FINAL REPORT

Land use change, biofuels and impacts on soil carbon dynamics in the La Plata Basin

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INTRODUCTION

The La Plata river basin (LPB) occupies an area of 3.1 million km^2, with a population of over 100 million people in Argentina, Bolivia, Brazil, Paraguay, and Uruguay.

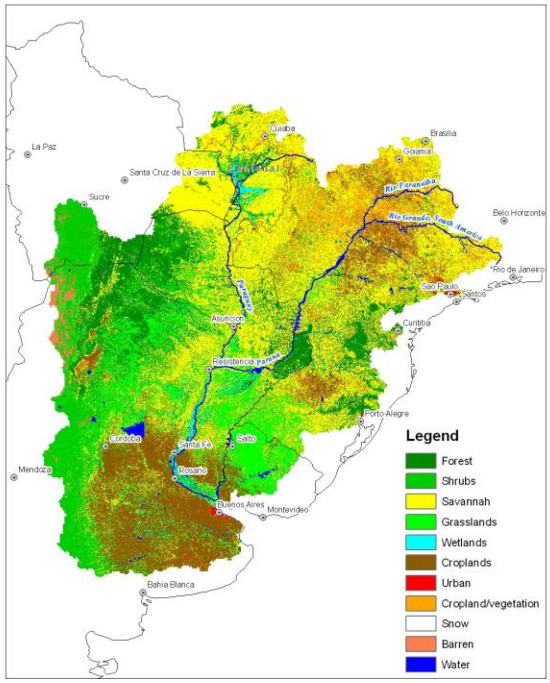


Figure 1. Land cover assessment of the entire Rio de la Plata Basin, as of 2004 (source: adapted from the MODIS/Terra Land Cover Type Product - MOD12Q1, produced by the Boston University Land Cover Research Team, http://edcdaac.usgs.gov/modis/mod12q1v4.asp)

The LPB spreads from South to North in a latitudinal gradient that results in the establishment of a high diversity of landscapes, characterized by heterogeneous soil-vegetation configurations, different climates and geological backgrounds. The variability of its topography adds natural complexity to the basin, resulting in a combination of extensive savannah-like plateaus (Cerrado in Brazil), grasslands and open fields (Pampas in Argentina and Uruguay), the largest tropical wetland area in the world (Pantanal in Brazil), as well as both dry and humid forest biomes (chaco and Atlantic forests, respectively) (Figure 1). The diverse societies that compose the LPB, associated with its environmental heterogeneity, resulted in complex patterns of land use change in the basin, accelerated during the last 40 years, with the occupation of the Cerrado and the Pampa with commodities such as soybeans, maize, wheat, sunflower, sugarcane and forestry. Rural land use and industry in the basin are responsible for over 70% of the Gross National Products of the LPB countries and are in a process of continuous change, as a response to drivers such as market trends, infra-structure and technology developments, societal evolution, and regulatory policies (Bonachea et al., 2010).

Land use changes (LUC) are also modulated by biophysical conditionants such as soil type, topography, and climate.

Effective and sustainable management of the LPB depends on the ability of land managers and policy makers from the five nations to predict the impacts of LUC on nature and society. Modeling efforts to predict environmental impacts in the LPB can benefit from knowledge acquired from impact assessments of major LUC processes.

The main processes of agricultural expansion that occurred and are currently happening in different regions of the LPB are described, followed by the presentation of results of impact assessments of land use change in the basin. Case studies in the Brazilian Cerrado will be highlighted in this report, with results and conclusions derived from literature reviews, field and laboratory analyzes of soil quality and carbon dynamics. We finalize with a suggestion of soil and crop management options to mitigate some of the resulting LUC environmental impacts and proposals for development of land use and management related policies.

IMPACTS ISSUES OF AGRICULTURAL LAND USE CHANGE IN THE LA PLATA RIVER BASIN

Four agricultural sectors have been responsible for most of the land use change (LUC) in the LPB in the last thirty years: international commodities (mainly soybeans, corn, sunflower, wheat), forestry (eucalypt and pine), meat (cattle) and agro-energy (sugarcane). Soybean and other grain crops, as well as cultivated pasture (*Brachiaria* spp., Alfalfa-grass mixtures) are widespread in the LPB, and have replaced portions of all of the basin´s biomes (Brossard and Barcellos, 2005). Forestry has been concentrated in the Southern portion of the basin (Vega *et al.*, 2009), and is increasingly expanding in Cerrado regions of Brazil, such as Mato Grosso do Sul. Biofuel crops, such as sugarcane, are in expansion as a result of growing international markets, and national policies (Cerqueira Leite *et al.*, 2009). Its cultivation is concentrated in the Brazilian State of São Paulo (aaproximately 60% of Brazilian sugarcane production), with the highest expansion rates in the States of Mato Grosso do Sul and Goiás (UNICA, 2010). Impacts of LUC processes will vary according to the biophysical and social configurations of the altered sites. During the last 40 years massive changes have occurred in the whole basin, with significant impacts both on nature and society.

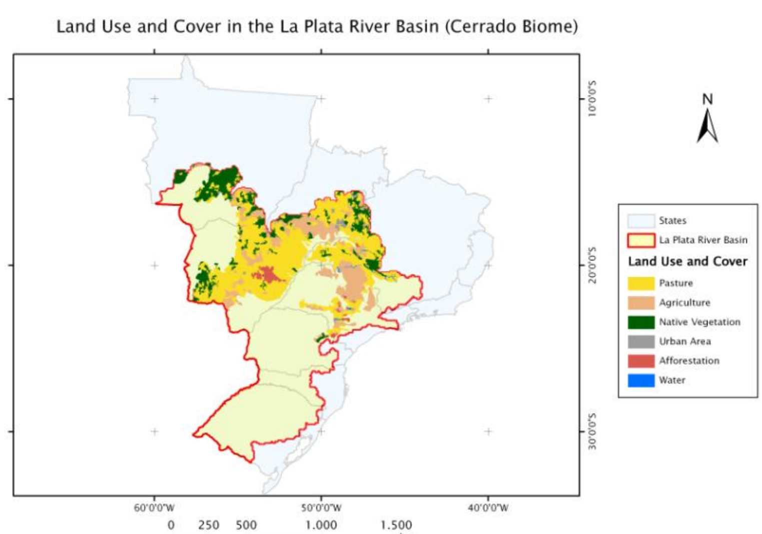
The first visible impact of land use change in the LPB was habitat fragmentation and a remarkable loss of biodiversity (Baldi *et al.*, 2006). The Atlantic Rainforest biome regions, as well as the Southern grasslands and Pampas concentrated the main agricultural, urban, and industrial development in the XIX and early XX centuries, with the Cerrado coming into play in the 1970´s (Neto *et al.*, 2010). The Cerrado original landscape suffered widespread transformation after agricultural technological development delivered varieties of the main commodity crops (mainly soybeans) adapted to the Cerrado soils and climate (Spehar, 1995).

The most common impacts of agricultural expansion on soil resources found in the literature are the depletion of soil organic matter, and consequent reduction of carbon stocks; soil compaction and reduction in water holding capacity; erosion and desertification; and biological degradation (de Oliveira *et al.*, 2004; Batlle-Bayer *et al.*, 2010). These changes in the soil ecosystem can result in severe disruptions in ecosystem functioning, affecting services such as the regulation of the hidrology (soil structure and water holding capacity), atmospheric composition (greenhouse gas emissions; carbon and nitrogen stocks), and erosion control (soil exposure to wind and rainfall) (Haygarth and Ritz, 2009).

LAND USE CHANGE IN THE BRAZILIAN CERRADO

The Cerrado biome covers about 2 million km^2, which represents approximately 25% of the Brazilian territory (Batlle-Bayer *et al.*, 2010). A vast portion of it contains the headwaters of the Parana and Paraguay river sub-basins, components of the La Plata river basin. Several authors suggest that the Cerrado is being destroyed due to land use expansion, particularly for grain crops and pastures (Klink and Moreira, 2002; Fearnside, 2001). The Southern portion of the Cerrado biome, located in the La Plata river basin, is where most of the land use conversion to agriculture and pastures has taken place (figure 1). The Brazilian states of São Paulo, Goiás and Mato Grosso do Sul were reported to have only 15 to 32% of native Cerrado vegetation still in place, based on land use data of 2002 (Sano *et al.*, 2008).

Figure 2. The Cerrado biome and its land use cover (source: Probio/MMA, 2002, published by Sano et al. (2008), in the limits of the Brazilian portion of the La Plata river basin



The agriculture expansion into the Brazilian Cerrado biome was driven mainly by incentives of the Brazilian Federal Government, as well as multilateral funding agencies. The POLOCENTRO (Cerrado Development Programme) invested USD 250 million between 1975 and 1984. The PRODECER (Nipo-Brazilian Cooperation Programme for the Development of the Cerrado), the CONDEPE (Cattle Raising Development Council) and the PROÁLCOOL (Alcohol Programme) also configured as significant drivers of the major land use changes imposed to the second largest ecosystem of Brazil, after the Amazon (Pinto, 2002). Scientific and technological development carried out mainly by Embrapa enabled the agricultural occupation of the Cerrado, correcting the high acidity and low fertility of its soils, and also adapting major commodity crops such as soybean and maize to the Cerrado environment (Spehar, 1995; Costa *et al.*, 2002).

Land use change in the Cerrado initially aimed at opening the frontier for cattle grazing. Usually the occupation begins with the transformation of native woody Cerrado vegetation to charcoal, used mainly as an energy source to steel mills located elsewhere in Brazil (Uhlig *et al.*, 2008). The opened fields are then sowed with *Brachiaria*, spp., an African grass well adapted to the Cerrado climate and soils. Although a large portion of the Cerrado landscapes are suitable for pasture cultivation, poor management is responsible for severe land degradation problems associated with soil compaction, loss of fertility, and erosion. The cultivated pastures were estimated to occupy 49.5 million ha, which represents 24% of the Cerrado area (Brossard and Barcellos, 2005).

The second major process of land use change in the region was the expansion of grain crops, especially soybeans, genetically tailored to produce high yields in the Cerrado soils and climate (Spehar, 1995). Soil management technology developed by Embrapa, based on acidity mitigation and fertilization, associated with an efficient biological nitrogen fixation research and development programme, enabled the highly successful occupation of Cerrado lands by soybeans (Boddey et al., 1997). Currently, more than 60% of Brazil´s soybeans are grown in the Cerrados (Souza *et al.*, 2007), occupying an estimated area of approximately 13 million ha. Considering 1980 as a reference baseline, the soybean crop area in the Cerrado has expanded 935% until 2006, while the total yield increased by 1,460% (Table 1 and Figure 2). These remarkable figures result from a significant increase in soybean productivity in the cerrados, approximately 50% from 1980 to 2006, reaching around 2.5 tonnes soy/ha. This shows how efficiently the farming community used the technology delivered by the agricultural sciences to boost the performance of their productive systems. This successful example of interaction between science and land users in the

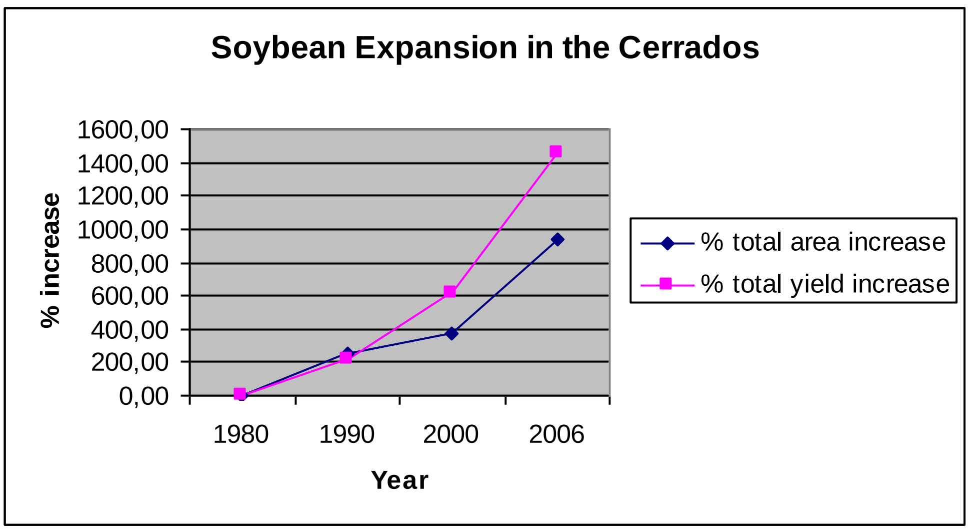
Brazilian Cerrado should be explored to effectively incorporate novel adaptive technology to cope with threats to the environmental and social integrity represented by major global change processes, such as climate change. Likewise, strategies to mitigate the significant impacts of Cerrados land use change on essential ecosystem services (atmospheric and hydrological regulation, soil erosion control and nutrient cycling, for example), should benefit from integration opportunities between scientists and decision makers opened up by the successes achieved by agricultural research during the last 40 years.

Table 1. *Soybean expansion rates in the Cerrados (1980-2006)*

	% total area increase	% total yield increase
1980	0.00	0.00
1990	250.09	217.14
2000	368.96	612.27
2006	935.29	1459.64

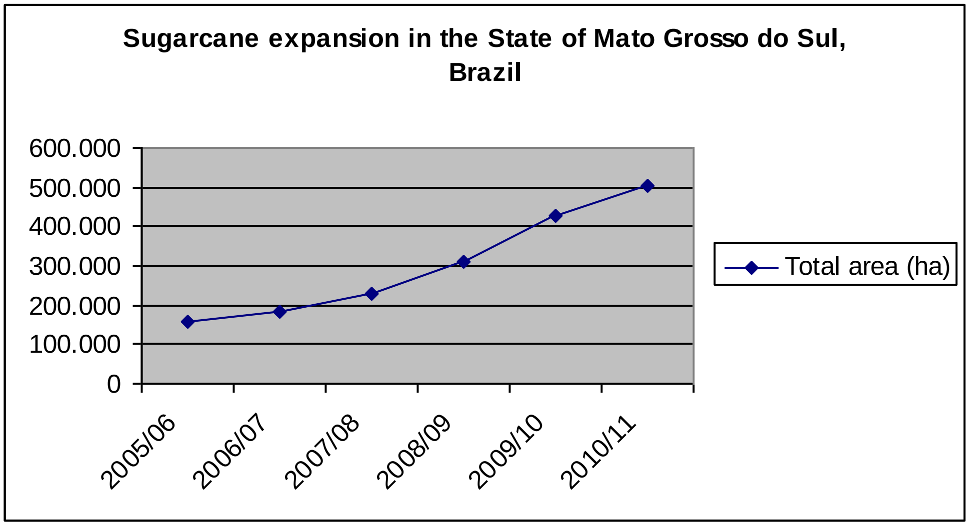
(Data sources for estimates: (CONAB, 2006; Souza *et al.*, 2007)

Figure 3. *Soybean expansion rates in the Cerrados (1980-2006)*



In the last decade, the expansion of Cerrado area occupied by sugarcane plantations for bioethanol and sugar production was remarkable. The current trend of land use change in the Cerrados is a response to the global demand for significant increases in the production of biomass for biofuel production (Gauder *et al.*, 2011). In Brazil, this major driver was amplified by national policies aimed at increasing the compulsory share of bioethanol in the gasoline sold in gas stations, and by the flex fuel technology development of the automotive industry, generating car engines running on both gasoline and bioethanol. As a result, the establishment of new bioethanol plants and sugarcane plantations is growing exponentially, especially in the Cerrados (Goes *et al.*, 2008; Cerqueira Leite *et al.*, 2009). Its generally flat topography, soil characteristics, water availability in the sugarcane growing season, and adequate climate, with plenty of sunlight and high temperature during most of the year, renders most of the Cerrado as a highly suitable biome for sugarcane expansion (Manzatto et al., 2009). Large portions of the Cerrado are currently covered by unproductive and degraded pastures over sandy soils that are suitable for sugarcane growth, and the lower price of these lands is very attractive to investors. The result has been a fast and steady expansion of sugarcane on the Cerrados, mainly in the states of Mato Grosso do Sul and Goiás (INPE, 2011) (figure 3).

Figure 4. *Sugarcane expansion in Mato Grosso do Sul, Brazil, between 2005 and 2011 (source: INPE, 2011).*



LAND USE AND MANAGEMENT IMPACTS ON CARBON DYNAMICS AND SOIL QUALITY

Brazilian Cerrados

Carbon stocks in Cerrado soils are close to those found under Brazilian rainforests, varying from 190 to 236 Mg ha^{-1} in the 0-100 cm layer (Lopes-Assad et al., 1997; Roscoe et al., 2000). Researchers have found that, in general, the conversion of native vegetation to agricultural systems, especially if conventional tillage is applied, results in significant reductions of these stocks (Corazza et al., 1999; Silva et al., 1994; Bayer et al., 2006; Oliveira et al., 2004; Silva et al., 2004; D'Andréa et al., 2004; Jantalia et al., 2007). Bustamante et al. (2006) have estimated that soils under Cerrado *stricto sensu* vegetation stock 99 Mg of carbon per hectare, and that 30 years of agricultural cropping reduced it to 69 Mg ha^{-1}.

Soil carbon stocks (SCS) under different land uses and soil classes of Brazil were estimated by processing data from the Embrapa Soil Information System´s database (www.bdsolos.cnptia.embrapa.br) and land use maps available at the Ministry of Environment website (Fidalgo et al., 2007). A sub-set of the database containing exclusively data from Cerrado soil profiles was created, and estimates of SCS distribution throughout different soil classes and land use categories were produced. The land uses "agriculture", "pasture", and "native vegetation" occurring on soil map units classified as latosols (oxysols, in the US Soil Classification system), the dominant soil class in the Cerrado biome (49% of total area), were analyzed. The low spatial distribution of the available data hampers spatially explicit estimates of soil carbon stocks, but the discrimination between land uses is noticeable (43.8, 40.6, and 34.2 tonnes C/ha, average for native vegetation, pasture, and agriculture in latosols, respectively) (figures 4 and 5; Balieiro et al., to be submitted).

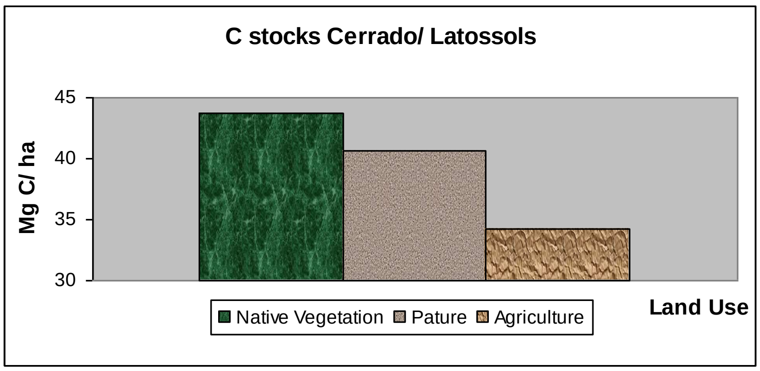


Figure 5. *Soil carbon stocks at 0-30 cm depth under different land uses in the Cerrados (average values per land use, from a total of 113 soil profiles; Cerrado land use map derived from Probio/MMA, 2004). (Balieiro et al., to be submitted)*

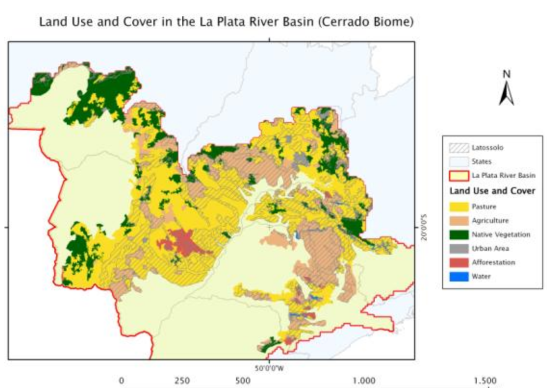
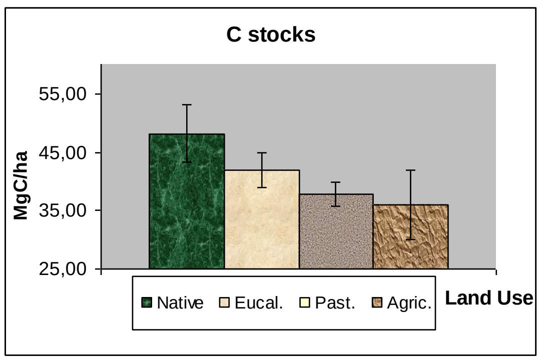


Figure 6. Land use (2004) in the Cerrado portion of the La Plata river basin. Areas dominated by latosols (oxysols, in the US Classification System) are highlighted (Balieiro et al., to be submitted)

In a case study including six municipalities (Rio Verde, Montividiu, Santa Helena de Goiás, Santo Antônio da Barra e Acreúna) of Southwest Goiás State (SW), Balieiro et al. (2008) sampled sixty nine sites under different land uses (14 sites under agriculture, 15 under pasture, 25 under silviculture, and 15 under natural vegetation - Cerrado) to compare their C stocks (0-40cm). In despite of a large variability in soil C stocks data obtained from each land use sampled in the Cerrados, the results are consistent with the literature, since they suggest that soil management could markedly influence soil C stocks, as in the Pampas. For NV, soil C stocks (0-40 cm) ranged from 11.75 to 83.28 Mg ha^{-1}, with an average (± *SE*) value about 48.36 ± 5.31 Mg ha^{-1}. The mean soil C stock values obtained from soils under eucalyptus, pasture and agriculture were 42.22 ± 3.74, 37.8 ± 2.67 and 36.04 ± 6.32 Mg ha^{-1}, respectively. Considering the mean NV value as a reference or baseline, these results show that land use in that region stimulated the degradation of both old and recently fixed soil C.

Figure 7. *Soil carbon stocks at 0-40 cm depth under different land uses in the microregion of Rio Verde de Goiás, in the southwest region of the Goiás State (total of 69 soil samples; Cerrado biome). (derived from Balieiro et al., 2010)*



A focus on the impacts of soil management on SCS showed a positive effect of no tillage systems on the accumulation and stabilization of soil organic matter and carbon stocks, agreeing with published data. Estimates of soil carbon stocks derived from the literature research done by the project team at Embrapa Soils showed that soils converted to no-tillage systems hold higher carbon stocks than those under conventional tillage (table 1).

Table 2. Average SCS values under native Cerrado vegetation and different land uses and management, at the depth of 0-40 cm, derived from meta-analysis of published literature (Balieiro et al., to be submitted).

	Soil Carbon Stocks	
	Mg ha^{-1}	
Native Vegetation	61.83	± 5.67
Pasture	59.38	± 4.64
Conventional Tillage	54.18	± 3.94
No Tillage	75.08	± 2.36

Several researches argue that C stocks in the Cerrado region could be improved if good agricultural practices were adopted. Systems under no till or zero tillage, rotation with nitrogen fixing legumes (green manure), and livestock-agriculture integrated systems are some of the most studied and recommended options to farmers in the Cerrados.

The responses of soil carbon stocks to different agricultural systems will vary according to soil type, as revealed by the literature research. Sandy soils have lower capacity of stocking carbon, and the biomass input from agricultural crops to these impoverished soils may result in a carbon build up (Table 2).

Table 3. Soil carbon stocks (SCS) in Cerrado soils, obtained from compilation of literature based information, considering a soil depth of 30 cm, and 3 land use classes (native vegetation - NV, pasture, and agricultural crops). The SCS values are categorized by soil class, according to the Brazilian Soil Taxonomy. The number of literature records, average, standard deviation, and error values are shown in the table.

Literature data			Soil depth 0-30 cm	
All soil classes				
	Average	Standard deviation	Error	Number of records (n)
NV	51,26	18,85	2,94	41
Pasture	46,24	15,33	2,80	30
Agriculture	50,12	17,50	1,94	81
Cambisols				
	Average	Standard deviation	Error	Number of records (n)
NV	25,89	11,26	7,96	2
Pasture	No data			-
Agriculture	No data			-
Argisols				
	Average	Standard deviation	Error	Number of records (n)
NV	51,20	19,79	11,42	3
Pasture	No data			-
Agriculture	52,53	18,34	5,80	10
Neosols				
	Average	Standard deviation	Error	Number of records (n)
NV	24,68	6,20	2,34	7
Pasture	23,96	5,86	2,93	4
Agriculture	25,09	5,35	1,89	8
Latosols				
	Average	Standard deviation	Error	Number of records (n)
NV	57,49	16,31	3,14	27
Pasture	50,10	13,13	2,68	24
Agriculture	52,91	15,91	2,00	63

IMPACTS OF LAND USE CHANGE TO PRODUCE BIOFUELS

CASE STUDY: IMPACTS OF SUGARCANE EXPANSION IN THE CERRADOS

Most of the available data on the impacts of sugarcane occupation on soil attributes derive from research on the Atlantic Forest biome, where most of Brazilian sugarcane is cultivated (Campos et al., 2004; Resende et al., 2007; Balieiro et al., 2008; Santana et al., 2009; Pinheiro et al., 2010). Few results have been found from research carried out in sugarcane plantations on the Cerrados (Galdos et al., 2010). This reflects the land use history of Brazil, that cultivates sugarcane for sugar production since colonial times, when it was the main Brazilian crop, mostly cultivated in coastal areas. Expansion to the Cerrado biome has been happening with greater significance in the last decade (Goes *et al*., 2008; Uriarte *et al*., 2009; Rudorff *et al*., 2010).

The majority of available publications report a significant reduction in the soil carbon and nitrogen stocks in sugarcane plantations, when compared with the native forests (Resende et al., 2007; Pinheiro et al., 2010; Campos et al., 2004). This impact is very much evident immediately after land use conversion (Silva et al., 2007; Galdo et al. 2009). Therefore, research on the impacts of different sugarcane management systems on soil carbon and nitrogen dynamics can aid land users to optimize the environmental performance of their production systems, adding value to their products (sugar and ethanol) in an increasingly competitive market.

The value of organic matter contents and carbon stocks do not, in the short term, reflect the soil modifications derived from changes in sugarcane management, such as the implementation of mechanical harvest or residue removal for secondary energy generation. However, labile organic matter fractions such as microbial biomass and particulate organic matter are more sensitive parameters to reveal impacts to soil quality and, consequently, to the provision of ecosystem services that are necessary for a sustainable agricultural system. Therefore, these soil attributes, along with physical measures such as aggregation, highly correlated with the capacity of a soil to stabilize and store organic carbon, are good choices of indicators to monitor changes in carbon dynamics (Graham e Haynes, 2006; Silva et al., 2007; Santana et al., 2009; Galdo et al., 2010).

Burning sugarcane fields prior to harvesting results in even higher soil carbon stock losses (Pinheiro et al., 2005; Resende et al., 2006; Balieiro et al., 2008; Galdo et al., 2010). Sugarcane fields devoid of pre-harvest burning for 14 years showed an increase of soil carbon stocks of 13 MgC ha^{-1} (Pinheiro et al., 2010). Maintenance of sugarcane crop residues over the soil can improve plant nutrition, and benefit the environment, with enhanced soil and water conservation due to mitigation of erosive processes and lower use of herbicides. An additional benefit is the potential for secondary energy generation with the residue biomass. However, little is known about threshold values of the amount of biomass that can be removed from the field without hampering the soil carbon sequestration and disrupting key soil ecosystem services linked to plant and environmental health (nutrient cycling, erosion control, hydrologic regulation).

Aiming at investigating some of the aspects cited above, two sites were selected for a more detailed analysis of the impacts on carbon dynamics and associated soil physical, chemical, and biological characteristics derived from sugarcane covered soils under different harvest and post-harvest management systems.

The initial observations aimed at investigating the effects of pre-harvest burning on the structure of soil bacterial communities and how they relate with soil properties and greenhouse gas emissions. The rationale for this research is that carbon sequestration and greenhouse gas emissions are processes conducted by soil microbial communities. The study was carried out in a sugarcane farm located in the municipality of Porteirão, State of Goiás, and compared soils under manual (burnt cane) and mechanical ("green" cane) harvest managements, having a native Cerrado forest as a reference (Figure 8). The results showed that the bacterial community structures differed between each treatment, and this differentiation correlated with changes in soil properties. The green cane treatment resulted in lower impacts on the soil bacteria community structure. A slight acidification was observed in the pre-harvest burnt sugarcane field followed by a general loss of fertility, and increased soil temperatures (Figure 5, Rachid et al., *to be submitted*).

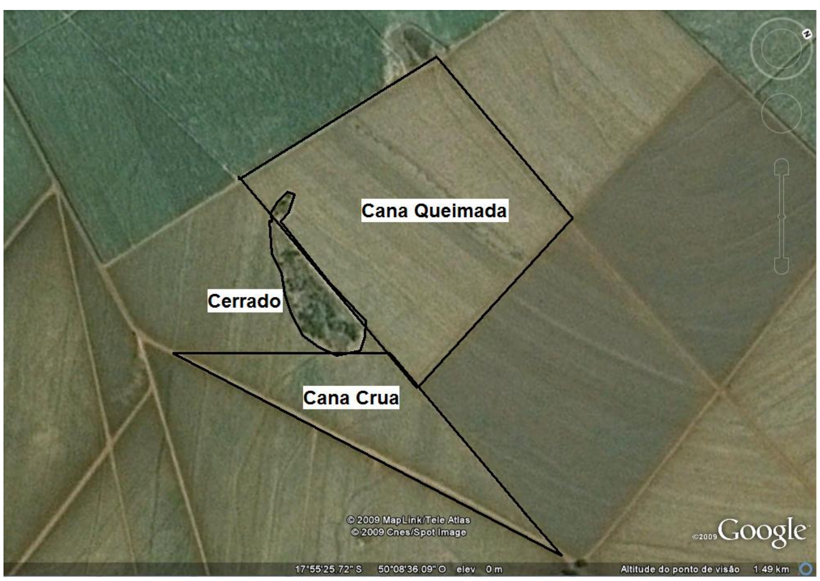
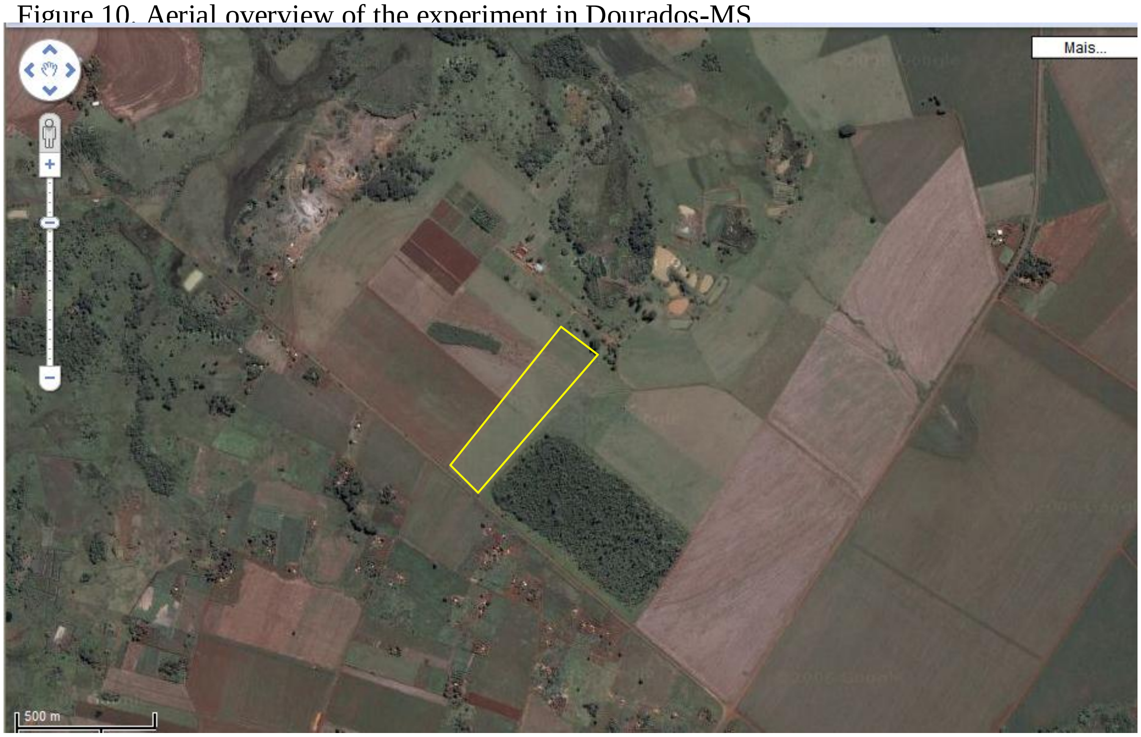


Figure 8 – Source: GoogleEarth 5.1.3533.1731) Cana queimada: burnt sugarcane; cana crua: "green sugarcane.

Figure 9. Soil bacterial community structures under different sugarcane harvest treatments, with the native cerrado vegetation as a reference. Ce: native cerrado; Gc: "green", unburnt sugarnce; Bc: burnt sugarcane. HMa, Ma, and Mi are field replicates. The figure shows on the right a composition of the PCR/DGGE gels, and on the left a dendrogram depicting the similarities between the sample analyzed (Rachid, 2010)

Another sugarcane area is being monitored in Dourados, State of Mato Grosso do Sul, in a field experiment set up in January 2009, managed by Embrapa Western Agriculture (Dourados), in association with a local ethanol and sugar mill ("Fazenda Cristal", belonging to Unialco, Dourados S.A. Álcool e Açúcar). The objective is to evaluate the effects of removing different quantities of sugarcane crop residues (straw) from the surface of soils under "green cane" (mechanical harvest) for the generation of energy (Figure 10). The IAI/IDRC projects activities aimed at assessing the impacts on soil properties, microbial diversity (including mycorrhizal fungi), and greenhouse gas emissions.

Figure 10. Aerial overview of the experiment in Dourados-MS



Mycorrhiza is a symbiotic association between fungi and plant roots (Berbara et al., 2006). Mycorrhizal associations are characterized by fungi that colonize plant roots and supplying ready-to-use soil nutrients and water while benefiting from carbon molecules produced by the plants. This association is generally highly beneficial to plants, especially in low fertility and dry soils. A further benefit to soil quality is the production of glycol-proteins (glomalines), that improve soil structure by enhancing aggregation processes (higher water retention and carbon storage) (Berbara et al., 2006). Our initial results show a significant increase in arbuscular mycorhizal structures in the rhizosphere of sugarcane plants when 100% of residues are left over the soil after harvest, indicating that trash removal is causing a reduction in the stability of mycorhizal associations, which may affect soil aggregation, carbon stabilization and water retention (figure 11). These results are being analyzed in conjunction with green house gas emissions data, as well as additional soil properties.

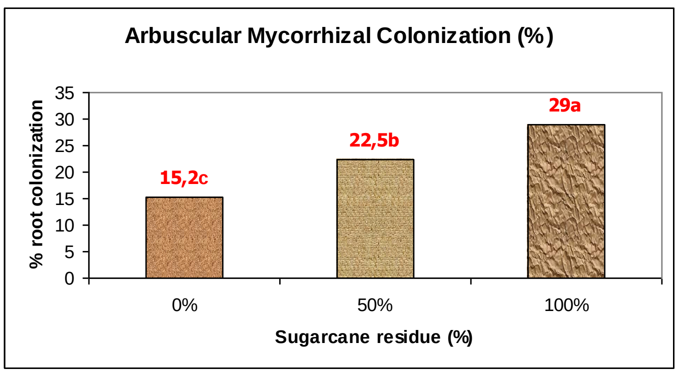


Figure 11. Percentage of arbuscular mycorrhizal structures in colonized roots, in soils covered with different proportion of sugarcane residue removal, in Dourados, MS. Average percentage values in red. Letters indicate statistical differences with 95% probability (Scott Knott test) (Angelini et al., 2010)

IMPACTS OF AFFORESTATION IN THE CERRADOS

Eucalyptus and pine forests are the most important sources of wood, cellulose and charcoal for industry worldwide, and therefore land used by these essences is expanding significantly. Between 1980 and 2005, the global industrial wood production increased from 1,450 to 1,710 million m^3 $year^{-1}$, while that for energy production increased from 1,530 to 1,840 million m^3 $year^{-1}$ (FAO, 2005). In 2008, eucalyptus and pine covered 6.13 million ha of land in Brazil, with a 4.8% increase compared with the previous year (ABRAF, 2009).

Soil water availability is a significant determinant of *Eucalyptus* spp. biomass production, as shown by several researchers in Brazil (Reis et al., 1985; Stape et al., 2004; Balieiro et al., 2008). Rain fall is another important factor to obtain high biomass production and carbon sequestration potential (Souza et al., 2006). Therefore, good agricultural practices for sustainable *Eucalyptus* production should contain management strategies leading to improved soil structure, with higher porosity, aggregation sizes and stability. Soil properties and fertility are also important for the build up of carbon stocks in soils. Soils with higher clay content will maintain more carbon when converted from Cerrado vegetation to *Eucalyptus*, as opposed to sandy soils, where carbon losses can reach 17% of the original stocks after conversion (Zinn et al., 2002).

In the Cerrados, most of the *Eucalyptus* plantations are on acid soils with low fertility. Considering the very slow decomposition rates of *Eucalyptus* leaves, and the organic carbon losses resulting from removal of the original vegetation, the re-establishment of soil carbon stocks is very low (Resh et al., 2002; Balieiro et al., 2004, 2008). This situation is aggravated by the low inputs of nitrogen fertilization to the Brazilian plantations, and the high export of this nutrient, stocked in the tree trunks.

The introduction of legume trees in consortium with *Eucalyptus* has been shown to be a good alternative to maintain high productivity, with greater capacity for enhancing soil carbon stock levels and soil fertility (Binkley et al., 1992; Balieiro et al., 2002; Forrester et al., 2006; Laclau et al., 2008).

In the Brazilian Cerrados, little has been done in terms of field research to evaluate the benefits of *Eucalyptus*-legume trees consortia to soil fertility, carbon and nitrogen stocks, productivity, and biomass production. A greater effort should be devoted to these research areas considering the expansion rates of forest plantations in Brazil, and novel potential lucrative markets associated with carbon sequestration and environmental quality of agriculture.

RECOMMENDATIONS TO POLICY AND FARMERS DECISION MAKING

In order to meet the increasing global demand for food and bioenergy, there is a pressing need for sharp increases in the output of agricultural activities in rural landscapes. Agricultural scientific research has developed soil and plant technology that allowed a tremendous expansion of commodity crops throughout the different biomes of the La Plata river basin, putting this region in the position of a leading global agricultural producer and exporter. However, much more could be done to enhance the sustainability of agriculture in the basin. Incorporation of new land for agricultural production is not an envisaged solution, due to the also urgent need to conserve the remnants of natural habitats and their biodiversity, which demands innovative solutions. The global need for a reduction of greenhouse gases in the atmosphere calls for the implementation of agricultural systems with lower carbon footprints. In addition, agricultural land use decision makers must be aware that the water crisis is just around the corner, and requires from them a landscape management approach, aiming at water resources conservation. Therefore, intensification of current agricultural and livestock production systems, using existing technology and developing innovative solutions, is the most effective way to ensure the sustainable development of rural areas.

Our data supports the importance of no tillage systems for soil carbon capture and storage, hydrologic regulation, soil erosion control, and resilience to extreme events. Our data also reinforce the essentiality of eliminating sugarcane burning before harvest. Other important measures to allow for sustainable agricultural development is the implementation of incentive policies aiming at the development of multi-cropping systems and multifunctional land use, rendering farmers with more options of marketable products, while increasing *in farm* agrobiodiversity and potential ecosystem services. The Integrated Crop-Livestock-Forestry System, under intense research by Embrapa in Brazil, is an example of such agricultural innovation (Lopes, 1996). In addition, development of novel varieties of the main commodity crops, able to maximize biomass production without losing grain yields, coupled high higher photosynthetic productivity, would improve the potential for soil carbon sequestration and add value to the agricultural products. The success of any innovative technology to intensify and diversify agricultural production will also depend on adequate transport and energy infra-structure, and the assurance of effective market options to guarantee economic sustainability of the production systems.

It should be stressed that strengthening of the rural extension system is crucial for the success of policies aiming at sustainable agriculture development. In Brazil, during the nineties, the national rural extension service was discontinued and this activity became a responsibility of the States, many of them impoverished and focusing their expenditures on other governmental priorities. The result is that most of technical assistance to farmers is made directly by the agricultural industry (machinery, agrochemicals, seed providers, etc.), which do not necessarily aim at improving the sustainability of the farming systems. In order to disseminate innovative agricultural systems based on rational and optimal use of fertilizers and pesticides, for example, technical assistance devoid of any interest in increasing sales of such products is needed. The rural extension system associated with the scientific community, would boost the technology transfer of agricultural innovations to the farmers. It is estimated that soybean productivity could raise from 3,000 to 3,600 kg/ha if current available techonologies, not dependent on increased use of fertilizers, were adopted, saving land for biodiversity conservation. Innovation highlights that could be considered are precision farming, integrated pest management, use of improved genetic materials, and optimized crop rotations.

The financial system is also a deterrent of rural sustainability. Innovative sustainable agricultural management needs time to consolidate and result in positive outputs to the farmer. The short term nature of agricultural credits do not favor sustainability, because farmers do not have enough time to recover from their crop and soil management transition costs and generate sufficient surplus to pay for their debts. Therefore, the financial sector play a crucial role in the road to agricultural sustainability, and should be effectively involved in the policy making arena.

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