CARBON SEQUESTRATION IN PASTURE AND SILVO-PASTORAL SYSTEMS UNDER CONSERVATION MANAGEMENT IN FOUR ECOSYSTEMS OF TROPICAL AMERICA

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ABSTRACT

This research aims at identifying pasture and silvo-pastoral systems that provide economically attractive solutions to farmers and offer environmental services, particularly the recovery of degraded areas and C sequestration, in four ecosystems of Tropical America vulnerable to climate change. Soil C stocks, C contents in biomass, and socio-economic indicators were evaluated in a wide range of pasture and silvo-pastoral systems under grazing, in commercial farms under conservation management practices. At each ecosystem and site, C evaluations were also performed for native forest (positive reference) and degraded soil (negative reference). Results of 5 years of research (2002-2007) show that improved and well-managed pasture and silvo-pastoral systems can contribute to the recovery of degraded areas as C-improved systems.

INTRODUCTION

The deforestation of native forests and the final conversion of these areas in pastures represent the most important change in land use in Tropical America (TA) in the last 50 years (Kaimowitz, 1996). Close to 77% of agricultural lands in TA are currently under pastures (FAO, 2002) and, due to poor management, more than 60% of these lands are severely degraded (CIAT, 1999-2005). Improved, well-managed pasture and silvo-pastoral systems represent an important alternative to the recovery of degraded areas and are a viable business activity for the producer (Toledo, 1985). Previous literature also suggest they have high potential for C sequestration (Veldkamp, 1994). The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC COP3, 1997) - last ratified on 16 February 2005- and subsequent agreements of the United Nations (UNFCCC COPs 4-13, 1998-2007) suggest the reforestation or afforestation of degraded areas, including those currently under degraded pastures. This policy could have a negative impact on the economic production and social welfare of livestock producers in TA, especially intermediate and small producers. Therefore it is necessary to find sustainable alternatives that combine mitigation of poverty with economic production and supply of environmental services, especially C sequestration.

This article presents the findings of 5 years of research (2002-2007) generated by an international research project implemented by two Colombian institutions (CIPAV and Universidad de la Amazonia) and three international research centres (CIAT, Cali, Colombia: CATIE, Turrialba, Costa Rica; and Wageningen University and Research Centre, The Netherlands) financed by The Netherlands Cooperation. This project evaluated C accumulation in soils and plant biomass in a range of tropical pasture and silvo-pastoral systems and compared these results with those for native forest (positive reference system) and degraded pasture (negative reference system) in four ecosystems of TA that are susceptible to the adverse effects of climate change: a) eroded hillsides of the Colombian Andes; b) tropical rainforests in Colombia's Amazon region; c) sub-humid tropical forests along Costa Rica's Pacific coast; and d) tropical rainforests along Costa Rica's Atlantic coast. The present research aims to identify the pasture and silvo-pastoral systems in each ecosystem that represent an alternative for farmers that is not only economically viable, but also environmentally beneficial, hence contributing to the recovery of degraded areas and to C sequestration.

Research results generated by this international project have been published in conference proceedings, international journals, and lately in the scientific book entitled *"Carbon Sequestration in Tropical Grassland Ecosystems"* edited by Leendert 't Mannetje, Maria Cristina Amézquita, Peter Buurman, and Muhammad Ibrahim, published by Wageningen Academic Publishers in 2008. Publications include Mannetje, *et al*., 2008*;* Amézquita *et al.* 2008a,b, 2006, 2005a,b; Buurman *et al.*, 2008, 2004; Gobbi *et al.*, 2008; Ramírez *et* al, 2008; Rodíguez-Becerra, 2008; *Van* Putten *et al.*, 2008. The present article summarizes project results referred to C evaluations (2002-2007).

MATERIALS AND METHODS

Experimental sites.- Field research was conducted on producer farms at sites representative of each target ecosystem. Sites selected in the eroded hillside ecosystem of the Colombian Andes were Dovio (1900 m.a.s.l, 1043 mm annual precipitation, 18.5 ºC annual mean temperature, slopes between 45%-65%, moderately acid poor soils with pH 5.2-6.2) and Dagua (1350 m.a.s.l. 1100 mm annual precipitation, 21.5 ºC annual mean temperature, slopes between 25%-45%, poor acid soils with pH 5.0-5.8). In humid tropical rainforest ecosystem of Colombia's Amazon region, evaluations were carried out at two sites with differing topography: 'La Guajira' farm (flat topography, 400 m.a.s.l., 4500 mm annual precipitation, 32 ºC mean temperature, and poor, very acid soils with pH 4.0-4.6) and the 'Beijing' farm (rolling topography, with <10% slope, 258 m.a.s.l., 4500 mm annual precipitation, 32 ºC annual mean temperature, and poor, very acid soils with pH 4.0-4.6). In Costa Rica's tropical rainforest ecosystem, evaluations were carried out in Esparza (200 m.a.s.l., 3500 mm annual precipitation, 29 ºC annual mean temperature, poor soils less acid than those of Amazon region, with pH 5.0-5.6). Finally, for Costa Rica's subhumid tropical rainforest, evaluations were carried out in Pocora (200 m.a.s.l., 2500 mm annual precipitation with 5-6 months of drought, 27 ºC annual mean temperature, and soils similar to those of Esparza).

Producers cattle farms where C evaluations were performed are managed under conservation practices such as minimum tillage, associations of forage grasses and legumes both herbaceous and tree-legumes as N supply, use of organic fertilization combined with minimum required applications of chemical fertilizers, and manual weed control among others – all these practices contributing to a sustainable use of soil, water, plant and animal resources.

C assessment.- The C accumulation in soil and plant biomass was assessed in pasture and silvo-pastoral systems already established (10-20 years) on commercial livestock farms. To achieve precise estimates, a sampling design that controlled the main sources of variation in C sequestration was used. Sources of variation were local site-specific conditions, such as altitude, temperature, precipitation, slope, and soil type; current land use; and history of use. Two spatial replicates/system were used with 12 sampling points/spatial replicate/system and 4 soil depths (0-10, 10-20, 20-40, and 40-100 cm). Apparent density, texture, pH, total C, oxidable C, total N, P and CIC were measured, using international analytical methods (USDA, 1996) at each sampling point/depth. Total C in fine roots, thick roots, and aerial biomass of pasture and trees was estimated using the methodology of CATIE and the University of Guelph (2000) to estimate the C in silvo-pastoral systems, multiplying the dry matter/hectare of each component by 0.35 (to estimate the C in pastures) and 0.42 (to estimate the C in roots and aerial biomass in silvo-pastoral systems). To statistically compare the soil C level among the different systems, C contents were corrected for apparent density and adjusted to a fixed soil weight using as reference value the sampling point of minimum weight in each ecosystem (Ellert et al., 2002; Buurman et al., 2004).

Socio-economic evaluations with producers.- The economic benefit of investing in improved pasture and silvopastoral systems was evaluated by surveys and workshops with producers in all project ecosystems. Detailed research findings are not presented in this article. Gobbi *et al* (2008) describe the methodology of socio-economic research. Ramírez *et al* (2008) show socio-economic results. They show the economic benefit of producers from the Andean hillsides ecosystem in Colombia who adopted improved pasture and silvo-pastoral systems as a five times increase in farm income/ha/year, an increase in self-sufficiency from 30 to 40%, and life conditions increase from 3 to 5 (under a 1-5 scale).

RESULTS AND DISCUSSION

Tables 1-3 present the averages of accumulation of C in the soil (adjusted to a fixed soil weight), C in pasture biomass, C in fine roots, and C in thick roots, trunks and leaves, together with the percentage that the C of each component represents of the C total of the system in each land use under study. Table 1 presents the results obtained for Colombia's Andean hillsides, Table 2 those corresponding to the tropical rainforest of Colombia's Amazon region, and Table 3 those corresponding to Costa Rica's subhumid tropical rainforest. The tables present global descriptive statistics (N, mean, CV (%), LSD_{10}), and the results of the statistical comparison of soil C among the different land use systems.

Table 1. Carbon in soil and biomass in each land use system in the hillsides of the Colombian Andes.[1]

Site 1: Dovio

Land use system	Total C in soil (t/ha per 1 meq)	%	Total C in pasture (t/ha)	%	Total C in fine roots (t/ha)	%	Total C in thick roots, trunks and leaves (t/ha)	%	Total C in system (t/ha)
Native forest	231 a[2]	61.7[3]	-	-	4.6	1.2	138.9	37.1	374.4
B. decumbens	147 b	97.2	0.9	0.6	3.3	2.2	-	-	151.2
Forage bank	131 c	95.1	-	-	4.3	3.1	2.5	1.8	137.8
Degraded pasture	136 c	96.5	0.5	0.4	3.9	2.8	0.6	0.3	141.0
N (sampling points/ system)	24		40		24		8		
Mean, CV (%), LSD_{10}	161, 20, 18								

Site 2: Dagua

Land use system	Total C in soil (t/ha per 1m-eq)	%	Total C in pasture (t/ha)	%	Total C in fine roots (t/ha)	%	Total C in thick roots, trunks and leaves (t/ha)	%	Total C in system (t/ha)
Forest (40 years old)	186 a[2]	61.7[3]	-	-	2.6	0.9	112.7	37.4	301.5
Forest (15 years old)	155 ab	61.7[2]	-	-	2.2	0.9	93.9	37.4	251.2
Natural regeneration of degraded pastures	142 b	97.1	0.5	0.3	3.2	2.2	0.6	0.4	146.3
B. decumbens	136 b	93.7	0.8	0.6	8.3	5.7	-	-	145.1
Forage bank	90 c	94.7	-	-	2.5	2.6	2.6	2.7	95.1
Degraded soil	97 c	98.4	-	-	1.6	1.6	-	-	98.6
N (sampling points/ system)	24		40		24		8		
Mean, CV (%), LSD_{10}	135, 25, 30								

[1] Results of 2002-2005, Carbon Sequestration Project- The Netherlands Cooperative Activity CO-010402", Internal Publication No. 14. June 2005.
[2] Means with different letters differ statistically, with an error probability of 0.10.
[3] The % obtained in the native forest of Costa Rica's subhumid tropical rainforest ecosystem was used.

Data show that the C accumulated in the soil represents the total cumulative C in the system: 61.7% in a native tropical forest, 90% in a silvo-pastoral system of *Acacia mangium* + *Arachis pintoi* (Table 3), and 95%-98% in pasture systems (Tables 1-3). The C accumulated in thick roots, trunks, and leaves in the silvo-pastoral system of *A. mangium* + *A. pintoi* accounts for 7% of the system's total (Table 3). The C accumulated in fine roots in pasture systems accounts for 3%-8% and the cumulative in pasture biomass, 0.5%-2.1% (Tables 1-3). The native forest shows the highest total cumulative C levels of the system (soil + biomass) of all ecosystems. However, differences in soil C were observed between ecosystems.

Table 2. Carbon in soil and biomass of tropical rainforests in Colombia's Amazon region.[1]

Site 1: 'La Guajira' farm (flat topography)

Land use system	Total C in soil (t/ha per 1m-eq)	%	Total C in pasture (t/ha)	%	Total C in fine roots (t/ha)	%	Total C in thick roots, trunks and leaves (t/ha)	%	Total C in system (t/ha)
B. humidicola	144 a[2]	95.5	1.9	1.3	4.9	3.2	-	-	150.8
B. humidicola + legume	138 b	94.8	2.1	1.4	5.5	3.8	-	-	145.6
Natural regeneration of degraded pasture	134 b	97.3	1.3	0.9	2.4	1.7	-	-	137.7
B. decumbens + legume	128 c	96.7	1.2	0.9	3.2	2.4	-	-	132.4
B. decumbens	124 c	97.7	1.1	0.9	1.8	1.4	-	-	126.9
Native forest	107 d	61.7[3]	-	-			66.4	38.3	173.4
N (sampling points / system)	27		45		27				
Mean, CV (%), LSD_{10}	129, 10, 5								

Site 2: 'Beijing' Farm (rolling hills topography)

Land use system	Total C in soil (t/ha per 1m-eq)	%	Total C in pasture (t/ha)	%	Total C in fine roots (t/ha)	%	Total C in thick roots, trunks and leaves (t/ha)	%	Total C in system (t/ha)
Native forest	181 a[2]	61.7[3]	-	-	-	-	112.4	38.3	293.4
B. decumbens + legume	172 b	98.1	0.9	0.5	2.4	1.4	-	-	175.3
B. humidicola	159 c	96.6	1.1	0.7	4.5	2.7	-	-	164.6
Degraded pasture	129 d	97.4	0.9	0.7	2.6	1.9	-	-	132.5
N (sampling points / system)	27		45		27				
Mean, CV (%), LSD_{10}	144, 11, 7								

The data of the hillsides of Colombia's Andes (Table 1) suggest that at sites of higher altitude, lower temperature, steep slopes, and relatively more fertile soils, the forest shows the highest levels of C accumulated in the soil (231, 186, and 155 t/ha per 1m-eq at sites 1 and 2), these means being statistically higher than those of the improved *Brachiaria decumbens* pasture (147 and 136 t/ha per 1m-eq at sites 1 and 2), which, in turn, statistically surpassed those of a degraded pasture and a degraded soil (136 and 97 t/ha per 1m-eq at sites 1 and 2).

The data corresponding to the tropical rainforest of Colombia's Amazon region (Table 2) and to Costa Rica's subhumid tropical forest (Table 3) show a situation that differs from that of the Andean hillsides regarding levels of C accumulated in the soil. In the flat Amazon region, characterized by warm, humid lowlands with poor, extremely acid soils with a high nutrient recycling rate, the improved pasture systems of *Brachiaria humidicola* alone, *B. humidicola* + native legumes, *Brachiaria decumbens* alone and *B. decumbens* + native legumes show soil C levels (144, 138, 128, and 124 t/ha per 1m-eq) that are statistically higher than those of the native forest (107 t/ha per 1m-eq.) On the rolling slopes of the Amazon region, improved pasture systems show soil C levels (172 and 159 t/ha per 1m-eq) statistically higher than those found in a degraded pasture (129 t/ha per 1m-eq). In Costa Rica's subhumid tropical forest (Table 3), located in the warm lowlands with a 6-month rainy season and a 6-month dry season and poor acid soils, the improved pasture and silvo-pastoral systems of *Brachiaria brizantha* + *Arachis pintoi*, *Ischaemum ciliare*, *Acacia mangium* + *A. pintoi*, and *B. brizantha* alone show levels of soil C accumulation (181, 170, 165, 138 t/ha per 1m-eq) statistically higher than those of the native forest (134 t/ha per 1m-eq) and to those of a degraded pasture (95 t/ha per 1m-eq).

Table 3. Carbon in soil and biomass in each land use system in the subhumid tropical forests of Pocora, Costa Rica.

Land use system	Total C in soil (t/ha per 1m-eq)	%	Total C in pasture (t/ha)	%	Total C in fine roots (t/ha)	%	Total C in thick roots, trunks and leaves (t/ha)	%	Total C in system (t/ha)
B. brizantha + *A. pintoi*	181 a [2]	98.4	1.5	0.8	1.5	0.8	-	-	184.6
I. ciliare grass	170 a	97.5	1.7	1.0	2.8	1.5	-	-	174.8
A. mangium + *A. pintoi*	165 b	90.0	1.0	0.6	4.4	2.4	12.9	7.0	183.3
B. brizantha	138 c	98.1	1.6	1.1	1.8	0.8	-	-	141.0
Native forest	134 c	61.7	-	-	-	-	83.7	38.3	218.5
Degraded pasture	95 d	95.0	1.6	1.6	3.8	3.4	-	-	100.6
N (sampling points/ system)	24		40		24				
Mean, CV (%), LSD_{10}	150. 24, 14								

[1] Results of 2002-2005, Carbon Sequestration Project- The Netherlands Cooperative Activity CO-010402", Internal Publication No. 14. June 2005.

[2] Means with different letters differ statistically, with an error probability of 0.10.

[3] The % obtained in the native forest of Costa Rica's subhumid tropical rainforest ecosystem was used.

The data obtained in the tropical rainforest and subhumid tropical ecosystems (Tables 2-3) suggest that in the warm, humid lowlands, with poor acid soils, with high nutrient recycling rates, the improved pasture and silvo-pastoral systems, adapted to these environments and well-managed by producers, play an important role in the recovery of degraded pasture areas because of their high C sequestration potential. On the other hand, the high level of C accumulated by the native forest in its biomass of roots, trunks, and leaves make it possible to estimate the potential loss of C when a native forest in these ecosystems is felled.

CONCLUSIONS

The findings of these 5 years of research (2002-2007) on target tropical ecosystems suggest, firstly, that in terms of C accumulated in the total system (soil + plant biomass), the native forest presents the highest levels of all land uses in all ecosystems, followed by improved pasture, silvo-pastoral system, natural regeneration of degraded pastures, and finally degraded pasture or degraded soils. The C accumulated in the soil accounts for a very high percentage of the total C of the system (61.7% in native forest, 90% in a silvo-pastoral system of *Acacia mangium* + *Arachis p*intoi, and between 95%-98% in pasture systems). Secondly, in terms of C accumulated in the soil, improved, well-managed pasture and silvo-pastoral systems show comparable or even higher levels than the native forest, depending on local climatic and environmental conditions. Research results indicate that improved and well-managed pasture and silvo-pastoral systems should be regarded as attractive alternatives from the economic and environmental viewpoints, especially because of their capacity to recover degraded areas and their C sequestration potential.

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