A review on soil carbon accumulation due to the management change of major Brazilian agricultural activities

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Abstract

Agricultural areas deal with enormous CO_2 intake fluxes offering an opportunity for greenhouse effect mitigation. In this work we studied the potential of soil carbon sequestration due to the management conversion in major agricultural activities in Brazil. Data from several studies indicate that in soybean/maize, and related rotation systems, a significant soil carbon sequestration was observed over the year of conversion from conventional to no-till practices, with a mean rate of 0.41 Mg C ha^{-1} $year^{-1}$. The same effect was observed in sugarcane fields, but with a much higher accumulation of carbon in soil stocks, when sugarcane fields are converted from burned to mechanised based harvest, where large amounts of sugarcane residues remain on the soil surface (1.8 Mg C ha^{-1} $year^{-1}$). The higher sequestration potential of sugarcane crops, when compared to the others, has a direct relation to the primary production of this crop. Nevertheless, much of this mitigation potential of soil carbon accumulation in sugarcane fields is lost once areas are reformed, or intensive tillage is applied. Pasture lands have shown soil carbon depletion once natural areas are converted to livestock use, while integration of those areas with agriculture use has shown an improvement in soil carbon stocks. Those works have shown that the main crop systems of Brazil have a huge mitigation potential, especially in soil carbon form, being an opportunity for future mitigation strategies.

Keywords: greenhouse gas, mitigation strategies, soil carbon stock, carbon dioxide, agriculture.

Uma revisão sobre o acúmulo de carbono no solo devido a mudança de manejo nas principais atividades agrícolas do Brasil

Resumo

Áreas agrícolas trocam enormes fluxos de CO_2, oferecendo uma oportunidade para mitigar o efeito estufa. Neste trabalho, estudou-se o potencial de sequestro de carbono em razão da conversão no manejo das principais atividades agrícolas do Brasil. Dados de vários estudos têm indicado que no sistema soja/milho e nas respectivas rotações, ocorre um sequestro de carbono no solo significativo ao longo dos anos de conversão do plantio convencional para o plantio direto, com uma média de 0,41 Mg C ha^{-1} ano^{-1}. O mesmo efeito tem sido observado nos canaviais, porém há maiores acúmulos de carbono no solo quando as áreas de cana-de-açúcar são convertidas da colheita baseada na queima para a mecanizada, em que grandes quantidades de palha são deixadas na superfície do solo (1,8 Mg C ha^{-1} ano^{-1}). Esse maior potencial de acúmulo de carbono no solo nos canaviais, comparado com outras culturas, está diretamente relacionado com a maior produção primária dessa cultura. Apesar disso, muito desse potencial de sequestro é perdido, uma vez que os canaviais são reformados, sob preparo intensivo do solo. As áreas de pasto mostram uma depleção nos estoques de carbono, quando convertidas de áreas naturais; porém, a integração dessas áreas com agricultura pode promover o aumento nos estoques de carbono do solo. Os trabalhos têm mostrado que as principais atividades agrícolas do Brasil possuem um grande potencial de mitigação, especialmente na forma de acúmulo de carbono no solo, sendo uma oportunidade para estratégias futuras.

Palavras-chave: gás de efeito estufa, estratégias de mitigação, estoque de carbono do solo, dióxido de carbono, agricultura.

1. Introduction

Brazilian agricultural activities play an important role in the employment opportunities and export balance of Brazil. In 2010, Brazilian agriculture-related exports attained a record of US$ 76.4 billion, 18% higher than in 2008. Among the major goods exchanged are soybeans, sugar and meat, with Asia and Europe being the main targets and receiving 30 and 27% of Brazilian exports, respectively. Brazil is a significant world player in food production, having the potential to increase its present production without causing further pressure on natural areas, simply by expanding into degraded lands, especially those abandoned after pasture usage (Tollefson, 2010). One of the main concerns of Brazilian agriculture is the expansion of production while minimising its environmental impact, including greenhouse gas (GHG) emission, such as the ones associated with deforestation caused by the conversion of natural areas to agricultural use. The federal government of Brazil has implemented new programmes to reduce deforestation, favouring the reduction of GHG emissions with the expansion of agriculture on degraded land, of which at least 15 million hectares are available (Tollefson, 2010). Other initiatives have been implemented in Brazil, such as the expansion of no-tillage agriculture (cropping performed directly on crop residues without soil tillage) (Amado et al., 2006) and the reduction of sugarcane burning in the southeast (associated with sugarcane harvest), as well as the more rational use of land for agricultural production.

2. Geographical Distribution of the Major Agricultural Activities in Brazil

Figure 1 presents the spatial distribution of the main agricultural activities in Brazil considering the land use. Soybean and maize crops have been responsible for important changes in land use, which occurred first in southern Brazil with the implementation of no-tillage agriculture in the early 1970s, reaching 80% of the agricultural areas in southern Brazil in the early 1980s (Mielniczuk et al., 2003). Then, annual cultures expanded to central Brazil, where, at first, they expanded under conventional tillage to most of the country. At the same time, a similar expansion was observed in livestock in central Brazil and most recently on the southern border of the Amazon region; in connection with livestock, it is estimated that approximately 100 million ha are degraded or abandoned (half of the pasture area), most of which is in central Brazil (Dias-Filho, 2005; Ronquim, 2007). The main agricultural activity that is not present in Amazonia is sugarcane growth; most of the production area for sugarcane is located in southern Brazil, especially in São Paulo state, with 50% of the Brazilian sugarcane cropped area and 4.4 million ha devoted to sugarcane production in 2010 and 2011.

World agriculture contributes to GHG emissions, with emissions estimated from 5.1 to 6.1 Gt CO_2eq year^{-1} (in 2005), or from 10 to 12% of the total annual anthropogenic greenhouse gas emission. The most recent data (from 2005) indicates that the majority of these emissions are related to methane (CH_4) and nitrous oxide (N_2O) at 3.3 and 2.8 Gt CO_2eq year^{-1}, respectively, and most of the emissions are from livestock and synthetic fertiliser use, respectively. Despite the enormous CO_2 fluxes between agricultural areas and the atmosphere (IPCC, 2007), the uncertainties associated with the possible benefits of conversion of annual crops and sugarcane to no-till and non-burn-based harvest, respectively, where large amounts of crop residues are left on the soil surface, must be recognised. In 2006, the IPCC suggested that conversion from conventional to no-till systems would be responsible for an increase from 10 to 22% in soil carbon stock but with an uncertainty of 4 to 8% depending on the climate zone, suggesting that caution is required when using these estimations (IPCC, 2006).

However, when the mitigation of GHG associated with agriculture is considered, CO_2 plays an important role. Agricultural practices, such as reduction of the intensity and frequency of soil tillage and the maintenance of crop residues on the soil surface after harvest, have been indicated as simple options that would mitigate the greenhouse effect. In this respect, soil carbon sequestration would have the highest mitigation potential, contributing 89% of the total projection for the coming years in agricultural areas (IPCC, 2007). Reductions in direct CH_4 and N_2O emissions would result in mitigations of 9 and 2%, respectively. This potential does not, however, consider the replacement of fossil fuels with biofuels, which would result in further mitigations associated with the transportation (mobile founts) and energy sectors, due to the replacement of coal with other fuels.

In recent studies, direct measurements of carbon capture by the biomass of northeastern agrosystems in several agricultural cultures in São Paulo state indicated a mean capture of 29.2 Mg C ha^{-1} year^{-1} in sugarcane crops, contributing to approximately 107 Mg CO_2 ha^{-1} year^{-1} (Ronquim, 2007). As the total sugarcane agricultural area cropped in Brazil corresponds to almost eight million hectares (half of which is located in São Paulo state), the photosynthesis-related capture in this culture would be almost 0.9 Gton CO_2 year^{-1} in the Brazilian sugarcane-cropped lands alone. This value is almost 20% of the emissions associated with agriculture and 1.5% of the total anthropogenic emissions of GHG in the world (referring to the 2005 values). Such a sink would not necessarily result in atmospheric CO_2 (or carbon) sequestration, as the final balance may be close to zero. The sugarcane crop is extracted, in many cases under a burn regime prior to harvest, and ethanol is produced, but this emits a significant amount of the CO_2 sequestered from the atmosphere back into the atmosphere; the same likely occurs with sugar production. However, of the mean capture of 29.2 Mg C ha^{-1} year^{-1} in Brazilian sugarcane crops, at least 11% of this carbon is present in roots, leaves and parts of the plant that could be left in or lying on the soil, especially by mechanised harvest instead of burning. Changes in the management system, harvest or tillage would result in a significant

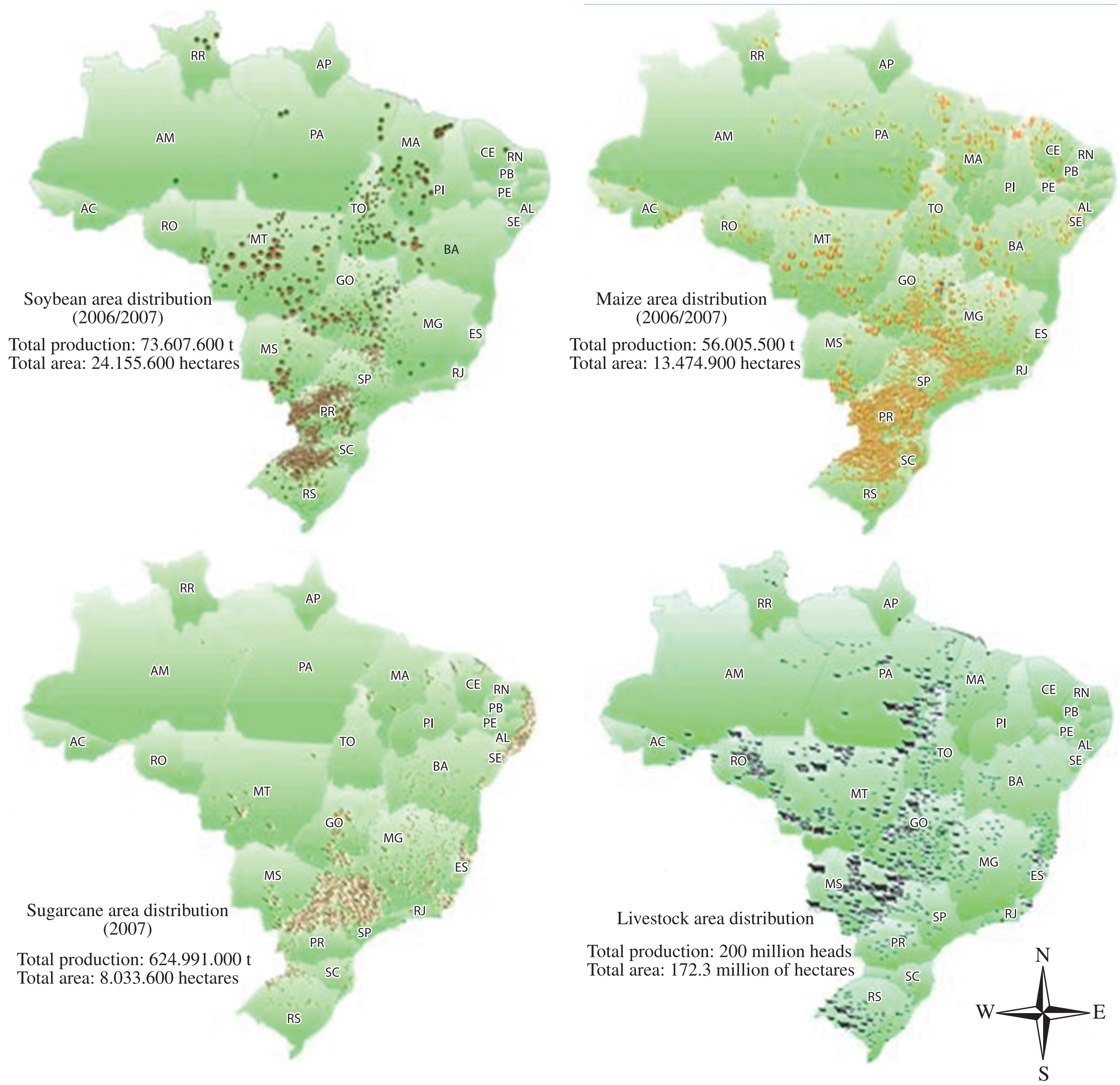

Figure 1. Spatial distribution, total production and cultivated area (hectares) of the main agricultural activities: soybean, maize, sugarcane and pasture (livestock) in Brazil. Total area and Production refers to 2010/2011. Source: CONAB - Companhia Nacional de Abastecimento.

increase in crop residue mass on the soil surface, nearly 12 t per hectare each year (equivalent to five tons of C), and in principle, this could result in soil C increases in those agricultural areas. Agricultural crops, especially sugarcane, which has a high capacity for absorbing CO_2 from the atmosphere, could therefore be managed in a more rational way, resulting in a net storage of some of the CO_2 captured by photosynthesis inside of the soil, helping in the mitigation of the greenhouse gas effect. In other agricultural crops such as soybean and maize, especially in southern Brazil, a great deal of effort has been exerted to characterise soil C sequestration after conversion from conventional to no-till, with the inclusion of crop rotation, especially with the use of leguminous crops. Those changes, in principle, are capable of changing the soil carbon regime, turning the soil into a sink for some of the carbon captured by photosynthesis.

Experiments performed in the last year have confirmed the capacity of agricultural production systems in Brazil to store C in the soil as well as in vegetation (in this case, primarily eucalyptus). This evidence is in accordance with IPCC (2006) methodology, which projects an increase of 11% in soil carbon stock in 20 years, when agricultural systems have been converted to retain large amounts of crop residues on the soil surface, as occurs in sugarcane upon conversion from burned to mechanised harvest. In addition, soil carbon sequestration would result from changes in the soil tillage system: once the agricultural system is converted from conventional to no-till, there could be an increase of 22 ± 7% in soil C stocks in 20 years, according to the IPCC methodology.

In several studies, researchers have calculated soil C stocks by means of soil organic carbon and soil density determinations, considering the appropriate depth. Those properties vary spatially and can have errors in their estimations. In addition, in 70% of the works considered in our study, soil organic C content was measured by means of dry combustion. According to Schrumpf et al. (2011), agricultural areas have smaller spatial variability in soil organic carbon and soil density in the first 10 cm of soil, especially when compared to pasture and natural vegetation areas, facilitating the detection of changes in soil C stocks with changes in management. The period needed to detect changes in soil C stocks would therefore depend on the spatial variability of soil properties, as well as their changes at a given depth. For those reasons, the present work was based on studies in which soil C stock changes were detected after at least three years of conversion to each of the systems considered.

3. On the Soil Carbon Accumulation

Figure 2 presents the geographical distribution of the main works considered for our analysis; these are publications where soil C sequestration studies were conducted in agricultural areas of Brazil. Those studies involved, necessarily, the direct measurement of the storage/loss of soil carbon due to changes in land use. Much interest in that issue has been seen recently in the literature, especially in agricultural areas of Brazil or in Amazonia, where large expanses of abandoned or degraded land exist. The same has occurred in southern Brazil when lands cropped with soybean or maize have been converted to no-till. In southern Brazil, there is particular interest in soil carbon storage in sugarcane areas that are converted from burned to so-called green harvest (mechanised), where large amounts of crop residue are left on the soil surface. According to some studies, eucalyptus has a greater potential to stock atmospheric C in aerial biomass or in soil, mainly when associated with pasture or annual crops and especially in the conversion of degraded land to productive land and for renewable energy sources.

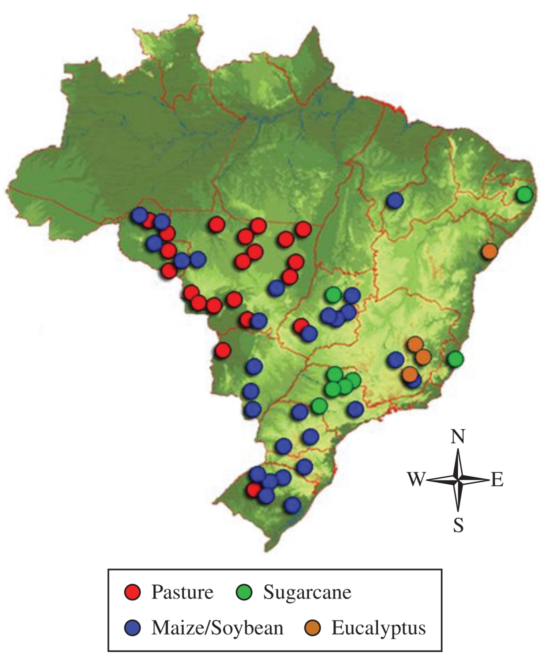

Figure 2. Spatial distribution of soil sequestration or sink potential studies of croplands in Brazil. Source: modified form Embrapa.

The works that we used as reference to obtain the data on soil C accumulation or storage once the main agricultural systems have been converted to more conservative practices are presented in Table 1, where the number of measurements performed in each of those works, the region location and the soil texture of the study are also shown.

3.1. Annual crops: no tillage option

Studies investigating soil C accumulation or storage in annual crops (soybean and maize), which were conducted mainly at depths of 0-30 cm (20% of the studies) and 0-20 cm (70% of the studies), have indicated mean soil C stock values of 0.41 ± 0.06 Mg C ha^{-1} year^{-1} (equivalent to 1.5 Mg CO_2 ha^{-1} year^{-1}) for sand and clay soils (Figure 3). This indicates that differences in soil texture did not result in significant differences in soil carbon sequestration, as similar accumulation rates were observed when more conservationist practices were implemented. In general, the primary factors contributing to the accumulation of C in the soil of annual crops are no-till practices and crop rotation sequences using leguminous plants, which remove atmospheric nitrogen via a symbiotic interaction, leaving large amounts of dry matter on the soil surface (Dieckow et al., 2005).

The conversion in this case would essentially require changing the tillage system from conventional, with successive soil tillage, to no-till with the addition of crop rotation and the resulting high residue input on the soil (Figure 3). It is noteworthy that the deviation of the C accumulation rate is small along the years of conversion to no-till, though some works have shown, for example, a depletion in soil C after 17 years of conversion. Many of the studies conducted in annual crops indicated a strong cause-and-effect relationship between C sequestration potential and soil tillage practices, as well as the amount of crop residue input on the soil, especially in strategies combining crop rotation with no-till practices (Dieckow et al., 2009).

3.2. Sugarcane fields: the green harvest option

The soil C accumulation rates of sugarcane fields after conversion from burned to green harvest indicate much higher sequestration potential than those observed in soybean/maize crops (Figure 4). A mean rate of 1.87 ± 0.20 Mg C ha^{-1} year^{-1} was observed; quite constant in all conversion years. Such C sequestration potential, observed in clay soils, is equivalent to 6,857 kg CO_2 ha^{-1} year^{-1}, which is extremely high and corresponds to 6.4% of the mean annual CO_2 absorption of this crop every year (Ronquim, 2007). This amount is much

Table 1. References of recent works with data on soil carbon accumulation due to changes in management of agricultural systems in Brazil

Reference	Number of register	Region					Textural	
		North	Northeast	Central	Southeast	South	Clay	Sand
Sugarcane								
Cerri et al. (2004)	4				×		×	×
Czycza (2009)	2				×		×	
Feller et al. (2001)	1				×		×	
Galdos et al. (2009)	1				×		×	
Pinheiro et al. (2010)	1				×			×
Razafimbelo et al. (2006)	1				×		×	
Resende et al. (2006)	1		×					×
Souza et al. (2005)	1				×			×
Szakács (2007)	3			×	×		×	
Maize/Soybean								
Amado et al. (2006)	4					×	×	×
Babujia et al. (2010)	1					×	×	
Bayer et al. (2000)	2					×		×
Bayer et al. (2006)	2			×			×	
Boddey et al. (2010)	5					×	×	
Calegari et al. (2008)	3					×	×	
Carvalho et al. (2009)	1	×					×	
Castro-Filho et al. (1998)	3					×	×	
Corazza et al. (1999)	1			×			×	
Corbeels et al. (2006)	1			×			×	
DeMaria et al. (1999)	1				×		×	
Dieckow et al. (2005)	4	×					×	
Dieckow et al. (2009)	4			×		×	×	×
Freitas et al. (2000)	1			×			×	
Freixo et al. (2002)	2					×	×	
Jantalia et al. (2007)	1			×			×	
Leite et al. (2004)	1				×		×	
Leite et al. (2009)	2		×		×		×	×
Lovato et al. (2004)	2					×		×
Maia et al. (2010)	11	×		×			×	×
Maltas et al. (2007)	1			×			×	
Metay et al. (2007)	1			×			×	
Oliveira et al. (2004)	1			×			×	
Roscoe and Buurman (2003)	1				×		×	
Sá et al. (2001)	1					×	×	
Salton (2005)	2			×			×	
Santos et al. (2011)	4					×	×	
Sisti et al. (2004)	2					×	×	
Zanatta et al. (2007)	3			×				×
Eucalyptus								
Lima et al. (2006)	2				×		×	
Stape et al. (2008)	2		×					×
Pasture								
Cardoso et al. (2010)	3			×				×
Carvalho et al. (2010b)	3	×		×			×	
Maia et al. (2009)	31	×		×			×	×
Nicoloso et al. (2008)	9					×		×

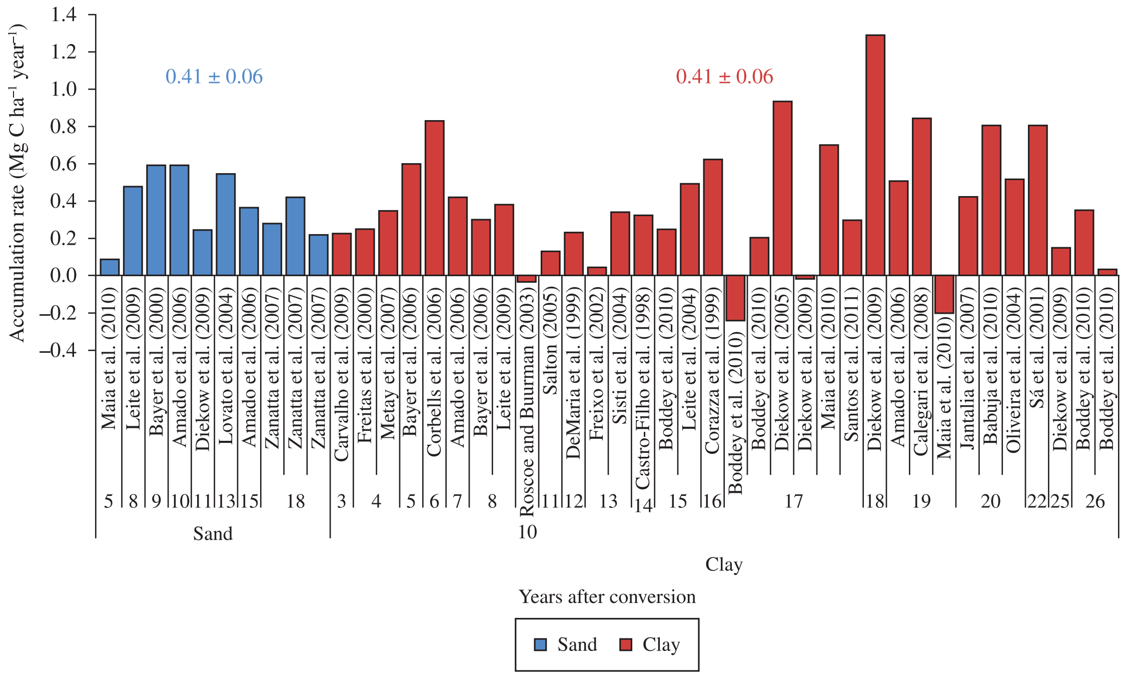

Figure 3. Accumulation or sink soil C potential (Mg C hectare^{-1} year^{-1}) in annual crops (maize, soybean and crop rotation).

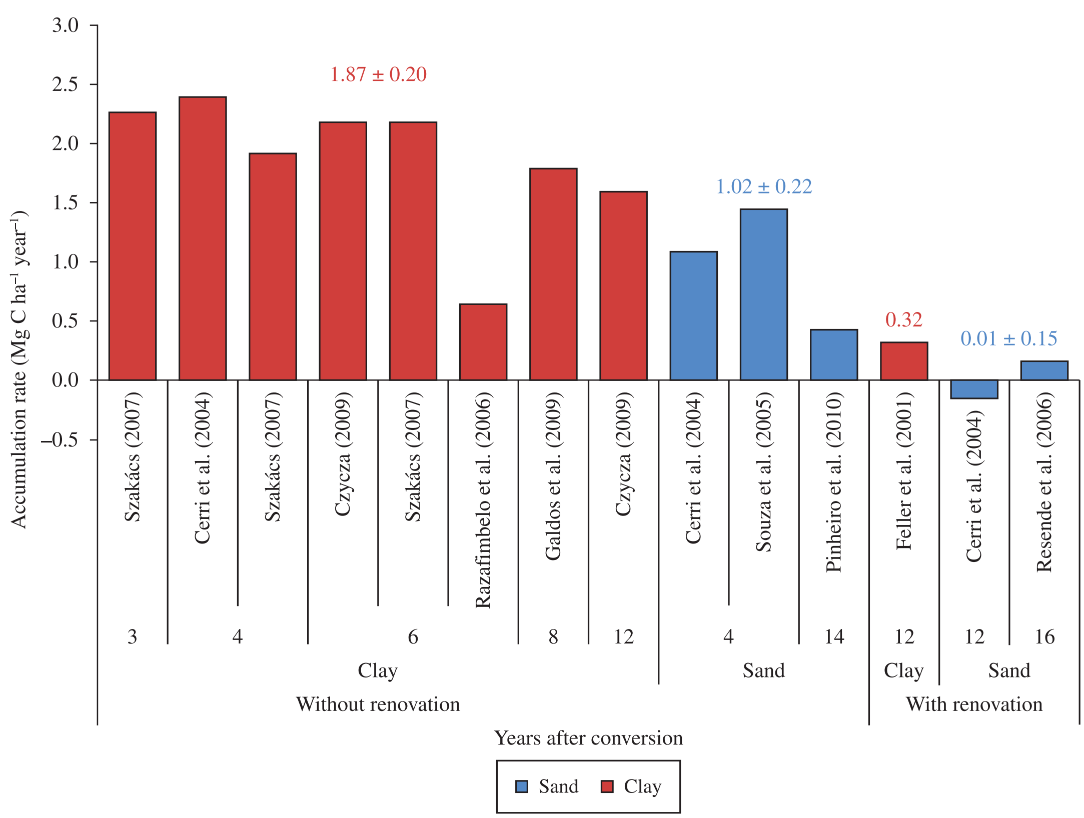

Figure 4. Accumulation or sink soil C potential (Mg C hectare^{-1} year^{-1}) in sugarcane areas after conversion from burn to green harvest.

higher than inventory-based balances accounting for N_2O, CH_4 and CO_2 emissions from diesel fuel use, N fertiliser use and other emissions from sugarcane production in southern Brazil, which equalled 3,100 kg CO_2eq ha^{-1} year^{-1} (De Figueiredo and La Scala Junior, 2011). The use of burned harvesting for sugarcane would be the worst-case scenario for emissions. The C sequestration potential in the soils of sugarcane fields would be sufficient to compensate for all emissions derived from the use of machinery and synthetic fertilisers, resulting in a mitigation equivalent to 3,757 kg CO_2 ha^{-1} year^{-1} (6,857-3,100).

Two additional facts must also be considered. First, the carbon sequestration rate seen in sugarcane areas that are converted from burned to mechanised harvest is lower in sandy soils (1.02 ± 0.22 Mg C ha^{-1} year^{-1}). Second, few studies in the literature consider sugarcane field renovation, which occurs every five or six years after seeding; this causes the sequestration potential to be almost totally lost. Figure 4 present a single study from Feller (2001), that includes the soil carbon accumulation rate of 320 kg ha^{-1} year^{-1} after 12 years of conversion from burned to green harvest, with one reform within this period. This rate would correspond to 1,733 kg CO_2 ha^{-1} year^{-1} sequestered from the atmosphere and incorporated in soil, in carbon form. As almost 4 million hectares in sugarcane fields are still cropped under burned harvest, the mitigation potential in the soil carbon accumulation potential would be close to 6.9 Tg CO_2 per year, once all the Brazilian burned sugarcane areas would be converted to green harvest. Some scenarios are presented in Carvalho et al. (2010a), based on higher residues input and better management practices that would be adopted resulting in mitigation potential from 26.4 to 78 Tg of soil C accumulated in a 20-year period in sugarcane areas.

Recent studies have indicated that the simple conversion of sugarcane fields from burned to green harvest would not ensure significant increases in soil C stocks over time, as there is little understanding of the mechanisms in favour of sequestration or of what occurs in terms of soil C losses after soil tillage, at reform (La Scala et al., 2006). Experimental results from sugarcane fields indicate soil CO_2 fluxes from 200 to 1,500 kg CO_2 ha^{-1} induced at some weeks after tillage only (La Scala et al., 2008). Both the magnitude and the exponential decay of the emission over time after tillage indicate that labile carbon not previously accessible to microbial activity is made available by tillage and is then emitted to the atmosphere as CO_2 (La Scala et al., 2006). This phenomenon has also been studied in annual cultures in southern Brazil, where high emissions with continuous decay over time have been observed after tillage (Chavez et al., 2009). We must therefore be cautious in stating that soil carbon sequestration occurs in sugarcane areas converted from burned to green harvest, which leaves high amounts of crop residue on the soil surface. It is imperative to consider the reform of sugarcane fields in those studies, as well as the contribution of emissions due to other mechanised operations in those areas. Other aspects of the stability of labile carbon, already investigated in southern Brazil (Dieckow et al., 2009), should also be incorporated in forthcoming studies with the aim of a better understanding of the possible causes and effects related to soil carbon sequestration in sugarcane areas. New strategies that would result in reduced frequency and intensity of soil tillage would be welcome, especially in sugarcane areas where the so-called no-till practice is not used, differently from annual cultures. However, recent publications have shown the high soil C sequestration potential of sugarcane areas.

3.3. On the restore of soil carbon in pasture and eucalyptus lands

In general, pasture areas are established where natural vegetation previously existed. There are several studies on changes of soil C stocks in such areas, including a dozen focussing on central Brazil (Figure 5). The studies can be divided into two groups based on the management regime and soil texture (clay and sand), in which changes in soil C stock were followed after conversion from natural vegetation to pasture or changes in stock due to the introduction of crop-pasture rotation practices. Recent results have shown that in areas where pasture was installed over natural vegetation, there was usually a reduction in soil C from 0.15 to 1.89 Mg C ha^{-1} year^{-1} (0-30 cm layer) in the initial years of conversion (Carvalho et al., 2010b; Maia et al., 2009). However, permanent pasture establishment on high–fertility soil could be responsible for a soil C sequestration rate of 0.72 Mg C ha^{-1} year^{-1} (Maia et al., 2009), as can also occur in permanent pasture areas managed with the addition of fertilisers and lime and with other practices. Among the management practices considered in pasture, higher soil C input resulted from the integration of crop-pasture production, where maize was rotated with soybeans and other crop rotations; this led to C sequestration rates from 0.82 to 1.35 Mg C ha^{-1} year^{-1} (Carvalho et al., 2010b). This is being considered as a new approach for degraded lands, increasing food production while mitigating the greenhouse effect.

Few works have studied carbon dynamics with soil C sequestration in eucalyptus-growing areas of Brazil. Eucalyptus cropping is expanding in Brazil, with the current area of six million hectares projected to increase to nine million hectares in 2020. Considering that this crop is quite efficient for atmospheric CO_2 capture, large amounts of C can be stored in its biomass and soil, in accordance with IPCC (2006) methodology.

Eucalyptus forests established in tropical regions have the potential to fix approximately 90 t of dry matter above ground per hectare, 49% of this being carbon, in the first 6 years. This would correspond to 162 t CO_2 ha^{-1} absorbed, including the carbon sequestered in roots, which is approximately 20% of that above ground (IPCC, 2006). The same methodology presents a sequestration rate for above-ground biomass in eucalyptus plantations in the tropical humid regions of South America of 7.84 t C ha^{-1} year^{-1} (Stape et al., 2004). This means that eucalyptus plantations associated with degraded pasture, where losses in soil

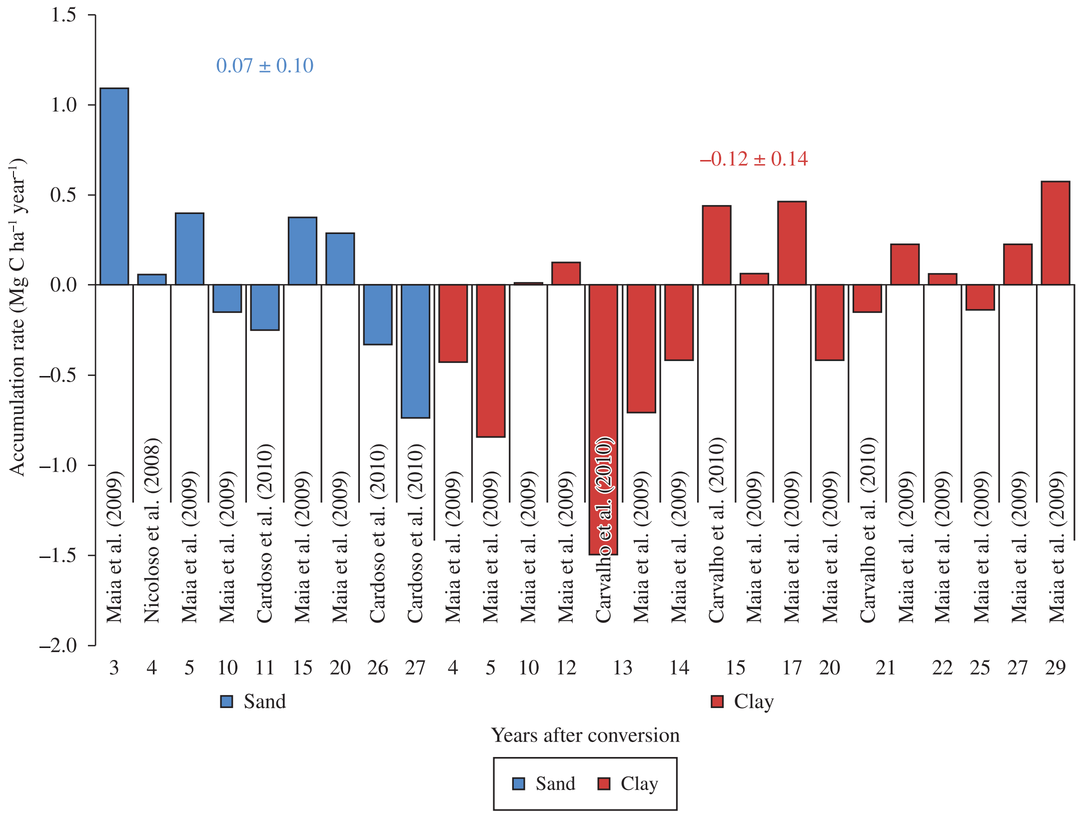

Figure 5. Accumulation or sink soil C potential (Mg C hectare^{-1} year^{-1}) in pasture under different management in Brazil.

carbon of as much as 1 t ha^{-1} year^{-1} have been reported, could absorb up to 28 t CO_2 ha^{-1} year^{-1} helping to mitigate the greenhouse effect.

4. Final Remarks

The changes in major agricultural activities in Brazil – soybean, maize and rotations, as well as sugarcane and pasture – have been evaluated in terms of their effects on soil carbon stocks. In general, this work indicates that no-till practices have resulted in a more constant rate of soil carbon sequestration after conversion from conventional tillage and that sugarcane crops have significant potential to increase soil carbon sequestration, though much of this is lost in the reform of sugarcane fields. Hence, the study of the soil CO_2 emission induced by tillage in sugarcane areas is an important aspect which should be included in future investigations. The majority of the land used in Brazilian agriculture is for pasture, which has some soil carbon sequestration potential when pasture is integrated with agriculture; this also has the benefit of increasing agricultural production. Other recent results published in the literature (Carvalho et al., 2010a; Campos et al., 2011) indicate that there are even more appropriate management practices available that would result in the storage of absorbed atmospheric CO_2 as soil carbon associated with the main agricultural activities in Brazil.

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