Carbon Sequestration in Soils of Latin America

Rattan Lal
Carlos C. Cerri
Martial Bernoux
Jorge Etchevers
Eduardo Cerri
Editors

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Chapter 11

Carbon Sequestration Potential of the Neotropical Savannas of Colombia and Venezuela

Marco A. Rondón
Dimas Acevedo
Rosa M. Hernandez
Yolanda Rubiano
Mariela Rivera
Edgar Amezquita
Mandius Romero
Lina Sarmiento
Miguel Ayarza
Edmundo Barrios
Idupulapati Rao

INTRODUCTION

Neotropical savannas of Latin America represent one of the last frontiers where agriculture could be expanded in the world. With an area of 269 million hectares (Mha), they account for nearly half of the total world's savannas. These savannas are located in Brazil (203 Mha), Venezuela (26.2 Mha), Colombia (23.6 Mha), Bolivia (13 Mha), and Guyana (4 Mha) (Rippstein et al., 2001). Savannas in Colombia and Venezuela are commonly known as *llanos* (the Spanish word for flatlands). Neotropical savannas are generally defined as continuous ecosystems dominated by perennial grasses with disperse woody species, where water availability follows distinct seasonal pat-

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terns, including a clear dry season. They are dominated by acidic soils with high aluminum toxicity and low nutrient availability, periodic burning, and moderate grazing pressure from herbivores (Walker, 1987; Huntley and Walker, 1982; Sarmiento, 1984; Bourlière, 1983). These factors not only regulate net primary productivity but also influence various ecological functional groups and their biodiversity within the ecosystem.

In contrast with the savannas in Brazil and Guyana, which have evolved over ancient Precambrian shields, the llanos from Colombia and Venezuela are quaternary plains linking the Andean and Caribbean piedmont to the west and north, with the borders of the Guyana shield to the south. The Llanos de Moxos or Beni in eastern Bolivia have clear commonalities with the llanos from the northern part of South America. They also link the Andes with the southern limit of the Brazilian shield (Sarmiento, 1990; Berroterán, 1988).

Although important physiographic, structural, functional, and ecologic differences exist within regions in these savannas, being a continuous ecosystem, the llanos of Colombia and Venezuela are comparatively more homogeneous in relation to climatic and edaphic conditions than the savannas in Brazil, Bolivia, or Guyana. On the other hand, the patterns of development and intensity of land use have been very contrasting in Colombia and Venezuela. Until approximately the mid-1950s, the llanos of both countries were exclusively used for low-intensity cattle ranching, with cattle feeding on native low-quality grasses. Stocking rates of less than 0.5 heads per hectare were common. In Venezuela, in the mid-1960s, government programs promoted the introduction of large-scale tree plantations of pines (*Pinus caribbea),* eucalyptus (*Eucalyptus deglupta*), and some commercial crops such as rice (Oryza *sativa*) and cotton (*Gossypium hirsutum*). With more than half a million hectares, the Venezuelan eastern llanos still host one of the largest continuous plantation of *Pinus caribbea.* In Colombia in the 1970s, research led by CIAT and ICA encouraged the intensification of livestock activities through the introduction of improved grasses (mainly *Brachiaria* species introduced from Africa) in association with forage legumes (*Arachis pintoi, Desmodium ovalifolium, Centrosema acutifolium*). More recently, rapid agricultural expansion is taking place in Colombia as well as livestock intensification in Venezuela. In spite of this, the dominant land use in the two countries is still extensive ranching on native pastures. The most important nonnative land use in the llanos is introduced grasses (5 Mha in Venezuela and 1 Mha in Colombia).

While in Brazil and Bolivia the main limitation is low soil fertility and high phosphorus fixation, in the llanos there are additional soil physical constraints such as low rainfall infiltration due to surface sealing and compaction in most of the Colombian llanos (Amézquita et al., 2002) or climatic constraints such as severe water deficits in the eastern parts of the Venezuelan llanos. There are also vast areas that are seasonally waterlogged land, thus limiting their use.

Soils in the llanos are considered fragile and very susceptible to degradation. Intensive tillage operations have resulted in serious loss of physical stability (Amézquita et al., 2002). Inadequate pasture management frequently results in rapid pasture degradation and associated decrease in soil quality. The recent development of appropriate agropastoral systems for the llanos enables, however, a sustainable use of the resources (Valencia et al., 2004). Long-term evaluations have shown that when properly managed, both crop and livestock systems could be sustainable activities in this ecosystem (Friesen et al., 1998; San José et al., 2003).

Pioneering research conducted in the elevated plateaus from Colombian savannas (Fisher et al., 1994, 1997) showed the high potential of improved pastures to accumulate carbon in the soil organic matter pool. Subsequent studies (Rondón, 2000) have shown that conversion of tropical savannas into pastures or even cropland with appropriate management could result in a net decrease in net fluxes of various greenhouse gases from the land into the atmosphere and could generate net carbon equivalent gains. These gains could potentially be traded in the emerging carbon markets.

Despite the apparent homogeneity of the llanos, the scenario of the changes in net carbon equivalent stocks when native land is converted into croplands or introduced pastures is very complex. Available information is very fragmented, and methodological homogeneity among countries, functional types, and physiographic units is lacking. Studies have been conducted using diverse approaches, ranging from ecology to agronomy and soil science, etc., which limits a proper extrapolation of available data, particularly for the Venezuelan savannas. Under these limitations, this chapter is aimed at estimating the current C stocks in the llanos, the maximum potential to sequester C in the soil, and the extent of sequestration that is realistic to expect with the likely development of the region in the coming decades. Estimated values should be viewed with some caution given the various assumptions in terms of homogeneity of functional subunits and carbon content in soils that we were forced to make to compensate for the lack of more precise data.

LANDSCAPE UNITS

The llanos are confined between the lower part of the Andes (3°N and 6°N) to the west, the Amazon forest margins to the south, the foothills of the coastal Caribbean range to the north, and the Orinoco River delta to the east

(Figure 11.1). Various important rivers cross the llanos from the Andes to the Atlantic. The Meta, Guaviare, Arauca, Apure, and Portuguesa are the most important, and they are also widely used for fluvial transportation of people and products (IGAC, 2002). Most of the rivers are tributaries of the Orinoco, which constitutes the main water stream in the llanos. The llanos cover 23.6 Mha in Colombia and 26.2 Mha in Venezuela, representing approximately 18 percent and 28 percent of the national territories, respectively.

Geology of the llanos is dominated by sedimentary deposits from the upper Tertiary and Quaternary. Central and eastern regions have been geologically elevated, favoring erosion and appearance of spots from the Tertiary on the surface. In the west, subsidence and accumulation of Quaternary deposits are dominant (González de Juana et al., 1980). The southernmost border shows undulated relief from the Pliocene and Pleistocene (Botero and Serrano, 1992).

For this study, areas for the various landscapes of the llanos as well as areas under different land uses were calculated based on satellite images from LANDSAT (Multispectral Scanner and Thematic Mapper). These images

FIGURE 11.1. Neotropical savannas (llanos) from Columbia and Venezuela. (*Source:* Adapted from IGAC, 1999a,b.)

have been used previously to estimate land-use patterns in Colombia (IGAC, 2003) and Venezuela (Arias, 1992; Berroterrán, 1988; Schargel, 2003). The images were reprocessed for this study to group the landscape according to the classification described in this chapter. Four main landscape positions can be differentiated in the llanos: (1) alluvial plains, (2) eolic plains; (3) elevated or high plateaus; and (4) rolling hillsides (Berroterrán, 1988; Schargel, 2003). In Venezuela, alluvial plains dominate in the west and northeast. The eolic plains, including stabilized sand dunes, are located in the geographical center of the llanos. The elevated plateaus have an average elevation of 200 masl in Colombia and central Venezuela, but can reach around 400 masl in the eastern llanos of Venezuela (Sarmiento and Pinillos, 2001). In Colombia, alluvial and eolic plains are dominant between the Andes and the Meta River, while in the eastern side of the Meta River rolling terrain is characteristic (Goosen, 1964; IGAC, 1983).

In this chapter, we have simplified the landscape composition by combining eolic and alluvial plains. Figures 11.2 and 11.3 show the resulting landscape positions for the Colombian llanos and Venezuelan llanos, respectively: low-lying, poorly drained, seasonally flooded plains; well-drained lowlands; elevated flatland plateaus; and intermediate rolling hills. All of them include areas of evergreen gallery forest that spread along the main rivers and secondary water streams. Gallery forest accounts for 10 percent of total area in the llanos in Colombia (Rippstein et al., 2000) and around 8 percent in Venezuela (Schargel, 2003). Table 11.1 shows the area under the main landscape positions of the llanos from both countries.

CLIMATE

The llanos have a typical isothermal climate with a well-defined unimodal rainfall distribution. Rains are concentrated between April and October (Figure 11.4). The llanos are considered humid environments, but there is a decreasing west-to-east gradient in annual precipitation, with values ranging from 2,700 mm in the Andean piedmont to around 800 mm on the easternmost part of Venezuela on the border with the Orinoco delta (Sarmiento and Pinillos, 2001). There is also a gradient in the duration of the dry season, from one to two months in the southwest, to five to six months in the east. Evapotranspiration is high during the whole year (1,800 to 2,700 mm), with a peak of around 300 mm in March. Mean annual temperature is 26°C. Differences on the average daily temperature are very small between the rainy and dry seasons, but more accentuated differences of up to 12°C can be found between the minimum and maximum daily values. Solar radiation is high in the llanos, with values between 16.1 and 17.2 $MJ \cdot m^{-2}$ reported for

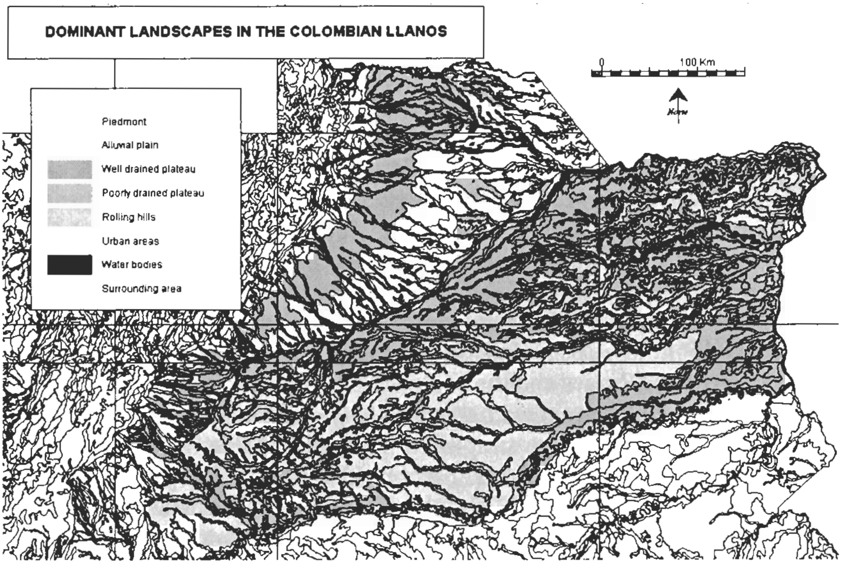

FIGURE 11.2. Dominant landscape positions in the Columbian llanos. (*Source:* Map prepared for this study using the soils map from IGAC [1983], and a landcover map for the Orinoco basin [IGAC, 1999a,b].)

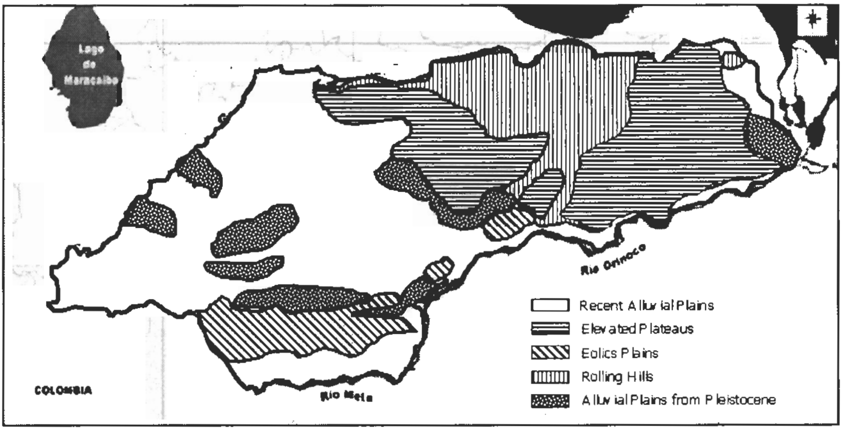

FIGURE 11.3. Dominant landscape positions in the Venezuelan llanos. (*Source:* Adapted from Schargel, 2003.)

TABLE 11.1. Areas under original main landscapes in the llanos (Mha).

Main landscape positions	Colombia[a]	Venezuela	Total per landscape
Elevated plateaus	8.27	6.48	14.75
Well-drained low plain savanna	2.85	6.42	9.27
Poorly drained lowland savanna	2.14	7.75	9.89
Rolling hills	6.98	3.15	10.13
Gallery and deciduous forest	2.65	1.52	4.17
Other (piedmont, urban, water bodies)	0.72	0.90	1.62
Total	23.6	26.2	49.8

Source: Based on data from Berroterán, 1988; Comerma and Luque, 1971; PINT, 1979, 1985, 1990; Schargel, 2003.

[a] Areas were calculated from a digital database on land use and land cover for the Orinoco basin of Colombia (IGAC, 1999a,b).

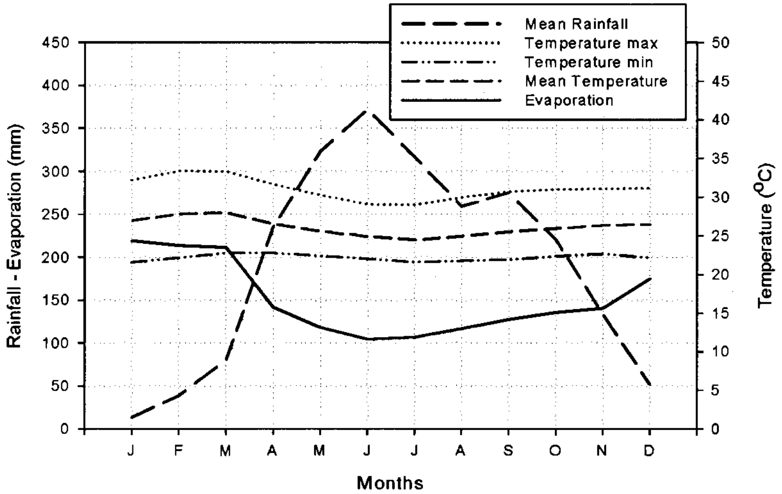

FIGURE 11.4. Climate data from Carimagua research station in the central llanos from Colombia. Rainfall data represent averages from a 20-year period. (*Source:* Adapted from Rippstein et al., 2001.)

the rainy and dry season, respectively, for the Carimagua research station in the middle of Colombian llanos (Hoyos et al., 2004).

This gradient in climatic conditions, associated with diverse landscape positions, results in a gradient in the species of the dominant vegetation, from dense gallery forest in the most humid areas to open savanna grasses and dispersed shrubs in the elevated plateaus, to semideciduous forest in the northern part of Venezuela. Native vegetation progressively dries with the advance of the dry season. Toward the end of it, natural or human-induced fires spread easily in the savanna. It is estimated that on average, native vegetation is burned every two years. Periodical burning plays a central role in maintaining the diversity and functions of the savanna ecosystem (Rippstein et al., 2001). Burning is also responsible in the llanos for important greenhouse gas emissions (CO_2, CH_4, and N_2O) to the atmosphere (Rondón, 2000). Though natural fires are still the dominant cause of biomass burning in the llanos, in recent decades, the use of controlled human-induced fires has increased. Controlled fires are promoted by ranchers to recycle the nutrients accumulated in the dry biomass and to promote the regrowth of more nutritious and palatable grasses for cattle, as well as to control cattle pests (e.g., ticks).

SOILS

Soils in neotropical savannas have been traditionally described as oligothrophic, with low to very low levels of organic matter and available nutrients. The diversity in the landscape, however, leads to a great diversity of soils. In the more recent alluvial plains, soils tend to be young Inceptisols, Entisols, and sparse spots of Vertisols, Alfisols, and even Mollisols. Dominant texture is clay-loam, and redox processes are common. The plains from the pleistocene have higher areas of sandy-loam to clay-loam Ultisols, low in organic matter (less that 1 percent). In the eolic plains, Ultisols are also dominant. Some soils located in the riverbanks or sand dunes have carbon content of <0.5 percent.

In the elevated plateaus, most of the soils are Oxisols with significant patches of Ultisols, though in the slopes of the hills separating one plateau from the next, Entisols are found, along with spots of Vertisols, Inceptisols, and Alfisols. Soils from the rolling hills are generally very superficial and dominated by Entisols in the higher slopes and Ultisols and Inceptisols in the lower slopes. Table 11.2 presents data for selected chemical characteristics of some of the most common soil types found in the llanos.

TABLE 11.2. Characteristics of some representative soil types found in the llanos.

Characteristic	**Carimagua (N W, Colombian elevated plains)**	**Guarico (Central Llanos Venezuela)**	**Arauca (Eastern Lowlands Colombia)**	**Monagas (Elevated Plateaus Venezuela)**
Soil type	Typic Haplustox	Ultisol	Humic Dystrudepts	Typic Kandiustult
pH	4.5	5.1	5.1	4.9
SOC (%)	2.0	1.3	1.6	0.5
CEC (cmol/kg)	4.2	4.6	8.0	1.9
Al saturation (%)	88	25	96	—
P (ppm)	3.9	—	23.3	2.0
K (cmol/kg)	0.08	0.40	0.12	traces
Ca (cmol/kg)	0.18	1.41	0.07	0.31
Mg (cmol/kg)	0.06	0.92	0.13	0.21
Bulk density (0-20 cm) (Mg·m^{-3})	1.38	1.46	1.27	1.55

Sources: Rao, 1998 (Carimagua); Hernández and López, 2002 (Guarico); Comerma and Chirinos, 1976 (Arauca); IGAC, 2003 (Monagas).

NATIVE VEGETATION

Seasonally dry climate, contrasting soil types, and varied landscape positions have generated a range of vegetation communities perfectly adapted to the environment. Ecologically, vegetation communities can be grouped into four main functional categories: seasonal savannas, hyperseasonal savannas, semiseasonal savannas, and gallery forest (Sarmiento, 1984). Seasonal savannas experience severe drought stress for four to six months annually. Vegetation is dominated by grasses with a C4 type of photosynthetic system such as *Trachypogon, Andropogon, Leptocoryphium, Axonopus, Paspalum, Panicum, Aristida, Echinolaena,* and *Tristachia.* Fire is common toward the end of the dry season, and burning usually removes most soil cover. Net primary productivity approaches 1kg·m^{-2} per year, with an estimated value of half of that from roots (Sarmiento, 1984). Hyperseasonal savannas are subject to shorter drought periods (two to three months) and a period of water excess favored by the location in the lower parts of the basin on poorly drained soils. Vegetation is mostly grasses (*Leersia, Paspalum, Sorghastrum,* and *Andropogon*), with little presence of woody species (*Copernicia tectorum* in Venezuela and *Caraipa llanorum* in Colombia). Sedge species are also important. Annual primary productivity is estimated at 1.2 kg·m^{-2} per year, with some 60 percent from aerial biomass.

Semiseasonal savannas are characterized by water excess, including flooding conditions during eight to eleven months per year. Dominant grasses are *Hymenachne, Leersia, Oryza,* and *Panicum,* although plants from *Ciperaceae* and *Amaranthaceae* are also abundant in the wettest parts. In the lower parts that remain flooded most of the year, Palmacea such as *Mauritia flexuosa* are dominant. Fire plays a minor role in these areas. Soils have not been studied in detail, but they usually have higher levels of organic matter compared to other savanna subregions. In the gallery forest, plant cover is dominated by diverse evergreen or deciduous trees (*Duguetria riberensis, Nectandra pichurni, Chomelia polyanta, Copaifera officinalis, Covvoloba ontusifolia*) subject to periodic flooding resulting from river overflows.

LAND USE

Historically, the llanos have been mostly used for extensive cattle ranching with some subsistence agriculture concentrated in the most fertile soils along the river and occasional timber extraction from the gallery forest (Sarmiento, 2000). The main management practice in the llanos has been the burning of native herbaceous vegetation to promote the regrowth of more palatable grasses. This production system has been intensified in recent decades through the introduction of exotic grasses such as *Brachiaria decumbens, B. brizantha, B. humidicola, B. dictyoneura, Panicum maximum, Digitaria swazilandensis,* and *D. decumbens*, among others. New breeds of cows have also been introduced. Crop species such as sorghum (*Sorghum bicolor*), maize (*Zea mays*), beans (*Phaseolus vulgaris*), rice (*Oryza sativa*), sunflower (*Helianthus annuus)*, sugar cane (*Saccharum officinarum*), cotton (*Gossypium hirsutum)*, sesame (*Sesamum indicum)*, cassava (*Manihot esculenta*), and some fruits such as watermelon (*Citrullus lanatus)* and bananas (*Musa acuminate*) are gaining space, particularly in the Venezuelan llanos. Forest plantations of pinus (*Pinus caribbea*), eucalyptus (*Eucalyptus spp.*), and teak (*Tectona grandis*) are now also important.

Land-use intensity varies according to the landscape position in the llanos and shows different trends between the two countries. Most of the cropland and pastures are concentrated in the elevated plateaus and in parts of the alluvial plains. In Colombia, the main land use has been and continues to be traditional extensive cattle ranching. However, recent decades have seen an intensification of livestock systems. Currently there are nearly 1 Mha of introduced pastures. The conversion into cropland started during the 1970s as a result of new agropastoral systems being implemented in the llanos to cultivate mainly upland rice as a preliminary step to establish pastures (Sanz et al., 2004). More recently, during the 1980s, some areas were planted to oil palm, and in the 1990s, with the development of acid-soil-adapted maize varieties and hybrids, this crop is gaining importance, especially when planted in rotation with acid-soil-tolerant soybeans (Narro et al., 2004). Currently, 0.4 Mha are sown to crops and 0.1 Mha are planted in Colombian llanos with tree species such as pines, rubber (*Hevea brasiliensis*), and oil palm.

In the Venezuelan llanos, the main land use is also extensive cattle ranching, but the history and distribution of land use in the elevated plains is quite different. The plateaus of the western llanos, in the piedmont of the Andes, have more fertile soils and have experienced strong agricultural expansion. The main crops in this region are cotton, sorghum, upland rice, and peanuts. The livestock has evolved into dual-purpose (milk and beef), intensive, and semi-intensive systems. Although the soils in the plateaus in the eastern llanos of Venezuela are not very fertile, the subregion has seen important agricultural expansion, but livestock continues to be the dominant activity. Main crops are peanuts (*Arachis hypogaea*), sugar cane (*Saccharum officinarum*), maize (*Zea mays*), sorghum (*Sorghum bicolor*), sesame (*Sesamum indicum*), and watermelon (*Citrullus lanatus*). In the plateaus of the central llanos, the main crops are cereals (sorghum and maize). There are around 1 Mha of croplands and at least 5 Mha under introduced pastures in the Venezuelan llanos. There are still important areas dedicated to extensive cattle ranching on large farms based on native vegetation. In the southern part of the Venezuelan llanos, a large-scale plantation of *Pinus caribbea* was established in 1969 and continues under production (Torres et al., 2003). Total area under tree plantations is 0.8 Mha.

The poorly drained areas from alluvial and eolic plains are located preferentially between the Meta and Apure Rivers, covering most of the Apure state in Venezuela and the Arauca and Casanare plains in Colombia. This seasonally flooded area accounts for 2.14 Mha in Colombia and 6.42 Mha in Venezuela (Sarmiento and Pinillos, 2001). Mean elevation ranges from 150 masl in Colombia to 75 masl in Venezuela. During three to six months of the year, depending on the altitude, the lowlands are flooded and cattle are forced to move somewhere else in search of pastures. At the end of the rainfall, the rapid grass regrowth again attracts the herds of cattle. This traditional livestock system has been used in the llanos for more than two centuries. In the Colombian llanos very little land from the poorly drained areas has been converted into other land uses. During the mid-1960s, the Venezuelan government promoted, and in most cases built, a system of low earth dykes, aimed to control flooding and to improve the economy based on livestock. The terrains encircled by dykes and river levees were called modules, as they operate both as hydrological and as grazing units. Some of these modules were planted later to improved grasses, and some patches of crops, but most of the area is still dominated by native vegetation. Due to edaphic constraints and water excess, agriculture is limited to the eolic plains and only traditional extensive livestock prevails.

The fourth main landscape of the llanos, the Lomerio, is used little for agriculture or pastures in Colombia, but receives greater use in Venezuela. Of the 7.75 Mha in Colombia, only some 0.01 Mha are used for crops, though some 0.05 Mha are now under pastures. The dominant use is extensive cattle raising. In Venezuela, this landscape coincides to most of the central llanos in the states of Cojedes and Guarico. This landscape occupies approximately 3.15 Mha. Extensive livestock on native vegetation (mostly of the genus *Trachypogon)* is the main land use. However, areas with lower slopes (less than 3 percent) have been converted to mechanized cropping (sorghum, maize), taking advantage of irrigation projects developed in the region. Forest plantations have replaced the patches of deciduous forest in Venezuela. Water is scarce in the region due to overuse of resources to cope with the high demand in the most populated areas that surround the region.

Table 11.3 summarizes current distribution by land use in Colombian and Venezuelan llanos. It is evident that the native savanna has preferentially been converted into introduced pastures in the llanos. As we mentioned before, the use of Venezuelan savannas is much more intensive than in Colombia, as a result of more access to infrastructure and clear government programs to develop the region. In Colombia, the lack of infrastructure in terms of roads, together with the remoteness of the region, contributed to relatively less intervention. The social conflict that the country has been facing for several decades has also played a role in limiting the interest of investors in the region.

TABLE 11.3. Distribution of the main land uses in the llanos (Mha).

Land use	**Colombia**[a]	**Venezuela**	**Llanos**
Native herbaceous vegetation	18.77	16.96	35.73
Improved pastures	0.98	5.00	5.98
Annual crops	0.39	1.00	1.39
Tree plantations	0.10	0.80	0.90
Gallery forest	2.65	1.52	4.17
Other (urban, water bodies)	0.72	0.90	1.62
Total llanos	23.6	26.2	49.8

Sources: Sarmiento, 1990; Schargel, 2003; PINT, 1990; Berroterán, 1988.

[a] Data were interpolated from a landcover map of Colombian llanos (IGAC, 2003).

CONSTRAINTS TO PRIMARY PRODUCTIVITY

Net standing biomass for the most prevalent open savanna type of vegetation is around 4.5 Mg C·ha^{-1} for the eastern Venezuelan llanos (San José et al., 1998) and 3.8 Mg C·ha^{-1} for the central part of the Colombian llanos (Rondón, 2000; Rippstein et al., 1996). This contrasts with the average 100 Mg C·ha^{-1} of a mature rainforest in the Amazon (Phillips et al., 1998). Apart from the limitations associated with a severe dry season, biomass productivity in the llanos is constrained by the low nutrient availability, high acidity, and very high aluminum saturation of the soils. As shown in Table 11.2, most soils are highly weathered Oxisols and Ultisols, with vast patches of Typic Haplustox Isohiperthermics (IGAC, 2003).

Fire is another important factor that limits productivity in the llanos. Some experiments to evaluate fire exclusion on native savanna vegetation have shown that secondary vegetation could accumulate much higher biomass (in the range of 10 Mg C·ha^{-1}) than the primary savanna on the uplands of the Colombian llanos (Garcia, unpublished data). Similarly, San José et al. (2003) indicate that when native savanna is protected from fire and grazing, a more dense type of vegetation can succeed even under the relatively drier conditions of the eastern llanos of Venezuela. Increases of up to 20 percent in aerial biomass have been observed in a period of 30 years by protecting the vegetation against fire in seasonal savanna from central Venezuela (Güerere, 1992). As was mentioned before, water deficits limit the photosynthetic activity during three to four months of the year. When these particular constraints are alleviated through liming, fertilization, and irrigation, very high net primary productivity can be obtained. Fisher and Thomas (2004) show that well-managed grass pastures can reach a net aerial primary productivity of 33.5 Mg·ha^{-1} per year. Biomass accumulation of 10 Mg·ha^{-1} per year have been reported for pine plantations in Venezuela (Hoyos, 1998). Solar radiation is not considered to be an important limiting factor for net primary productivity in the llanos.

CURRENT CARBON STOCKS IN SOILS

The Carbon Content of the Soils

A detailed survey of soils in the Colombian llanos reports carbon content in soils (0 to 30 cm depth) ranging from 1.2 to 3.5 percent (IGAC, 2003) in the well-drained upland savannas and from 1.0 to 4.0 percent in the poorly drained soils. Friesen et al. (1998) reported values of 2.3 percent for the 0 to 30 cm depth at the Carimagua Research Station, where the dominant soils have silty-loam texture representing around 70 percent of total soils in Colombian savannas. Soils with a more sandy texture show values of 0.7 percent. Values reported for Matazul near Puerto Lopez, representing the areas where most of the intensification is occurring in the Colombian llanos, are 2.3 percent for loam textures and 1.6 percent for sandy texture (Hoyos et al., 2004).

In the Venezuelan llanos, seasonal savannas account for 56 percent of the area. Soil carbon levels range from 0.8 to 3.5 percent, while values in the range of 2 to 2.5 percent are found in the high plateaus of the western llanos, where the more fertile soils are located. This contrasts with levels of 0.5 to 0.8 percent for the sandier Ultisols of the central llanos (Hernández and López, 2002; Schargel, 2003). In general, the eastern llanos in Venezuela have the lowest C content, with values as low as 0.6 percent. Soil carbon under gallery forest is usually higher, with values ranging between 3.4 and 5.5 percent (Schargel, 2003). Not surprisingly, much more soil data are available for agricultural soils than for areas under native vegetation, particularly on the poorly drained savannas. Values for the flooding lowlands in Venezuela range from 0.6 to 1.8 percent (Sarmiento and Pinillos, 2001), while C values between 1.1 and 1.6 percent have been reported for the Arauca drainage plain in Colombia (IGAC, 1991, 2003). Table 11.4 shows estimates of C content and stocks for different landscape positions and vegetation types for areas of the Venezuelan savannas. The western llanos of Venezuela store higher levels of carbon in soils, while the eastern llanos have consistently lower carbon stocks, due in part to their geologic origin associated with igneous acidic rocks from the Guyana shield.

A trend seems to exist in the C content in soils with the increase in distance from the Andes. The piedmont soils are clearly more fertile with higher organic C content, and for the elevated plateaus, the Colombian soils tend to have slightly higher C content than those of the equivalent landscape position in Venezuela. This could be the result of the contribution of eroded soil and nutrients coming from the Andes to lower areas which is progressively reduced eastward. However, more data are needed to support this hypothesis. As shown by previous data, within each landscape position, SOC (soil organic carbon) is relatively heterogeneous. This makes it difficult to extrapolate values to the overall landscape. Despite these limitations, an attempt is made herein to estimate a weighted average for C content in the top 30 cm of the soils for each landscape position in both countries, using an extensive literature review.

TABLE 11.4. Carbon content and stocks in the top 30 cm of soils from Venezuelan llanos.

Region	**Landscape**	**C stock (Mg C·ha^{-1})**	**C content (%)**
Young alluvial plains			
West:	Deciduous forests	77.0 ± 19.4	5.0 ± 1.3
	Hyperseasonal savannas (lowlands)	45.2 ± 17.3	3.2 ± 1.4
	Semiseasonal savanas (lowlands)	61.5 ± 12.0	5.2 ± 1.1
Alluvial plains from the Pleistocene			
West:	Hyperseasonal savannas (lowlands)	39.0 ± 8.5	2.6 ± 0.6
	Seasonal savanas	33.5 ± 6.4	2.2 ± 0.5
East:	Seasonal savanas	42	0.9
	Seasonal savanas	46	2.9
Eolic Plains			
West:	Poorly drained savanas	65 ± 7.1	4.2 ± 0.3
	Well-drained savanas	22 ± 4.2	1.4 ± 0.2
Elevated Plateaus			
West:	Seasonal savanas	24 ± 9.9	1.6 ± 0.7
East:	Seasonal savanas	17.7 ± 7.5	0.8 ± 0.5
Central:	Seasonal savanas	51.3 ± 22.5	3.5 ± 1.6
Rolling hills			
Central:	Seasonal savanas	31	3.3

Sources: Original data from Campos, 1999; Colmenares et al., 1974; Comerma and Chirinos, 1976; Gómez, 2004; Güerere, 1992; Hernández-Hernández et al., 2004; Hernández-Hernández and Dominguez, 2002; Hernández-Hernández and López-Hernández, 2002; Malavé, 1981; Pérez-Materán et al., 1980; PINT, 1979, 1985, 1990; Schargel, 1972, 1978; Westin, 1962; Zinck and Stagno, 1966.

Data on Soil Bulk Density Are Missing

Quantifying total C stocks in soils from the llanos depends on the availability of data on both SOC and soil bulk density (SBD). But there are considerably more data on SOC than the corresponding SBD. This missing information contributes to most of the uncertainty in the estimation of total C stocks, because SBD data are probably more heterogeneous than SOC in the llanos (Lozano et al., 2000).

SBD values have been reported for Colombian savannas for clay-loam and sandy soils (IGAC, 2003, 1991, 1983) as part of detailed soil surveys in the region. The SBD of soils at the Carimagua Research Station in the middle of Colombian llanos have been intensively measured (Amézquita et al., 2002), as well as the values for the clay-loam savannas near Puerto Lopez, where most agricultural intensification is taking place in Colombia (Hoyos et al., 2004). Values (in $Mg{\cdot}m^{-3}$) for high plateaus in Colombia range from 1.25 to 1.32 in the top 10 cm layer to 1.4 to 1.6 at 30 cm depth. Data on SBD are scarce for river floodplains. IGAC (2003) reported values ranging from 1.1 to 1.7 for the seasonally flooded lowlands in Arauca and Casanare. In Venezuela, SBD values between 1.46 and 1.7 are reported by Hernández and López (2002) for the rolling hills of the central llanos, and 1.4 for the Apure floodplains (Pinillos, 1999). Lobo et al. (2002) found values between 1.32 and 1.62 for the rolling hills of central Venezuela. Values for the gallery forest are also scarce. Rondón (2000) measured SBD values for the gallery forest in Colombian plateaus and reported an average value of 1.1 for the top 30 cm of the soil. In Venezuela, data from the soil survey (MARNR, 1986) indicated values ranging between 1.2 and 1.4 for native forest. For Venezuelan eastern plateaus, values range between 1.3 and 1.8 (San José and Montes, 1991; Sarmiento and Acevedo, 1991). For this analysis, data are considered down to 30 cm soil depth for two reasons: (1) the lack of available sufficient data for lower depths, and (2) the overarching assumption that it is in the 0 to 30 cm layer where most of the changes in SOC occur due to erosion, oxidative processes, or accretion of SOM from root and litter turnover.

Carbon Stocks

Using weighed averages for carbon content and SBD for the top 30 cm of the soil, total soil carbon stocks are calculated for the areas under native vegetation in various landscape positions, as well as for the areas under more intensive use: pastures, crops, and forest plantations. Data for Venezuela are the result of an extensive review of the literature in the country, while data for Colombia have been taken mainly from a detailed soil survey conducted by IGAC (2003) in the Colombian llanos, as well as data accumulated from 30 years of research from CIAT and CORPOICA. Table 11.5 shows integrated stocks calculated for the main landscape positions and land use in both countries to estimate global carbon storage in the top 30 cm of soils in the llanos.

Covering an area of nearly 50 Mha, the native savannas account for around 1 percent of the total area of 4,968 Mha of the humid tropics (Lal,

TABLE 11.5. Estimated carbon stocks for the main land-use systems in the llanos from Colombia and Venezuela.

	Area (Mha)		Estimated carbon stocks (0-30 cm depth)			
Landscape position/ land use	**Colombia**	**Venezuela**	**Colombia (Mg C·ha^{-1})**	**Venezuela (Mg C·ha^{-1})**	**Colombia (Tg C)**	**Venezuela (Tg C)**
Remaining natural systems						
Elevated plateaus	7.29	5.04	73.98	35.66	539.3	179.8
Well-drained lowlands	2.51	4.81	83.54	43.16	209.7	207.6
Poorly drained low plains	2.13	5.45	89.92	59.41	191.5	323.8
Rolling hills	6.84	1.66	48.07	40.00	328.8	66.4
Gallery and deciduous forest	2.65	1.52	138.60	75.00	367.3	114.0
Subtotal	21.42	18.48			1636.6	891.6
Modified systems						
Introduced pastures	0.98	5.00	98.20	78.00	96.2	390.0
Annual crops conventional tillage	0.39	0.83	70.49	38.10	27.5	31.6
Annual crops reduced tillage	0.001	0.17	72.90	43.20	0.07	7.34
Tree plantations	0. 1	0.80	73.39	27.00	7.34	21.6
Urban, water bodies, etc.	0.72	0.90			—	—
Subtotal	2.19	7.70			131.1	450.6
Total per country					1767.7	1342.2
Total for the llanos						3110

2002) and store in the top 30 cm of the soil an estimated 3.1 Pg of SOC. This is roughly 0.64 percent of the estimated 496 Pg of carbon stored by tropical soils down to 1 m depth (Lal, 2002). If we assume that a similar amount of C is stored by savanna soils between 30 and 100 cm depth, this results in estimates of total C stocks of around 1.3 percent for tropical savannas, indicating that soils from the neotropical savannas are similar to other tropical environments with regard to their ability to stock C in the soil profile (Houghton, 2003).

EFFECTS OF LAND-USE INTENSIFICATION

The llanos of Colombia and Venezuela have experienced different degrees of agricultural development or livestock intensification. In Colombia, essentially all agricultural lands have been opened on upland savannas in the vicinity of the main cities (Villavicencio, Puerto Lopez, Granada, Puerto Gaitan) and along the main connecting roads. There are currently some 0.01 Mha under plantation crops of oil palm and rubber, and 0.4 Mha dedicated to field crops (mainly maize, soybean, rice, and sorghum); most of the land-use intensification occurred on 0.98 Mha of improved pastures (*B. dictyoneura, B. decumbens*). Figure 11.5 shows that the total area under crops, pastures, and forestry plantations in Colombia is around 6 percent of the total area of the llanos. In Venezuela, agricultural lands account for 1 Mha, of which 0.8 Mha are on forest plantations, mainly of *Pinus caribbea,* and some 5 Mha are on improved pastures. The proportion of managed land is around 26 percent, indicative of the more intensive use of the llanos in Venezuela. Both countries still have vast areas of savannas that could be converted into more intensive land-use systems.

It is widely documented that agricultural intensification results in net changes in the amounts of carbon stored in soils (Bravo, 2000; Gomez, 2004). Conventional tillage management usually decreases the C from the topsoil by 20 to 40 percent over a 20-year period (Cihacek and Ulmer, 1995). There are limited data about C dynamics under cultivated lands in the llanos (Lozano, 1999; Hernández and López, 2002). Data from a long-term experiment conducted in the Carimagua Research Station in the mid-

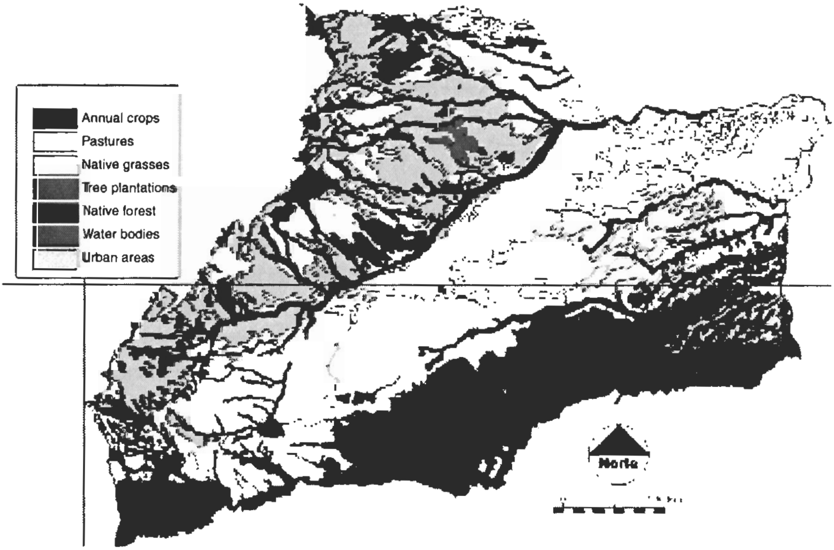

FIGURE 11.5. Current land-use distribution in the llanos from Colombia. (*Source:* Adapted from IGAC, 2003.)

dle of the Colombian llanos, to study the sustainability of different land-use options, including maize-based and rice-based systems, is presented herein. The experimental details were reported before (Friesen et al., 1998). Continuous cultivation of upland rice, maize, and rotation of these two crops with soybean or cowpea were evaluated during an eight-year period. Other systems included grass-legume pastures (*B. humidicola* and *A. pintoi; Panicum maximum and Phaseolus phaseoloides)* and native savanna. Each experimental plot measured 200 × 18 m (0.36 ha), and the experiment was replicated four times. The soil is a typic Haplustox (Table 11.1). At the time of establishment in 1993, a detailed soil sampling was done in the area. Soil C was determined to 40 cm depth with 5 cm increments to 20 cm, and then for every 10 cm depth. SBD was measured for the same soil increments. The plots were monitored annually until the end of the experiment in 2003. The data from the initial and final measurements for some of the treatments are summarized in Figure 11.6 for total carbon stocks as well as stocks in each soil layer increment for the maize-based systems.

After eight years of cultivation, there were no significant differences in the C stored in the top 40 cm of the soil among the savanna plots, the *P. maximum* plots, and the maize-based systems plots. The higher nitrogen inputs to these plots could probably explain this trend, which has been also reported previously for other soils (Halvorson and Reule, 1999). These results

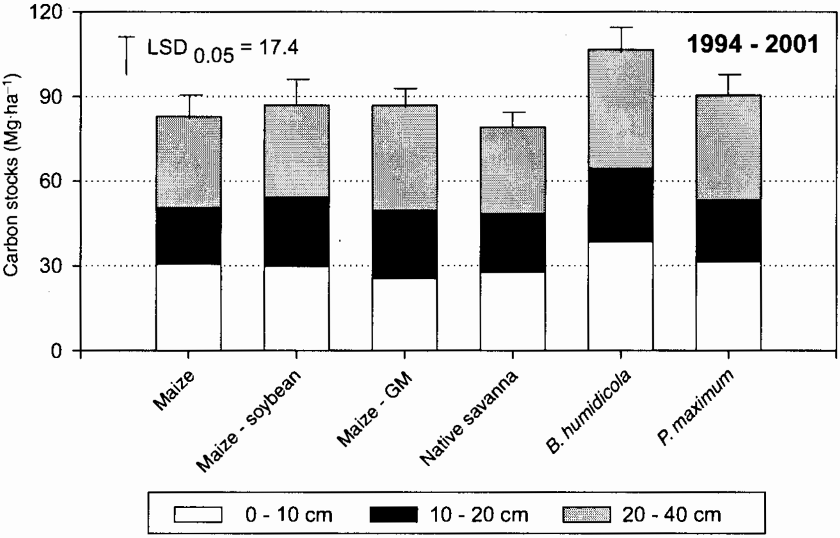

FIGURE 11.6. Soil carbon stock under a long-term experiment on clay-loam Oxisols from central Colombian llanos.

contrast with several studies both in temperate and tropical regions, indicating that cultivation usually a result in net losses of C (Reicosky et al., 2003; Freixo et al., 2002). However, long-term studies reported by San José et al. (2003) for the eastern Venezuelan llanos indicate also that after 30 years of continuous cultivation, there was a nonsignificant decrease in the net soil C stocks. For soils of the central llanos in Venezuela, intensive tillage resulted in net losses of up to 20 percent in 20 years (Hernández and López, 2002), while the use of no-till caused a net increase in total C stocks of 7 percent compared to native savanna (Hernández and López, 2002). The C accrual in no-till maize occurred at the rate of 0.8 Mg C per year in regions of the Venezuelan rolling hills (Hernández and López, 2002). Most of the new carbon goes to the soil maccroagregates and to the light fraction of soil organic matter. The data showed that there was no net loss in C from cropping in the Colombian llanos, compared with a weighted average loss of 2 Mg C·ha^{-1} estimated for Venezuelan croplands under conventional tillage systems. No-till cropping increased C content by 4 Mg C·ha^{-1} on average for the lands where this practice has been implemented in Venezuela. The area under no till is still incipient in Colombia. As shown in Figure 11.6, the conversion of native savannas on clay-loam soils into pastures of *B. humidicola* and *A. pintoi* resulted in net increases in soil C stocks of 25 Mg C·ha^{-1} over eight years. Very similar rates of SOC accumulation (3 Mg C·ha^{-1} per year) have been reported on pastures of *B. dictyoneura* associated with *C. macrocarpum* on a sandy soil from well-drained plains in Venezuela (Hernández et al., 2004). These results confirm previous findings (Rao, 1998; Trujillo, 2000) in clay-loam soils from central llanos in Colombia, indicating that introduced pastures can significantly enhance total C in soils. Though the magnitude of the accumulated C found in this study is smaller than previously reported in similar soils down to 2 m soil depth (Fisher et al., 1994), the C pool in this study was estimated to 1 m depth. However, our values are in agreement with a net average increase of around 18 Mg C·ha^{-1} in savannas converted to pasture (San José et al., 2003).

Figure 11.6 shows that most of the accumulation in grasses occurs in the top 10 cm of the soils. This may be the result of higher influence of litter added to surface layers and also of the high biomass of roots concentrated in that layer. Fisher and Thomas (2004) report that the rate at which litter decays at the soil surface has been grossly underestimated in the past. Rao (1998) evaluated different grasses in the same area and indicated that introduced grasses have up to 5.7 Mg·ha^{-1} of root biomass compared to 1.4 Mg·ha^{-1} for native savannas down to 80 cm depth. Rao also observed that up to 73 percent of the root biomass from the grasses is concentrated in the top 20 cm layer. Trujillo (2000) found in Colombian high plateaus that standing root biomass was about three times more in pastures of *B. dictyoneura* (8.6 Mg·ha^{-1}) than in native savanna (2.9 Mg·ha^{-1}).

The amount of total C that can be accumulated in soils when native savanna is converted into pastures with *Brachairia* species varies among locations in the llanos. Fisher et al. (1994) reported accumulations during a nine-year period in the top 1 m of soil of 25.6 Mg C·ha^{-1} for *B. humidicola* grass and of 70.4 Mg·ha^{-1} for associated pastures of *B. humidicola* and *A. pintoi* in the middle of the Colombian llanos. In contrast, San José et al. (2003) reported no net change in C stocks in the top 30 cm of the soil after 30 years of a pasture of *B. decumbens* in the state of Monagas in the eastern Venezuelan llanos. Estimates presented herein are based on values repeated in Figure 11.6 as representative of the high plateaus of Colombia, assuming that appropriate management, fertilization, and maintenance could prevent pasture degradation. It is uncertain, however, the span of time that pastures could maintain high productivity (Acevedo, 2003). For crops in the hillsides of Venezuela, values reported by Hernández and López (2002) were used which indicated a net decrease of 18 percent in SOC by conventional till versus a net gain of 7 percent relative to the native savanna by no-tillage systems. Data reported in the literature are used to estimate net change in C stock due to land-use change in other regions of the Venezuela llanos (Bravo, 2000; Campos, 1999; Larreal et al., 1975; Hernández and Domínguez, 2002; Hernández et al., 2004). Data from Campos (1999) report no net changes in C storage in the soil under a 30-year-old pine plantation in eastern Venezuela, despite high production of litter. Due to lack of data to calculate the C change under tree plantation in Colombia, no net change in soil C stocks under these plantations is assumed.

Using these data, net change in soil C stocks that have resulted from the conversion of native savannas into more intensive land use (i.e., agriculture, pasture, or forestry land) in the llanos have been estimated (Table 11.5). Given the relative small area converted into crops and the reported low or no losses of C due to cultivation in the region, agriculture and forestry are not seen to have caused large impacts on total stocks of C in soils from the llanos, accounting for a net loss of 1 Tg C. Pastures dominate the managed lands in the llanos and have had a clear impact in increasing the overall C stocks of the llanos to 115 Tg C . The available data show that tree plantations are neutral in terms of soil C stock change. Overall, a net increase in C stocks in the top 30 cm of soil from the llanos of 114 Tg C has been estimated as a result of land intensification in this ecosystem. With an estimated total C stock in the llanos prior to changes in land use of about 2,985 Tg C, the soil C accrual due to pastures represents an increase of about 4 percent over the baseline level.

CARBON SEQUESTRATION POTENTIAL

The previous analysis was based on the assumptions that 12 percent of current cropland is managed with no-till systems. If all current crops in the llanos can be transformed into no-till systems, this could result in a net additional increase of 5 Tg C in the soil C stocks. Intensification expected to occur in the region in the two coming decades foresees an additional 2 Mha converted to agriculture. Assuming that no-till may be able to increase soil C by 4 Mg C·ha^{-1} relative to savannas (Hernández and López, 2002), and that the new land is managed using conservation practices, this may result in a an additional 8 Tg C being sequestered in soils. Prospects of increases in C stocks associated with cropping seems, therefore, to be modest in the llanos.

It is expected that the area under forestry plantations will grow steadily at an average rate of 0.05 Mha per year. With currently available data there is no indication that net changes in soil C stocks will result from expansion of tree plantations. However, planting trees has the advantage that significant amounts of C can be accumulated in the tree biomass, as compared with other land-use systems. Recently, the Ministry of Agriculture of Colombia launched a program to promote the plantation of rubber, pines, and oil palm in vast regions of the central Colombian llanos. It is feasible that tree plantation under soils of higher clay and SOM content than the soils from the eastern Venezuelan llanos, where most of current forest plantations are located, may result in net increases in SOM of soil under these plantations.

An important opportunity for C sequestration in the region lies in the restoration of degraded pastures in the area and the establishment of productive new grass-legume pastures to intensify cattle raising. With current expansion, it is foreseen that some 5 Mha of new land will be converted into pastures in the next two decades, 2 Mha of which is in Colombia. This would in itself result in approximately 148 Tg C sequestered in soils. If intensification of livestock occurs in lieu of converting part of the savannas to pastures, other areas of savanna could be protected against fire through proper policies and incentives. This could accelerate the recolonization of woody vegetation with potentially high C gains in the biomass in the range of 1 Mg C·ha^{-1} per year. (San José et al., 2003) to 8 Mg C·ha^{-1} per year (Güerere, 1992), depending on the original vegetation cover. This possibility is, however, more remote, as it would require further management strategies to protect the vegetation against fire, at least during the initial years. Present analysis is based on the assumption that the area under gallery forest will continue to be unaffected. This is desirable for several reasons, ranging from preserving endemic biodiversity hosted in such areas to maintaining high levels of SOC. It is unlikely than any alternative land use may increase soil carbon levels beyond the levels of the gallery forest. Gallery forests are very important to moderate the hydrological cycles in the llanos; therefore governments must aim at their preservation.

The establishment of agroforestry systems has been very slow in the llanos, and high labor requirements for these activities would probably limit the areas that may be converted in the near future. Oil palm plantations are promising alternatives for expansion of agroforestry systems. Trees are, however, expected to play a central role in the future development of the llanos in both countries. The introduction of silvopastoral systems offers probably the most beneficial option to enhance C in the system, by combining accumulation in both soils and biomass.

The maximum potential of the llanos to sequester carbon in the soils would result from a total conversion of available land into improved pastures. This may theoretically generate a total increase of soil C stocks of about 1.02 Pg C. Given current trends in the development of the llanos, it may be expected that approximately 160 Tg C can be added to soil C stocks in the next 20 years.

UNCERTAINTIES IN THE SOCIAL AND INTERNATIONAL CONTEXTS

Although the estimates presented here have still a range of uncertainty due to limited availability of data for C content in more points of the landscape and principally due to poor data on SBD profiles, estimates presented within this study provide a reasonable gross estimate of the potential of the region. Nevertheless, much higher uncertainties appear in the social and political context, to foresee how much of the total potential to accumulate C in soils from the llanos may be realized in the coming decades.

Livestock intensification will be the main avenue for enhancing C stocks in soils, but whether the projected expansion will happen depends on numerous factors beyond the control of farmers, regional, and even national authorities. The influence that the common-market schemes which are being negotiated between the governments of Colombia and Venezuela and other countries in Latin America, as well as the ALCA, the free trade agreement with the United States, will have on agricultural expansion is difficult to predict. Most economists seem to agree that this will result in a deceleration of the agricultural expansion in the llanos (L. Rivas, personal communication). Nevertheless, current political trends in Venezuela strongly oppose the ALCA and propose an alternative economic model based on endogenous development, agrarian reform, strengthening of cooperatives, and the egalitarian access to credits, which could result in agriculture expansion and livestock intensification. However, this political process is new and it is too soon to predict its agricultural and environmental impacts.

In Colombia, the effect of the social conflict which has afflicted the country during past decades has already had a negative effect on agricultural expansion and slowed governmental plans to increase maize production in the region. This has moved investors to look into plantations of industrial crops such as oil palm or rubber trees, which are considered safer than annual crops or livestock. It is likely that at least this sector will continue to grow at the expected rate in Colombia. Indications of this were recently given by the government when launching a development plan for the central llanos of Colombia.

OPPORTUNITIES FOR CARBON TRADING IN THE LLANOS

Despite all uncertainties, the vast area of land that is suitable for intensive land use in the llanos makes the region a good candidate for carbon trading projects when suitable markets materialize through the CDM (Clean Development Mechanism) under the Kyoto Protocol or other mechanisms which are being promoted by the European community. Nevertheless, under current agreements, for the first period of the Kyoto Protocol (2008 to 2012), soils are excluded for trading within the CDM (UNFCC, 2004). This makes forest plantations, agroforestry, or silvopastoral systems the most economically acceptable options available now to trade C and the ones that most likely could start materializing in the region.

Currently, the economic margin of agricultural activities is modest in the llanos. Any additional income resulting from carbon trading would make investments in the llanos an attractive alternative for current farmers and for new investors. The monitoring of C trading projects in this area is easier and should be less expensive than in other more heterogeneous environments such as the hillsides. Establishment of forestry plantations, silvopastoral, or agroforestry systems in the region are the most attractive options, given that in addition to possible C accumulation in the soils, large amounts of C could be accumulated in the standing biomass of trees. For the pine plantations in Venezuela, as much as 50 Mg $C{\cdot}ha^{-1}$ can be accumulated in the biomass in a 10-year period (Hoyos, 1998). This is twice the equivalent amount accumulated in the soils under improved pastures. Combining trees and improved pastures in properly managed silvopastoral systems offers a win-win situation to sequester C in the llanos. Gains in soil C stocks favored by the pastures may be complemented by CO_2 capture in tree biomass. Nevertheless, tree plantations present important agronomic challenges, as evidenced by the large single-species plantations at Uverito, Venezuela, where plantation health and timber production are hampered by several pests and diseases difficult to control. The selection of the most appropriate combinations of pastures, forage legumes, and trees and its effect on total C balances will need further research.

This chapter has focused only on the carbon in soils. Nevertheless, it has been reported that in the llanos, net balances of greenhouse gases are strongly influenced by the emissions resulting from burning the native vegetation (Scharfe et al., 1990). As much as 41 percent of total methane and 35 percent of the nitrous oxide emissions in savannas from high plateaus in Colombia result from periodic burning (Rondón, 2000). Conversion of native vegetation into permanent crops, pastures, agroforestry, or silvopastoral systems eliminates annual emissions due to fire and may greatly contribute to net CO_2 equivalent gains in the system. Although some advances have been made in understanding the role of agriculture and livestock intensification on net balances of greenhouse gases in the region (Rondón, 2000), a proper accounting of the integrated balance of emissions associated with land-use intensification is still a major challenge that national and regional research institutions need to address to successfully implement any potential C trading scheme in the region.

CONCLUSIONS AND FUTURE PERSPECTIVES

Soils from the llanos have a large potential to sequester up to 1.02 Pg C, assuming that all the native land could be converted into well-managed and sustainable pastures. However, this option is not necessarily desirable. Neotropical savannas play key roles in planetary biogeochemical cycles that could seriously change if a few exotic species completely displaced the large biodiversity of this ecosystem. Savannas are a major repository of animal diversity as well, particularly birds, and even serve as a summer habitat for migratory birds coming from as far as Alaska. Savannas should be preserved and protected to ensure that coming generations of humans may enjoy their diverse environmental services and functions. On the other hand, the countries with savannas probably need and are willing to develop parts of these environments to improve the production of food, services, and income for a continuously increasing population.

Technologies are currently available to allow sustainable agriculture, livestock, and forestry in the region. Most of these technologies also sequester atmospheric carbon in the biomass or in the soils. The payments for equivalent carbon accumulation in the llanos that could result from implementing these methodologies may accentuate the adoption process. The decision to use these technologies lies in the hands of farmers and local and national governments. However, the final decision to what extent the llanos may exploit its inherent potential to sequester carbon in soils and biomass mostly lies with international policymakers and negotiators. Fortunately, for the sake of the soils, most trends are showing an interest in the region to move into sustainable agriculture, and this will result in more organic matter being sequestered into the soils of the llanos. This could have important benefits not only for the global environment through reductions in the net fluxes of greenhouse gases from the llanos to the atmosphere, but most importantly to the health status of the soils of the region. Healthier and more resilient soils are the best legacy that current farmers could leave for the future generations. It is a great challenge for researchers, institutions, farmers, and local and national authorities to find the mechanisms to enable that payments from environmental services resulting from land-use intensification in the llanos could be translated into sustainable development of the region. Another similarly daunting task will be to find the proper balance between development and conservation, so the neotropical savanna ecosystem may continue playing its important, though not properly understood role in the planet.

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