Soil ecosystem services in Amazonian pioneer fronts: Searching for socioeconomic, landscape and biodiversity determinants

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Abstract
In two Amazonian regions of Brazil and Colombia that represent most of the diversity of the pioneer front landscapes, we searched for relationships among socioeconomic environments, landscape composition and structure, biodiversity, and production of goods and ecosystem services. An original sampling protocol was applied to collect fully compatible socioeconomic, landscape, agronomic and ecological datasets allowing rigorous statistical analyses. In each country, 153 farms belonging to three different kinds of land use and practices were characterized on the basis of socioeconomic and landscape variables. Biodiversity, goods and ecosystem services were measured on a selection of 27 (26 in Colombia) farms most representative of the whole diversity in each country. Among the groups chosen for biodiversity survey, plants, earthworms, termites and ants were major ecosystem engineers that play a critical role in the provision of goods (agrosilvipastoral products) and ecosystem services (ES). The investigated ES were climate regulation through carbon sequestration in soil and biomass, soil conservation and water cycle regulation through infiltration, and finally indices of soil quality. Co-variations among the different sets of variables assessed by multiple co-inertia analysis were highly significant. Significance of these results are discussed.

Key Words
Land use change, socioeconomic drivers, carbon sequestration, soil quality, Brazil, Colombia.

Introduction
Amazonian pioneer fronts are highly dynamic areas where deforestation occurs at a very high rate, although in rather diverse ways since land use may vary considerably depending on the socioeconomic environment, local geographical conditions, biodiversity and land use strategies (Fearnside 2005).
Pioneer agriculture, right after deforestation, is often based on very simple slash and burn systems. They have negative effects on soil quality and result in a general decrease in the production of soil ecosystem services. A large number of studies show significant decreases in climate regulation processes through depletion in carbon and decreases in plant biomass (Nepstad *et al.* 2008, Kauffman *et al.* 2009). The ability of soil to sustain primary production is also endangered through a variety of mechanisms, nutrient depletion being the most conspicuous one. Water resource services are also impaired through decreased infiltration, storage and transfers of water as soils get compacted in pastures and suffer erosion (Zimmermann *et al.* 2006). Biodiversity is severely decreased, especially that of soil ecosystem engineers (earthworms, termites and ants), although with relatively diverse patterns (Mathieu *et al.* 2005). However, some specific practices e.g., cropping systems with perennial tree productions, may be less detrimental than others. Furthermore, landscape composition and structure, i.e, the composition of the mosaic of different types of land uses that people create from the original forest- is likely to influence the whole dynamics (Barros *et al.* 2002).

The present study assesses the relationships among the production by soils of goods and ecosystem services, socio economic parameters, landscape composition and structure, biodiversity in two rather contrasted regions, an area of relatively recent colonization (10-15 years) in North Eastern Brazil (state of Pará) and a region colonised 60 years ago in South West Colombia (Caqueta). We tested the hypothesis that socio economic levers amenable for changes via public policies are key determinants of a suite of interactions that determine soil functions. The construction of different landscapes that host different biodiversities eventually affects parameters of soil functions.

Methods

In each country, three landscape "windows" each formed by 3 replicate groups of 17 contiguous farms were selected with different ages of deforestation and/or different land tenure (Table 1).

Table 1. Main characteristics of the surveyed landscape "windows"

Country	Landscape "windows"	Beginning of the deforestation	Average area of the exploitations (ha)	% forest
BRAZIL	Palmares II	1990	25	44
	Maçaranduba	1994	60	40
	Pacajá	1997	60	70
COLOMBIA	Traditional	1950	64	2
	Agrosilvipastoral	1940	20	2
	Agroforestry	1950	21	6

Socio-economic characterisation was performed on 153 farms in each country with three different questionnaires that addressed respectively individual life histories (32 variables describing migrations, studies, professional abilities, family), economic situation (15 variables describing different kinds of incomes and access to credits) and production systems (21 variables).
Landscape analysis done after maps of the 28 different types of land use identified allowed to quantify landscape composition (amount and % of the different types of land use) and structure (patchiness, diversity, distance among patches of a similar type of habitat) using FRAGSTAT program.
In a selection of 53 farms representing the diversity of socioeconomic situations in each of the 6 landscape windows, detailed studies of biodiversity and soil ecosystem services were performed.

- Biodiversity of plants, soil invertebrate engineers (termites, earthworms, ants, and general soil macro invertebrate communities), birds, moths (Saturnidae, Sphingidae), Drosophilidae and bees was assessed in each of the 53 farms, at five points regularly spaced 200 m apart along a line located in the middle of the farm. Main types of land use in each farm were thus rather well represented in our sampling.
- Production of forest, agriculture and cattle breeding activities were measured accurately in each farm and expressed either as amounts produced or caloric and protein equivalents.
- Soil attributes were thoroughly measured through physical, chemical, organic matter and morphology characteristics. They were then grouped by categories and indices of soil quality were calculated according to the GISQ methodology (Velasquez *et al.* 2007a).

Once obtained entirely compatible data tables, co-inertia analysis (Dolédec and Chessel 1994) were performed among each pair of tables to test for significant co-variations (i.e., correlations among tables measured as the as the vectorial correlation and noted RV, Robert and Escoufier 1976).

Results

Co-inertia analyses among the 12 different tables provided a large number of significant relationships (Figure 1). The hypothesis of cascading effects from socioeconomic to landscape, biodiversity and the production of services and agrosilvipastoral goods was thus validated.

	WP4_PROD	WP4_PRKC	WP1_SYPRO	WP1_SOCF	WP1_SOCQ	WP2_STRU	WP2_COMP	WP2_USA	WP3_BIODIV	WP4_MORP	WP4_PHCH
WP4_PRKC	**0.37**										
WP1_SYPRO	**0.48**	**0.23**									
WP1_SOCF	0.23	**0.18**	**0.42**								
WP1_SOCQ	**0.35**	**0.18**	**0.38**	**0.47**							
WP2_STRU	**0.35**	*0.09*	**0.29**	**0.35**	**0.26**						
WP2_COMP	**0.30**	**0.26**	**0.27**	**0.27**	**0.31**	**0.27**					
WP2_USA	**0.49**	**0.24**	**0.33**	**0.36**	**0.30**	**0.18**	**0.20**				
WP3_BIODIV	**0.43**	*0.13*	**0.38**	**0.46**	**0.46**	**0.29**	**0.28**	**0.52**			
WP4_MORP	**0.33**	**0.19**	**0.24**	**0.34**	**0.29**	**0.18**	**0.25**	**0.38**	**0.44**		
WP4_PHCH	**0.40**	*0.10*	**0.36**	**0.50**	**0.40**	**0.23**	**0.24**	**0.47**	**0.69**	**0.52**	
WP4_GISQ	**0.38**	**0.17**	**0.28**	**0.19**	**0.35**	**0.25**	**0.24**	**0.41**	**0.49**	**0.48**	**0.58**

Figure 1. Matrix of RV coefficients among the 12 tables of data obtained for the Colombian and Brazilian sites. In bold, permutation tests (n=999) significant (with p< 0.01 (often < 0.001); in italics, tests with a p<0.05 significance.

WP4_PRKC: Agrosylvipastoral productions expressed in Kcal and amount of glucids, lipids and proteins produced; WP1_SYPRO: production systems; WP1_SOCF: life histories and other social information; WP1_SOCQ: economic information; WP2_STRU: landscape structure in a 100m radius circle around sampling point; WP2_COMP: landscape composition; WP2_USA: land uses at the sampling point; WP3_BIODIV: biodiversity of plants and 7 groups of animals; WP4_MOR: soil morphology as assessed by the Velasquez *et al.* (2007b) method. WP4_PHCH: soil physicochemical variables; WP4_GISQ: indicators of soil quality.

The main results regarding determinants of soil ecosystem services were as follows:

1. There was a significant effect of socioeconomic parameters over land use intensification. People living closer to cities, or with good quality infrastructures, would generally get a better access to education and credit and have more intensified practices. Under such conditions, less C is stored into plant biomass and soil degradation tends to be higher, especially when livestock breeding is the main activity.
2. Chemical fertility was higher in all derived systems in Brazil due to the incorporation of ashes in soil; differences among sites were mainly due to differences in soil texture. In Colombia, acidic soils with high Al saturation and lower base contents were found thus showing that the initial correction of pH observed in Brazil may no longer persist 30 to 40 years after deforestation. However, comparison among sites show differences in Colombia, since silvipastoral and agroforestry systems respectively show improved conditions as compared to the traditional system.
3. Soil C storage is greatly dependent on clay concentrations and soil depth. As a result, Colombian soils have higher C contents in general; in Brazil, the Palmares site that has significantly higher clay contents and soil depths than the other two, also stores more C. Soil C storage was not significantly affected by land use types (neither in Brazil nor in Colombia).
4. Soil aggregation was greatly influenced by clay contents in Brazil. However land use types also had effects and a larger proportion of biogenic aggregates were found in improved systems in Colombia as compared to the traditional system.
5. Compaction was generally observed in pasture sites as compared to other types of land use. In Brazil, field measurements showed a clear correlation between bulk density values and infiltration rates. In pastures, infiltration rates were 10 times slower in pastures than in adjacent forests.
6. Soil macrofauna was greatly affected by land use types. While no difference was observed at the order level among Brasilian sites, a longer period of use resulted in significant decrease in Colombia, with the greatest impact measured in the intensive livestock traditional site (CTR) where continuous grazing of degraded pastures in a largely deforested areas severely decreased the diversity, if not the abundance, of macroinvertebrate communities (Figure 2). Termites were the most affected group while earthworms suffered shifts in community composition with a very high predominance of the invasive species *Pontoscolex corethrurus.*

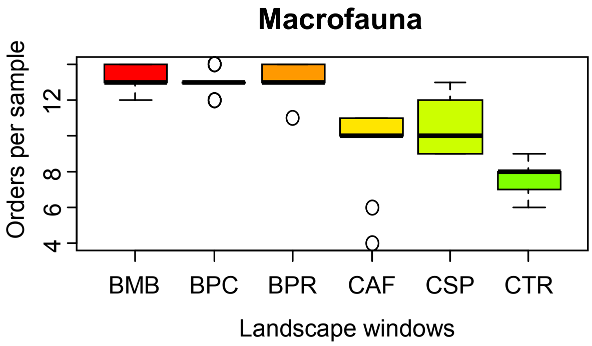

Figure 2. Variation of soil macrofauna diversity (order level) among surveyed sites of Brazil (BMB: Maçaranduba, BPC: Pacajá, BPR: Palmares II) and Colombia (CAF: Agroforestry, CSP: Agrosilvipastoril, CTR: Traditional)

Conclusion

Land use types and their distribution in Amazonian landscapes profoundly affect soil chemical, physical and biological parameters. Deforestation and conversion to pasture or cropland degrade all parameters of soil quality, and hence the production of ecosystem services. Degradation, however, proceeds at different rates according to the production system implemented and also to time elapsed since first deforestation. Systems that maintain trees (e.g., extractivist exploitation or agroforestry systems) have less detrimental effects. On the other hand recently deforested areas of Brazil seemed to have kept better abilities for production of ecosystem services than Colombian systems deforested since a much longer time. Our study also revealed a particular importance of landscape composition and structure, showing that intensive systems when limited in area and associated to more conservative systems in a diverse landscape mosaic may have less detrimental effects.

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