

Chapter 15B

Potential of Soil Carbon Sequestration for the Brazilian Atlantic Region

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INTRODUCTION

The Brazilian Atlantic region (Figure 15B.1) includes the south and southeastern Brazilian states (Rio Grande do Sul, Santa Catarina, Parana, Sao Paulo, Rio de Janeiro), part of Minas Gerais state, and small portions of the northeastern states (Espírito Santo, Bahia, Sergipe, Pernambuco). It encompasses the oldest and most important Brazilian agricultural ecosystems. Covering an area of 1.1 Mkm², the region comprises 13 percent of Brazil's territory and 50 percent of its population.

The area is recognized worldwide because of its high level of diversity. Besides the immense animal diversity, a record number of woody species varieties, with as many as 454 species per hectare, are reported in southern Bahia. The forest, called "Mata Atlântica" or Atlantic forest, is the typical vegetation of the Brazilian Atlantic region. Compared to other Brazilian areas, the Atlantic forest represents the most endangered biome: In terms of remaining forest areas, it covers only 16 percent (20 percent in the study area) of the forested area that was documented in the year 1500. This decline can be attributed to the European immigration to South America, including the exploitation of Brazil-wood (*Caesalpinia echinata* Lam.) followed by mining of gold and cultivation of sugar cane (*Saccharum* spp.).

The importance of the region was also recognized by the United Nations (UN). Parts of the area are included in the Mata Atlântica Biosphere Re-



FIGURE 15B.1. Location of the Brazilian Atlantic region.

serve, which was declared an International Biosphere Reserve by UNESCO in 1991 and designated as a World Heritage site in 1999. As early as 1988, the Atlantic forest was declared a national heritage by the federal constitution of Brazil (Fundação SOS Mata Atlântica and INPE, 2002). Yet information on the soil organic carbon (SOC) sink capacity is not known for the Atlantic region. Therefore, the main objective of this study was to estimate the potential of soil carbon sequestration for the Brazilian Atlantic region, and to discuss land-use and management practices that will enhance and stabilize SOC sequestration.

DESCRIPTION OF THE STUDY AREA

The region is characterized by a wet climate, either tropical or subtropical, and forest is the major vegetation of this biome.

Physiographic

The major feature of the region is the mountainous landscape, which extends from 30°S near Porto Alegre to 13°S near Salvador. It corresponds to the eastern slopes of the Brazilian highland facing the Atlantic Ocean. The highest summits, over 1,600 m high, are located in the Serra do Mar, whereas the elevation ranges from approximately 500 to 1,000 m in most other areas. Pre-Cambrian rocks predominate the mountain chain. Sedimentary low-plateaus (“tabuleiros”) and marine deposits occur along the coastal zone, between Rio de Janeiro and Recife.

In the west, the Brazilian Atlantic region is directly connected to the central Brazilian plateau. In the north, prolongation of the central Brazilian ancient plateaus constitutes the coastal mountain range. In the center, at approximately the latitude of Rio de Janeiro, is a distinct transition with the central Brazilian plateau. This transition occurs over a wide area characterized by a hilly topography of about 1,000 masl and pre-Cambrian rocks. Some high slopes of Serra da Mantiqueira are >1,800 masl. This extension of the Brazilian Atlantic mountain is also connected to the southern part of these mountains which form the Serra do Mar.

The western plateau, which is an extension of the central Brazilian plateau, occupies the interior regions of the Sao Paulo and Parana states on the eastern side of the Parana River. The altitude ranges from 600 masl in the east to 300 masl in the west. The plateau corresponds to the sedimentary Parana basin, of which the upper strata is composed of various sandstone types and extensive intrusions of eruptive rocks, mainly basalts. In the southern part of the region, i.e., in Santa Catarina and Rio Grande do Sul, the basaltic plateau reaches the coastal area. Its elevation is about 1,000 m or more in the east, and about 500 m in the west. Deep, large valleys running from east to west (Iguaçu, Uruguay Rivers) dissect it.

Climate

Due to its latitude and its mean altitude over 600 masl, the dominant climate in the region is subtropical/temperate (Figure 15B.2). The tropical climate occurs only in latitudes north of Belo Horizonte. The tropical portion of the Atlantic Brazilian region is characterized by a wet climate (Af) in most of the coastal zone of Bahia (1,200 to 1,800 mm of rainfall distributed throughout the year), and a semihumid climate (Am) inland as well as toward the south, with an average annual rainfall from 1,000 to 1,500 mm and a dry period occurring from May through September.

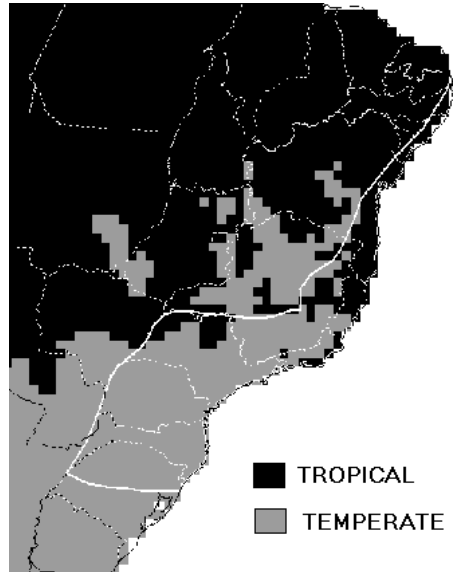


FIGURE 15B.2. General climate in the Atlantic region. (Source: Adapted from FAO SDRN, 1997.)

The subtropical (or temperate) part of the Brazilian Atlantic is subdivided in three regions: (1) the northern region, which has an annual rainfall of 1,500 to 2,000 mm and as high as 4,000 mm in the Serra do Mar, and a dry winter (Cw climate according to Koeppen's classification); (2) the central and southeastern zone, which also has annual rainfall of 1,500 to 2,000 mm, but has hot summers and a dry season from April through September, and variations between the wettest and driest months are less than those for the first zone (Cfa climate according to Koeppen's classification); and (3) the southeastern zone, which corresponds to the southern part of the basaltic plateau, and has annual rainfall of 1,300 mm to 2,000 mm with cool summers and no defined dry season (Cfb climate according to Koeppen's classification).

Vegetation

Forest is the major vegetation of the entire region. It represents the Brazilian Atlantic forests and is composed of several types of tropical and subtropical moist broadleaf forests (Figure 15B.3).

- (a) Evergreen forests (or Atlantic Evergreen forests) extend from Bahai to the Serra do Mar, in the coastal Bahia region, and in the central and southern coastal slopes of Brazilian Atlantic mountains.
- (b) Semideciduous forests (or semievergreen rain forests) cover most of the remaining areas of the region.
- (c) Brazilian Araucaria moist forests (or mixed ombrophylous forests) are in the eastern part of the southern basaltic plateau.
- (d) Savannas are represented by the cerrado vegetation in the central western border of the Brazilian Atlantic region.
- (e) Campos vegetation occurs as inclusions in the middle of the forest, mainly in the southern basaltic plateau.

The data in [Table 15B.1](#) show that the 1.1 million km² of the Brazilian Atlantic forest region was originally dominated by seasonal semideciduous forest (V5) and Atlantic evergreen forest (V3), together covering more than

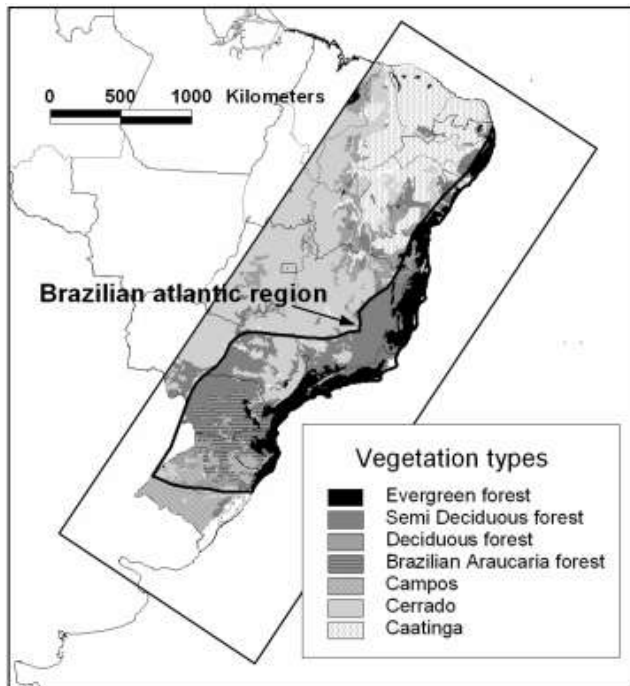


FIGURE 15B.3. Main vegetation types in the Atlantic region. (Source: Adapted from IBGE, 1988.)

TABLE 15B.1. Areas of selected native vegetation types in states of the Atlantic region.

State	Percent of state area	Area originally covered by selected native vegetation (in 1000 km ²)						
		V5	V3	V6	V9	V7	V4	Other
Espirito Santo	100	10	33					1
Parana	100	78	7	91	13	5		1
Rio de Janeiro	100	17	21		<1			3
Santa Catarina	100		27	45		14	7	<1
Sao Paulo	100	90	46	4	99			<1
Alagoas	51	3	9					2
Rio Grande do Sul	51	3	1	30		57	37	9
Sergipe	44	4			4			2
Minas Gerais	38	167	19	1	30		6	
Bahia	16	14	60		4		7	5
Pernambuco	12	4	7					1
Paraiba	5	1			1			
Total	43	392	231	170	152	76	58	26

Source: Adapted from Bernoux et al., 2002.

Note: V5: Semideciduous forest; V3: Evergreen Atlantic forest; V6: Brazilian araucaria forest; V9: Cerrado; V7: Campos; V4: Deciduous forest.

half of the total area and extending into most of the states. The mixed ombrophylous forest (V6) represents the third largest vegetation type, and it primarily occurs in the southern region (Parana, Santa Catarina, and Rio Grande do Sul). Savanna vegetation or cerrado (V9) is the dominant vegetation in Sao Paulo state and also occurs in parts of Minas Gerais state. South savanna or campos vegetation (V7) and seasonal deciduous forest (V4) occur mainly in the southern part of Brazil.

In the description of the vegetation map of IBGE (1988), seasonal semi-deciduous forest is related to the climate of two seasons in the area, a rainy season and a dry season (with mean temperature of 21°C), or with a short dry period accompanied by pronounced low temperature in the subtropical area (with mean temperatures of 15°C). Dominant arboreal elements occur, which are adapted to the cold or dry season whereby the proportion of deciduous trees ranges from 20 to 50 percent. This vegetation system occurs predominantly at dissected plateau areas that divide the drainage of the Amazon river and cover the lower hillsides of Serra do Mar and Mantiqueira, as well as the river basins Paraguai and Paraná.

This vegetation system consists of alluvial, lowland, submontane, and montane formations. The mixed ombrophyllous forest (or conifer forest) exclusively covers the south Brazilian plateau regions, with distinct disjunctions in high areas of Serra do Mar and Mantiqueira. It prevails in an ombrophyllous climate without a dry season, with an annual average temperature of 18°C. The temperature is <15°C for three to six months.

The arboreal formations of the southern plateau areas enclose two Brazilian floras; the Afro-Brazilian and the temperate Austro-Brazilian flora with a predominance of conifers (*Araucaria angustifolia*). These areas were intensively exploited by the timber industry and subsequently used for agriculture and pastures. Rizzini (1997) defined the Atlantic forest as a vegetation system covering the coastal contour from Rio Grande do Sul to the northeast in an ocean strip, including some eastern ranges such as Serra do Mar and Mantiqueira, as well as the states of São Paulo, Minas Gerais, Rio de Janeiro, and Espírito Santo.

Soils

Most soils in the region are highly weathered, due to the persistence of wet, tropical, and subtropical climates and the soil age. Intense weathering is indicated by the presence of very deep saprolites in the crystalline basement rocks. Also, geomorphic evidence shows that many features of the Atlantic Brazilian region landscape are directly connected to equivalent features in the central Brazilian region and the same ancient erosional and depositional surfaces, and comparable old soils are found in both regions.

Soils are mainly Ferralsols, derived from either sedimentary, volcanic, or crystalline rocks. Ferralsols are always associated with Acrisols. The dominant clay mineral of these soils is kaolinite. These are normally unsaturated, with high exchangeable Al⁺³. In the wet subtropical climatic environment, vermiculite-Al is normally associated with kaolinite. Consequently, exchangeable Al⁺³ contents are very high and many soils have allic properties. Another consequence of the relatively cold and humid subtropical environment is the increase in soil organic matter (SOM) concentration in the soil profile and the frequent occurrence of umbric horizons.

In the Brazilian Atlantic region, the nature of the soils changes according to the parent material, the altitude, and the geomorphic or landscape position. The general distribution of the soil types is depicted in the Brazilian Soil Map (EMBRAPA, 1981).

In the north, the dominant soil is Latossolo Amarelo (Xanthic Ferralsol) on the low coastal plateaus ("tabuleiros") and Latossolo Vermelho Amarelo (Haplic Ferralsol) on the high plateau where it is associated with Podzolic

Vermelho Amarelo distrófico (Ferric Acrisols) on the hilly regions of mountain slopes. Podzólico vermelho amarelo eutrófico (Ferric Luvisols) occurs in the dryer regions (Jequitinhonha Valley).

In the central-eastern mountain and hilly zone, which is underlain by crystalline basement, Latossolo vermelho amarelo distrofico (Haplic Ferralsol) is the dominant soil type. It is associated with Podzólico vermelho amarelo distrofico (Ferric Acrisol) and Cambissolo distrofico (Dystric Leptosol).

In the central-western part, (i.e., the sedimentary and basaltic plateau of Sao Paulo and Parana), the dominant soils are Latossolo vermelho escuro and Latossolo roxo (Rhodic Ferralsol) on the predominantly basaltic substrate, and Podzólico vermelho amarelo distrofico (Ferric Acrisol) and Latossolo vermelho Escuro (Rhodic Ferralsol) on sandstones. Podzólico Vermelho Amarelo eutrófico (Haplic Lixisol) occurs in the Marilia region on calcic sandstone parent material.

In the southern basaltic plateau, Latossolo Roxo and Latossolo Vermelho Escuro (Rhodic Ferralsol), and Terra Roxa Estruturada distrofica (Rhodic Nitosol) occur on the plateau, while Solo Litólico eutrófico (Eutric Leptosol) occurs on the basaltic slopes. Latossolo bruno distrofico (Humic Ferralsol), and its associated Solo Litólico húmico distrofico (Humic Cambisol) in the slopes, occur on the higher eastern parts of the basaltic plateau.

Carbon Pools Under Native Conditions

For the Atlantic Forest, Bernoux and Volkoff (Chapter 4) estimated a total C pool of about 5,657 Tg for 0 to 30 cm depth (Table 15B.2), which corresponds to a potential sink capacity under native vegetation. The mean C pool for the studied area was estimated at 5.5 kg C·m⁻², and represents a 10 percent higher value compared to the overall mean for the Latin American region. Detailed information about C pools under selected vegetation and main soil types, and the respective states are given in Tables 15B.2 and 15B.3.

Table 15B.4 reports the total and mean C pools by state according to the simplified soil classification proposed by Bernoux et al. (2002) based on criteria recommended by IPCC/UNEP/OECD/IEA (1997) such as soil texture, base saturation, and soil water status. The IPCC/UNEP/OECD/IEA (1997) proposed six categories that are characterized as high-activity clay (HAC) mineral soils, low-activity clay (LAC) mineral soil, sandy soils, volcanic soils, wet soils, and organic soils. Definitions of the Brazilian soil classification system were taken into account to separate HAC (soils with cation-exchange capacity ≥ 24 cmol_c·kg⁻¹ clay) from LAC (soils with cation-exchange capacity < 24 cmol_c·kg⁻¹ clay). The original Brazilian soil

TABLE 15B.2. Carbon pools under selected native vegetation types in different states of the Brazilian Atlantic region.

State	Total C pool under native vegetation (Tg)							Total
	V5	V3	V6	V9	V7	V4	Other	
Espirito Santo	43	164					8	215
Paraná	316	44	707	49	28		4	1148
Rio de Janeiro	72	137		1			15	225
Santa Catarina		129	344		96	28	1	598
Sao Paulo	365	212	31	385			2	995
Alagoas	11	42					6	60
Rio Grande do Sul	11	4	272		433	161	50	931
Sergipe	14			12			8	34
Minas Gerais	688	93	10	113		20		925
Bahia	54	340		17		31	15	457
Pernambuco	16	34					4	54
Paraiba	5	1		4				9
Total	1599	1200	1363	582	557	240	117	5657

Source: Adapted from Bernoux et al., 2002.

TABLE 15B.3. Mean C pool under selected native vegetation types in different states of the Brazilian Atlantic region.

State	Percent of state area	Mean pool under native vegetation (kg·m ⁻²)							Mean
		V5	V3	V6	V9	V7	V4	Other	
Espirito Santo	100	4.1	4.9					5.1	4.1
Parana	100	4.0	6.1	7.8	3.7	6.1		4.9	5.8
Rio de Janeiro	100	4.1	6.6		3.9			4.7	5.4
Santa Catarina	100		4.7	7.6		6.8	4.0	4.5	6.4
Sao Paulo	100	4.1	4.6	8.4	3.9			4.9	4.0
Alagoas	51	4.0	4.6		3.6			3.3	4.2
Rio Grande do Sul	51	3.9	4.1	9.2		7.5	4.3	5.5	6.7
Sergipe	44	3.7			3.5			3.8	3.6
Minas Gerais	38	4.1	4.9	8.8	3.8		3.5	4.9	4.1
Bahia	16	4.0	5.7		3.9		4.1	3.3	5.1
Pernambuco	12	3.8	4.9					3.8	4.4
Paraiba	5	3.7	4.5		3.2			3.3	3.5
Total area	43	4.1	5.2	8.0	3.8	7.3	4.2	4.5	5.5

Source: Adapted from Bernoux et al., 2002.

TABLE 15B.4. Soil organic carbon pool by state and soil type.

State	Variable	S1	S2	S3	S4	S5	S6	Total
Espírito Santo	Pool (Tg)	4	134	61	9	7	1	215
	Area (1000 km)	1	27	15	2	2	<0	45
	Mean (kg C·m ⁻²)	5.1	5.1	4.1	5.6	4.2	41.8	4.8
Paraná	Pool (Tg)	195	445	484	5	6	13	1148
	Area (1000 km)	27	63	103	1	1	<0	196
	Mean (kg C·m ⁻²)	7.3	7.0	4.7	6.3	5.3	41.8	5.9
Rio de Janeiro	Pool (Tg)	2	68	86	5	11	52	225
	Area (1000 km)	1	15	21	1	2	2	41
	Mean (kg C·m ⁻²)	4.5	4.7	4.1	5.3	5.0	26.7	5.4
Santa Catarina	Pool (Tg)	135	186	262	12	4		598
	Area (1000 km)	17	22	52	2	1		93
	Mean (kg C·m ⁻²)	8.2	8.3	5.1	6.1	3.6		6.4
Sao Paulo	Pool (Tg)	1	567	396	26	5		995
	Area (1000 km)	<0	129	103	12	1		245
	Mean (kg C·m ⁻²)	2.8	4.4	3.8	2.3	5.0		4.1
Alagoas	Pool (Tg)	1	23	34	2	<0		60
	Area (1000 km)	<0	5	9	1	<0		14
	Mean (kg C·m ⁻²)	2.8	5.0	4.0	4.0	3.7		4.3
Rio Grande do Sul	Pool (Tg)	292	447	185	1		6	931
	Area (1000 km)	46	53	37	<0		2	138
	Mean (kg C·m ⁻²)	6.4	8.4	5.0	6.3		2.7	6.7
Sergipe	Pool (Tg)	3	4	19	2	1	5	34
	Area (1000 km)	1	1	5	1	0	1	10
	Mean (kg C·m ⁻²)	3.2	4.4	3.6	4.4	4.6	3.1	3.6
Minas Gerais	Pool (Tg)	11	581	333	<0			925
	Area (1000 km)	2	131	89	<0			222
	Mean (kg C·m ⁻²)	5.0	4.4	3.8	1.9			4.2
Bahia	Pool (Tg)	36	198	151	10	4	58	457
	Area (1000 km)	8	39	37	2	1	3	90
	Mean (kg C·m ⁻²)	4.6	5.1	4.1	4.5	4.9	21.3	5.1
Pernambuco	Pool (Tg)	<0	28	25	<0		1	54
	Area (1000 km)	<0	6	6	<0		<0	12
	Mean (kg C·m ⁻²)	4.1	5.0	3.9	5.0		3.3	4.4

TABLE 15B.4 (continued)

State	Variable	S1	S2	S3	S4	S5	S6	Total
Paraíba	Pool (Tg)			8	1		<0	9
	Area (1000 km)			2	<0		<0	3
	Mean (kg C·m ⁻²)			3.7	2.2		3.3	3.5
Total area	Pool (Tg)	680	2681	2044	73	44	135	5657
	Area (1000 km)	102	491	479	21	10	9	1112
	Mean (kg C·m ⁻²)	6.7	5.5	4.3	3.5	4.4	15.2	5.1

map lists no soil type corresponding to volcanic and organic soils. Based on these observations, soil types can be theoretically split into HAC soils, LAC soils, sandy soils, and wet soils. But, the Brazilian order named Latossolos, which pertains to LAC soils, alone covers 38.8 percent of the country. The Brazilian Latossolos correspond to well-drained Oxisols in the U.S. Soil Taxonomy, and to Ferralsols in the FAO-UNESCO (FAO-UNESCO) soil map legend. Then, the LAC soils were divided into LAC-Latossolos (S2) and LAC-non-Latossolos (S3). The other soil categories were named HAC soils (S1), sandy soils (S4), and wet soils (S5). An additional category contains all the soils that did not match with one of the other groups, and were marked as other soils (S6). Two soil types (S2 and S3) cover 87 percent of the total area and contribute 84 percent of the total C pools. States where HAC soils (S1) are prevalent contain higher mean soil C pools than those where these soils are absent.

ACTUAL LAND USE

The deforested area was calculated by subtraction of the remaining areas from original forest areas (Table 15B.5) taken from Conservation International of Brazil (2000) and Fundação SOS Mata Atlântica and INPE (2002).

On the basis of the description given previously; the information on land use for the entire Atlantic region was taken from the databases of IBGE and SIDRA (Table 15B.6). Information on pastures was obtained from ANUALPEC (FNP, 2003). The sum of the production areas of all states is defined as the production area of the Atlantic region.

In order to obtain a more accurate estimate, production data of the used agricultural crops as well as the data of the remaining areas of the year 2000 were compared. More recent estimates of the pasture areas and the reforested areas were taken from 2002 and 1996, respectively.

TABLE 15B.5. Original areas and remaining and deforested areas of the Atlantic forest.

State	Original area (Mha)	Area of the state (Mha)	Atlantic forest		
			in the state (%)	Remaining areas (Mha)	Deforested area (Mha)
Alagoas	1.4	2.75	51	0.07	1.33
Bahia	9.0	56.25	16	2.63	6.37
Espírito Santo	4.4	4.40	100	1.40	3.00
Minas Gerais	22.3	58.68	38	4.19	18.11
Paraíba	0.2	4.00	5	0.05	0.15
Pernambuco	1.2	10.00	12	0.09	1.11
Paraná	19.5	19.50	100	3.92	15.58
Rio de Janeiro	4.1	4.10	100	0.84	3.26
Rio Grande do Sul	13.7	26.86	51	2.13	11.57
Santa Catarina	9.3	9.30	100	3.00	6.30
Sergipe	1	2.27	44	0.09	0.91
São Paulo	23.9	23.90	100	3.00	20.90
Total	110	222		21.41	88.59

Source: Adapted from Conservation International do Brasil, 2000; and from Fundação SOS Mata Atlântica and INPE, 2002.

TABLE 15B.6. Areas under different land uses in the Atlantic region in 2000.

Land use	Area	
	Mha	% of total
Forest	21,396,553	19.45
Well-managed pasture	27,993,940	25.45
Degraded pasture	27,993,940	25.45
Annual crops under conventional tillage	6,855,078	6.23
Annual crops under no-tillage	8,022,030	7.29
Sugarcane with burning	2,415,863	2.20
Sugarcane without burning	1,035,370	0.94
Reforestation	3,093,012	2.81
Fruitculture	2,690,374	2.45
Horticulture/gardening	999,350	0.91
Others	7,504,490	6.82
Total	110,000,000	100

Source: Adapted from FNP, 2003; IBGE-SIDRA, 2004.

The actual land use was grouped in eight categories to give a general characterization of the productive area of the Atlantic region: (1) forest, (2) annual crops, (3) sugarcane, (4) pasture, (5) reforestation, (6) fruit plantation, (7) horticulture/gardening, and (8) others or nonagricultural areas.

SCENARIOS AND POTENTIAL OF SOIL CARBON SEQUESTRATION

The carbon sequestration potential was estimated by multiplication of carbon accretion rate for the soil under each land use with the corresponding area.

The Atlantic region presents four main groups of agricultural uses/practices which can be changed to a recommended land use: (1) convert sugarcane areas harvested by burning (manual cut) into areas without burning and mechanical harvest, (2) convert conventional tillage into no-till systems for production of grain crops, (3) increase reforested areas, and (4) recover degraded pasture areas into productive pastures.

It is possible to increase the amount of carbon sequestered by increasing the area under recommended land use. Hence, a scenario about changes of the actual land use was established (Figure 15B.4), and considers the following new land-use practices: (1) adoption of conservative agricultural practice, such as no-till in areas where annual crops are cultivated conventionally or where soil loss and organic matter degradation occur; (2) mechanized harvesting of sugarcane in areas where burning is still practiced; (3) restoration of degraded pastures or converting these to other crops, such as sugarcane without burning, and (4) reforestation.

Another important factor in support of the proposed scenario is an estimation carried out by FNP (2003). Their calculation shows a decrease in area under pasture in Brazil and an increase in area under meat production. This trend is attributed to restoration of degraded pastures for other land uses (e.g., no-tillage practice for soybean and corn cultivation).

Thus, alternative scenarios are (1) conversion of degraded pasture areas in flat topographical regions to sugarcane cultivation, (2) reforestation of areas unsuitable for mechanization of sugarcane cultivation, and (3) increase in cultivated areas under no-till soybean and corn cultivation through conversion of degraded pastures, as estimated by FNP (2003). The following estimates were based on the assumption that pastures will be converted to other land uses in the same proportion as it is occurring presently, and (4) degraded pastures are converted to productive pastures.

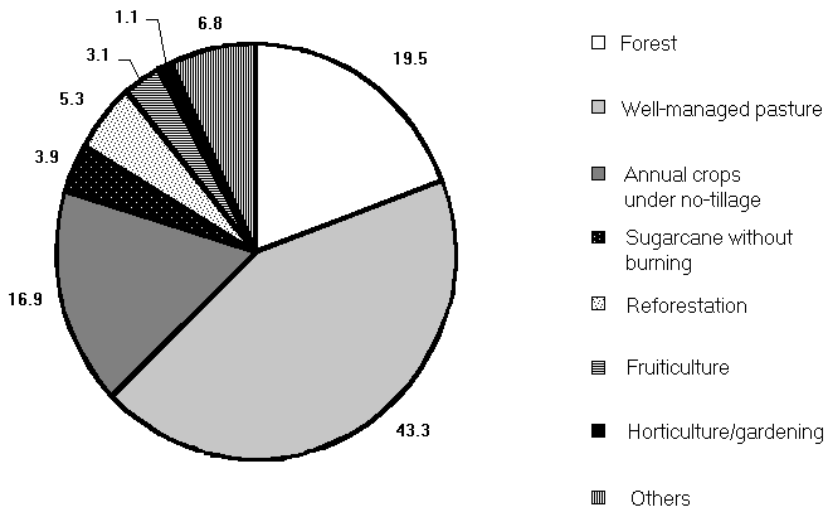


FIGURE 15B.4. Possible land-use scenarios.

Conversion of Sugarcane with Burning to Sugarcane Without Burning

Brazil is the largest producer of sugarcane worldwide, with about 26 percent of the world cultivated area and 29 percent of world production (FAO, 2004). Considering the Atlantic region, area under sugarcane in Sao Paulo is 2.5 Mha (FNP, 2004), which represents 72 percent of the total Atlantic area.

Sugarcane is one of the most important crops in Brazil. In contrast to fossil fuels, it produces an efficient alternative as a renewable fuel. Further, 100 percent of the production technology of sugarcane is indigenous to Brazil.

Most of the sugarcane harvest is still done manually. It is costly and is a significant source of CO₂ emissions to the atmosphere, because it involves burning of sugarcane leaves. Furthermore, most of the cultivated areas are located in regions unsuitable for mechanical practices due to steep slope gradient >15 percent. In Sao Paulo state, only 44 percent of the area under sugarcane is cultivated on sites suited to mechanical harvesting (Toledo et al., 1991). Of this, 30 percent of the area is mechanically harvested. Thus, the mechanized harvesting can be extended to the additional 14 percent of the cultivated area.

According to new environmental laws, sugarcane must be totally harvested without burning and, consequently, by mechanized operations. Hence, land-use changes are necessary in areas unsuitable for mechanized sugar-

cane harvest. It implies alterations of an area of about 1.9 Mha. One alternative would be to convert the unsuitable areas to forest plantations, mainly by *Pinus* species, because the production areas of such forest plantations have been static.

In consideration of the projected national demand for the year 2020, wood production must be increased by 37 Mm³ of *Pinus* wood (*Pinnus elliottii*) (Paim, 2003). Thus, sugarcane production would have to be concentrated on level degraded pasture areas, where mechanized harvesting is feasible. In this context, land-use changes required would involve conversion of degraded pastures to sugarcane cultivation for mechanized harvesting and conversion of sugarcane on steep lands to forest plantations.

Estimates of the carbon sequestration potential in consideration of these scenarios/assumptions are given in Table 15B.7. The carbon sequestration

TABLE 15B.7. Potential of soil carbon sequestration in the 0 to 20 cm layer for the Atlantic region.

Land use	Total area (Mha)	Soil carbon sequestration rate (Mg·ha ⁻¹ per year)	Source	Potential of soil C sequestration (Tg per year)
Sugarcane burning to without burning	3.30	1.62	1	5.35
Degraded pasture to sugarcane without burning	1.93	0.1 - 0.8	1	0.19 - 1.54
Existent sugarcane without burning	1.03	1.62	1	1.67
Conventional to no-tillage	6.85	0.2 - 0.8	2, 5	1.37 - 5.58
Degraded pasture to no-tillage	3.80	0 - 0.71	6, 2	0 - 2.70
Existent no-tillage	8.02	0.2 - 0.8	2, 5	1.60 - 6.41
Degraded to well-managed pasture	19.65	2.71	3, 4	53.25
Existent well-managed pasture	28.00	2.71	3, 4	73.88
Sugarcane with burning to reforestation	1.93	0.66	4	1.27
Degraded pasture to reforestation	0.78	0 - 1.63	6, 4	0.078 - 1.27
Existent reforestation	3.10	2.42	4	7.50

Source: (1) Cerri, Bernoux, Cerri, and Feller, 2004; (2) Cerri, Bernoux, Feller, et al., 2003; (3) Manfrinato, 2002; (4) Campos, 1998; (5) IPCC, 2000; (6) Szakács, 2003.

rates were taken from Cerri, Bernoux, Cerri, and Feller (2004) and extrapolated and upscaled to the whole study area.

Conversion from Conventional Grain Crop Production to a No-Till System

Land area under no-till farming is rapidly increasing throughout Brazil. According to Federação Brasileira de Plantio Direto na Palha (FEBRAPDP, 2004), about 22 Mha of conventional tillage were converted to no-till system in Brazil by 2003. About 50 percent of the total area under no-till farming in Brazil was located in the Atlantic region in 2001 (Figure 15B.5).

In a no-till system, chemical and physical soil properties are improved, which enhances carbon sequestration capacity and offsets CO₂ emissions (Lal, 1997). Séguy et al. (2001) concluded that cultivation practices such as plowing for monocultures of annual crops cause severe losses of organic matter. The soil organic matter content is controlled by edapho-climatic factors.

The Atlantic region has a high potential for expansion of the no-till system. Presently, only some states (e.g., Sao Paulo, Santa Catarina, Rio Grande do Sul, and Paraná) have adopted no-till farming. These states have additional cropland areas in which no-till can be adopted (Figure 15B.6).

The potential of soil C sequestration under a no-till system is shown in Table 15B.7. Estimates of C sequestration rates were taken from those pub-

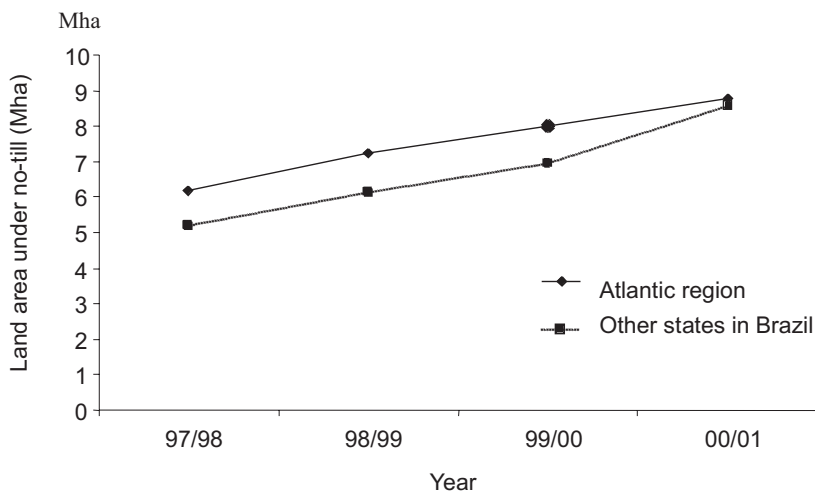


FIGURE 15B.5. Temporal changes in no-till areas in the Atlantic region and other Brazilian states. (Source: Adapted from FEBRAPDP, 2004.)

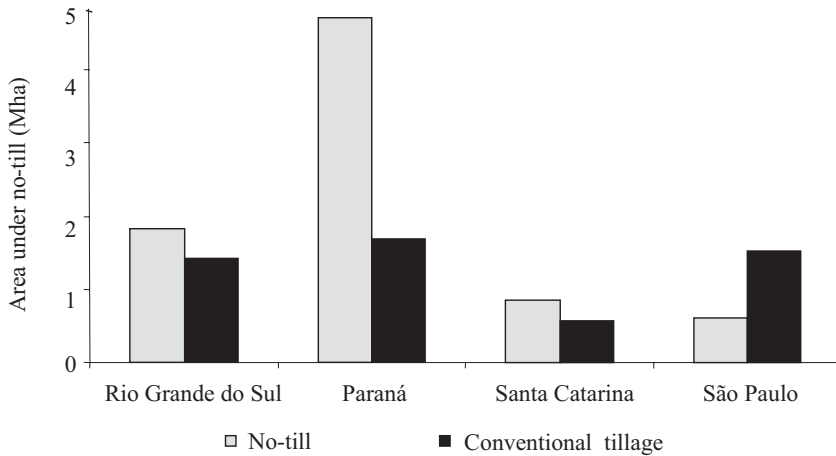


FIGURE 15B.6. Cropland area under conventional and no-till farming in principal grain-producing states of the Atlantic region. (Source: Adapted from FEBRAPDP, 2004.)

lished by Cerri, Bernoux, Feller, et al. (2004) and IPCC (2000), and were extrapolated to the entire Atlantic region. A strong possibility exists of achieving the C sequestration potential, because the conversion from conventional tillage to no-till needs only routine changes in crop management compared to the complex process of afforestation or reforestation.

Restoration of Degraded Pastures

Total area under pasture represents the largest area among different land uses in the Atlantic region, covering almost 56 Mha. About 50 percent of this area is prone to some degree of soil degradation (Zimmer et al., 1994) (Figure 15B.4). Soil C sequestration rates in pastures were taken from those published by Manfrinato (2002) and Campos (1998), and were extrapolated to the entire Atlantic region.

Using the estimates reported by FNP (2003), decline in the area under pasture provides an opportunity to expand cropland under no-till farming and convert to other restorative land uses. Assuming that the entire area under pasture land would be degraded, approximately 6.5 Mha are available for conversion to improved land use with high C sequestration/sink capacity.

Therefore, C sequestration potential will be achieved through restoration of an estimated degraded area of about 19.5 Mha, over and above the 28 Mha already under improved pastures (Table 15B.7).

Reforestation

Reforestation can be done in areas where mechanized harvest of sugarcane is not feasible, and it could increase the forest area by 2 Mha. Moreover, if pastures were also reforested, total reforested area would increase to 2.7 Mha. Reforestation would increase the wood production area in the Atlantic region by about 85 percent, and it would also enhance soil C sequestration by 18 to 34 percent (Table 15B.7). Carbon sequestration rates for forested areas were taken from those published by Campos (1998), and extrapolated to the entire Atlantic region.

The data in Table 15B.7 show a large range in rates of SOC sequestration because of difference in pasture species, severity of soil degradation, forest species, and soil type. For example, conversion of a pasture, at the initial stage of degradation by weed infestation, into no-till farming may lead to little or no SOC sequestration. However, conversion of a pasture at an advanced stage of degradation, with a large proportion of bare soil in between, can have a high rate of SOC sequestration. In general, the SOC sequestration rate is low when slightly degraded pasture land is converted to no-till crop production, and high when severely degraded pasture is restored to no-till farming.

CONCLUSIONS

The potential of SOC sequestration in the Atlantic region, in the 0 to 20 cm soil layer, ranges from 144 to 154 Tg C per year (150 Tu Tg per year). Total carbon sequestration over 20 years is 3 Pg C. The estimation shows the importance of improving the use of the already deforested areas in the Atlantic region, which corresponds to 88 Mha. This region is home to 50 percent of Brazil's population and includes some of the largest cities of Brazil.

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