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Changes in soil carbon stocks in Brazil due to land use: paired site comparisons and a regional pasture soil survey

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Abstract

In this paper we calculated soil carbon stocks in Brazil using 17 paired sites where soil stocks were determined in native vegetation, pastures and crop-livestock systems (CPS), and in other regional samplings encompassing more than 100 pasture soils, from 6.58° S to 31.53° S, involving three major Brazilian biomes: Cerrado, Atlantic Forest, and the Pampa. The average native vegetation soil carbon stocks at 10 and 30 cm soil depth were equal to approximately 33 and 65 Mg ha^{-1}, respectively. In the paired sites, carbon losses of 7.5 Mg ha^{-1} and 11.9 Mg ha^{-1} in CPS systems were observed at 10 cm and 30 cm soil depth averages, respectively. In pasture soils, carbon losses were similar and equal to 8.3 Mg ha^{-1} and 12.2 Mg ha^{-1} at 10 cm and 30 cm soil depths, respectively. The average soil δ^{13}C under native vegetation at 10 and 30 cm depth were equal to −25.4 ‰ and −24.0 ‰ , increasing to −19.6 ‰ and −17.7 ‰ in CPS, and to −18.9 ‰ , and −18.3 ‰ in pasture soils, respectively; indicating an increasing contribution of C_4 carbon in these agrosystems. In the regional survey of pasture soils, the soil carbon stock at 30 cm was equal to approximately 51 Mg ha^{-1}, with an average δ^{13}C value of −19.6 ‰ . Key controllers of soil carbon stock at pasture sites were sand content and mean annual temperature. Collectively, both could explain approximately half of the variance of soil carbon stocks. When pasture soil carbon stocks were compared with the average soil carbon stocks of native vegetation estimated for Brazilian biomes and soil types by Bernoux et al. (2002) there was a carbon gain of 6.7 Mg ha^{-1}, which is equivalent to a carbon gain of 15 % compared to the carbon soil stock of the native vegetation. The findings of this study are consistent with differences found between regional comparisons like our pasture sites and local paired study sites in estimating soil carbon stocks changes due to land use changes.

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1 Introduction

Soil has long been recognized as the largest organic carbon reservoir of terrestrial systems of the Earth (Post et al., 1982). It has been estimated that globally approximately 1500 Pg of carbon is stored in the first meter of topsoil. Of this total, tropical soils store approximately 40 % of this total, with tropical evergreen forests being the single largest reservoir of soil carbon (Jobbágy and Jackson, 2000). Soil carbon exchange with the atmosphere through soil respiration is also an important component of the global carbon cycle and it was estimated to be approximately 80 Pg C yr^{-1} (Raich and Potter, 1995).

It is now also well established that carbon pools in the soil have distinct residence times. The more recalcitrant material composing the majority of soil carbon is a low cycling carbon that it is not affected much by recent land use changes (Trumbore et al., 1995; Zinn et al., 2005; Lisboa et al., 2009; Eclesia et al., 2012; Chen et al., 2013). On the other hand, there is a much faster cycling pool, that although in lower amounts than the recalcitrant material, plays a key role because of its quick response to recent land use changes (Trumbore et al., 1995; Zinn et al., 2005; Lisboa et al., 2009; Eclesia et al., 2012; Chen et al., 2013). As a consequence, this soil plasticity, so to speak, allows humans to manage soils in order to accumulate carbon or avoid high losses of it with cultivation (Lal, 2010).

One of the most intense land use changes has taken place in Brazil over recent decades (Leite et al., 2012). This land use change has increased the agricultural area of Brazil to approximately 270 million hectares, being 200 million hectares of pasture and 70 million hectares of arable land (Martinelli et al., 2010). As a consequence, land use changes in Brazil are responsible for 25 % of the carbon emissions linked to global land use changes, and also responsible for almost 80 % of the total carbon emissions in Brazil in 2005 (MCT, 2010).

It is reasonable to conclude after several regional and global studies that, in general, the conversion of natural vegetation to arable lands tend to decrease the soil carbon

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stocks (Davidson and Ackerman, 1993; Amundson, 2001; Guo and Gifford, 2002; Ogle et al., 2005; Don et al., 2011; Eclisa et al., 2012). However, it has also been shown that in several cases, depending on the type of land use change, climate, and agricultural practices, soil carbon stocks may increase or become neutral compared to the soil stocks under original vegetation (Guo and Gifford, 2002; Ogle et al., 2005; Zinn et al., 2005). Especially relevant for this study was the regional survey made in South America that showed a gain of carbon in surface soils where primary vegetation were replaced by pastures, and the fact that in the case of replacing native vegetation with croplands, under low rainfall there was a gain of carbon and a loss under high rainfall areas (Eclisa et al., 2012).

It is also relevant that the adoption of agriculture practices like no till and crop-livestock systems leads to an increase soil carbon stocks (Sá et al., 2001; Ogle et al., 2005; Zinn et al., 2005; Bayer et al., 2006). No-till is already present in more than 27 million hectares in Brazil and crop-livestock systems have been more readily adopted, mainly in the southern region of the country (Boddey et al., 2010).

A particular program was proposed by the Brazilian government that encourages the adoption of good agricultural practices to promote agriculture with low carbon emissions (Low Carbon Emission Program – ABC Program). This program, which is prescribed by law (Law no. 12187 of 29 December 2009), establishes that mitigation should be adopted such as: (i) recovery of degraded pastures, (ii) no-tillage system, (iii) integrated livestock-crop-forest systems, and (iv) re-forestation in order to reduce 36 % to 39 % of projected greenhouse gas emissions by 2020.

Based on the above discussion, the main objective of this paper was to establish a baseline by which the future effectiveness of the actions described in the ABC Program could be evaluated. A second objective was to evaluate the effects of land use changes on carbon soil stocks in several Brazilian biomes. In order to achieve this objective, two approaches were taken. One was a series of 17 paired site studies comparing soil stocks among native vegetation, pastures and crop-livestock systems; the other was a regional survey of pasture soils where more than 100 sites were sampled

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and compared with the averages of native vegetation soil stocks obtained in the literature. The stable carbon isotopic composition of soil organic matter (δ^{13}C) was also determined in sites to evaluate the origin of the carbon incorporated in the soil organic matter (Lisboa et al., 2009). This technique is especially useful in Brazil were land conversion in most cases involves the replacement of a C_3 vegetation (native forest) by a C_4 pasture or crops like maize (Bernoux et al., 1998).

This is the first time that such a large number of sites have been analyzed in a single study. These sites encompass a broad range of climatic conditions and soil composition, spanning 6.58° S to 31.53° S, including mean annual temperatures (MAT) between approximately 17 °C to 27 °C, and a mean annual precipitation (MAP) ranging from approximately 900 mm to 2100 mm. This vast range allowed us to establish main control factors of carbon soil stocks, and allowed for a consistent analysis of the effects of land use changes on soil carbon stocks.

2 Material and methods

2.1 Study area

The regional pasture survey that encompassed soils from more than 100 pastures located between 6.58° S and 31.53° S were randomly sampled independent of the grazing conditions of the pastures in November and December of 2010 (Fig. 1). Soil samples of the 17 paired study sites were sampled between November and December 2011. In these sites, soil samples were taken in areas of pasture, crop-livestock systems (CPS) and native vegetation (Table 1). Both designs were carried out in three major Brazilian biomes: Cerrado, Atlantic Forest and Pampa (Fi. 1). With exception of one pasture soil site located in the southern region of the country cultivated with a C_3 grass (*Lolium perenne*), all other pastures were cultivated with a C4 grass species, especially grasses of the genus *Brachiaria*.

As much as possible, the history of the land-use changes was investigated by talking with local farmers. However, such information is always difficult to obtain with accuracy in Brazil. Therefore, we cannot guarantee, for instance, that the native vegetation was undisturbed primary vegetation. In this regard we use the $\delta^{13}C$ values of soil organic matter in order to investigate the presence of C_4 carbon that would be indirect evidence of past native vegetation disturbance.

2.2 Precipitation and temperature

The precipitation and temperature were obtained using the Prediction of Worldwide Energy Resource (POWER) Project, which is funded through the NASA Applied Sciences Program within the Earth Science Mission Directorate (http://power.larc.nasa.gov).

2.3 Sample collection and analysis

The samples were collected by using stainless steel rings with a diameter and height of 5 cm from four specific depths: 0–5, 5–10, 10–20 and 20–30 cm for soil bulk density, while texture and total carbon concentration were collected from a 60 cm × 60 cm pit.

Air-dried soil samples were separated from plant material and stones, homogenized and ground. The samples were then run through a sieve for chemical and physical analysis (2.0 mm) and for an analysis of soil carbon (0.15 mm).

The particle size to determine the amount of sand, silt and clay soil was assessed after chemical dispersion, using the hydrometer method (Embrapa, 1997). The concentration of soil carbon and stable carbon isotopic composition was determined by using the elemental analyzer and mass spectrometry at the Laboratory of Isotopic Ecology Center for Nuclear Energy in Agriculture, University of São Paulo (CENA-USP) in Piracicaba, Brazil. Isotopic analyses were performed in a Thermo Finnigan Delta Plus spectrometer. Ratios were expressed by the classical δ per mil notation:

$$\delta = (R_{\text{sample}} - R_{\text{standard}} - 1) \times 1000 \quad (1)$$

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where R_{sample} and $R_{standard}$ are the $^{13}C:^{12}C$ or $^{15}N:^{14}N$ ratio of samples and standard, respectively. The standard use for carbon was Vienna Peedee Belemnite (VPDB). The analytical precision values were obtained based on duplicate measurements of internal, calibrated standards routinely used in the laboratory and samples from the present study. The analytical error for $\delta^{13}C$ was 0.2 ‰ .

2.4 Soil carbon stocks

Carbon stocks expressed in $Mg\,ha^{-1}$ were calculated for the soil depth intervals 0–10 cm and 0–30 cm by sum stocks obtained in each sampling intervals (0–5, 5–10, 10–20 and 20–30 cm) as follows:

$$S = [E] \times \rho \times z \quad (2)$$

where S is the soil carbon stock, $[E]$ is the carbon concentration, ρ is the soil density, and z is the soil depth interval.

For the pair site comparisons, carbon stocks were corrected to soil mass following the method of Ellert and Bettany (1995).

For the paired sites, changes in carbon stocks between current land use and native vegetation were obtained by comparing differences between the two stocks. The absolute difference (ΔC_{abs}) was expressed in $Mg\,ha^{-1}$ and the relative difference compared to the native vegetation was expressed in % (ΔC_{rel}).

For the regional survey of pasture soils, changes carbon stocks were compared against the soil carbon stocks of native vegetation. Due to time and financial constraints, we were not able to sample soil from native vegetation near each one of the pasture sites. This poses a challenge because it is important to compare changes in the soil carbon stocks compared to native vegetation as done in the paired study sites. In order to overcome the lack of original carbon soil stocks, we used estimates of native vegetation found in the literature. The most comprehensive of this type of survey was done by Bernoux et al. (2002) for a 0–30 cm interval (denominated $\Delta C_{Bernoux}$ in

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Table 4), which encompassed all the major biomes of the country. In order to make these comparisons we assumed from Bernoux et al (2002) the following soil carbon stocks according to the biome and soil type: Cerrado (42 $Mg\,ha^{-1}$); Atlantic Forest (45 $Mg\,ha^{-1}$); Pampas (79 $Mg\,ha^{-1}$).

Using $\delta^{13}C$ of the soil organic matter, we estimated the proportion of C_3 (C_{3p}) and C_4 (C_{4p}) carbon in the soil according to the following isotopic dilution equation:

$$C_{4p} = \frac{\delta^{13}C_{soil} - \delta^{13}C_{C_3}}{\delta^{13}C_{C_4} - \delta^{13}C_{C_3}} \quad (3)$$

where C_{4p} is the proportion of C_4 plants, $\delta^{13}C_{soil}$ is the carbon isotopic composition of the soil's organic matter; $\delta^{13}C_{C3}$ is the carbon isotopic composition of the C_3 source, and the $\delta^{13}C_{C4}$ is the carbon isotopic composition of the C_4 source. We use the lowest $\delta^{13}C$ of our paired sites as the $\delta^{13}C_{C3}$ (−26.7 ‰, and −26.1 ‰, for 0–10 cm and 0–30 cm, respectively), and the highest $\delta^{13}C$ as the $\delta^{13}C_{C4}$ (−13.1 ‰, and −13.7 ‰, for 0–10 cm and 0–30 cm, respectively). The C_{3p} proportion was estimated as $1 - C_{4p}$.

2.5 Statistical analysis

The $\delta^{13}C$ followed a normal distribution, but soil carbon stocks must be transformed using Box-Cox techniques to achieve normality. All statistical tests were performed using transformed soil carbon stocks, but non transformed values were used to report average values.

Differences between land uses were tested with ANCOVA being the dependent variable $\delta^{13}C$ with transformed carbon soil stocks at the soil depth intervals of 0–10 cm and 0–30 cm; the independent variables were land use type. As MAT, MAP, soil density and soil texture may influence $\delta^{13}C$ and carbon soil stocks, these were also included in the model as co-variables. The Tukey Honest Test for unequal variance was used as a post-hoc test. In order to test if changes in carbon stocks between current land use and native vegetation were statistically significant, we used a one-sample *t* test, where the null hypothesis showed the population mean to be equal to zero.

As our database encompasses different biomes, climates, and land management, all tests were reported as significant at a level of 10 %. Statistical tests were performed using a STATISTICA11 package.

3 Results

3.1 Paired study sites

3.1.1 Stable carbon isotopic composition

It is important to point out that in Ponta Grossa in Paraná State, and Bagé and Capão do Leão in Rio Grande do Sul State, the native vegetation is composed of C_4 grasses or a mixture of C_4 and C_3 plants. The $\delta^{13}C$ of the topsoil (0–10 cm) these regions were equal to −15 ‰, −21.2 ‰, and −15.4 ‰, respectively. $\delta^{13}C$ data from these sites were not included in the discussion that follows.

The average $\delta^{13}C$ of the C_3 native vegetation topsoil (0–10 cm) obtained by averaging values from 0–5 cm and 5–10 cm of soil depth intervals in the paired study sites (Table 2) was equal to −25.4 ‰, decreasing to −19.5 ‰ in the crop-pasture systems (CPS) and to −17.7 ‰ in the pasture soil ($F_{(2.53)} = 16.42$, $p < 0.01$). The post-hoc Tukey test showed that only the average $\delta^{13}C$ of the C_3 native vegetation soil was significantly different than pasture and CPS systems ($p < 0.01$). The same tendency was observed for the 0–30 cm soil depth interval (obtained by the weighted average among soil depth intervals) (Table 3). The average $\delta^{13}C$ of the C_3 native vegetation soil in the paired sites was significantly lower than pasture and CPS soils ($F_{(2.53)} = 10.76$, $p < 0.01$); again the $\delta^{13}C$ of CPS soils were not different than pasture soils (Table 3).

In the paired study sites, the average proportion of C_4 plants (C_{4p}) was approximately 0.12 in the native vegetation topsoil (0–10 cm), increasing to 0.55 in CPS and reaching

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a maximum of approximately 0.70 in pasture soils (Table 2). In the 0–30 cm depth interval, the C_{4p} in the native vegetation soils was approximately 0.17, increasing to approximately 0.60 in CPS and again reaching a maximum of approximately 0.64 in pasture soils (Table 3). The fact that there is C_4 carbon especially in the topsoil of native vegetation is an indication that not all native forests were primary forests.

There was great depth variability in the $\delta^{13}C$ of soils under native vegetation (Fig. 2). This was in part due to the fact that three sites located in the southern region of the country were natural C_4 grasslands – Ponta Grossa (PG), Bagé (BA) and Capão do Leão (CL). Ponta Grossa had the highest soil $\delta^{13}C$ in all depths, indicating that these soils are almost entirely composed of C_4 carbon (Fig. 3). Capão do Leão had lower $\delta^{13}C$ than Ponta Grossa, but still is indicative of a high C_4 presence (Fig. 2). On the other hand, Bagé had the lowest $\delta^{13}C$ among all three grassland sites, showing a mixture of C_3 and C_4 vegetation in their soils. The presence of C_4 carbon increases with depth in this last site (Fig. 2). Two other sites, Arroio dos Ratos (AR) and Tuparacetã (TU), also showed an increasing contribution of C_4 carbon with depth; however, in the soil surface both sites had characteristic $\delta^{13}C$ from C_3 carbon (Fig. 2). At the other end of the spectrum, showing typical forest depth profiles, there is São Carlos (SC), Cafeara (CS), Iporã (IP), and Nova Esperança do Sul (NS) soil profiles (Fig. 2).

The $\delta^{13}C$ in pasture paired site soil profiles were also highly variable, reflecting constant changes in land use. There are profiles like Ponta Grossa (PG) where the original vegetation is composed of C_4 plants therefore, there was not much change between native grasslands and introduced C_4 grasses (Fig. 2). The São Carlos profile (SC) is also a good example of the predominant C_4 presence (Figure 2), but in this case, it probably denotes the presence of a cultivated pasture, since the original forest has a clear C_3 signal throughout the entire profile (Fig. 2). On the other hand, there are profiles, which, although they have been converted to pasture, also show a large contribution of C_3 plants. These profiles are best illustrated by Sete Lagoas (SL) and Iporã (IP) (Fig. 2). These profiles show a higher proportion of C_4 at the surface, with increasing contributions of C_3 plants at deeper depths (Fig. 2). Finally, the soil profiles in Coronel

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Xavier (CX), Campo Mourão (CM) and Nova Esperança do Sul (NS) show a mixture of C_3 and C_4 carbon throughout the soil depth, with $\delta^{13}C$ varying from approximately −18 ‰ to −16 ‰ (Fig. 2).

3.1.2 Soil carbon stocks

The average carbon stock of the native vegetation soils corrected to soil mass at the topsoil (0–10 cm) was 33.4 Mg ha^{-1} decreasing ($F_{(2.51)} = 3.48$, $p = 0.04$) to 26.3 Mg ha^{-1} in the CPS and to 24.5 Mg ha^{-1} in pasture soils (Table 2). In the 0–30 cm of the soil depth interval, the carbon stock corrected to soil mass of the native vegetation soils was 72.3 Mg ha^{-1} decreasing again ($F_{(2.51)} = 2.56$, $p = 0.09$) to 61.1 Mg ha^{-1} in the CPS and to 59.5 Mg ha^{-1} in pasture soils (Table 3).

Most of the paired sites either for CPS or pasture soils showed a decrease in carbon stocks compared to native vegetation areas (Fig. 3). As a consequence, there was a net loss of carbon stocks between native vegetation and current land uses in both soil depth intervals (Tables 2 and 3). For the topsoil (0–10 cm), in the forest-CPS pairs both the $\Delta C_{abs} = -7.5$ Mg ha^{-1} ($t = -3.99$, $p < 0.01$), and the $\Delta C_{rel} = -20$ % ($t = -3.71$, $p < 0.01$) were statistically significant, and the same was true for the 0–30 cm depth interval, where the $\Delta C_{abs} = -11.9$ Mg ha^{-1} ($t = -2.67$, $p = 0.02$) and the $\Delta C_{abs} = -15$ % ($t = -2.96$, $p = 0.01$). In the forest-pasture pair sites also both the $\Delta C_{abs} = -8.3$ Mg ha^{-1} ($t = -3.25$, $p < 0.01$) and the $\Delta C_{rel} = -20$ % ($t = -3.71$, $p < 0.01$) were statistically significant. For the 0–30 cm depth interval losses in the forest-pasture pair sites were $\Delta C_{abs} = -12.2$ Mg ha^{-1} ($t = -2.67$, $p = 0.02$), and $\Delta C_{rel} = -16$ % ($t = 2.96$, $p = 0.01$).

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3.2 Regional survey of pasture soils

3.2.1 Stable carbon isotopic composition

There was a large variability of the δ^{13}C of pasture soils with soil depth (Fig. 4), and consequently in the proportion of C4 carbon incorporated into the soil. The average δ^{13}C of pasture soil at 0–10 cm depth interval was -18.7 ± 2.8 ‰, with the average contribution of C_4 carbon to the soil being equal to 0.58 ± 0.20. The average δ^{13}C of pasture soils at 0–30 cm was similar and equal -19.3 ± 2.7 ‰ and C_4 carbon contribution to the soil decreased slightly to 0.54 ± 0.20 (Table 4). No significant correlation was found between the C_4 carbon contribution, and climatic variables like MAT and MAP nor soil texture.

3.2.2 Soil carbon stocks

At the depth interval 0–10 cm the average total carbon soil stock was equal to 21.6 ± 10.7 Mg ha^{-1}, with values varying from < 10 Mg ha^{-1} up to > 40 Mg ha^{-1} (Fig. 5). The average total carbon soil stock was equal to 50.6 ± 23.2 Mg ha^{-1}, with values varying from < 20 Mg ha^{-1} up to > 100 Mg ha^{-1} (Fig. 5).

Compared with carbon stocks from Bernoux et al. (2002), the absolute change in the soil carbon stocks from pastures compared to carbon stocks of native vegetation ($\Delta C_{\text{Bernoux-abs}}$) were mostly positive (Fig. 6), indicating an average gain of carbon of 6.7 Mg ha^{-1} ($t = 3.07$, $p = 0.01$) compared to the native vegetation (Table 4). In relative terms ($\Delta C_{\text{Bernoux-rel}}$), there was a gain of 15 % ($t = 3.23$, $p < 0.01$).

3.2.3 Controls of carbon soil stocks

Many variables may control carbon soil stocks. At the regional level, climatic variables like temperature and rainfall are important, while at the local level, soil properties like texture, density and fertility are also key variables. We used stepwise regression to choose the best set of variables that control soil carbon stocks. Among all parameters for both soil depth intervals (10 cm and 30 cm), the higher adjusted correlation was obtained using the mean annual temperature (MAT) and soil sand content as a predictor of variables.

The adjusted correlation coefficient (r^2_{adj}) for carbon was approximately 0.50, which means that half of the variance of carbon soil stocks can be explained by MAT and sand content (Table 4). All coefficients of the following multiple regression equations have a $p < 0.01$.

$$C_{s\text{-}10} = 59.03 - 1.12(\text{MAT}) - 0.21(\text{SAND}) \quad (4)$$

$$C_{s\text{-}30} = 138.27 - 2.72(\text{MAT}) - 0.46(\text{SAND}) \quad (5)$$

Where $C_{s\text{-}10}$ and $C_{s\text{-}30}$ represent the soil carbon stocks expressed as Mg ha^{-1} at 10 cm and 30 cm soil depth, respectively; MAT represents the mean annual temperature expressed in Celsius, and SAND represents the soil sand content expressed in percentage.

Figure 7 shows the surface area produced by Eq. (5) in the upper panel, and the observed and predicted values of carbon soil stock at 30 cm depth as an example in the lower panel. Carbon stocks at 10 cm produced very similar graphs and are not shown. There is a tendency for colder regions and lower sand content to contain higher soil stocks than warmer regions with sandy soils (Fig. 7).

4 Discussion

4.1 Changes in carbon stocks with soil cultivation – paired study sites

The average soil carbon stocks correcting for soil mass for the native vegetation was equal to approximately 72 Mg ha^{-1} (Table 3) and 65 Mg ha^{-1} if soil mass correction is not applied. The latter value is similar to the carbon soil stock for soils with high activity clay (HAC) considering the moist tropical climate region adopted by the IPCC that encompasses most of Brazil except the Amazon region and the Northeast caatinga (IPCC, 2006). On the other hand, the average value of 65 Mg ha^{-1} found in this study for native vegetation is higher than the carbon stock for soils with low activity clay (LAC) considering the same climate region, that was equal to 47 Mg ha^{-1} (IPCC, 2006). Compared with carbon soil stocks estimated for different biomes and soil types of Brazil (Bernoux et al., 2002), the average carbon stock found in this study for native vegetation was 25 % to 35 % higher than the soil carbon stock found for the Cerrado and Seasonal semi-deciduous forest biomes considering HAC and LAC soils, respectively. However, our paired study sites also includes four sites that belong to the southern savanna biome (Fig. 1), and for this region Bernoux et al. (2002) estimated carbon soil stocks varied from approximately 71 to 88 Mg ha^{-1} for LAC and HAC soils, respectively; being larger than the average carbon stock of native vegetation found in this study.

The results found in our paired study sites confirmed the tendency found in regional and global studies of soil carbon losses with soil cultivation (Davidson and Ackerman, 1993; Amundson, 2001; Guo and Gifford, 2002; Ogle et al., 2005; Don et al., 2011). The net balance for the native vegetation-pasture conversion was −8.3 Mg ha^{-1} for carbon (−26 %) and −12.2 Mg ha^{-1} (−16 ‰), for 0–10 cm and for 0–30 cm depth intervals, respectively (Tables 2 and 3). These losses are similar to losses reported by Don et al. (2011) who found through a meta-analysis that the native vegetation-pasture conversion was −12.6 Mg ha^{-1} at 0–30cm depth, which corresponds to a relative loss of −12 ‰, a little higher than the −16 % found in this study.

On the other hand, the results found in this survey (Fig. 3) also confirmed other studies, especially on pasture soils, that showed that depending on local conditions, the soil carbon stocks may increase compared to the local native vegetation (Guo and Gifford, 2002; Ogle et al., 2005; Zinn et al., 2005; Eclisa et al., 2012). For both soil depth intervals investigated in paired sites, 2 out of 13 sites where native vegetation-to-pasture conversions were investigated, showed higher carbon stocks than the native vegetation, and two others were virtually neutral (Fig. 3). For native vegetation-to-cropland system conversion, a third of the sites showed an increase in soil carbon stocks and the remaining two-thirds showed losses of stock (Fig. 3). In general, it seems that losses or gains of carbon are affected by the management system (Carvalho et al., 2010). For instance, well-managed pastures have the capability of increasing carbon soil stocks, while poorly managed pastures may lose carbon compared to the original vegetation (Guo and Gifford, 2002; Maia et al., 2009). In addition, the CPS systems sampled in this work were well-managed agriculture systems, including no till, and crop-livestock integration, which may help to accumulate carbon in the soil (Bernoux et al., 2006, Govaerts et al., 2009; Powlson et al., 2011). Bayer et al. (2006) have estimated for the 0–20 cm depth interval a carbon gain in the soil under no till of almost 0.50 Mg ha^{-1} yr^{-1} and 0.35 Mg ha^{-1} yr^{-1} in the southern region of Brazil and in the Cerrado area, respectively.

4.2 Changes in carbon stocks with soil cultivation – regional soil pasture survey

The regional survey of pasture soils done in this study produce contradictory results in terms of changes in carbon soil stocks as is common in the literature, where pasture soils may gain or lose carbon mainly according to their level of management (Camargo et al., 1999; Trumbore et al., 1995; Maia et al., 2009). When comparing pasture soils with the native vegetation carbon stocks estimated by Bernoux et al. (2006), which is very similar to the values adopted by the IPCC (Batjes et al., 2011), 40 % of the sites showed a soil carbon stock loss, and 60 % of the sites showed a soil carbon stock gain compared to the native vegetation (Fig. 6). Compared to native vegetation, on average there was a carbon gain of approximately 7 Mg ha^{-1} yr^{-1} (equivalent to +15 %) (Table 4). The increase in soil carbon stock (0–30 cm depth) with the replacement of the original vegetation by pasture was also observed in a regional survey done in South America (Eclisa et al., 2012). However, the same authors also showed that there was a decrease in soil carbon stock from 30 cm to 100 cm depth to counterbalance the carbon

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gains observed in the topsoil; as a result, there was not a significant change in carbon stocks considered at a depth of 100 cm.

In conclusion, our paired study sites showed a soil carbon stock loss, and our regional pasture survey showed a gain in the native vegetation-pasture conversion (Table 3). It is very difficult to know which soil carbon change is more accurate (paired study vs. regional pasture survey) because the study of Bernoux et al. (2002) was very well conducted using a mixture of a high number of real soil data surveyed by the RADAM BRASIL project and interpolation techniques at the biome level. On the other hand, although based on much less data, their study was conducted in paired sites and specifically designed for local comparisons between original vegetation and agricultural systems.

Perhaps more importantly, these contradictions indicate a difficulty in comparing Tier 1 (regional pasture surveys) with Tier 2 (paired study sites) type strategies established by IPCC in data poor regions of the world. At the same time, such contradictions are clearly indicative of the fact that, at least in Brazil, there is a need for detailed studies on changes in soil carbon stocks due to land use change.

4.3 Depth variability of δ^{13}C in forests and pastures of paired study sites

It is generally accepted that an increase of up to 3–4 ‰ in the profile is caused by organic matter decomposition. Soil depth increases in δ^{13}C higher than this threshold are generally interpreted as a sign of the presence of C_4 carbon in the soil's organic matter (Martinelli et al., 1996; Ehleringer et al., 2000; Schwendenmann and Pendall, 2006; Yonekura et al., 2012). The presence of C_4, in turn, could be due to some recent land changes that introduced C_4 into one of the cropping systems, or due to a natural shift in vegetation (Martinelli et al., 1996; Ehleringer et al. 2000; Schwendenmann and Pendall, 2006; Yonekura et al., 2012). In three of our sites, the increase in δ^{13}C was higher than 3–4 ‰, indicating a past presence of C_4 vegetation. Two of them, Passo Fundo (PF), and Arroio dos Ratos (AR) are experimental stations of EMBRAPA and Universidade Federal do Rio Grand 2e do Sul, respectively (Fig. 2). Therefore, it is possible that the dominant vegetation (forest) replaced old pastures, although it is not possible to completely rule out the existence of a natural paleo grassland. The third place is in Coronel Xavier (CX), which is not an experimental station, and is difficult to establish the origin of the C_4 material (Fig. 2). If the hypothesis of introduced C_4 pasture prevails, it is clear that a secondary forest was established in these sites.

4.4 Controls of carbon soil stocks

Saiz et al. (2012) found along a transect in West Africa encompassing different African vegetation types that more than 0.80 of the variance of soil carbon stocks could be predicted by soil sand content and the difference between precipitation and evapotranspiration. In this study, in the regional survey of pasture soils, approximately 0.50 of the variance could be explained by the soil sand content and MAT. The adjusted coefficient correlation found in this study was lower than that found by Saiz et al. (2012). This was somewhat expected since pasture sites on regional surveys encompass several types of management that exert a key role in determining soil carbon stocks (Camargo et al., 1999; Trumbore et al., 1999; Maia et al., 2009; Carvalho et al., 2010).

Another interesting point already noted by Saiz et al. (2012) is that soil sand content was more important than clay as a predictor of soil carbon stocks under pasture. Remembering that throughout the literature, clay content generally has a direct correlation with soil carbon content (Feller and Bearer, 1997) since clay may exert a protection against organic matter decomposition. However, it seems that such protection depends more on the type of clay and contents of Al and Fe sesquioxides than the amount of clay (Bruun et al., 2010). In turn, sesquioxides in the same cases, impart a sand-like texture to tropical soils; this type of texture interferes with the soil water retention capacity and soil bulk density that are key components in the soil organic matter liability and soil carbon stocks (Saiz et al., 2012).

Therefore, besides management practices, if the main goal is to implement grasslands that are able to maintain at least the same soil carbon stock compared to the native vegetation, sandy soils should be avoided.

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Mean annual temperature was also important in the control of soil carbon content in the case of pasture soils. This fact is mainly due to the effect of the temperature on decomposition rates of soil organic matter (e.g. Raich et al., 2006; Wagai et al., 2008). Temperature increases were shown to enhance organic matter decomposition and soil respiration, leading to carbon losses through CO2 emissions into the atmosphere (Dorrepaal et al., 2009).

5 Conclusions

Our paired study sites showed an average loss of carbon soil stocks compared to either pasture or crop-livestock systems. The fact that some pasture sites and one-third of the crop-livestock systems showed a gain of carbon compared to the native vegetation calls attention to the fact that suitable management practices may exert an important influence in carbon accumulation in the soil.

Although we fully recognized the importance of using regional average carbon stocks in data-poor tropical regions of the world, we also should call attention to the fact that the use of such averages leads to different results comparing to pasture soils (paired study sites vs. regional pasture survey), without it being feasible to clearly discern which was the most accurate comparison.

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Table 1. Characterization of sampled sites: native vegetation (NV), pastures (P), crop-livestock systems (CL), livestock-forest systems (LF), crop-forest systems (CF) and crop-livestock-forest systems (CLF).

City (Code)-State	Point	Latitude	Longitude	Characterization	Years	Biome
Sete Lagoas (SL)-MG	1	19°29′57″	44°11′03″	Pasture	–	Cerrado
	2	19°29′24″	44°10′48″	CL (pasture and corn)	3	Cerrado
	3	19°29′11″	44°11′19″	CLF (corn, pasture and eucalyptus)	3	Cerrado
	4	19°29′37″	44°11′09″	Native Vegetation	–	Cerrado
	5	19°29′28″	44°11′08″	CL (pasture and soybean)	3	Cerrado
Coronel Xavier (CX)-MG	6	21°01′06″	44°12′53″	Native Vegetation	–	Atlantic Forest
	7	21°01′13″	44°12′56″	Pasture	–	Atlantic Forest
	8	21°01′12″	44°12′53″	CLF (corn, pasture and eucalyptus)	2	Atlantic Forest
	9	20°59′35″	44°10′18″	Pasture	–	Atlantic Forest
	10	20°59′36″	44°10′18″	Native Vegetation	–	Atlantic Forest
	11	20°59′40″	44°10′20″	CLF (corn, pasture and eucalyptus)	2	Atlantic Forest
Mar de Espanha (ME)-MG	12	21°48′34″	42°58′35″	CLF (corn, pasture and eucalyptus)	3	Atlantic Forest
	13	21°48′01″	42°58′02″	Pasture	–	Atlantic Forest
	14	21°47′00″	42°57′55″	Native Vegetation	–	Atlantic Forest
São Carlos (SC)-SP	15	21°58′49″	47°51′10″	Pasture	–	Cerrado
	16	21°58′27″	47°51′10″	LF (pasture and eucalyptus)	1	Cerrado
	17	21°58′38″	47°51′17″	Native Vegetation	–	Cerrado
	18	21°57′47″	47°51′00″	LF (pasture and eucalyptus)	4	Cerrado
Cafeara (CS)-PR	19	22°50′38″	51°42′28″	CL (pasture and soybean)	8	Atlantic Forest
	20	22°50′02″	51°42′52″	Native Vegetation	–	Atlantic Forest
	21	22°52′12″	51°43′37″	Pasture	–	Atlantic Forest

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Table 1. Continued.

City (Code)-State	Point	Latitude	Longitude	Characterization	Years	Biome
Iporã (IP)-PR	22	24°00′26″	53°45′01″	CL (pasture and soybean)	3	Atlantic Forest
	23	24°00′06″	53°45′32″	Pasture	–	Atlantic Forest
	24	24°01′20″	53°45′38″	Native Vegetation	–	Atlantic Forest
Xambrê (XA)-PR	25	23°47′34″	53°36′20″	Pasture	–	Atlantic Forest
	26	23°47′14″	53°36′10″	CL (pasture and soybean)	11	Atlantic Forest
	27	23°47′23″	53°36′31″	CF (soybean and eucalyptus)	1	Atlantic Forest
	28	23°48′29″	53°35′25″	Native Vegetation	–	Atlantic Forest
Campo Mourão (CM)-PR	29	24°06′25″	52°21′40″	Pasture	–	Atlantic Forest
	30	24°06′21″	52°21′34″	CL (corn and pasture)	5	Atlantic Forest
	31	24°06′18″	52°21′34″	Native Vegetation	–	Atlantic Forest
Juranda (JU)-PR	32	24°18′21″	52°42′17″	CL (rotation (soybean + corn) and pasture)	5	Atlantic Forest
	33	24°18′34″	52°42′16″	Pasture	–	Atlantic Forest
	34	24°18′10″	52°42′18″	Native Vegetation	–	Atlantic Forest
Ponta Grossa (PG)-PR	35	25°06′37″	50°03′04″	CLF (soybean, pasture and eucalyptus)	5	Atlantic Forest
	36	25°06′32″	50°03′26″	CL (rotation (corn + soybean) and pasture)	10	Atlantic Forest
	37	25°06′43″	50°03′49″	Native Vegetation	–	Atlantic Forest
	38	25°06′54″	50°03′49″	Pasture	–	Atlantic Forest
Arroio dos Ratos (AR)-RS	39	30°06′14″	51°41′32″	CL (rotation (corn + soybean) and pasture) intense grazing	9	Pampa
	40	30°06′12″	51°41′33″	CL (rotation (corn + soybean) and pasture) moderate grazing	9	Pampa
	41	30°06′06″	51°41′58″	Native Vegetation	–	Pampa
	42	30°06′06″	51°41′31″	Pasture	–	Pampa

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Table 1. Continued.

City (Code)-State	Point	Latitude	Longitude	Characterization	Years	Biome
Tupanciretã (TU)-RS	43	28°56′34″	54°21′35″	CL (soybean and pasture) intense grazing	10	Pampa
	44	28°56′11″	54°21′25″	CL (soybean and pasture) moderate grazing	10	Pampa
	45	28°56′31″	54°20′02″	Pasture	–	Pampa
	46	28°55′48″	54°20′29″	Native Vegetation	–	Pampa
Nova Esperança do Sul (NS)-RS	47	29°27′12″	54°48′40″	CLF (sorghum, pasture and eucalyptus)	4	Atlantic Forest
	48	29°27′33″	54°49′17″	Pasture	–	Atlantic Forest
	49	29°27′31″	54°49′18″	Native Vegetation	–	Atlantic Forest
Bagé (BA)-RS	50	31°22′11″	54°00′11″	CL (rice and pasture)	4	Pampa
	51	31°22′01″	54°00′28″	Native Vegetation (Campos), also used as pasture	–	Pampa
	52	31°28′30″	53°58′15″	CLF (sorghum, pasture and eucalyptus)	6	Pampa
	53	31°19′17″	54°00′12″	CL (soybean and pasture)	4	Pampa
Capão do Leão (CL)-RS	54	31°49′57″	28°28″	Native Vegetation (Campos), also utilized as pasture	–	Pampa
	55	31°49′19″	52°28′40″	CL (soybean and pasture)	4	Pampa
	56	31°49′19″	52°28′11″	CL (rotation (soybean + rice) and pasture)	4	Pampa
Passo Fundo (PF)-RS	57	28°13′32″	52°24′30″	CL (rotation (corn + soybean) and pasture)	15	Atlantic Forest
	58	28°13′31″	52°24′28″	CL (rotation (corn + soybean+wheat) and pasture)	15	Atlantic Forest
	59	28°13′30″	52°24′24″	Native Vegetation	–	Atlantic Forest

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Table 2. Mean, standard-deviation (Std.Dev.), minimum and maximum for $\delta^{13}C$, C_3 proportion (C_3), C_4 proportion (C_4), and carbon stocks (C_{stock}) at 0–10 cm soil depth layer for forest, crop-livestock systems and pasture soils at the paired study sites. ΔC_{abs} is the difference between the carbon soil stock of native vegetation and crop livestock systems and pasture soils obtained in the paired study sites. ΔC_{rel} is the same difference expressed as percentage. Carbon losses are indicated by a minus sign (–).

	Native Vegetation (0–10 cm)				
	N	Mean	Std.Dev.	Minimum	Maximum
$\delta^{13}C$ (‰)*	13	–25.4	1.4	–26.8	–22.9
C_4*	13	0.10	0.11	0	0.97
C_3*	13	0.90	0.11	0.04	0.3
C_{stock} ($Mg.ha^{-1}$)	16	33.4	14.7	12.7	57.7
	Crop-livestock (0–10 cm)				
	N	Mean	Std.Dev.	Minimum	Maximum
$\delta^{13}C$(‰)	27	–19.6	2.6	–23.6	–13.7
C_4	27	0.52	0.2	0.24	1
C_3	27	0.48	0.2	0	0.76
C_{stock} ($Mg.ha^{-1}$)	27	26.3	11.85	8.06	44.79
ΔC_{abs} ($Mg.ha^{-1}$)	27	–7.53	9.81	-29.76	12.13
ΔC_{rel} (%)	27	–20	28	–53	44
	Pasture (0–10 cm)				
	N	Mean	Std.Dev.	Minimum	Maximum
$\delta^{13}C$ (‰)	13	–17.7	2.2	–23.1	–14.5
C_4	13	0.66	0.17	0.28	0.94
C_3	13	0.34	0.17	0.06	0.72
C_{stock} ($Mg.ha^{-1}$)	13	24.5	14.5	6	47.7
ΔC_{abs} ($Mg.ha^{-1}$)	13	–8.3	9.2	–24	8.8
ΔC_{rel} (%)	13	–26	26	–67	25

* Ponta Grossa, Bagé and Capão do Leão, which are predominantly C_4 sites, were not included.

Table 3. Mean, standard-deviation (Std.Dev.), minimum and maximum for $\delta^{13}C$, C_3 proportion, C_4 proportion, and carbon stocks (C_{stock}) at 0–30 cm soil depth layer for forest, crop-livestock systems and pasture soils at paired study sites. ΔC_{abs} is the difference between the carbon soil stock of native vegetation and crop livestock systems and pasture soils obtained in the paired study sites. ΔC_{rel} is the same difference expressed as percentage Carbon losses are indicated by a minus sign (–).

	Forest (0–30 cm)				
	N	Mean	Std.Dev.	Minimum	Maximum
$\delta^{13}C$ (‰)*	13	–24	1.7	–26.1	–20.3
C_4*	13	0.17	0.14	0.52	1
C_3*	13	0.83	0.14	0	0.48
C_{stock} ($Mg.ha^{-1}$)	16	72.3	33.2	27.3	123
	Crop-livestock (0–30 cm)				
	N	Mean	Std.Dev.	Minimum	Maximum
$\delta^{13}C$ (‰)	27	–18.9	2.5	–22.5	–14
C_4	27	0.58	0.21	0.29	1
C_3	27	0.42	0.21	0	0.71
C_{stock} ($Mg.ha^{-1}$)	27	61.1	28.6	15.5	115
ΔC_{abs} ($Mg.ha^{-1}$)	27	–11.9	22.2	–55.7	36.4
ΔC_{rel} (%)	27	–15	27	–60	52
	Pasture (0–30 cm)				
	N	Mean	Std.Dev.	Minimum	Maximum
$\delta^{13}C$ (‰)	13	–18.3	2.4	–23.5	–14.9
C_4	13	0.63	0.19	0.22	0.93
C_3	13	0.37	0.19	0.07	0.78
C_{stock} ($Mg.ha^{-1}$)	13	59.5	31.4	15.9	100.9
ΔC_{abs} ($Mg.ha^{-1}$)	13	–12.2	16.5	–36.5	12.4
ΔC_{rel} (%)	13	–16	20	–59	14

* Ponta Grossa, Bagé and Capão do Leão, which are predominantly C_4 sites, were not included.

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Table 4. Mean, standard-deviation (Std.Dev.), minimum, and maximum, standard-deviation (Std.Dev.) for $\delta^{13}C$, C_3 proportion, C_4 proportion, and carbon stocks (C_{stocks}) at 0–30 cm soil depth layer for pasture soils included in the regional survey. ΔC_{abs} is the difference between the carbon soil stock of native vegetation obtained by Bernoux et al. (2002) and pasture soils. ΔC_{rel} is the same difference expressed as percentage.

	N	Mean	Std.Dev.	Minimum	Maximum
$\delta^{13}C$	103	−19.3	2.7	−26.0	−13.3
C_3	103	0.46	0.20	0.04	0.95
C_4	103	0.54	0.20	0.05	0.96
C_{stocks} ($Mg.ha^{-1}$)	103	50.6	23.3	11.2	142.6
ΔC_{abs} ($Mg.ha^{-1}$)	103	6.7	22.1	−32.8	97.4
ΔC_{rel} (%)	103	15.0	45.0	−6.0	141.0

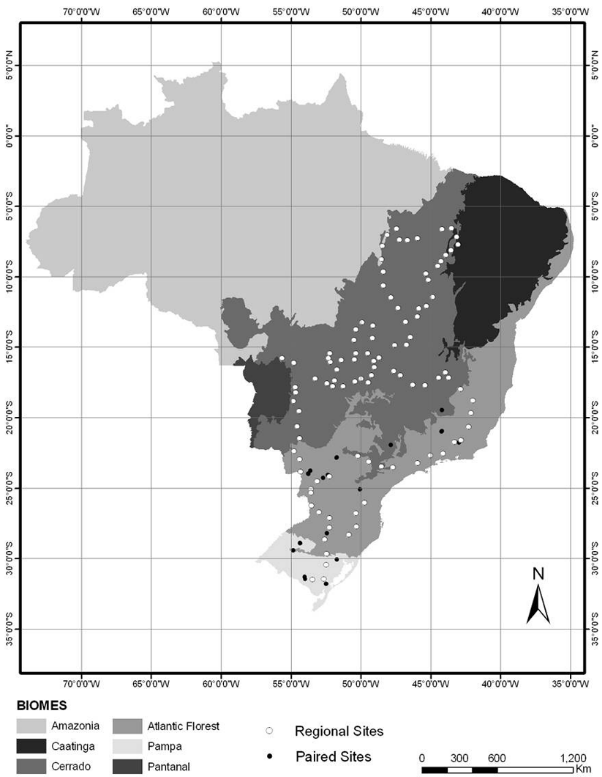

Fig. 1. Sampling sites distributed throughout Brazil. Open circles indicate pasture sites of the regional survey, closed circles indicate paired study sites, and gray shadows, Brazilian biomes.

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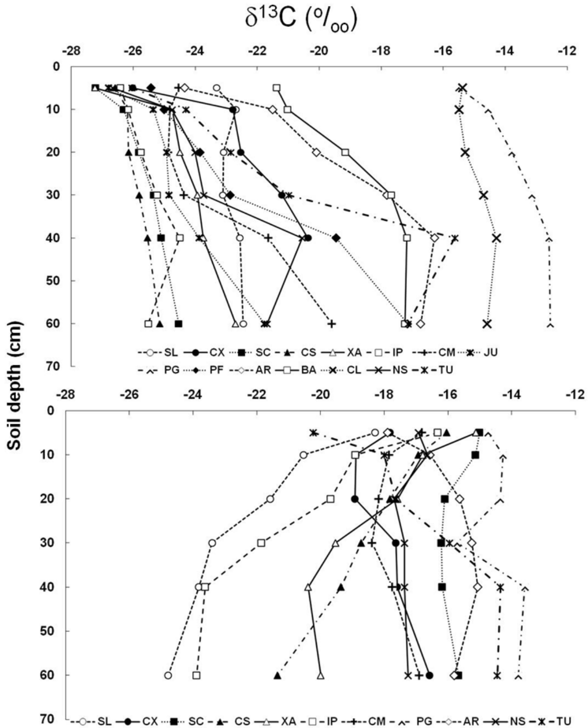

Fig. 2. Variability of $\delta^{13}C$ of soil organic matter with soil depth of native forests (upper panel) and pastures of the paired study-sites (lower panel). Legends are latitudes of sampling sites.

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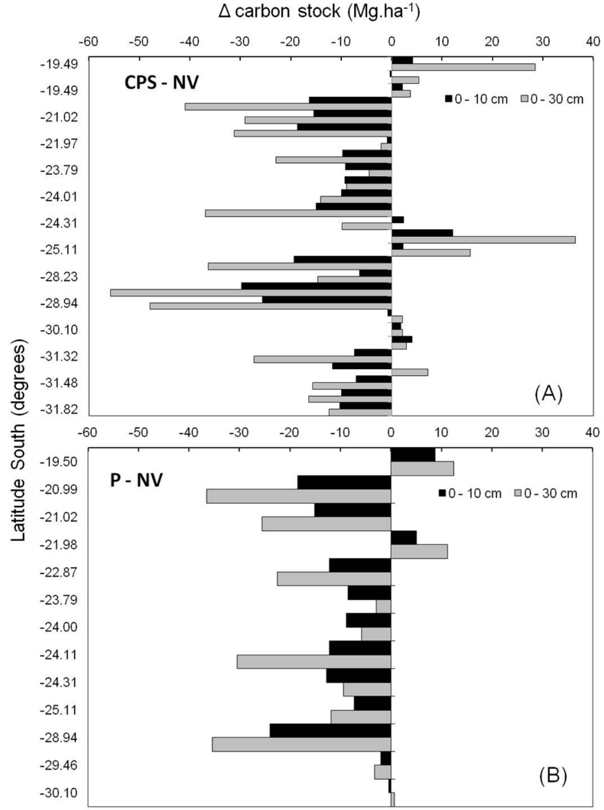

Fig. 3. Absolute difference of carbon soil stocks between: **(A)** crop-livestock systems (CPS) and native vegetation (NV); and **(B)** pasture (*P*) and native vegetation (NV) at different paired study sites. Losses are indicated by a minus sign (–).

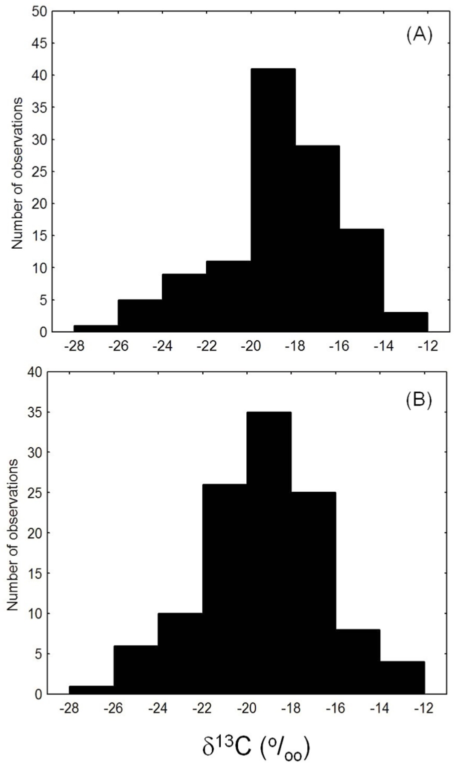

Fig. 4. Histograms of **(A)** the δ^{13}C of soil organic matter in the pasture sites at 0–10 cm depth interval and **(B)** at 0–0 cm depth interval.

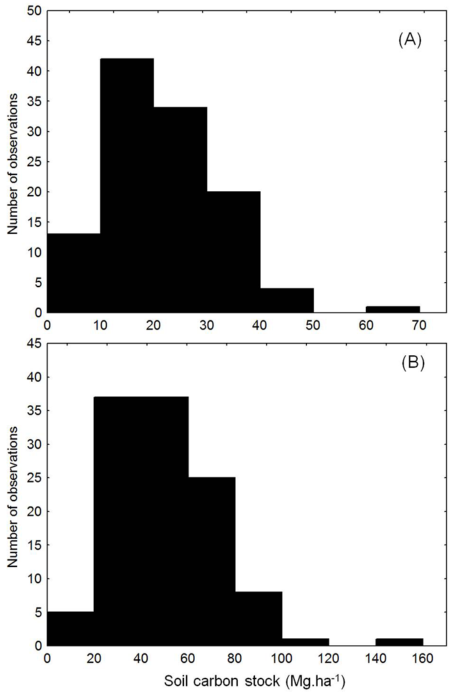

Fig. 5. Histograms of **(A)** soil carbon stock in the pasture sites at 0–10 cm depth interval and **(B)** at 0–30 cm depth interval.

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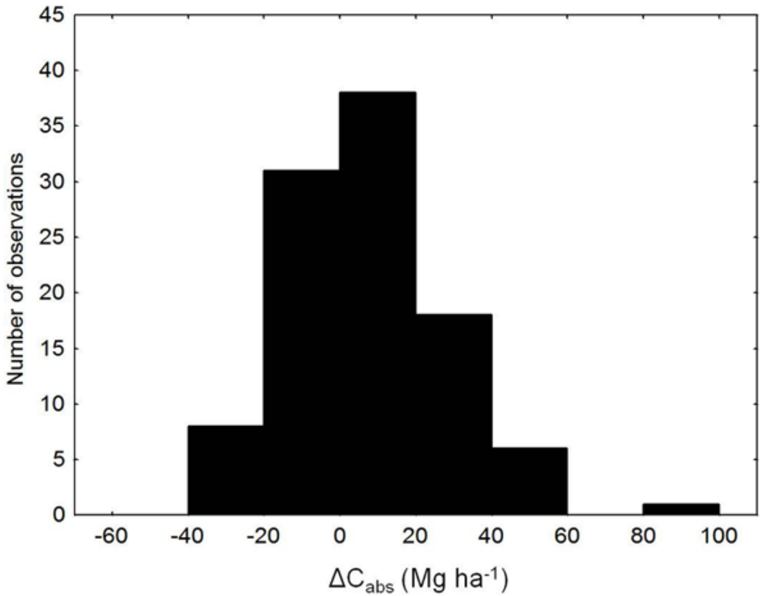

Fig. 6. Histograms of differences in carbon soil stocks between pasture soils and the carbon soil stock of native vegetation (ΔC_{abs}) obtained by Bernoux et al. (2002).

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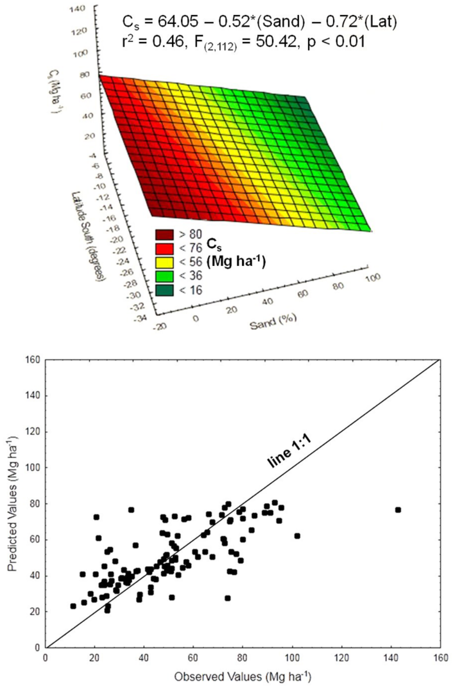

Fig. 7. Upper panel: tri-dimensional plot of soil carbon stocks at 0–30 cm in pasture soils in relation to mean annual temperature (MAT), and sand content (%) according to Eq. (5). Lower panel: Scatter plot of observed soil carbon stocks at 0–30 cm in pasture soils compared to predicted soil carbon stocks by Eq. (5).

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