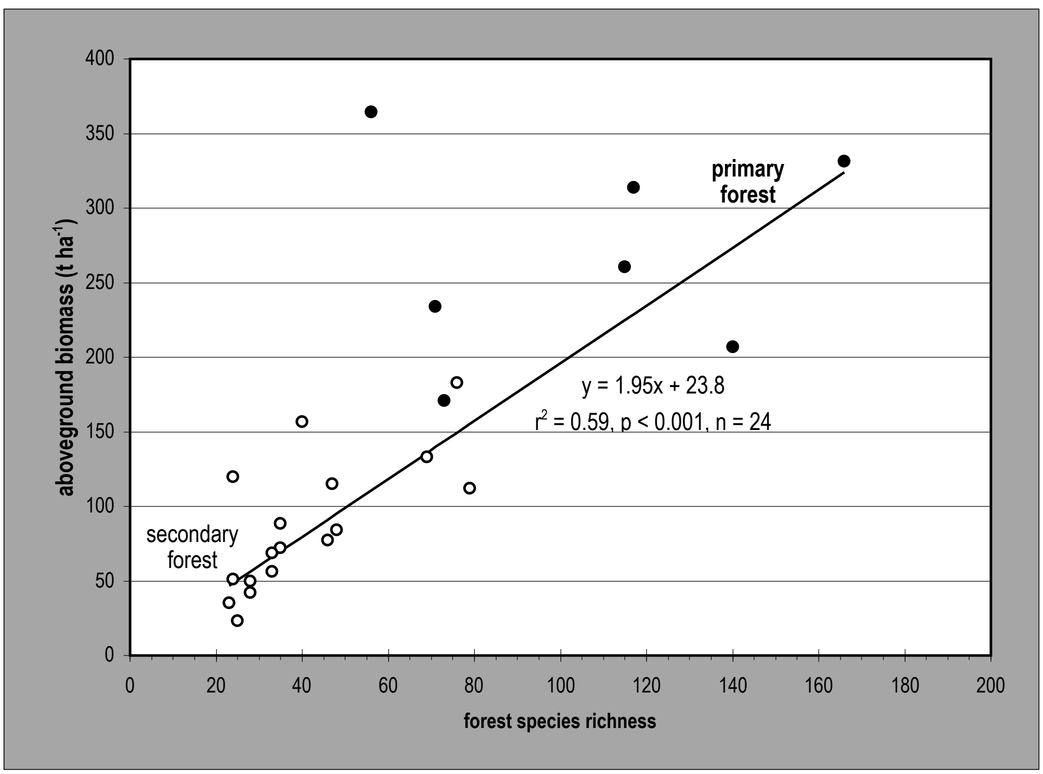


Figure 4. Aboveground biomass and forest species richness.

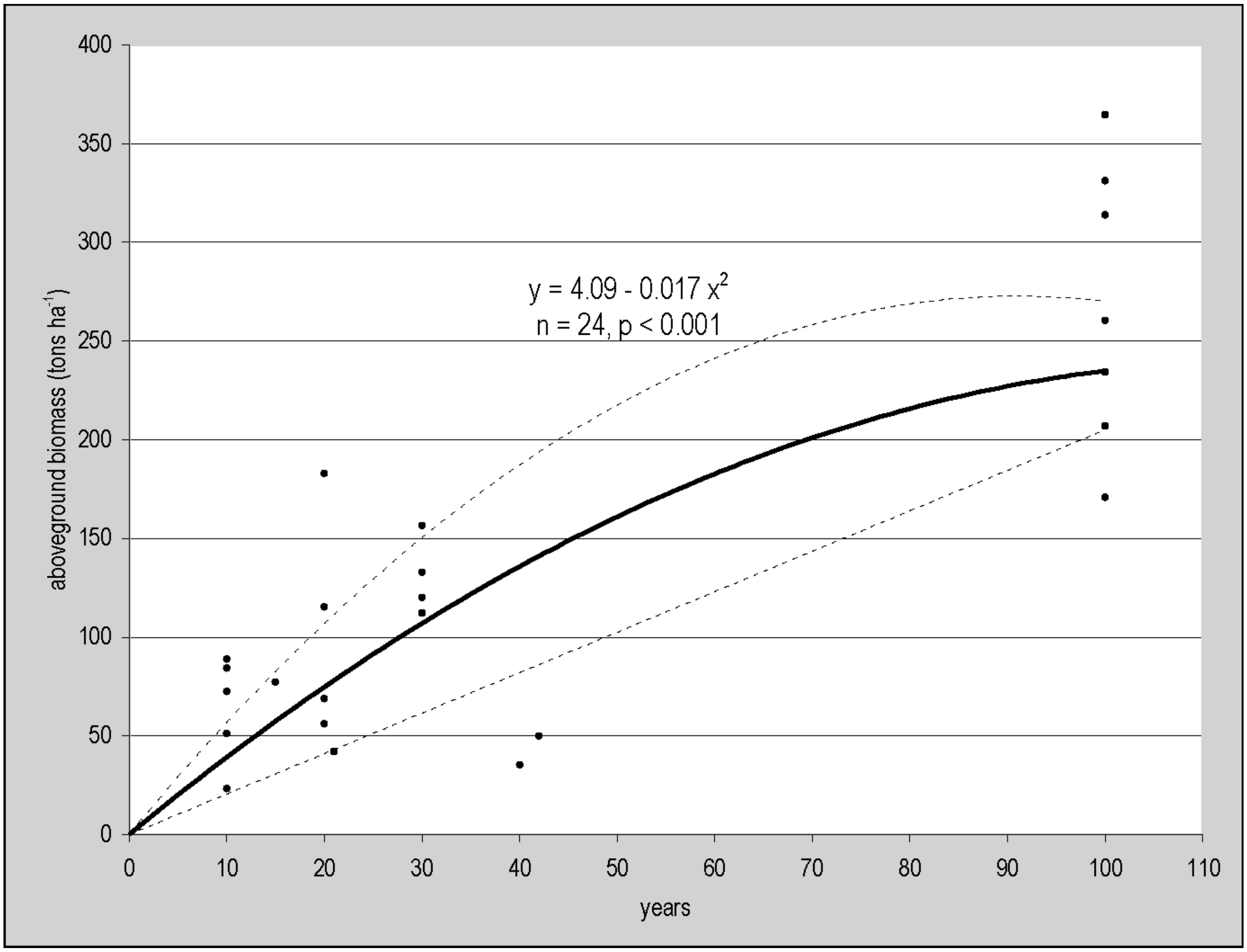


Figure 5. Biomass growth curve of Amazon forest at Selva Central. Confidence intervals at p = 0.05.

The biomass growth curve reflects the form and magnitude of other measured curves of Neotropical rainforest biomass growth (Hughes et al. 1999, Feldpausch et al. 2004, Neeff and dos Santos 2005, Zarin et al. 2005).

Step 6 Change detection using forest inventories and Landsat images

The project area covers 4800 km^2, of which 3700 km^2 were free of clouds, shadow, and water in Landsat scenes for 1987 and 1999 (Figure 1). In 1987 (Figure 6) and 1999 (Figure 7), forest covered 90% of the research area (Table 6). In the period 1987-1999, the gross area of deforestation of 32 000 ha exceeded the gross area of reforestation of 12 000 ha (Table 7), leading to net deforestation in the research area of 20 000 ha, proceeding at a rate of 0.005 y^{-1}.

Deforestation (Figure 8) clustered along roads, consistent with other measurements in Amazon rainforest (Laurance et al. 2002, Walker et al. 2004, de Barros Ferraz et al. 2005). It also clustered along rivers, contrary to measurements in Southeast Peru (Alvarez and Naughton-Treves 2003). Reforestation (Figure 8) also concentrated along rivers. We analyze the statistic trends of deforestation and reforestation factors in Steps 7-11.

Of those areas that were closed forest in 1987, only 89% remained closed forest in 1999. Conversion to secondary forest or complete clear-cutting converted the remaining 11% of closed forests to other land cover types at double the net rate of deforestation. This demonstrates that the net rate of deforestation as detected by Landsat does not completely indicate the degree of disruption of intact forest ecosystems, a phenomenon documented for other parts of the Amazon (Asner et al. 2005).

Even though the research area experienced a net deforestation in the period 1987-1999, the adjacent protected areas experienced only negligible deforestation *(Bosque de Protección San Matías-San Carlos, Parque Nacional Yanachaga-Chemillén)* or even net reforestation *(Reserva Comunal Yanesha)* (Table 8). Because the Government of Peru declared the three protected areas close to the start of the analysis period (1987), the data strongly suggest that the protection has succeeded. Another interpretation would judge that the areas were not under threat, but the proximity of the protected areas to private lands that experienced significant deforestation implies that protection status did determine the fate of the forest.

The deforestation analyses show that 26 000 ha within the project area were not in forest in 1987 and are eligible for forest carbon trading under the Clean Development Mechanism.

Table 6. Land cover, 1987-1999, Selva Central, Peru.

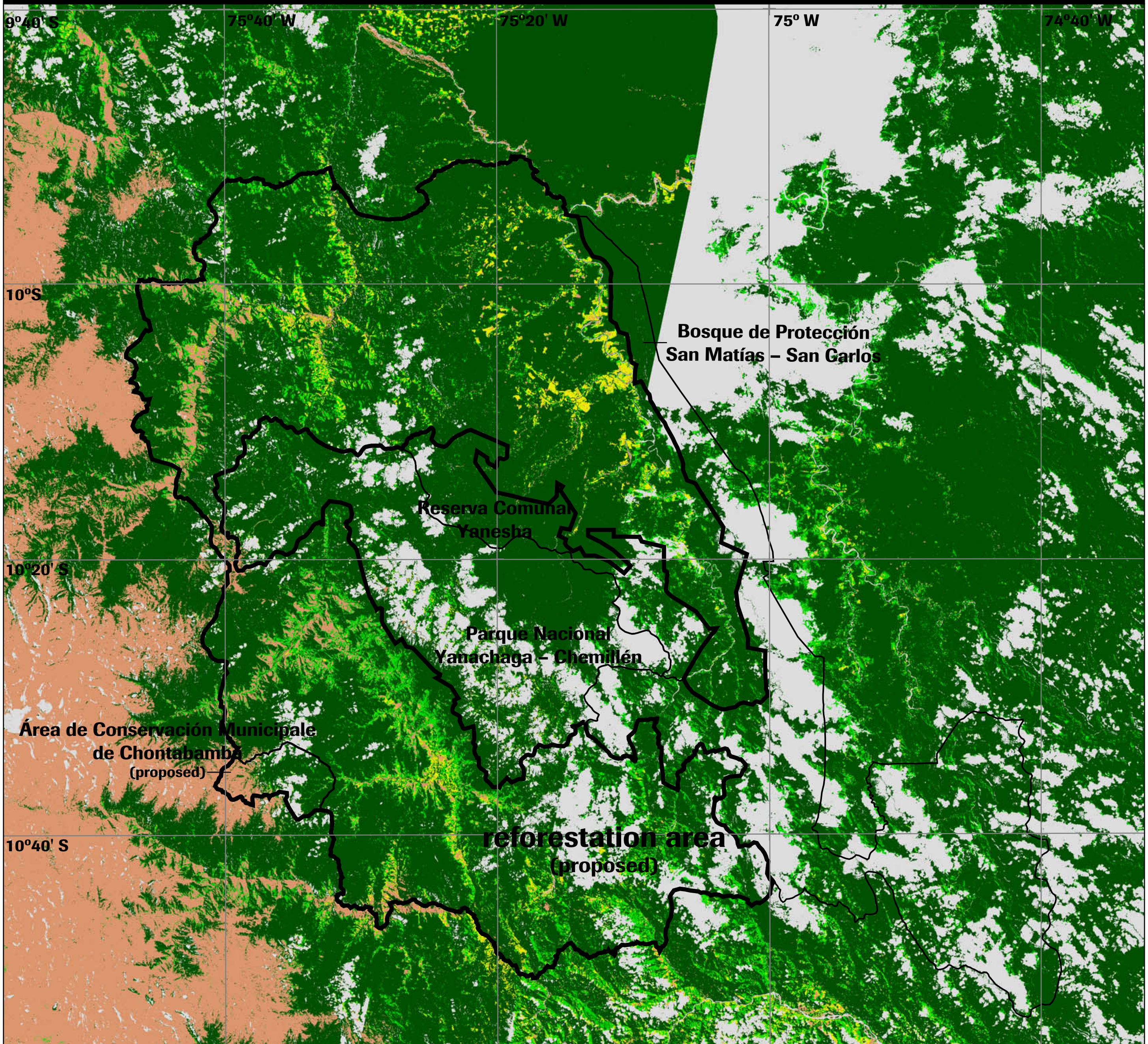
	1987 ha	1999 ha	net change 1987-1999 ha	net change 1987-1999 ha y^{-1}	net change 1987-1999 y^{-1}
closed forest	285 000	281 000	-4 000	-400	-0.001
open forest	44 000	28 000	-16 000	-1300	-0.030
total forest	**329 000**	**309 000**	**-20 000**	**-1700**	**-0.005**
low vegetation	15 000	28 000	13 000	1100	0.073
sparse vegetation	23 000	30 000	7 000	600	0.026
total non-forest land	**38 000**	**58 000**	**20 000**	**1700**	**0.045**
total non-cloud land	**366 000**	**366 000**	**0**	**0**	**0**
clouds, shadow, water	109 000	109 000	0	0	0
total research area	**476 000**	**476 000**	**0**	**0**	**0**

Table 7. Gross changes in forest area, 1987-1999, Selva Central, Peru.

forest change	initial condition 1987 ha	gross change 1987-1999 ha	gross change 1987-1999 ha y^{-1}	gross change 1987-1999 y^{-1}
forest		297 000		
reforestation	non-forest 38 000	12 000	1 000	0.026
deforestation	forest 329 000	32 000	2 700	-0.008
no forest		26 000		
total non-cloud land		**366 000**		

Figure 6.

Selva Central, Perú



Land Cover 1987

- closed forest
- open forest
- low vegetation (e.g. agriculture, pasture)
- sparse vegetation (e.g. cleared fields, grassland)
- clouds, shadows, water

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forest inventories: ProNaturaleza 2001-2003; remote sensing: U.S. Geological Survey; analyses: Gonzalez, P., B. Kroll, and C.R. Vargas. 2004. Forest restoration carbon analysis in moist tropical forest at La Selva Central, Perú. Ecological Society of America Annual Meeting Abstracts 89: 182.

0 12.5 25 km
scale 1:800 000

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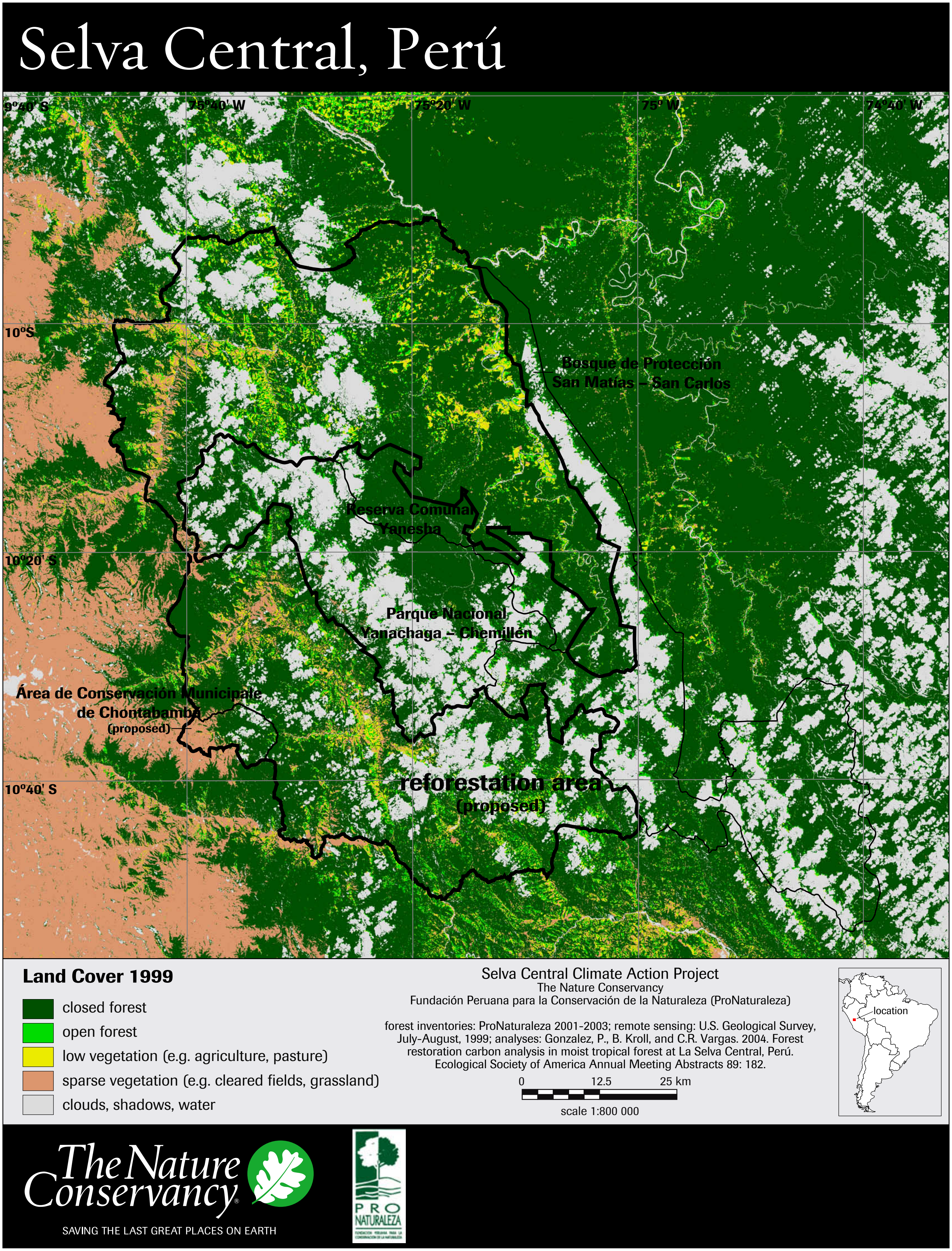
Figure 7.



Selva Central, Perú
9°40' S
75°40' W
75°20' W
75° W
74°40' W
10°S
10°20' S
10°40' S
Bosque de Protección
San Matías – San Carlos
Reserva Comunal
Yanesha
Parque Nacional
Yanachaga – Chemillén
Área de Conservación Municipale
de Chontabamba
(proposed)
reforestation area
(proposed)
Land Cover 1999
closed forest
open forest
low vegetation (e.g. agriculture, pasture)
sparse vegetation (e.g. cleared fields, grassland)
clouds, shadows, water
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forest inventories: ProNaturaleza 2001-2003; remote sensing: U.S. Geological Survey, July-August, 1999; analyses: Gonzalez, P., B. Kroll, and C.R. Vargas. 2004. Forest restoration carbon analysis in moist tropical forest at La Selva Central, Perú. Ecological Society of America Annual Meeting Abstracts 89: 182.
0
12.5
25 km
scale 1:800 000
location
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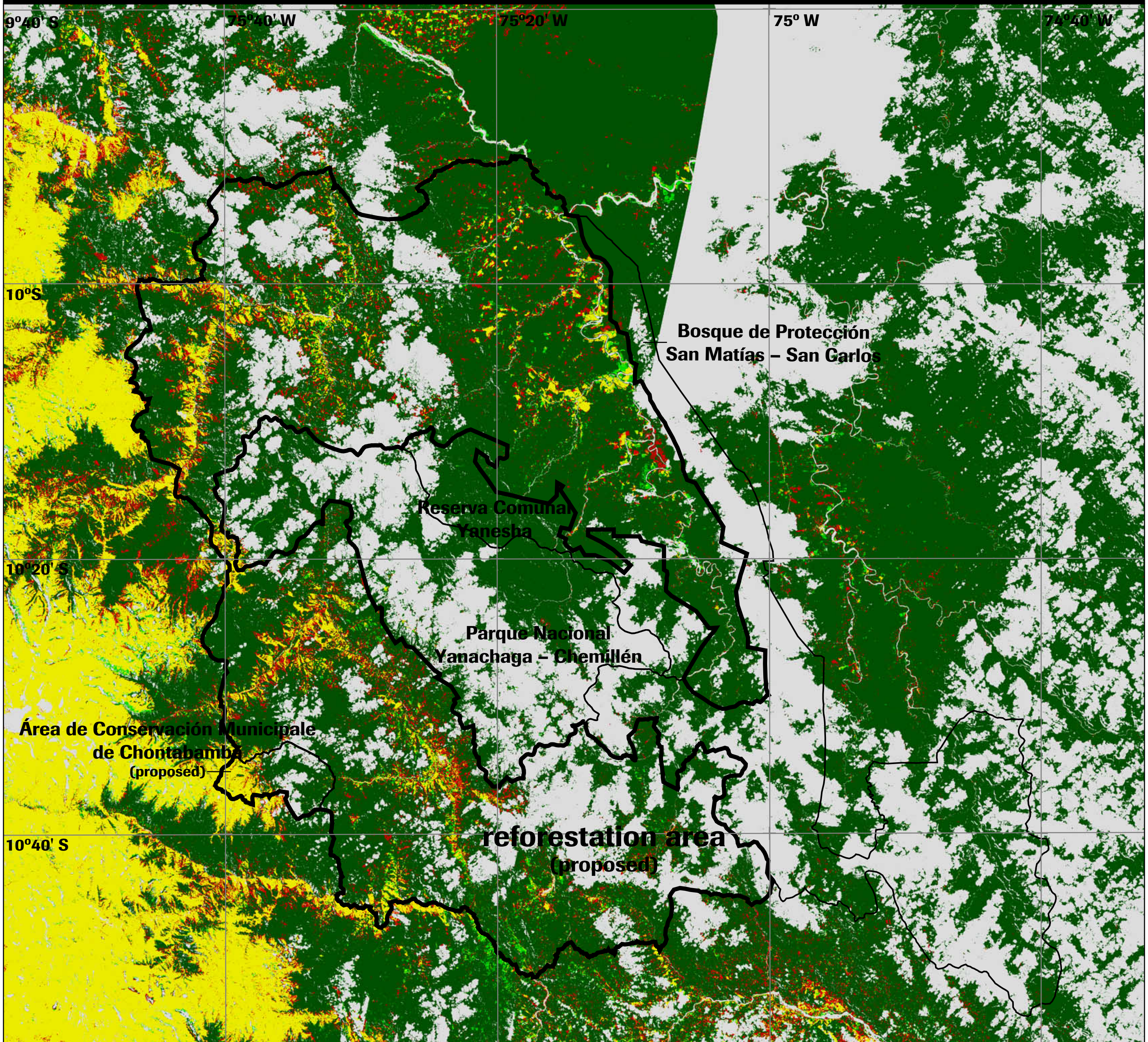
Figure 8.

Selva Central, Perú



Forest Cover Change 1987-1999

- forest
- reforestation
- deforestation
- no forest
- clouds, shadows, water

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forest inventories: ProNaturaleza; remote sensing: U.S. Geological Survey; analyses: Gonzalez, P., B. Kroll, and C.R. Vargas. 2004. Forest restoration carbon analysis in moist tropical forest at La Selva Central, Perú. Ecological Society of America Annual Meeting Abstracts 89: 182.

0 12.5 25 km

scale 1:800 000

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Table 8. Forest cover change 1987-1999, Selva Central project and protected areas.

		Selva Central project area	Parque Nacional Yanachaga-Chemillén	Bosque de Protección San Matías-San Carlos	Reserva Comunal Yanesha
			established 1986	established 1987	established 1988
forest	ha	297 000	48 000	61 000	24 000
reforestation	ha	12 000	600	500	100
deforestation	ha	32 000	700	700	80
no forest	ha	26 000	400	40	5
non-cloud area	ha	366 000	50 000	62 000	24 000
clouds, shadow, water	ha	109 000	62 000	90 000	9 000
total	ha	476 000	112 000	152 000	33 000
net change 1987-2011		**deforestation**	**deforestation**	**deforestation**	**reforestation**
net rate	y^{-1}	-0.005	-0.0002	-0.0003	0.00008

Step 7 Compilation of spatial data of major deforestation and reforestation factors

The values of the six deforestation and reforestation factors (Figure 9) ranged from zero to the following maxima in the research area:

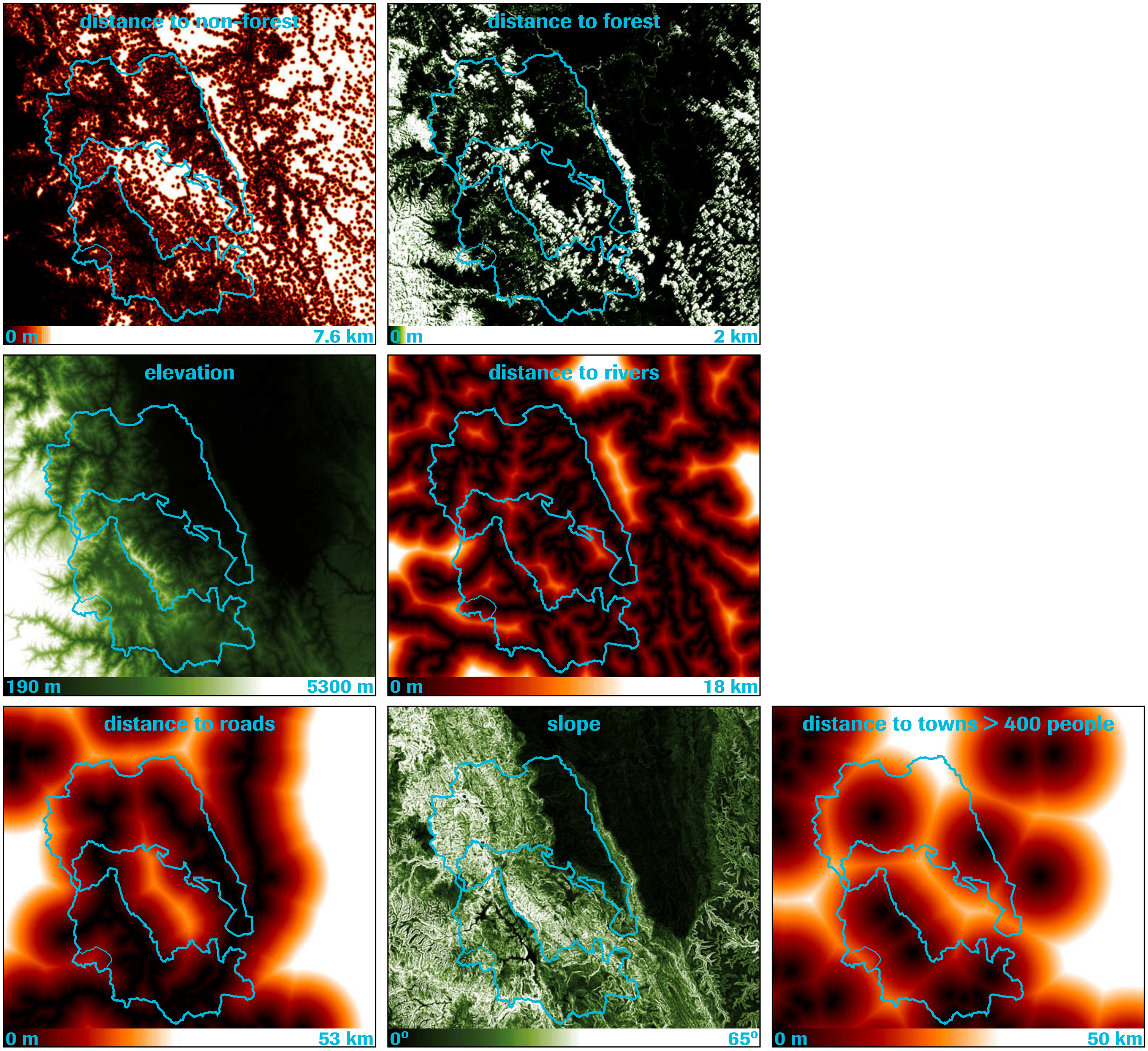
1. distance to non-forest (for deforestation analysis): 2600 m
   distance to forest (for reforestation analysis): 2000 m
2. elevation: 4400 m
3. distance to rivers: 45 000 m
4. distance to roads: 45 000 m
5. slope: 57º
6. distance to towns of population > 400 44 000 m

Step 8 Principal components analysis to calculate weight of factors in explaining observed deforestation and reforestation

Principal components analysis showed that distance to non-forest was the factor that best explained observed patterns of deforestation while distance to forest best explained observed patterns of reforestation (Table 9). Principal components analysis indicated that these factors were more significant than elevation, distance to rivers, distance to roads, slope, and distance to towns of population > 400, though the weights are relatively close to tight bivariate functions of deforestation and reforestation with individual factors (Step 9). Distance to cleared areas may best explain deforestation due to the physical ease in clearing forest that is next to a cleared area. Moreover, edge effects increase mortality in Amazon forest fragments (Laurance et al. 1997, D'Angelo et al. 2004).

Figure 9.

Selva Central, Perú



Deforestation and Reforestation Factors

Selva Central Climate Action Project

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Forest Restoration Carbon Analysis

Gonzalez, P., B. Kroll, and C.R. Vargas. 2004. Forest restoration carbon analysis in moist tropical forest at La Selva Central, Perú. Ecological Society of America Annual Meeting Abstracts 89: 182.

distance to non-forest, forest: U.S. Geological Survey (USGS), Landsat, 1999; ProNaturaleza, forest inventories, 2001, 2003;
elevation, slope: National Aeronautics and Space Administration, Shuttle Radar Topography Mission, February 2000
rivers, roads: USGS, Landsat, 1999; Instituto Geográfico Nacional (IGN)
towns: USGS, Landsat, 1999; IGN; Instituto Nacional de Estadística e Informática

0 50 100 km
scale 1:2 500 000

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Step 9 Derivation of deforestation and reforestation probability functions

Observed patterns of deforestation and reforestation closely fit polynomial probability functions for each factor (Figures 10, 11, Tables 10, 11). Deforestation was highest close to cleared areas, rivers, roads, and towns. Deforestation declined with distance to roads, but rose again far away from roads, a possible sign of illegal cutting. Reforestation was highest close to forest areas and rivers and far from roads and towns. Reforestation was also greater in flat areas and at lower elevation.

Step 10 Calculation of deforestation and reforestation probability for each pixel

The 1999-2011 deforestation probability distribution exhibits a Gaussian form (Figure 12). The projected average probability of deforestation is 0.071 (min. 0.66, max. 0.075) and the threshold probability is 0.119 (min. 0.112, max. 0.125). The 1999-2011 reforestation probability distribution exhibits a bimodal form (Figure 13). The projected average probability of reforestation is 0.147 (min. 0.122, max. 0.171) and the threshold probability is 0.238 (min. 0.224, max. 0.245). Deforestation probability is elevated close to cleared areas, roads, and rivers (Figure 14) while reforestation probability is high next to existing forests (Figure 15.)

Step 11 Projection of future deforestation and reforestation

Projected net deforestation in the research area would total 13 000 ± 3000 ha in the period 1999-2011, proceeding at a rate of 0.003 ± 0.0007 y^{-1}, and would total 33 000 ± 7000 ha in the period 2006-2035 (Tables 12, 13). The projected gross area of deforestation in the proposed 7000 ha *Área de Conservación Municipale de Chontabamba* would total 100 ha (min. 70 ha, max 150 ha) in the period 2006-2035.

Projected gross reforestation in the research area would total 8500 ± 1500 ha in the period 1999-2011, proceeding at a rate of 0.0012 y^{-1} (min. 0.01y^{-1}, max. 0.014 y^{-1}), and would total 24 000 ± 4000 ha in the period 2006-2035 (Tables 13, 14). The projected gross area of reforestation in the proposed 7000 ha of reforestation by *fajas de enriquecimiento* would total 2600 ± 400 ha in the period 2006-2035.

These trends would produce a 2011 land cover of more sparse and low vegetation along most rivers and more open forest along the *Río Palcazú* (Figure 16). Projected 1999-2011 deforestation concentrates along rivers and in the Villa Rica area while projected 1999-2011 reforestation concentrates along the *Río Palcazú* (Figure 17).

Table 9. Weight of factors in explaining observed deforestation and reforestation, from principal components analysis.

	deforestation 241 842 pixels		**reforestation** 94 641 pixels	
factor	weight	rank	weight	rank
distance to forest			0.186	1
distance to non-forest	0.190	1		
elevation	0.174	3	0.165	4
rivers	0.143	6	0.151	5
roads	0.161	4	0.176	2
slope	0.175	2	0.150	6
towns > 400 people	0.157	5	0.171	3

Table 10. Probability functions of 1987-1999 deforestation (y) for six factors (x) (Figure 10).

factor	distance to non-forest	elevation	distance to rivers	distance to roads	slope	towns > 400 people
units	m	m	m	m	degrees	m
equation no.	33	34	35	36	37	38
equation	$y = a + bx + cx^{-0.5} + dx^{-1.5} + ex^{-2}$	$y = a + bx + cx^{2} + dx^{2.5} + ex^{3}$	$y = a + bx + cx^{2} + dx^{3} + ex^{4}$	$y^{-1} = a + bx + cx^{2} + dx^{3} + ex^{4}$	$y = a + bx + cx^{2} + dx^{3} + ex^{4}$	$y = a + bx + cx^{2.5} + dx^{3} + ex^{-2}$
a	-0.08911672	0.490039516	0.15829998	4.972140575	0.112534116	0.18194664
b	3.37154E-05	-0.00225374	-8.78809E-05	0.005207765	-0.00152327	-1.7944E-05
c	2.355132636	5.35471E-06	2.60611E-08	-4.564E-07	-0.00026059	1.16266E-11
d	-54.7479287	-1.4846E-07	-3.35114E-12	-3.8729E-12	1.40061E-05	-5.098E-14
e	241.4932368	1.15875E-09	1.54616E-16	7.87603E-16	-1.689E-07	6677.179773
r^2	0.9999	0.7120	0.9832	0.9355	0.9194	0.8740
p	0.0009	0.0273	0.0042	0.0090	0.0048	0.0099
p <0.05	*	*	*	*	*	*
p <0.01	**		**	**	**	**

Table 11. Probability functions of 1987-1999 reforestation (y) for six factors (x) (Figure 11).

factor	distance to forest	elevation	distance to rivers	distance to roads	slope	towns > 400 people
units	m	m	m	m	degrees	m
equation no.	39	40	41	42	43	44
equation	$y = a + bx + cx^{1.5} + dx^{-0.5} + ex^{-1}$	$y = a + bx + cx^{1.5} + dx^{2} + ex^{2.5}$	$y = a + bx + cx^{2.5} + dx^{3} + ex^{-2}$	$y = a + bx + cx^{2} + dx^{2.5} + ex^{3}$	$y = a + bx + cx^{2} + dx^{2.5} + ex^{3}$	$y = a + bx + cx^{1.5} + dx^{2} + ex^{2.5}$
a	0.182169351	0.339842962	0.224755224	0.200446029	0.422098933	0.084122595
b	-0.000313406	0.001929361	-3.9003E-05	-2.7249E-05	-0.07785421	-7.2423E-06
c	7.26745E-06	-0.000106633	4.35446E-11	6.19503E-09	0.010347023	4.14889E-07
d	-3.20597861	1.87614E-06	-2.2562E-13	-5.9792E-11	-0.00224112	-4.4258E-09
e	20.48926241	-1.09366E-08	2906.309883	1.6449E-13	0.000139034	1.40742E-11
r^2	0.9999	0.9511	0.9975	0.9067	0.9611	0.6779
p	0.0005	0.0336	0.0036	0.0143	0.0121	0.0281
p <0.05	*	*	*	*	*	*
p <0.01	**		**			

Table 12. Observed forest cover 1987-1999, projected forest cover 1999-2011, Selva Central, Peru.

	1987 ha	1999 ha	central 2011 ha	high 2011 ha	low 2011 ha	central 1999-2011 ha	high 1999-2011 ha	low 1999-2011 ha	central 1999-2011 y^{-1}	high 1999-2011 y^{-1}	low 1999-2011 y^{-1}
closed forest	285 000	281 000	266 000	265 000	267 000	-15 000	-16 000	-14 000	-0.004	-0.005	-0.004
open forest	44 000	28 000	30 000	28 000	31 000	2 000	0	3 000	0.002	0.000	0.007
total forest	**329 000**	**309 000**	**295 000**	**293 000**	**298 000**	**-13 000**	**-16 000**	**-11 000**	**-0.003**	**-0.004**	**-0.003**
low vegetation	15 000	28 000	33 000	34 000	31 000	5 000	6 000	3 000	0.027	0.033	0.013
sparse vegetation	23 000	30 000	38 000	39 000	37 000	9 000	10 000	8 000	0.031	0.035	0.026
total non-forest land	**38 000**	**58 000**	**71 000**	**74 000**	**68 000**	**13 000**	**16 000**	**11 000**	**0.029**	**0.034**	**0.024**
total non-cloud land	**366 000**	**366 000**	**366 000**	**366 000**	**366 000**	**0**	**0**	**0**	**0**	**0**	**0**
clouds, shadow, water	109 000	109 000	109 000	109 000	109 000	0	0	0	0	0	0
total analysis area	**476 000**	**476 000**	**476 000**	**476 000**	**476 000**	**0**	**0**	**0**	**0**	**0**	**0**

Figure 10. Probability functions of deforestation, derived from 1987-1999 observations (Table 10).

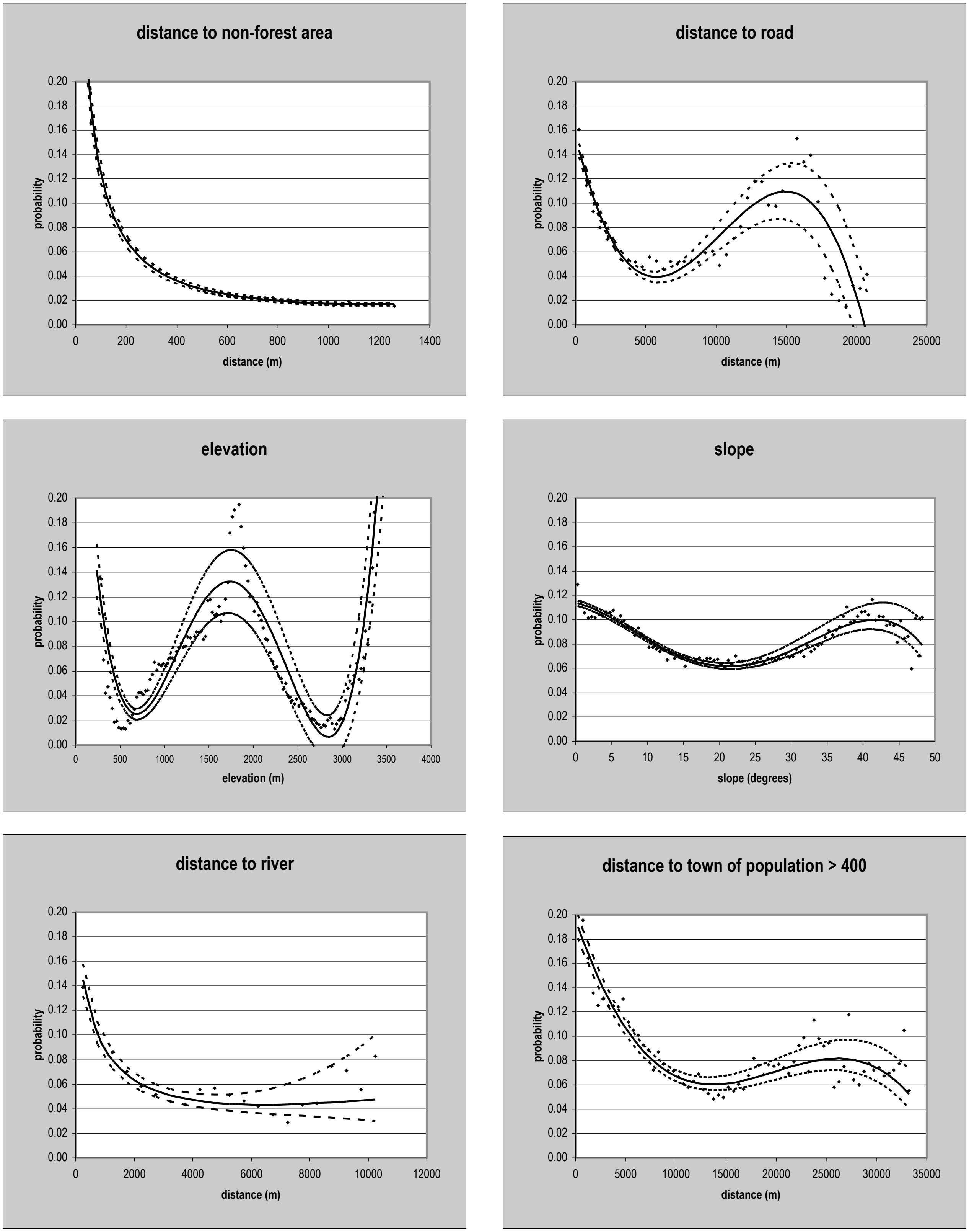
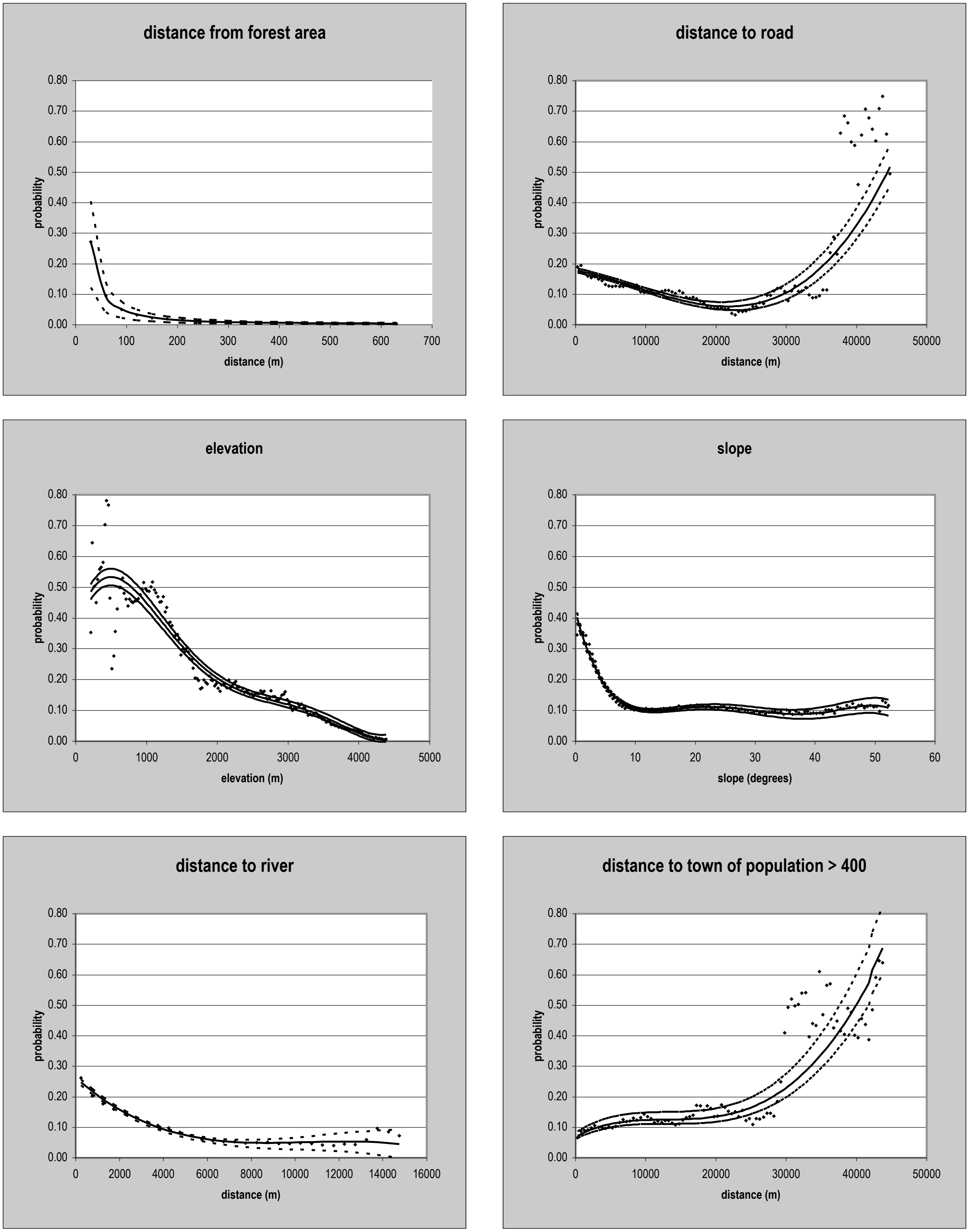


Figure 11. Probability functions of reforestation, derived from 1987-1999 observations (Table 11).



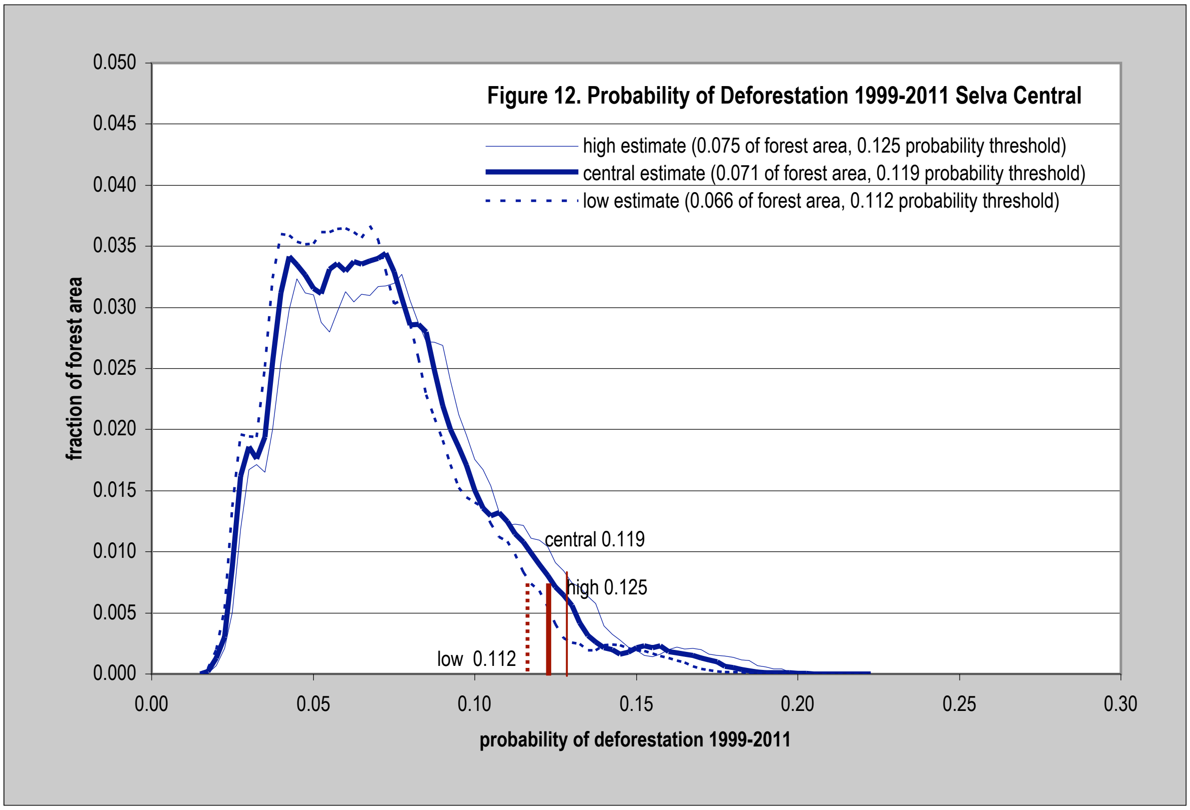


Figure 12. Probability of Deforestation 1999-2011 Selva Central
high estimate (0.075 of forest area, 0.125 probability threshold)
central estimate (0.071 of forest area, 0.119 probability threshold)
low estimate (0.066 of forest area, 0.112 probability threshold)
central 0.119
high 0.125
low 0.112
fraction of forest area
probability of deforestation 1999-2011
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.00
0.05
0.10
0.15
0.20
0.25
0.30

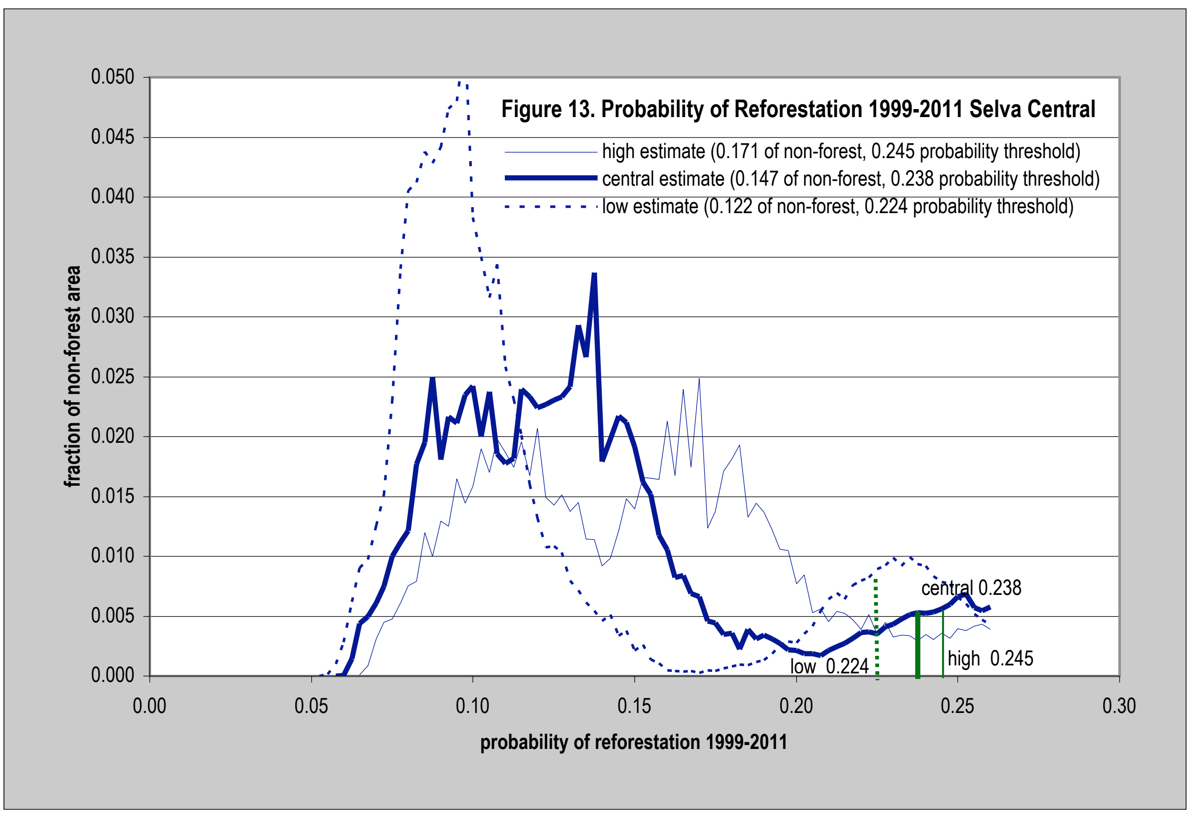


Figure 13. Probability of Reforestation 1999-2011 Selva Central
high estimate (0.171 of non-forest, 0.245 probability threshold)
central estimate (0.147 of non-forest, 0.238 probability threshold)
low estimate (0.122 of non-forest, 0.224 probability threshold)
central 0.238
high 0.245
low 0.224
fraction of non-forest area
probability of reforestation 1999-2011
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0.00
0.05
0.10
0.15
0.20
0.25
0.30

Figure 14.

Selva Central, Perú

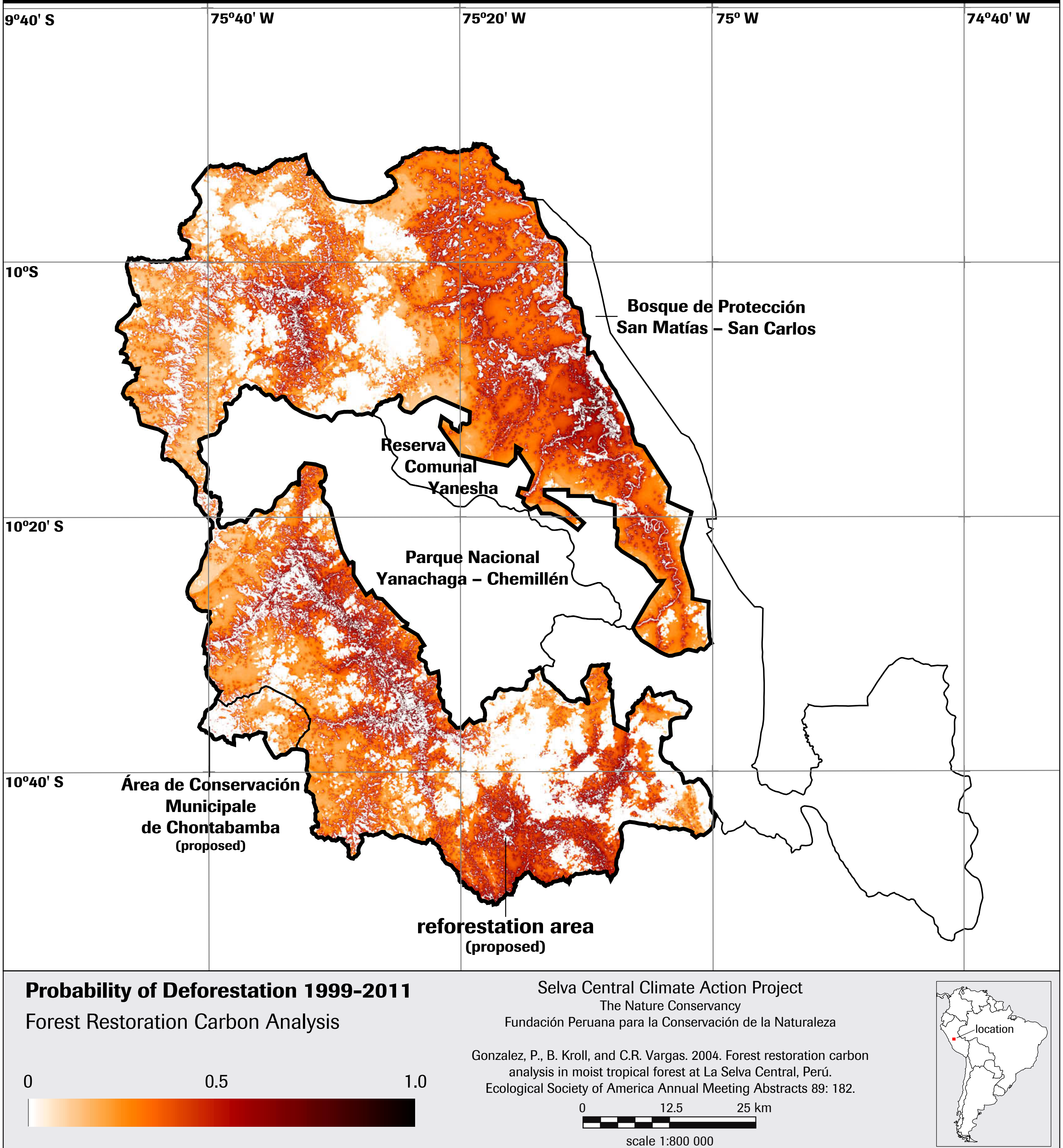


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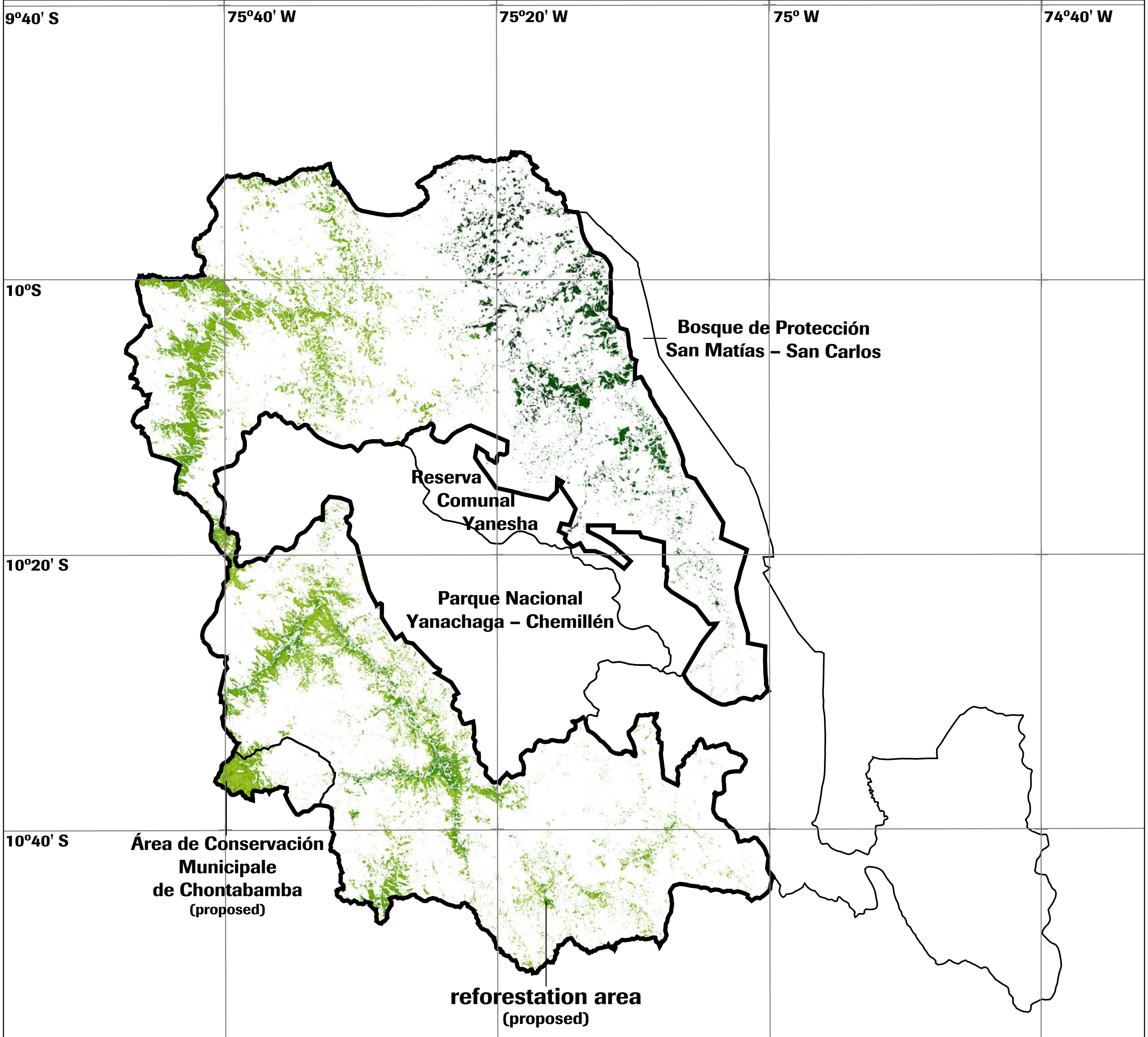
Figure 15.

Selva Central, Perú



Probability of Reforestation 1999-2011

Forest Restoration Carbon Analysis

0 0.5 1.0

Selva Central Climate Action Project

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Fundación Peruana para la Conservación de la Naturaleza

Gonzalez, P., B. Kroll, and C.R. Vargas. 2004. Forest restoration carbon analysis in moist tropical forest at La Selva Central, Perú. Ecological Society of America Annual Meeting Abstracts 89: 182.

0 12.5 25 km

scale 1:800 000

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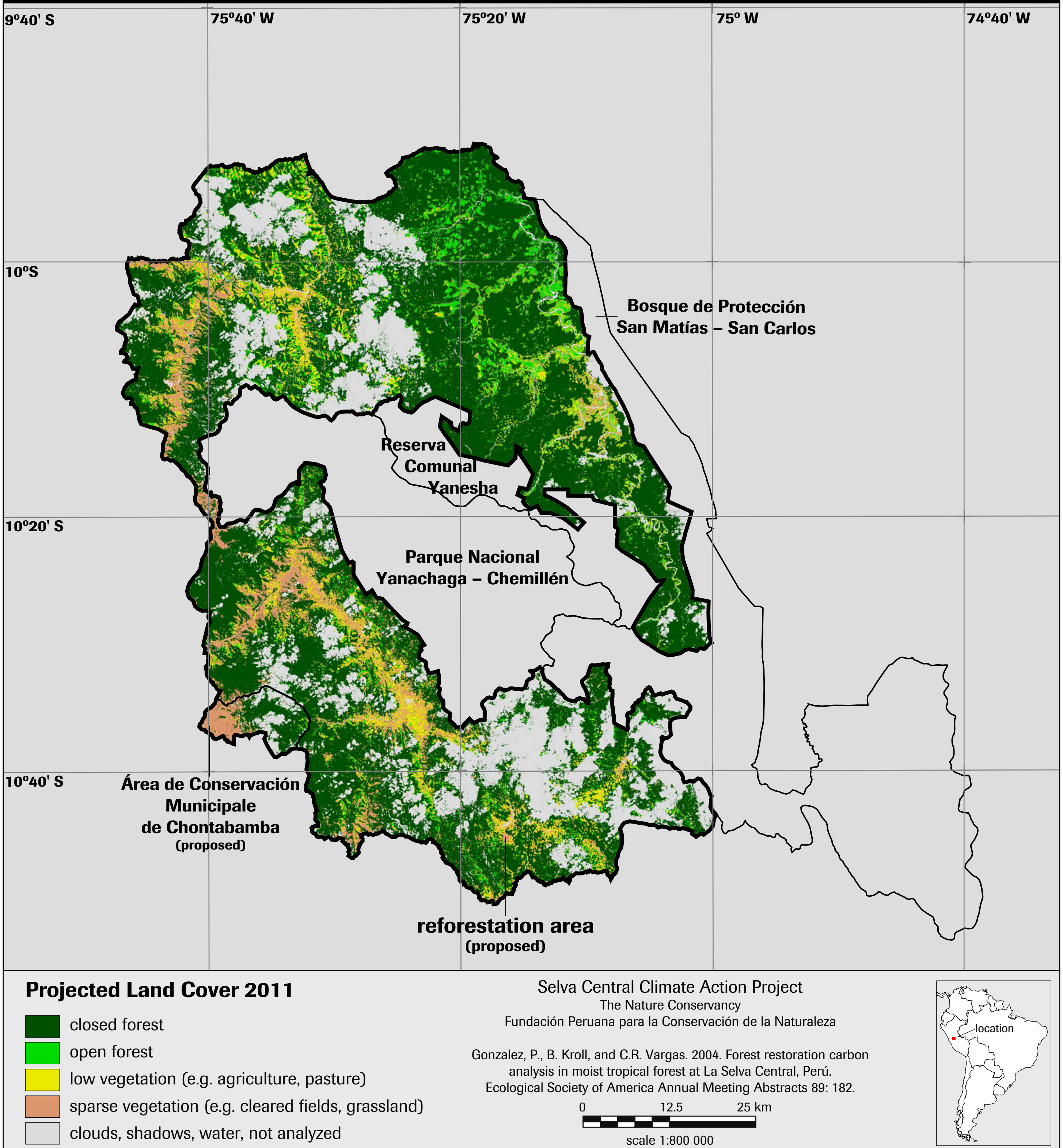
PRO NATURALEZA

Figure 16.

Selva Central, Perú



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Gonzalez, P., B. Kroll, and C.R. Vargas. 2004. Forest restoration carbon analysis in moist tropical forest at La Selva Central, Perú. Ecological Society of America Annual Meeting Abstracts 89: 182.

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Figure 17.

Selva Central, Perú

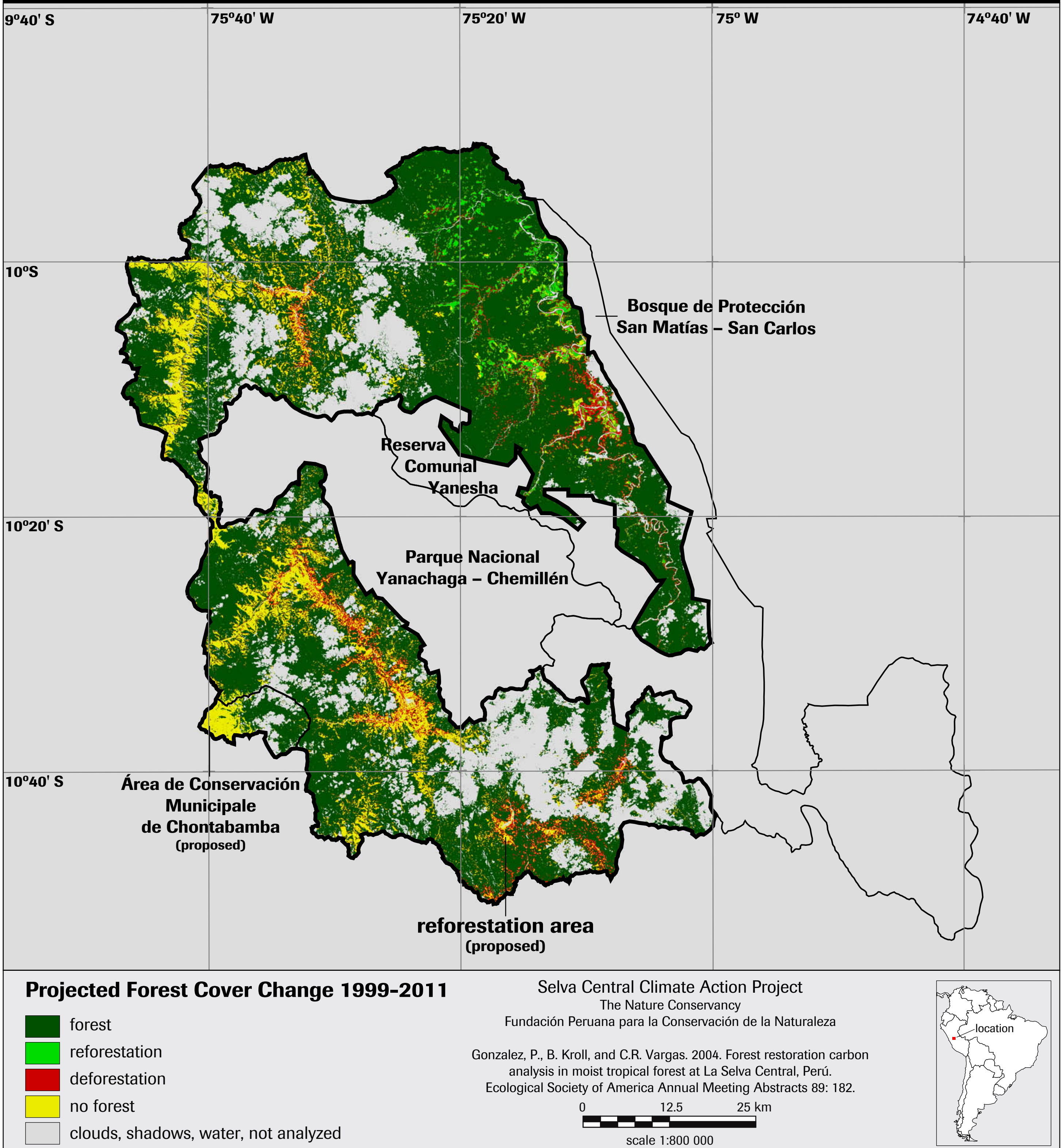

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Table 13. Observed forest cover change 1987-1999, projected forest cover change 1999-2011, Selva Central, Peru.

forest change	gross change 1987-1999 ha	gross change 1987-1999 y^{-1}	central 1999-2011 ha	high 1999-2011 ha	low 1999-2011 ha	central 1999-2011 y^{-1}	high 1999-2011 y^{-1}	low 1999-2011 y^{-1}
forest	297 000		287 000	286 000	288 000			
reforestation	12 000	0.026	9 000	7 000	10 000	0.012	0.01	0.014
deforestation	32 000	-0.008	22 000	23 000	20 000	-0.0059	-0.0062	-0.0055
no forest	26 000		49 000	51 000	48 000			
total non-cloud land	**366 000**		366 000	366 000	366 000			

Table 14. Estimated 2006-2035 forest carbon sequestration of the Selva Central project.

reforestation carbon sequestration	area (ha)	central estimate (t)	high estimate (t)	low estimate (t)
natural regeneration	5 600	270 000	170 000	370 000
contour plantation	1 400	40 000	30 000	60 000
sum	7 000	310 000	200 000	430 000
baseline reforestation	2600±400	70 000	40 000	120 000
project additional carbon		**230 000**	**160 000**	**310 000**

conservation avoided deforestation	area (ha)	central estimate (t)	high estimate (t)	low estimate (t)
Chontabamba	7000	10 000	14 000	8 000

Step 12 Projection of future baseline carbon emissions and removal

Baseline carbon emissions in the proposed 7000 ha *Área de Conservación Municipale de Chontabamba* would total 10 000 t (min. 6 000 t, max. 18 000 t) in the period 2006-2035. Baseline carbon removal in the proposed 7000 ha of *fajas de enriquecimiento* would total 73 000 t carbon (min. 30 000 t, max. 120 000 t) in the same period.

Aboveground carbon in live vegetation in the project area decreased from 35 million ± 4 million t in 1987 to 34 million ± 4 million t in 1999. Projected aboveground carbon in live vegetation would fall to 33 million ± 4 million t in 2006, 32 million ± 4 million t in 2011, and 29 million ± 3 million t in 2035 (Figure 18). Projected net baseline carbon emissions in the entire 4800 km^2 research area would total 4.1 million t (min. 3.2 million t, max. 5.1 million t) in the period 2006-2035.

Step 13 Estimation of future carbon sequestration due to the proposed forest project

The proposed 7000 ha *Área de Conservación Municipale de Chontabamba* could avert carbon baseline emissions of 10 000 t (min. 6 000 t, max. 18 000 t) in the period 2006-2035.

The proposed 7000 ha of *faja de enriquecimiento* (contour planting) could produce 310 000 t (min. 170 000 t, max. 430 000 t) carbon in the period 2006-2035. Therefore, the proposed reforestation project could sequester 230 000 t (min. 140 000 t, max. 310 000) additional carbon above baseline carbon removal in the period 2006-2035 (Figure 19, Table 14).

Figure 18. Aboveground carbon in the research area 1987-2035.

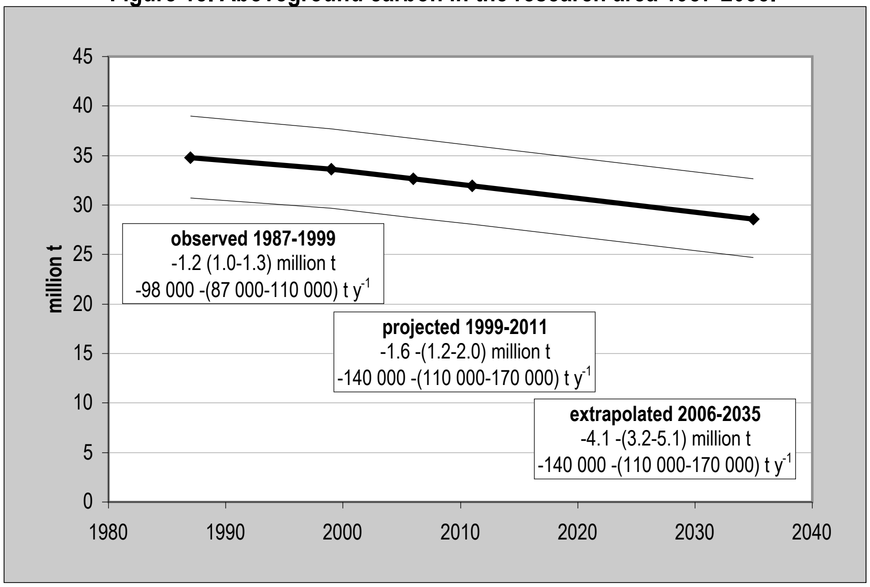
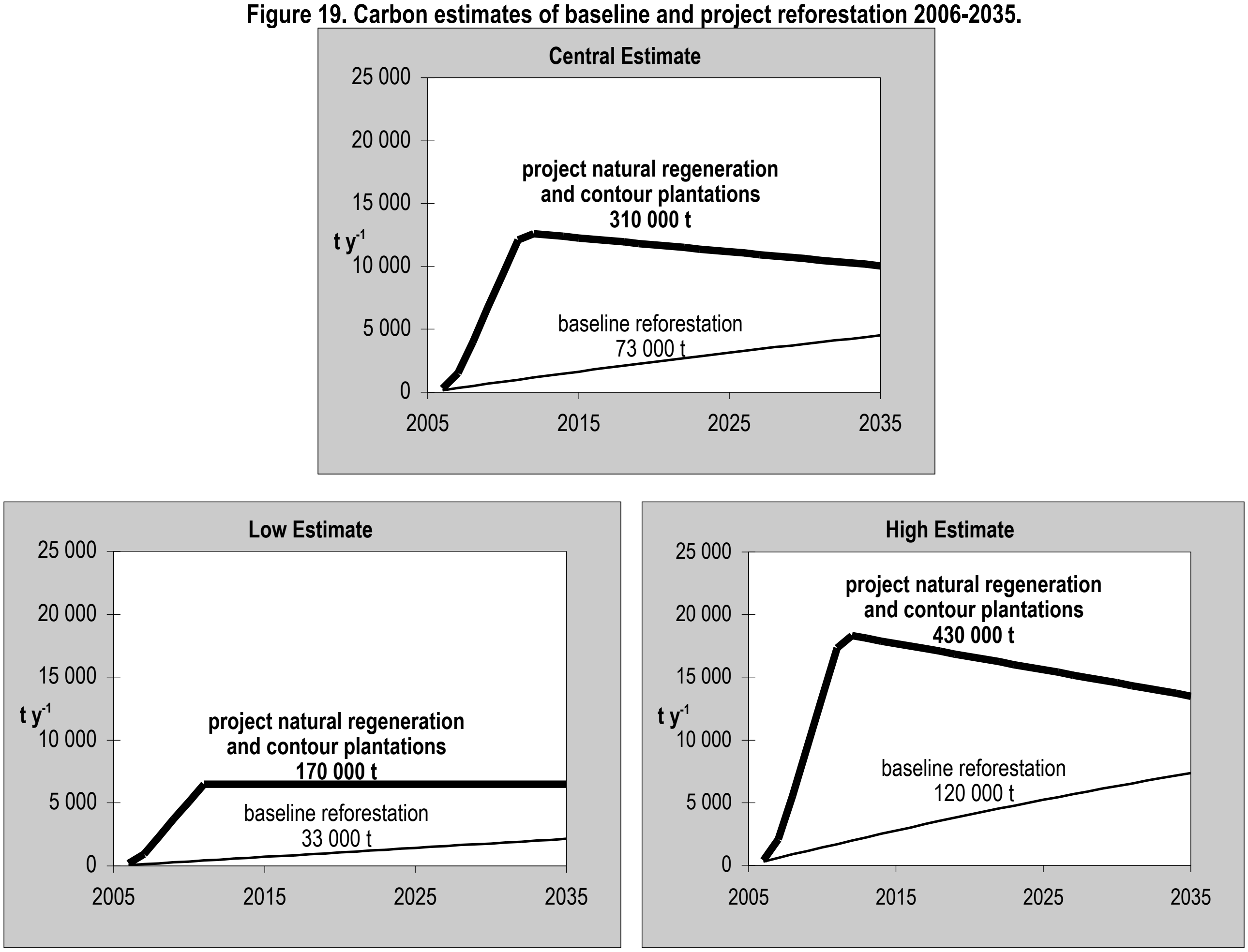


Figure 19. Carbon estimates of baseline and project reforestation 2006-2035.



Conclusion

This applied research has produced new forest inventory and remote sensing data on forest species patterns, measures of conservation success, forest carbon density, and deforestation threats. The data reveal that Selva Central harbors significant biological diversity and important stores of forest carbon. A planned forest conservation and reforestation project could significantly increase the provision of ecological services of this tropical rainforest. Through this applied research, we have developed forest restoration carbon analysis (FRCA), a method that assesses forest species patterns, quantifies deforestation and reforestation rates, and projects future baseline carbon emissions and removals in the restoration of biologically significant forests.

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