

Carbon Pools and Emissions from Deforestation in Extra-Tropical Forests of Northern Argentina Between 1900 and 2005

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ABSTRACT

We estimated carbon pools and emissions from deforestation in northern Argentine forests between 1900 and 2005, based on forest inventories, deforestation estimates from satellite images and historical data on forests and agriculture. Carbon fluxes were calculated using a book-keeping model. We ran 1000 simulations for a 105-year period with different combinations of values of carbon stocks (Mg C ha^{-1}), soil carbon in the top 0.2 m, and annual deforestation series. The 1000 combinations of parameters were performed as a sensitivity analysis that for each run, randomly selected the values of each variable within a predefined range of values and probability distributions. Using the simulation outputs, we calculated the accumulated C emissions due to deforestation from 1900 to 2005 and the annual emission as the average of the 1000 simulations, and uncertainties of our estimates as the standard deviation. We found that northern Argentine forests contain an estimated 4.54 Pg C (2.312 Pg C in biomass and 2.233 Pg C in soil). Between 1900 and 2005 approximately 30% of the forests were deforested, yielding carbon emissions

of 0.945 (SD = 0.270) Pg C. Estimated average annual carbon emissions between 1996 and 2005, mostly from deforestation of the Chaco dry forests, were 20,875 (SD = 6,156) Gg C y^{-1} (1 $\text{Gg} = 10^{-6}$ Pg). These values represent the largest source of carbon from land-cover change in the extra-tropical southern hemisphere, between 0.9 and 2.7% of the global carbon emissions from deforestation, and approximately 10% of carbon emissions from the Brazilian Amazon. Deforestation, which has accelerated during the last decades as a result of modern agriculture expansion, represents a major national source of greenhouse gases and the second emission source, after fossil fuel consumption by fixed sources. We conclude that Argentine forests are an important carbon pool and emission source that need more attention for accurate global estimates, and seasonally dry forest deforestation is a key component of the Argentine carbon cycle.

Key words: carbon pool; carbon emissions; forest biomass; deforestation; book-keeping model; *Chaco*; *Yungas*; Atlantic Forest; soybean.

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INTRODUCTION

Forests play a major role in the global carbon cycle and deforestation is a major source of global carbon

emissions to the atmosphere (Houghton 2003a). Although the importance of deforestation for global change is indisputable, there are uncertainties in its quantification, which in turn are reflected in important differences in annual carbon flux estimates from tropical deforestation (Houghton 2003b) and ongoing debates about deforestation rates (Eva and others 2003; Fearnside and Laurence 2003, 2004). Most estimates use historical records of forest and croplands (Houghton 1999; Houghton and others 1991a, b) and/or country level statistics of forest cover compiled by the Forest Resource Assessment program (FRA) of the Food and Agriculture Organization (Houghton 2003a). However, despite methodological improvements and the use of remote sensing data in most countries for the 1990 and 2000 FRA analyses (FAO 1993, 2001), the program shows important inconsistencies, particularly in the tropical forest area time series (Grainger 2008), and significant uncertainties remain. Other recent efforts to improve estimates are based on improved satellite image analyses of tropical deforestation (Achard and others 2004; De Fries and others 2002) and estimates of carbon pools and fluxes from ground-based forest inventory data (Goodale and others 2002; Houghton 2005).

Current global estimates indicate an overall pattern of carbon sinks in the northern hemisphere due to forest re-growth and carbon sources in the tropics due to deforestation. This generalization largely neglects the effects of extra tropical land-use cover change (LUCC) in the southern hemisphere. For example, the last revision by Houghton (2003a) considered that the temperate areas of the southern hemisphere have no major LUCC. Dixon and others' (1994) estimate of world forest carbon pools and fluxes only included Australia for the southern hemisphere. Achard and others (2004) and Fearnside (2000) did not include Chile, Argentina and Uruguay in their estimates of emissions for Latin America. Only early works by Houghton and others (1991a, b) considered all countries of South America, but they used poor quality maps in the subtropical area. Argentina has the largest extra-tropical forest area in South America and the largest area of dry shrublands in the world (Sanderson and others 2002). But, in maps used by Houghton and others (1991a) most subtropical forests of northern Argentina are mapped as grassland or deserts, hence, agriculture expansion in these areas was not considered as deforestation. Later analyses by Houghton (1999, 2003a) included historical LUCC of Argentina but did not include deforestation in the north of the country,

the region with the largest forested area and the most dynamic agriculture frontier.

Northern Argentina has extensive forest ecosystems, including the southern end of the tropical montane Andean forests (*Yungas*); more than half of the *Chaco* (the largest remaining continuous dry forest in America); and the largest remaining continuous area of Atlantic Forest. Similarly to their tropical counterparts in Bolivia, Paraguay, and Brazil, these ecosystems are undergoing rapid deforestation due to a combination of favorable conditions for agribusiness oriented to global markets and climatic change (Boletta and others 2006; Gasparri and Grau 2006; Grau and others 2005a, b; Zak and others 2004). As a result, Argentina currently experiences the 16th highest absolute deforestation rate and the highest outside the tropics (FAO 2007). Preliminary estimates of carbon emission from deforestation in Argentina suggested this process is a major source of carbon at the country scale (Gasparri and Manghi 2004).

During the last decade, Argentina has set an extensive system of forest inventory plots and a detailed satellite-based assessment of land-cover change between 1997 and 2006. Additionally, works of Boletta and others (2006), Grau and others (2005a) and Zak and others (2004) assessed deforestation in large fractions of these forests since the early 1970s using Landsat satellite images. We took advantage of these data sources and made historical estimates of national deforestation (1900–1989) to compute carbon pools in Argentine subtropical forests and carbon emission due to deforestation from 1900 to 2005. Based on this, we assessed the relative role of Argentine subtropical forest in the national and global carbon cycle and revised the impact of deforestation in the country carbon budget compared with previous estimates for Argentine green house gases.

MATERIALS AND METHODS

Study Area and General Approach

We analyzed the three main forest ecosystems of northern Argentina (from 22° to 33° S): *Chaco* Forest, Atlantic Forests, and *Yungas* Forest (Figure 1). Together, these three ecosystems represent more than 95% of the Argentine forests north of 33° S. The other subtropical forest types (for example, *Prosopis* open woodland in arid zones) likely contain much lower per-hectare biomass and have not experienced significant deforestation. Major ecosystems of Argentina located south of 33° S, not included in this analysis, are 80 million hectares of temperate

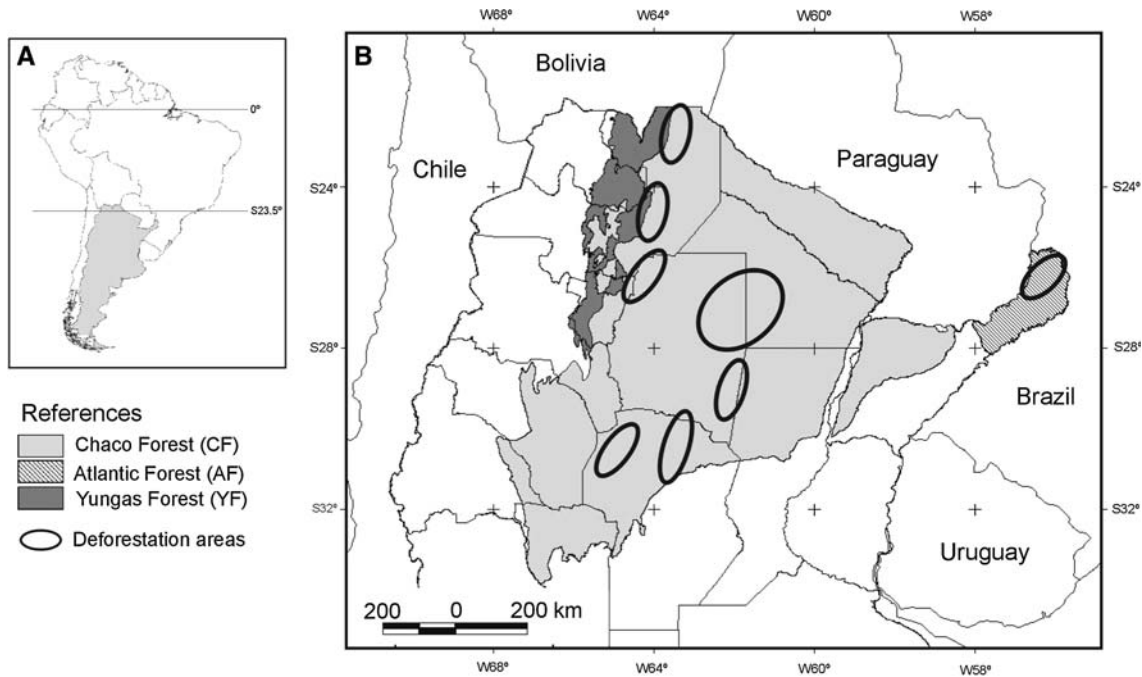


Figure 1. Study area with major forest ecosystems of extra-tropical northern Argentina (UMSEF) and current deforestation areas.

shrublands and savannas (*Monte* and *Espinal*, sensu Cabrera 1976) and the temperate Patagonic Forests (2 million ha sensu SAYDS 2004). *Chaco* Forest is the largest Argentine forest ecosystem with 23 million hectares in the country in 1998 (SAYDS 2004). It is a seasonally dry forest with a summer rainy season. The forest structure and diversity reflects a rainfall gradient from 1200 mm y^{-1} to less than 400 mm y^{-1} (Cabrera 1976; Prado 1993). Argentine *Chaco* is undergoing rapid deforestation (Boletta and others 2006; Grau and others 2005a; Zak and others 2004) largely driven by global factors, including expanding global soybean markets and regional rainfall increase (Grau and others 2005b).

The *Yungas* Forest is an evergreen and semi-evergreen forest that extends along an elevation gradient from 400 to 3000 m in the foothills and eastern slopes of the Andes from Bolivia to the NW of Argentina (Brown and others 2001). In Argentina, *Yungas* Forest covered 3.7 million hectares in 1998 (SAYDS 2004). Although the montane sectors of the *Yungas* are not experiencing deforestation, the drier lowland sector (*Selva Pedemontana*), with flat topography, annual rainfall above 1000 mm y^{-1} , and deep fertile soils, have been partially cleared for agriculture (mostly sugar cane and citrus) during the 19th and 20th centuries; and underwent a re-acceleration of agriculture expansion (mostly soybean) during the last two decades (Brown and Malizia 2004; Gasparri and Grau 2006).

The Atlantic Forest is an evergreen, highly diverse, humid (about 2000 mm y^{-1}) forest, located in the NE corner of Argentina, which currently covers approximately 1.2 million hectares (Placci and DiBitetti 2006; SAYDS 2004). Because this forest is the largest remaining continuous patch of the southern portion of this ecosystem (which also extends into Brazil and Paraguay), it is considered a global conservation priority. Atlantic Forests of Argentina face transformation for forestry plantations and shifting cultivation in a complex socio-economic context including population migration from Brazil to Paraguay.

We combined forest area (ha) and average carbon stocks estimated from national inventory samples of each forest ecosystem (Mg C ha^{-1}) to calculate carbon pools (Pg C). We estimated absolute annual deforestation for the period 1900–2005 using original forest area reported in the literature, historical statistics of the cultivated area for major regional crops growing on areas where potential vegetation is forests, and recently published spatially explicit assessments of deforestation. Most data for annual deforestation in the period 1990–2005 are from the Argentine Forest Monitoring Program, based on interpretation of Landsat satellite images (UMSEF 2007). We combined absolute annual deforestation (ha y^{-1}) with average carbon stocks of each forest ecosystem in a book-keeping model (Houghton 2003a, b) to estimate

annual carbon emission (Mg C y^{-1}), including historical deforestation (1900–1990) in the models to avoid underestimates of current emissions (Ramankutty and others 2006). And, we report accumulated carbon emissions from 1900 to 2005 (Pg C) and average annual carbon emission for the last 10 years (Gg C y^{-1}).

Biomass and Carbon Pools Estimates

We estimated an average carbon stock per hectare (Mg C ha^{-1}) for each forest ecosystem, based on data from plots surveyed by Argentina National Forest Inventory in 1999 and 2000, the most updated and comprehensive sampling effort in Argentina. For the *Yungas* Forest, we used 65 sample plots of 0.5 ha (10×500 m) located in a 20 by 20 km grid distributed across an area of about 200 by 700 km ($22\text{--}28^\circ$ S). For the *Chaco* Forest we used 55 sample plots of 0.8 ha (10×800 m) located in a grid of 50 by 50 km distributed across an area of continuous forest of about 500 by 400 km ($22\text{--}28^\circ$ S and $60\text{--}64^\circ$ W). For Atlantic Forest, we used 120 sample plots of 0.5 ha (clusters of five 10 by 100 m plots) located in a grid of 10 by 10 km distributed across an area of about 160 by 80 km ($24.5\text{--}27^\circ$ S and $54\text{--}55^\circ$ W). In all cases, sampling consisted of standard forest inventory procedures including measuring diameter at breast height (dbh) and height estimation of all trees with dbh greater than 10 cm (PINBN 2007).

To estimate aboveground biomass (AGB) we used allometry functions from Chave and others (2005) for trees, and Frangi and Lugo (1985) for palms (Table 1). We used the wood density (oven-dry mass per unit of green volume) from the database of INTI-CITEMA (2007), which includes more than 200 species. For species without wood density data (20%) we applied the regional average. Finally, using data for AGB from each sample plot, we calculated the region average and its confidence interval at 90% of probability (computed as the multiplication of the standard error of

the mean from the inventory by the t value obtained from Student's t distribution with 90% of probability and $n - 1$ degrees of freedom).

For other carbon compartments (AGB of understory vegetation; belowground biomass; dead wood biomass; litter and soil organic carbon (SOC) in the top meter of soil) we used different sources and procedures. We estimated the AGB of understory vegetation (including tress with $\text{dbh} < 10$ cm) as 3% of the AGB of inventoried trees ($\text{dbh} > 10$ cm) (Brown 1997), and belowground biomass and dead wood as a proportion of the AGB (IPCC 2003, 2006). For litter and SOC in the top 0.2 m we used data from local studies in *Chaco* (Abril and Bucher 2001) and Atlantic Forest (Vaccaro and others 2003) and values from the IPCC (2003) for *Yungas* Forest. Finally SOC in the top meter of soil was estimated by assigning fractions for different soil depths (at 0.2 m intervals) according to climate and vegetation types following Jobbagy and Jackson (2000). Details on computations are presented in Table 2. For all the regions and compartments we assumed that 50% of the biomass is carbon.

Additionally, we included the carbon pool in shrublands for the three forest ecosystem. We used data from Vaccaro and others (2003) for ABG in shrublands of Atlantic Forest. For *Chaco* forest we computed a synthetic “typical” shrubland vegetation structure, defined as a monospecific stand of the most common species (*Larrea divaricata*) with 1400 plants 3 m tall that represent a total site cover. This structure represents an ABG of 14 Mg ha^{-1} (10 kg each individual) based on the allometry function developed for this species (Gaillard de Benitez and others 2002). For *Yungas* Forest, biomass data of shrublands are not available and we arbitrarily assumed that shrublands have half the carbon stock of the forest. Following previous work that found no clear differences between SOC in shrublands and forests (Bonino 2006), we used the same values for shrublands and forest SOC in the three regions. The shrubland area was an estimation based on satellite image interpretation

Table 1. Allometry Functions Used to Calculate AGB of Trees in the Different Regions

Applied to	Function
<i>Chaco</i> Forest ^a (trees $\text{dbh} < 60$ cm)	$(\text{AGB}) = p * \exp(-0.667 + 1.784 \ln(D) + 0.207(\ln(D))^2 - 0.0281(\ln(D))^3)$
<i>Chaco</i> Forest ^a (trees $\text{dbh} > 60$)	$\ln(\text{AGB}) = 1.589 + 2.284 \ln(D) + 0.129(\ln(D))^2 - 0.0197(\ln(D))^3 + \ln(p)$
Atlantic Forest and <i>Yungas</i> Forest ^a (all trees)	$(\text{AGB}) = p * \exp(-1.499 + 2.148 \ln(D) + 0.207(\ln(D))^2 - 0.0281(\ln(D))^3)$
Palms in all regions ^b	$\text{AGB} = 10 + 6.4 * \text{TH}$

(AGB) aboveground biomass; (p) oven dry wood over green volume; (D) diameter at the breast height; (TH) total height. ^aChave and others (2005); ^bFrangi and Lugo (1985).

Table 2. Biomass Estimates and Carbon Stock for Each Forest Ecosystem

	Chaco Forest	Atlantic Forest	Yungas Forest
AGB in trees (dbh > 10 cm) ^a (Mg ha ⁻¹)	78(±7.9)	256.5(±14.7)	199.7(±23.5)
AGB in understory vegetation ^b (Mg ha ⁻¹)	2.3	7.7	5.9
Biomass below ground ^c (Mg ha ⁻¹)	22.5	63.4	45.3
Biomass in dead wood ^d (Mg ha ⁻¹)	10.9	28.2	22.0
Carbon in litter (Mg C ha ⁻¹)	2.3 ^e	5.0 ^f	2.8 ^g
Total carbon in biomass (Mg C ha ⁻¹) ⁱ	59.2(±5.7)	182.9(±10.2)	139.3(±16.1)
Carbon in top 0.2 m soil (Mg C ha ⁻¹) ⁱ	31 ^e	35 ^f	65 ^g
Carbon in top meter soil ^h (Mg C ha ⁻¹)	51.8	54.6	108.6

^aValues of AGB in trees with dbh greater than 10 are calculated with data from the national forest inventory (90% confidence intervals are given in parentheses); ^bCalculated as 3% of the AGB in trees with dbh greater than 10 (Brown 1997); ^cCalculated as 28% of AGB for Chaco forest, 24% for Atlantic Forest and 22% for Yungas Forest (IPCC 2006); ^dCalculated as 14% of AGB in Chaco forest and 11% in Atlantic and Yungas Forest (IPCC 2003); ^eValue from Abril and Bucher (2001) for moderately degraded forests; ^fValue from Vaccaro and others (2003) for intermediate succession stage; ^gDerived from IPCC (2003) methods; ^hValues calculated assuming that carbon in the top 0.2 m of soil represents 33% in Chaco and Yungas Forest and 44% in Atlantic Forest of carbon in top meter soil (Jobbagy and Jackson 2000); ⁱCarbon stocks employed in the book-keeping model simulations.

for the year 1998 from the Argentina National Forest Inventory (SAyDS 2004).

To estimate C pools, we used C stock per hectare (Table 2) and the above described estimates for shrublands, multiplied by the forest/shrublands area in 1998 estimated for the Argentina National Forest Inventory (SAyDS 2004).

Deforestation

To estimate annual deforestation from 1900, we used different approaches depending on data availability for each region. We used literature references for original forest area, statistics of major crops and recent work with spatially explicit data of deforestation derived from remote sensing analyses to estimate deforestation rates. Most information on deforestation between 1990 and 2005 is based on the national forest monitoring program. This program uses the definition of forest from the FRA initiative adapted for Argentina: forests are defined as sites with tree cover over 20%, mapped by visual interpretation of Landsat images (UMSEF 2007). The method has an accuracy of more than 80% (UMSEF 2007; Grau and others 2005b).

Atlantic Forest area in 1900 was estimated at 2.6 ± 0.2 million hectares using the average value of four sources: Laclau (1994), MERNRyT (2004), Placci and Dibitetti (2006), and PLN (1948). Annual deforestation was calculated by periods using forest cover data cited in Laclau (1994) for 1930 and in MERNRyT (2004) for 1960, 1970 and 1985, assuming constant rates within each period. For the period 1990–2005, we assumed a constant absolute annual deforestation (ha y⁻¹) rate equal to that estimated by the Forest Monitoring Program of Argentina (UMSEF 2007) between 1998 and 2002

and with the forest area of 1998 (SAyDS 2004) as baseline, we computed the forest area in the years 1990 and 2005.

Yungas Forest area in 1900 was estimated at 4.2 million hectares obtained by adding the current forest area to the current cropland area within the eco-region –30% of the cropland area that was likely deforested prior to 1900 (Pacheco and Brown 2006; Gasparri and Menendez 2004). To estimate deforestation from 1900 to 1980, we used the expansion rate of sugar cane, which has ecological requirements that correspond to the area of *Selva Pedemontana* (the low-elevation sector of the Yungas forest) and was the principal economic driver for the NW Argentina agriculture expansion. To estimate deforestation, we used the area of sugar cane reported in Ferreres (2005) in years that represent temporal maxima in the time series (1910, 1915, 1929, 1936, 1940, 1945, 1950, 1956, and 1979). For the period 1990–2005 we assumed a constant annual deforestation rate (ha y⁻¹) equal to that estimated by the Forest Monitoring Program of Argentina (UMSEF 2007) between 1998 and 2002 and with the forest area of 1998 (SAyDS 2004) as baseline, we computed the forest area in years 1990 and 2005.

For the Chaco Forest area in 1900, we produced two alternative estimates: (1) using 9.5 million hectares deforested by 1990, as estimated by Cozzo (1992) based on literature and expert opinions; and (2) using 7.5 million hectares deforested by the year 2000, as estimated by Brown and Pacheco (2006) based on the combination of a continental land-cover map (Eva and others 2004) and an updated Argentine eco-regions map. We used literature sources that quantify deforestation since about 1970 in different sectors of the region using

Landsat images: Grau and others (2005b) for eastern Salta, our own unpublished data for eastern Tucumán, Zak and others (2004) for Córdoba, and UMSEF data from the national forest monitoring program for other provinces (Catamarca Chaco, Formosa, Jujuy, Santiago del Estero, Santa Fe, San Luis and La Rioja). The UMSEF's data cover the entire region for the period 1998–2002 and more than 80% for the periods 1990–1998 and 2002–2005. Deforestation inferred from remote sensing analyses adds up to 5 million hectares in 2005. Additionally we used the cultivated area of cotton to estimate the deforestation in Chaco and Formosa provinces from 1900 to 1990 following the same approach that we used for sugar cane in *Yungas* forests. In this case, we considered that increases in cotton area (Ferrerres 2005) represent 90% of the total agriculture expansion, based on Manoilloff (2001) who reported cotton represented 90% of the cultivated area in 1950 in Chaco province (the principal cotton producer area of Argentina). We calculated the accumulated deforestation from remote sensing methods and cotton expansion in 1990 and we subtracted this amount from the 9.5 million hectares estimated by Cozzo (1992) and the difference was used to calculate a constant absolute additional annual deforestation value from 1900 to 1990. We repeated the same procedure with the 7.5 million hectares estimated by Brown and Pacheco (2006). Hence, the use of Cozzo's and Brown and Pacheco's estimates of deforested area yielded two additional alternative constant deforestation rates not explained with remote sensing data or cotton crop expansion.

Carbon Flux from Deforestation and Simulations

We estimated gross carbon emission from deforestation. To calculate emission during the clearing events and decomposition of dead organic material left on site, we assumed that all the deforested area in *Yungas* Forest and *Chaco* Forest is converted to agriculture and in Atlantic Forest to shifting cultivation. We assumed that both agriculture and forests have a stable carbon balance, and that gross emissions are only due to forest conversion (that is, we did not compute carbon fluxes due to selective logging, fires, reforestation, forest regrowth, or new industrial forest plantations replacing native forests). Although this assumption limits the accuracy of short-term estimates, it should not be a major error source for the overall trends because these processes are expected to balance themselves.

To estimate annual carbon emissions, we applied the book-keeping method (Houghton 2003a, b) that is commonly used to estimate carbon emission from deforestation (Achard and others 2004; De Fries and others 2002; Houghton 2003a, 1999; Houghton and others 1991b). When a forest is cleared, biomass (above- and below-ground, dead biomass and litter) can follow four different pathways, which release carbon at different rates (Houghton 1999): (1) the fraction burnt on site generates emissions to the atmosphere in the year of clearing; (2) the fraction left on site decomposes exponentially at different rates depending on climate and characteristic of the material ($0.1\text{--}0.4\text{ y}^{-1}$); (3) the fraction removed as forest products turns over with time constants, typically 0.1 y^{-1} ; and (4) the small fraction converted to elemental carbon decomposes at a very slow rate (0.001 y^{-1}). In addition, a fraction of soil carbon is released to the atmosphere in 25 years. Houghton and others (1991b) and Houghton (2003a) assume that the soil carbon emission is a fraction of the top meter, but in our work we considered that the soil carbon emissions are only from the top 0.2 m. These different carbon turn over rates imply that fractions of the emissions originated in a particular deforestation event occur gradually during several following years. Therefore, for accurate estimations of carbon emission using the book-keeping model, historical deforestation records are necessary (Ramankutty and others 2006).

For calculations of carbon fluxes before 1990 we used parameters (turnover rates and fractions of carbon removed or left on site) used by Houghton and others (1991b) to estimate emission from South America; considering the dominant land-use type after conversion: permanent crops for *Chaco* and *Yungas* and shifting cultivation in Atlantic Forest. For the period after 1990, in *Chaco* Forest and *Yungas* Forest we used specific parameters that we considered more appropriate for current deforestation practices in Argentina. In these systems, heavy machinery is used for clearing and most belowground biomass is exposed and burned on site, and large roots are removed to facilitate future agriculture machinery operations. In addition, exports of wood products are negligible due to comparatively high costs. In consequence, in the last 15 years, we increased the carbon fraction for combustion and reduced the fractions assigned to forest products and carbon left on site as debris and slash (Table 3). Similar modifications have been suggested in Mato Grosso (Brazil), with similar agriculture and deforestation practices (Morton and others 2006).

Table 3. Parameters for Simulations in Each Forest Ecosystem

		<i>Chaco</i> Forest	Atlantic Forest	<i>Yungas</i> Forest
From 1900 to 1990	Fractions (e; p; c; d)	(0.02; 0.30; 0.30; 0.38)	(0.02; 0.35; 0.30; 0.33)	(0.02; 0.30; 0.30; 0.38)
	Turn over rates (i; j; k)	(0.001; 0.1; 0.30)	(0.001; 0.1; 0.40)	(0.001; 0.1; 0.40)
	SOC depletion	25% in 25 years	15% in 2 years	25% in 25 years
From 1990 to 2005	Fractions (e; p; c; d)	(0.02; 0.08; 0.55; 0.35)	(0.02; 0.35; 0.30; 0.33)	(0.02; 0.08; 0.55; 0.35)
	Turn over rates (i; j; k)	(0.001; 0.1; 0.30)	(0.001; 0.1; 0.40)	(0.001; 0.1; 0.40)
	% SOC depletion	15% in 25 years	15% in 2 years	15% in 25 years

(e) Carbon fraction to elemental carbon; (p) carbon fraction removed from site as products; (c) carbon fraction burned on site; (d) carbon fraction left on site; (i) constant of decomposition for elemental carbon; (j) constant of turn over for carbon in products removed from site; and (k) constant of decomposition for carbon left on site as slash and debris.

In Atlantic Forest 15% of the carbon in the soil was assumed to be depleted at a constant rate during the first 2 years following deforestation. In *Chaco* Forest and *Yungas* Forest for the period prior to 1990 we assumed carbon loss is 25% of the original SOC (Houghton and others 1991b) from the top 0.2 meter of soil. For years after 1990 we arbitrarily reduced the fraction of carbon loss from the top 0.2 m of soil to 15% from the 25% used from 1900 to 1990. We made this reduction because the dominant crop in deforested areas is herbicide resistant transgenic soybean cultivars managed with no-till practices, which conserve more SOC than conventional tillage (Grandy and Robertson 2007). Local studies in the *Chaco* region showed that after 5 years of minimum tillage, SOC incorporation in the topsoil is evident (Abril and others 2005). Our reduction in SOC loss after deforestation represents an emission reduction in *Chaco* Forest of $0.12 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ and made the soil emission from croplands with non-till, equal to emissions from shifting cultivation. Values of SOC incorporation under no-till practices in Argentina are between 0.7 and $1.2 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ after 10 years (Casas 2005), so our estimation is conservative because our reduction in estimated emissions is approximately one order of magnitude lower than the estimated gains in soil carbon through non-tillage practices.

To run the simulations, we built the book-keeping model in STELLA program (isee systems). We ran 1000 simulations for a 105-year period with different combinations of values of C stocks (Mg C ha^{-1}), SOC in the top 0.2 m of soil and annual deforestation series. The 1000 combinations of parameters were performed as a sensitivity analysis that for each run randomly selected the values of each variable within a predefined range of values and probability distributions. In the case

of C stocks (Mg C ha^{-1}) we defined a normal distribution with a mean (Table 2) and standard deviation (SD) for each forest ecosystem (*Chaco* Forest mean = $59.2 \text{ Mg C ha}^{-1}$ and SD = $25.6 \text{ Mg C ha}^{-1}$; Atlantic Forest mean = $182.9 \text{ Mg C ha}^{-1}$ and SD = $63.5 \text{ Mg C ha}^{-1}$; *Yungas* Forest mean = $139.3 \text{ Mg C ha}^{-1}$ and SD = $81.8 \text{ Mg C ha}^{-1}$). For SOC in the top 0.2 m of soil we used a constant distribution defined by minimum and maximum values. In *Chaco* forest the range was $15\text{--}70 \text{ Mg C ha}^{-1}$ (Abril and Bucher 2001); in Atlantic Forest the range was $20\text{--}40 \text{ Mg C ha}^{-1}$ (Vaccaro and others 2003), and in *Yungas* Forest we arbitrary defined a range of $50\text{--}80 \text{ Mg C ha}^{-1}$. Based on Grau and others 2005b, who found an error of 10% for cartographically derived data from the National Forest Inventory (SAyDS 2004), we multiplied deforestation in the years after 1990 in *Chaco* Forest and the complete deforestation time series of *Yungas* and Atlantic Forest by a correction factor that varied between 0.9 and 1.1 with a constant probability distribution. For years before 1990 in *Chaco* Forest, we used the deforestation times series derived from remote sensing data and cotton crop statistics plus a constant additional deforestation rate, ranging between the Brown and Pacheco's estimates ($25,941 \text{ ha y}^{-1}$) and the Cozzo's estimate ($75,521 \text{ ha y}^{-1}$) with a constant probability distribution. Parameters and fractions used in each simulation are shown in Tables 2 and 3.

Using the simulation outputs, we calculated the accumulated carbon emissions due to deforestation from 1900 to 2005 and the annual emissions for each year as the average of the 1000 simulations. To estimate the uncertainty of our estimates, we also computed the standard deviation. Additionally, for comparative analysis we computed the average annual emission for the last 10 years for each region.

RESULTS

Biomass and Carbon Stocks

Atlantic Forest showed the largest values of AGB followed by *Yungas* and *Chaco* Forest. Carbon in the top meter of soil accounts for 40% of total C per hectare in *Chaco* and *Yungas* Forest, and 23% in Atlantic Forest (Table 2). The total carbon pool of forest and shrublands was estimated at 2.31 Pg C in biomass and 2.23 Pg C in the top meter of soil. Carbon in soil is 49% of the total carbon pool in northern Argentine forests (Table 4). Forests represent 85% of the C pool and shrublands 15%. Despite its lower per hectare carbon content, the *Chaco* Forest is the largest carbon pool (58% of the total), due to its much larger area.

Deforestation

Our reconstruction of deforestation shows that the original forest area was 37.5 million hectares, 2.6 of Atlantic, 4.2 of *Yungas*, and 30.7 of *Chaco*. By 2005, 28% (10.6 million hectares) of this area was transformed into non-forest cover types. Estimated annual deforestation showed an overall increasing trend during the last 100 years. Prior to 1970, deforestation was limited due to the ecological restrictions of the dominant regional crops (sugar cane over *Yungas*, cotton over the humid portion of *Chaco* Forest, and the *Yerba Mate* in Atlantic Forest), and increased rapidly to about 50,000 ha y^{-1} afterwards, reflecting the expansion of annual crops (black beans during the 1970s and mostly soybean since the 1980s) in *Chaco* and *Yungas* Forest (Grau and others 2005b; Zak and others 2004) and monoculture tree plantations in Atlantic

Forest (MERNRyT 2004) (Figure 2A and B). Annual deforestation for different regions is shown in supplementary material: *Annual deforestation time series*.

Carbon Emissions

The annual carbon emission curve generally follows the annual deforestation curve (Figure 2C, supplementary material *Carbon emissions*). Emissions from deforestation for the 1996–2005 period were estimated at 20,875 Gg C y^{-1} (1 Gg = 10^{-6} Pg) and 75% of these emissions are from the *Chaco* Forest (Table 5). The last decade showed a decrease in deforestation rate and in consequence also in emissions for the period 1997–2002 reflecting the Argentine economic recession and 2001 crisis, but emissions for the last 3 years increased again reaching the maximum historical values in 2005, and doubling the early 1970s values (Figure 2C). The accumulated carbon emission from 1900 to 2005 in the three ecosystems was estimated at 0.945 (SD = 0.270) Pg, 69% of which corresponds to *Chaco* Forest, 23% to Atlantic Forest, and 8% to *Yungas* Forest (Figure 2D). Total carbon emissions from soil were only 8% of the total accumulated carbon emissions. Annual carbon emissions for different regions are shown in supplementary material: *Carbon emissions*.

DISCUSSION

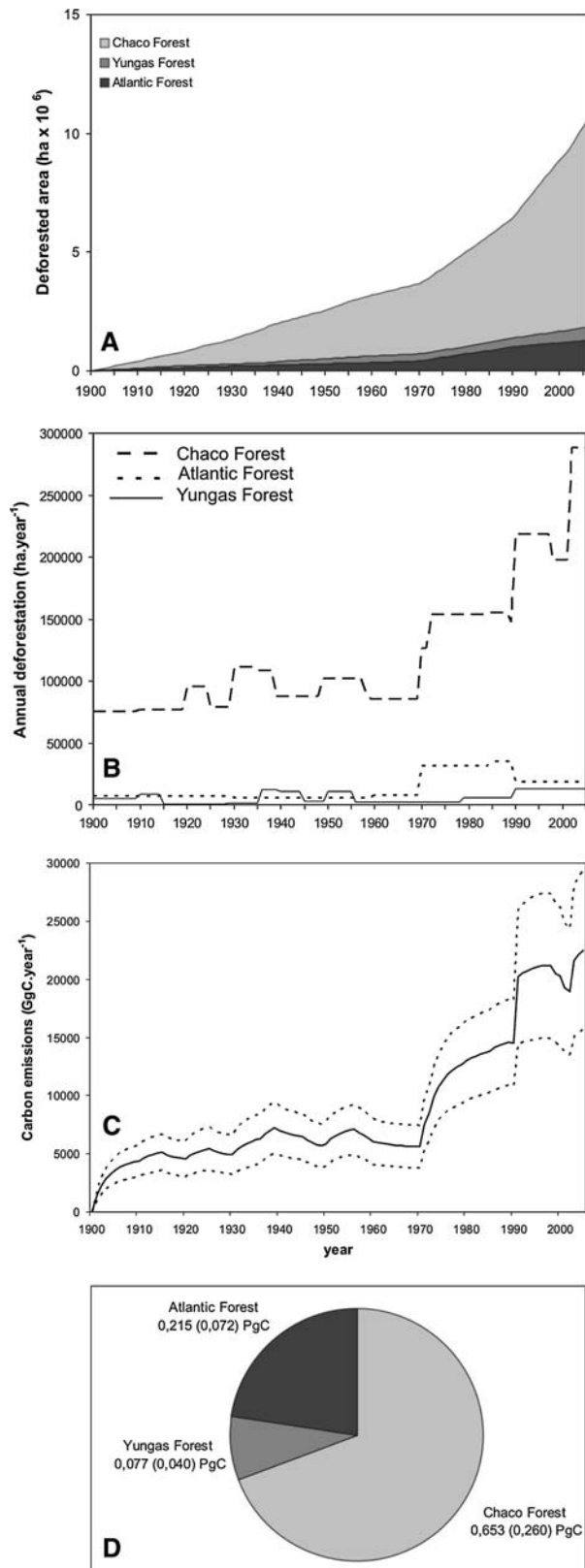
Biomass and Carbon Stocks

Our estimates of biomass stocks are generally within the range of previous studies of the same or comparable ecosystems (Table 6). The estimated

Table 4. C-Pools in Extra-Tropical Forest Ecosystems of Northern Argentina

	<i>Chaco</i> Forest	Atlantic Forest	<i>Yungas</i> Forest	Northern Argentina
Forest area ^a (ha $\times 10^6$)	23.4	1.4	3.7	28.5
Carbon in biomass (Mg C ha ⁻¹)	59.2	182.9	139.3	
Carbon in top meter soil (Mg C ha ⁻¹)	51.8	54.6	108.6	
Forest biomass C pools (Pg)	1.385	0.256	0.515	2.156
Forest soil C pool (Pg)	1.212	0.076	0.402	1.690
Forest total C pool (Pg)	2.597	0.332	0.917	3.846
Shrubland area ^a (ha $\times 10^6$)	9.9	0.05	0.2	10.2
Carbon in biomass (Mg C ha ⁻¹)	14	84	69.6	
Shrubland biomass C pool (Pg)	0.138	0.004	0.014	0.156
Shrubland soil C pool (Pg)	0.513	0.002	0.022	0.537
Shrubland total C pool (Pg)	0.651	0.007	0.036	0.694
Forest total + shrubland total (Pg)	3.248	0.339	0.953	4.540

^aData from the last complete forest area estimation of northern Argentina at year 1998 (SAyDS 2004).



AGB of *Chaco* Forest is similar to estimates in a dry sector of the Argentine *Chaco* (Bonino 2006), the *Chiquitano* dry forest in Bolivia (Dauber and others

◀ **Figure 2.** (A) Accumulated deforested area in northern Argentina between 1900 and 2005; (B) annual deforestation used in simulations; (C) simulated annual carbon emission (solid line is the average of 1000 simulations and dotted lines are \pm standard deviation); (D) accumulated carbon emission between 1900 and 2005 by forest region. Data for this figure are in supplementary material: *Annual deforestation time series* and *Carbon emissions*.

2002), *Cerradao* in Brazil (Fearnside 2000), and dry forest of Mexico (Jaramillo and others 2003). The estimated AGB of Argentine Atlantic Forest falls within the range of estimates for the same forest ecosystem in Brazil (Rolim and others 2005), and is similar to the Amazon rainforests (Fearnside 2000). Our figures for the Argentine *Yungas* are similar to Pre-Andean Amazona forest in Bolivia (Dauber and others 2002) and deciduous tropical forest in Mexico (Masera and others 1997). By using newly developed allometric functions (Chave and others 2005) we improved the quality of our previous estimates (Gasparri and Manghi 2004), yielding generally lower values. Our estimates of carbon stocks are less than 6% different than values employed in Houghton and others (1991b), but our estimates assigned comparatively more carbon to biomass and less to soil. In contrast, Achard and others (2004) used values 30–70% lower than ours, derived from FAO data.

Northern Argentina Forest Carbon Pools and Deforestation Emissions

Our estimate of 4.54 Pg C in the biomass and soil carbon pool of subtropical Argentina forest is not negligible at the global scale (Table 7). For example, aboveground biomass is equivalent to 56% of the aboveground carbon pool of Chinese forests (Pan and others 2004; Fang and others 2001). Argentina has the largest area of dry shrublands in the world (Sanderson and others 2002) and preliminary estimates indicate that adding the carbon content in 80 million hectares of temperate shrublands and savannas not included in this analysis (Monte and Espinal, sensu Cabrera 1976) and the temperate Patagonic Forests (2 million ha sensu SAYDS 2004) would double the carbon pool in woody ecosystems of Argentina for northern forests analyzed here to 8–9 Pg including SOC and biomass. Our estimate of carbon emission from deforestation in Northern Argentina in the last 10 years (20,875 Gg C \cdot year $^{-1}$) represents 2.7 and 0.9% of gross carbon emission from global tropical deforestation estimated by Achard and others (2004) and Houghton (2003a), respectively. It is two times the emissions from deforestation in the

Table 5. Recent Annual (1996–2005) and Accumulated Long-Term (1900–2005) Carbon Emissions by Region

	<i>Chaco</i> Forest	Atlantic Forest	<i>Yungas</i> Forest	Northern Argentina
Annual carbon emissions (biomass and SOC) 1996–2005 (Gg C y ⁻¹)	15,803 (SD = 6,037)	3,332 (SD = 1,121)	1,740 (SD = 935)	20,875 (SD = 6,156)
Annual carbon emissions from soil 1996–2005 (Gg C y ⁻¹)	1,463 (SD = 548)	74 (SD = 14)	99 (SD = 13)	1,629 (SD = 548)
Accumulated carbon emissions 1900–2005 (biomass and SOC) (Pg)	0.653 (SD = 0.260)	0.215 (SD = 0.072)	0.077 (SD = 0.040)	0.945 (SD = 0.270)
Accumulated carbon emissions from soil 1900–2005 (Pg)	0.065 (SD = 0.025)	0.005 (SD = 0.001)	0.006 (SD = 0.001)	0.079 (SD = 0.025)

Average values from 1000 simulations and standard deviations given in parentheses.

Table 6. Comparisons of Forests in Argentina AGB and Carbon Stocks with Comparable Ecosystems

	Carbon stocks (biomass + SOC top meter) (Mg C ha ⁻¹)			AGB (Trees (dbh > 10 cm) + understory) (Mg ha ⁻¹)		
	<i>Chaco</i> and comparable forests	Atlantic and comparable forests	<i>Yungas</i> and comparable forests	<i>Chaco</i> and comparable forests	Atlantic and comparable forests	<i>Yungas</i> and comparable forests
This work	111	237.5	247.9	80.3	264.2	205.7
Achard and others (2004)	44 ^a	186 ^c	129 ^b	–	–	–
Houghton and others (1991a, b)	124 ^d	238 ^e	238 ^e	–	–	–
Jaramillo and others (2003)	–	–	–	94–126	–	–
Bonino (2006)	–	–	–	51 ^f	–	–
Dauber and others (2002)	–	–	–	97–114 ^g	–	86–191 ^h
Fearnside (2000)	–	–	–	92 ⁱ	300 ^j	–
Massera and others (1997)	–	–	–	–	–	135 ^k
Rolim and others (2005)	–	–	–	–	241–437 ^l	–
Vaccaro and others (2003)	–	–	–	–	160 ^m	–

^aWoodlands and dry forest; ^bPan-Amazonia forest; ^cAmazonia forest; ^dDry forest; ^eMoist forest; ^fSouthern dry chaco forest (rainfall less than 500 mm y⁻¹); ^gChiquitano forest; ^hPre-Andean moist forest; ⁱCerradao formation; ^jAmazonia forest; ^kDeciduous moist forest; ^lAtlantic Forest; ^mSecondary Atlantic Forest in Argentina.

Peruvian Amazon (Naughton-Treves 2004), is larger than emissions from deforestation in Australia (AGO 2006) and it is very close to carbon emissions from deforestation in tropical Mexico (Cairns and others 2000). Our estimate represents about 10% of the emissions from deforestation in the Brazilian Amazon (Houghton and others 2000; Fearnside 1997).

At a national level, our estimates of carbon emissions are larger than the last estimate of emissions by forest ecosystems and grassland conversion in the national inventory of greenhouse gases of Argentina (NIGGA) that indicate an emission from biomass elimination of 9,249 Gg CO₂ y⁻¹ (Fundación Bariloche 2005), which is equivalent to 2,527 Gg C y⁻¹. The NIGGA carbon emission

estimate was based on unrealistic values of AGB per hectare, particularly for *Chaco* Forest (15–20 Mg ha⁻¹, which is 17% of the AGB used in this work) but also for *Yungas* Forest (80 Mg ha⁻¹ that is 39% of the AGB used in this work) and Atlantic Forest (177 Mg ha⁻¹ that is 67% of the AGB used in this work) and neglects belowground biomass. The difference between this work and the NIGGA estimates makes the net balance shift in the Argentinean silviculture and land-use sector, from a carbon sink to a source. Carbon emissions for year 2000 (20,271 Gg C y⁻¹) show that northern Argentina deforestation is a major source of carbon at the country level (Figure 3), equivalent to 89% of the emissions from fossil fuel combustion in non-mobile sources (for example, industries and

Table 7. Comparative Data for Carbon Emission from Deforestation

Carbon emission from deforestation	Gg C y ⁻¹
Global Tropical (Houghton 2003a, b)	2,200,000
Global Tropical (DeFries and others 2002) ^a	970,000
Global Tropical (Achard and others 2004) ^a	760,000
Latin America (DeFries and others 2002) ^a	460,000
Brazilian Amazon (Fearnside 1997)	220,000
Brazilian Amazon (Houghton and others 2000)	180,000
Colombia (Gonzalez 1998)	30,500
Northern Argentina (this work) ^{a,b}	20,875
Tropical Mexico (Cairns and others 2000)	19,066
Australia (AGO 2007) ^a	13,666
Peruvian Amazon (Naughton-Treves 2004)	7800

^aGross carbon emissions; ^baverage for years from 1996 to 2005.

house consumption) and 47% larger than emissions from fossil fuel combustion from the transport system (Fundación Bariloche 2005). Computing all

the carbon emissions from deforestation as CO₂ values, they represent a larger source than emission from fossil fuel combustion for the energy industry (35,565 Gg CO₂ y⁻¹) or transport system (38,969 Gg CO₂ y⁻¹) and 62% of the CO₂ emission from the total country fossil fuel combustion (117,660 Gg CO₂ y⁻¹) (Fundación Bariloche 2005) (Figure 3).

Uncertainties and Limitations

Annual deforestation derived from satellite image interpretation applied in this work between 1990 and 2005, and in some sectors from the 1970s is very reliable. The largest uncertainty is historical (that is, pre 1990) annual deforestation, which is nevertheless necessary to include delays in emissions after deforestation (Ramankutty and others 2006). In the Atlantic and *Yungas* forests, geographic limits are clearly defined and the 1900 cultivated area is minor and comparatively well quantified, hence their original forest area is fairly

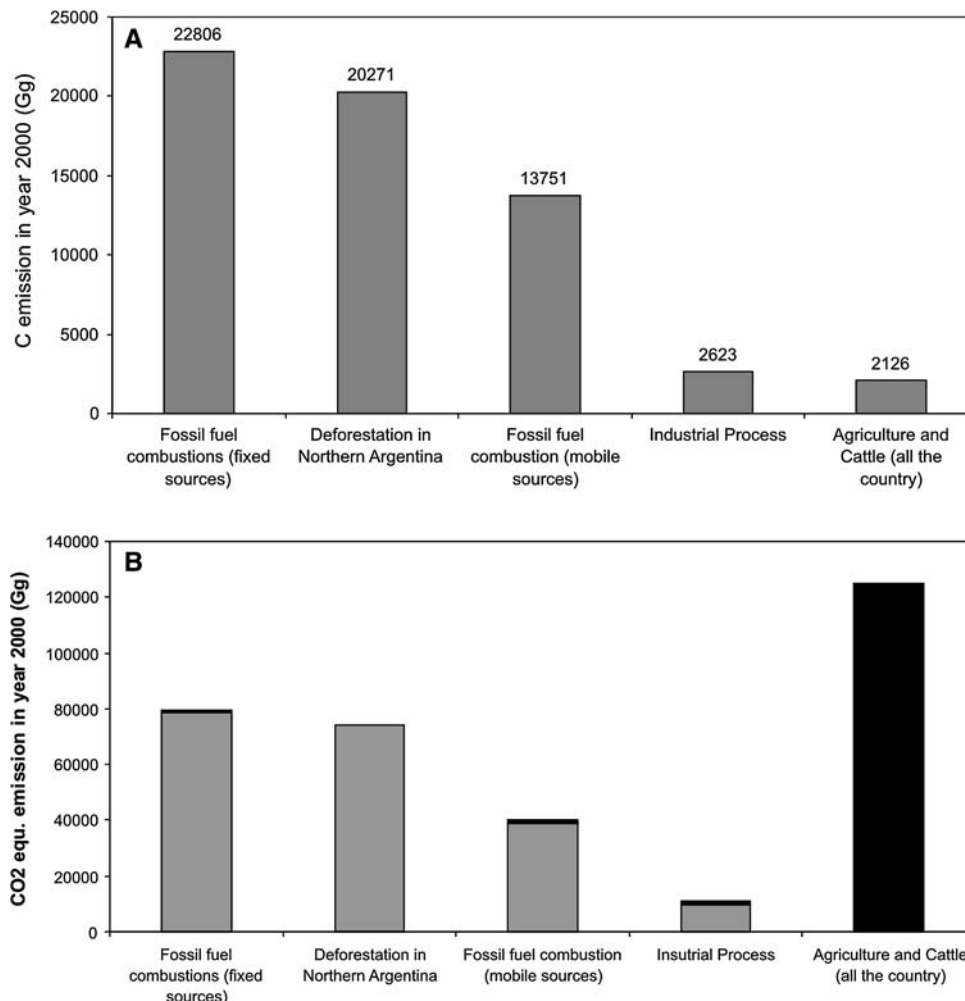


Figure 3. (A) Carbon emissions from Argentina in 2000 by principal sectors and (B) greenhouse gas emissions by sectors (gray bars are CO₂ and black bars are other gases expressed in CO₂ equivalent units). All the data for sectors different than deforestation are from Fundación Bariloche (2005).

reliable. *Chaco* Forests have less defined limits between forests, shrublands, and grasslands, generating uncertainties, but these should be limited to the range between the two estimates of the original area used in our study (Cozzo 1992; Brown and Pacheco 2006). Since the early 1970s, our estimates include trends based on accurate satellite analysis (UMSEF 2007; Grau and others 2005b; Zak and others 2004), and the annual average emissions of the last 10 years (1995–2005) are based on highly reliable deforestation estimates. Time resolution for deforestation and emission time series are also affected by the data sources. Most fluctuations for years before 1970 could be an artifact of the different data employed to estimate historical deforestation. But, after 1970 more remote sensing information was used and time resolution increased, especially for the last 10 years (forest area was estimated every 4 years). Therefore, fluctuations in deforestation and emission during the last decade likely reflect real fluctuations, including for example the 1997–2001 Argentinean economic recessions and the 2001–2005 recovery.

Our simulations show average annual emissions for the last decade of 20,875 Gg C y⁻¹, which is the average of 1000 different combinations of values for carbon stocks, SOC and deforestation rates in the book-keeping model. The use of the best data available for the three critical aspects to calculate carbon emissions (carbon stock, SOC, and deforestation rate) in 1000 combination of values allowed us to explore the range of carbon emission from northern Argentina, the best estimate (average) and its uncertainty (standard deviation). Some errors could result from the ranges of SOC values used for simulations, originating in the poor sampling of the region. But, for our simulations carbon emissions from soil only represent less than 10% of the total carbon emissions. Thus, it is a comparatively minor error source for the total emission estimate. To be conservative we suggest the use of our results as a range of probable carbon emissions using both the average and the standard deviation reported in this work (Table 5).

We did not include other LUCC processes, for which there is no easily accessible reliable quantitative information. All the ecosystems considered experience selective logging, charcoal and firewood extraction (mainly in the *Chaco*), and livestock grazing, and these land uses are likely to be changing through time. We did not consider land-cover change following deforestation because most deforestation leads to permanent agriculture in *Chaco* and *Yungas* Forest. However, post clearing land use and secondary succession processes can be

particularly important in Atlantic Forest where shifting cultivation and plantations with *Pinus* are major uses of deforested sites. However, our estimate using the coniferous plantations area in the Atlantic Forest reported by MERNRYT (2004) and biomass stocks (Mg ha⁻¹) from the NIGGA (Fundación Bariloche 2005) indicates for plantations in the year 2000 a pool of 0.018 Pg C that represents about 10% of the accumulated emissions by deforestation from 1900 to 2000 in this region.

On the other hand, there are indications of forest re-growth in forest ecosystems of northern Argentina not suitable for modern agriculture, and historically used for extensive grazing. For example, forests are regenerating into abandoned pastures (Grau and others 2007), are expanding across the high elevation treelines (Grau 1985; Morales and others 2005), and are re-growing in sectors of degraded forest in the *Chaco* region (Grau and others 2008). Although these processes are much slower than deforestation, the potentially large area that is affected could represent a significant carbon sink. Other ways to refine our estimates would be to use spatially explicit models of biomass and deforestation and re-growth to capture geographic differences in forest types, and to improve the quality of local estimates of biomass (particularly in soils, vegetation types, and discrimination in different compartments of biomass).

CONCLUSION

- (1) Considering the last estimate of 300 Pg C in global forest biomass (Kauppi 2003) the extratropical forests of northern Argentina are a non-negligible and previously unreported carbon pool at the global scale (approximately 0.8%).
- (2) Deforestation in Northern Argentina is the largest carbon source from the land in the extra-tropical southern hemisphere and is not a negligible carbon source at the continental (5%) and global scale (1–3%). Hence, it should be included in the current efforts to improve estimates of global carbon fluxes due to LUCC, which so far have largely assumed that the only significant changes occur in tropical and extra-tropical northern hemisphere zones.
- (3) Differences in carbon emissions estimates from deforestation between the national inventory of greenhouse gases of Argentina and this work indicate the need of a serious reassessment for the role of natural forests in the country carbon budget. Additionally, deforestation clearly should be a central topic in the political agenda

of Argentina, in relation to ongoing debates related to global climate change.

- (4) The most important source of carbon emissions in subtropical Argentina is deforestation in the *Chaco* forest due to its extent and rapid land-use change dynamics. In South America, globalization-related socioeconomic trends are favoring a shift in the location and driving forces of deforestation, from rainforest deforestation driven by shifting agriculture and cattle ranching to deforestation of seasonally dry forests driven by agribusiness companies (Grau and others 2005a; Morton and others 2006). Argentina is the third largest world exporter of soybean and agricultural commodity exports are a key factor in the current Argentina economy. If current global factors do not change and the economy of Argentina continues to be based on soybean exports, large areas of subtropical forest, especially *Chaco* Forest, will be cleared during the coming decades (Dros 2004; Grau and others 2005b) resulting in large impacts on national and continental carbon budgets.

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