Changes in soil carbon, nitrogen, and phosphorus due to land-use changes in Brazil

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Abstract

In this paper soil carbon, nitrogen and phosphorus concentrations and related elemental ratios, as well as nitrogen and phosphorus stocks were investigated in 17 paired sites and in a regional survey encompassing more than 100 pasture soils in the Cerrado, Atlantic Forest, and Pampa, three important biomes of Brazil. In the paired sites, elemental soil concentrations and stocks were determined in native vegetation, pastures and crop-livestock systems (CPS). Overall, there were significant differences in soil element concentrations and ratios between different land uses, especially in the surface soil layers. Carbon and nitrogen contents were lower, while phosphorus contents were higher in the pasture and CPS soils than in forest soils. Additionally, soil stoichiometry has changed with changes in land use. The soil C:N ratio was lower in the forest than in the pasture and CPS soils; and the carbon and nitrogen to available phosphorus ratio (P_{ME}) decreased from the forest to the pasture to the CPS soils. The average native vegetation soil nitrogen stocks at 0-10, 0-30 and 0-60 cm soil depth layers were equal to approximately 2.3, 5.2, 7.3 Mg ha^{-1}, respectively. In the paired sites, nitrogen loss in the CPS systems and pasture soils were similar and equal to 0.6, 1.3 and 1.5 Mg ha^{-1} at 0-10, 0-30 and 0-60 cm soil depths, respectively. In the regional pasture soil survey, nitrogen soil stocks at 0-10 and 0-30 soil layers were equal to 1.6 and 3.9 Mg ha^{-1}, respectively, and lower than the stocks found in the native vegetation of paired sites. On the other hand, the soil phosphorus stocks were higher in the CPS and pasture of the paired sites than in the soil of the original vegetation. The original vegetation soil phosphorus stocks were equal to 11, 22, and 43 kg ha^{-1} in the three soil depths, respectively. The soil phosphorus stocks increased in the CPS systems to 30, 50, and 63 kg ha^{-1}, respectively, and in the pasture pair sites to 22, 47, and 68 kg ha^{-1}, respectively. In the regional pasture survey, the soil phosphorus stocks were lower than in the native vegetation, and equal to 9 and 15 kg ha^{-1} at 0-10 and 0-30 depth layer. The findings of this paper illustrate that land-use changes that are currently common in Brazil alter soil concentrations, stocks and elemental ratios of carbon, nitrogen and phosphorus. These changes could have an impact on the subsequent vegetation, decreasing soil carbon, increasing nitrogen limitation, but alleviating soil phosphorus deficiency.

1. Introduction

The demand for food will continue to grow in order to feed a population that will reach near 9 billion people worldwide in 2050 (Tilman et al., 2011). Brazil is one of the pivotal countries that will have a key role in the global food production system (Martinelli et al., 2010). There is already a consensus that an increase in food production cannot be achieved by replacing native vegetation with agricultural fields (Tilman et al., 2011). One of the alternatives that has been proposed is agricultural intensification, which not only means an increase in productivity but also an attempt to increase sustainability (Godfray et al., 2010). Sustainable agriculture (SA) has been proposed as one way to achieve both goals. The SA tries to mimic natural ecosystems by adding layers of complexity in an attempt to depart from simplistic monoculture fields (Keating et al., 2010). Crop livestock systems (CPS) are a suitable example of this attempt to add a layer of complexity to agricultural fields. Integrated crop-livestock or crop-livestock-forest, and agroforestry systems (CPS) are not a new idea. However, these systems have only been consolidated in recent decades (Machado et al., 2011). The system consists of diversifying and integrating crops, livestock and forestry systems, within the same area, in intercropping, in succession or rotation. The system can provide environmental benefits such as soil conservation, building up soil carbon, reducing environmental externalities and ultimately increasing productivity. CPSs include but are not restricted to the following: no till, the use of cover crops, elimination of agricultural fires (slash-and-burn), and restoration of vast areas of degraded pastures (Machado et al., 2011; Bustamante et al., 2012; Lapola et al., 2014). Additionally, the Brazilian law (Law no. 12187 of December 29, 2009) encourages the adoption of good agricultural practices to promote low carbon emission (Low Carbon Emission Program – ABC Program) and stipulates that mitigation should be conducted by adopting: (i) recovery of degraded pastures, (ii) a no-tillage system, (iii) integrated livestock-crop-forest systems, and (iv) re-forestation, in order to reduce approximately 35% to 40% of Brazil’s projected greenhouse gas emissions by 2020 (Assad et al, 2013).

These integrated agricultural systems have been positively evaluated in several ways. For example, it seems that carbon gain with cultivation seems to be faster and higher when agricultural practices like no till, green manure, crop rotation and crop-livestock systems are adopted (Sá et al., 2001; Ogle et al., 2005; Zinn et al. 2005; Bayer et al., 2006; Baker et al., 2007).

On the other hand, there are few regional studies considering how nitrogen and phosphorus soil contents will be affected in these integrated agricultural systems. Plot-level studies have reported a decrease in soil nitrogen stocks with cultivation in several N-fertilized areas of Brazil and under different cropping systems (Lima et al., 2011; Fracetto et al., 2012; Barros et al., 2013; Sacramento et al., 2013; Cardoso et al., 2010; Silva et al., 2011; Guareschi et al., 2012; Sisti et al., 2004; Santana et al., 2013; Sá et al. 2013). The same trend has been observed in Chernozen soils in Russia and in prairie soils of Wisconsin in the US (Mikhailova et al., 2000; Kucharik et al., 2001).

In unfertilized pasture soils of Brazil, nitrogen availability decreased as the age of pastures increased. In theses soils, there was an inversion in relation to forest soils, and an ammonium dominance over nitrate was observed, followed by lower mineralization and nitrification rates that in turn were followed by lower emissions of N_2O (Davidson et al., 2000; Erickson et al., 2001; Wick et al., 2005; Neill et al., 2005; Cerri et al., 2006; Carmo et al., 2012).

Therefore, it seems that receiving N-fertilizer inputs or not, agro-ecosystem nitrogen losses via leaching, gaseous forms, and harvesting exports are higher than N-inputs resulting in decreased soil nitrogen stocks.

Phosphorus is particularly important in the tropics due to phosphorus adsorption on oxides and clay minerals rendering them unavailable to plants (Uehara and Gillman, 1981; Sanchez et al., 1982; Oberson et al. 2001; Numata et al., 2007; Gama-Rodriguez et al., 2014). This widespread lack of available phosphorus in tropical soils also affects crops, consequently there is a rich body of literature on phosphorus dynamics in tropical soils and how land-use changes result in different phosphorus fractions (e.g. Garcia-Montiel et al., 2000; Oberson et al., 2001; Townsend et al., 2002; Numata et al., 2007; Pavinatto et al., 2009; Fonte et al., 2014; Fujii, 2014), but there have been considerably fewer studies on changes in soil stocks of phosphorus with cultivation.

The P-adsorption by the clay fraction in tropical soils (Oberson et al., 2001), as well as the fact that phosphorus does not have a gaseous phase like nitrogen, renders phosphorous less mobile in the soil-plant-atmosphere system than nitrogen (Walker and Syers, 1976). One consequence of this lower phosphorus mobility throughout the soil profile is that when P-fertilizers are applied, they tend to increase soil phosphorus concentration on the soil surface, but also make phosphorus available by loss through the soil erosion process and surface runoff (Messiga et al., 2013). The use of agricultural practices like no-till may further increases phosphorus concentration in the surface soil due to the non-movement of the soil layer (Pavinatto et al., 2009; Messiga et al., 2010; 2013). Soil phosphorus is also affected by physical characteristics of the soil, such as how the size of soil aggregates influences the extent of soil phosphorus availability to plants (Fonte et al., 2014). Therefore, agricultural practices have the potential to alter soil phosphorus concentration and consequently soil phosphorus stocks (Tiessen et al., 1982; Tiessen and Stewart, 1983; Ball-Coelho et al., 1993; Aguiar et al., 2013).

Besides concentrations and stocks, agricultural management are also capable of altering the ratios between carbon, nitrogen and phosphorus (C:N:P) (Tiessen et al., 1982; Tiessen and Stewart, 1983; Ding et al., 2013; Jiao et al., 2013; Schrumpf et al., 2014; Tischer et al., 2014). For instance, soil microorganisms adjusting their stoichiometry with that of the substrate may release or immobilize nitrogen depending on the substrate C:N ratio (Walker and Adams, 1958; Mooshammer et al., 2014a). In turn, litter decomposition also depends on the stoichiometry of the litter, especially on the C:N ratios (Hättenschwiler et al., 2011). These adjustments guided by C:N:P ratios may ultimately interfere in crop production, that in turn will affect soil carbon sequestration, and, consequently, agro-ecosystems responses to climate change (Hessen et al., 2004; Cleveland and Liptzin, 2007; Allison et al., 2010).

Agricultural land in Brazil has increased dramatically over recent decades and part of this increase contributed to increase deforestation rates in all major Brazilian biomes (Lapola et al., 2014). Particularly important in Brazilian agriculture is the area covered with pasture that includes approximately 200 million hectares encompassing degraded areas with well-managed pasture (Martinelli et al., 2010). Arable land comprises almost 70 million hectares, with approximately 30 million hectare under no-till cultivation (Boddey et al., 2010), with crop-livestock systems being especially important in the southern region of the country.

Most studies in Brazil on the effects of agricultural practices on soil properties deal with soil carbon stocks due to its importance for a low-carbon agriculture (Sá et al., 2001; Bayer et al., 2006; Marchão et al., 2009; Maia et al., 2009; Braz et al., 2012; Assad et al, 2013; Mello et al., 2014). On the other hand, there are fewer studies on agricultural practices affecting soil nitrogen concentration, and especially stocks, and even fewer studies on changes in soil phosphorus stocks. Based on this, this paper aims to investigate effects of agricultural practices on carbon concentration, and nitrogen and phosphorus soil concentration and stocks, and on the soil stoichiometry (C:N:P ratio) in several Brazilian regions, using the same study sites and methodology used by Assad et al. (2013) who evaluated changes in soil carbon stocks due to different land uses. Two sampling approaches were used in Assad et al. (2013), one, at the plot level, addressed 17 paired sites comparing soil stocks among native vegetation, pasture and crop-livestock systems, and the second was a regional survey of pasture soils in more than 100 sites.

2. Material and Methods

2.1 Study area

A full description of the study area can be found in Assad et al. (2013). Briefly, we conducted two types of surveys: one at the regional level, exclusively in pasture soils, and a second, in which seventeen paired sites were sampled encompassing soils of pastures, crop-livestock systems (CPS) and native vegetation. The regional pasture survey was conducted in November and December of 2010, and 115 pastures located between 6.58°S and 31.53°S were selected based first on satellite images in an attempt to broadly encompass three major Brazilian biomes: Cerrado, Atlantic Forest and Pampa, and, secondly, sites were also selected based on their ability to be accessed by roads (Figure 1). A bias in this scheme is that sampling sites were not randomly selected. A second bias is that, although all pastures were in use at the time they were sampled, it was difficult to visually assess their grazing conditions or stocking rates, which may affect the soil nutrient stocks (Maia et al., 2009; Braz et al. 2012; Assad et al., 2013).

Paired sites were selected by the EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária) regional offices and sampled between November and December 2011. In these sites, there was an attempt to sample areas of native vegetation, pasture and sites that encompass crop rotation integrated with livestock (CPS). A detailed description of crop rotation and sites that combine crops and livestock management is shown in Table 1. Native vegetation is composed of wood vegetation either in the Atlantic Forest and Cerrado biomes. In sites located in the southern region of the country (Arroio dos Ratos, Tuparecetã, Bagé, and Capão do Leão) the original vegetation is grassy temperate savanna locally referred to as *Campos*, which belongs to the Pampas biome (Table 1). For the sake of simplicity, forests and *Campos* soils were grouped under the category named "original vegetation". Pasture was composed mostly of C_4 grass species of the genus *Urochloa* (ex-*Brachiaria*); exceptions were in sites located in the southern region of the country where a C_3 grass (*Lolium perenne*) was cultivated. In Brazil, land-use history is always difficult to obtain with accuracy, but Assad et al. (2013) using $\delta^{13}C$ values of soil organic matter showed that most pastures have been in this condition for a long time, and most of the native vegetation seems to have been in this state also for a long time.

2.2 Precipitation and temperature

The precipitation and temperatures were obtained using the Prediction of Worldwide Energy Resource (POWER) Project (http://power.larc.nasa.gov).

2.3 Sample collection and analysis

Soil sampling is described in detail in Assad et al. (2013). Briefly, in each site, a trench of 60 cm by 60 cm, yielding an area of approximately 360 cm^2 was excavated. For the regional pasture survey, the depth of the trench was approximately 30 cm, and in the paired sites, the depth was approximately 60 cm. Trenches were excavated according to interval depth samples for bulk density were collected first, and after this approximately 500 g of soil was collected for chemical analysis. Bulk soil density was determined by using a metal ring (core) pressed into the soil, and determining the weight after drying. Due to the high number of sampling sites and interval depths, only one soil sample for bulk density was collected by soil depth. In order to access the soil bulk density data, see Assad et al. (2013).

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

The concentration of soil nitrogen and carbon, which may also include fine charcoal, was determined by using the elemental analyzer at the Laboratory of Isotopic Ecology Center for Nuclear Energy in Agriculture, University of São Paulo (CENA-USP) in Piracicaba, Brazil.

Phosphorus concentration was determined by extracting soil phosphorus using the Mehlich-3 method of extraction (Mehlich, 1984), and phosphorus concentration was quantified by the colorimetric blue method. Accordingly, the C:P and N:P ratios shown here did not use organic phosphorus (Po) concentration as usual (e.g. Walker and Adams, 1958; McGill and Cole, 1981; Stewart and Tiessen, 1987) or total phosphorus (P_T) like used by Cleveland and Liptzin (2007), and Tian et al. (2010), but Mehlich phosphorus concentration (P_{ME}), which is a mixture of inorganic and organic phosphorus fractions that are at least theoretically more available to plants (Gatiboni et al., 2005). As this is less common, because most paper presents C:Po or C:P_T ratios; the use of P_{ME} makes difficult comparison with results obtained elsewhere; this fact constrains the use of C:P_{ME} or N: P_{ME} ratios only useful for an inter comparison between our study sites. On the other hand, the use of such ratios could induce a more widespread use of them, since P_{ME} determination is much less laborious than the determination of Po by the sequential extraction proposed by Hedley et al. (1982).

2.4 Soil nitrogen and phosphorus stocks

Carbon stocks were reported in Assad et al. (2013). In this paper, besides carbon concentrations, nitrogen stocks expressed in Mg ha^{-1} and phosphorus stocks expressed in kg ha^{-1} were calculated for the soil depth intervals 0 - 10 cm, 0 - 30 cm, and 0 - 60 cm for the paired sites and 0 - 10 cm, and 0 - 30 cm for the pasture regional survey by sum stocks obtained in each sampling intervals (0 - 5, 5 - 10, 10 - 20, 20 - 30, 30 - 40, 40 - 60 cm). Soil nitrogen and phosphorus stocks were estimated based on a fixed mass in order to correct differences caused by land-use changes in soil density (Wendt and Hauser, 2013) using the methodology proposed by Ellert et al. (2008), for details of this correction see Assad et al. (2013).

The cumulative soil nitrogen and phosphorus stocks for fixed depths were calculated by the following equations:

$$S = [X] . \rho . z$$

where S is the cumulative soil nitrogen or phosphorus stock for fixed depths in the soil mass < 2 mm in gram per gram of soil, and [X] is the soil nitrogen or phosphorus concentration at the designated depth (z), and ρ is the bulk soil density.

For the paired sites, changes in nutrient stocks between current land use and native vegetation were obtained by comparing differences between the two stocks. The absolute difference (ΔN_{abs} or ΔP_{abs}) was expressed in Mg ha^{-1} for nitrogen or kg ha^{-1} for phosphorus and the relative difference compared to the native vegetation was expressed in percentage (ΔN_{rel} or ΔP_{rel}).

2.5 Statistical analysis

In order to test for differences in element concentrations and their respective ratios, we grouped element contents by land use (forest, pasture, CPS) and soil depth (0-5 cm, 5-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-60 cm). Carbon, nitrogen and phosphorus concentration, and soil nitrogen and phosphorus stocks must be transformed using Box-Cox techniques because they did not follow a normal distribution. Accordingly, statistical tests were performed using transformed values, but non-transformed values were used to report average values. The element ratio was expressed as molar ratios and ratios followed a normal distribution and were not transformed.

For the paired sites, differences between land uses (native vegetation, CPS and pasture) were tested with ANCOVA, with the dependent variables being transformed nutrient concentrations at the soil depth intervals described above, and stocks at the soil layers of 0 - 10 cm, 0 - 30 cm, and 0 - 60 cm; the independent variables were land-use type. As mean annual temperature (MAT), mean annual precipitation (MAP), and soil texture may influence soil nutrient concentration, ratios, and stocks, these variables were also included in the model as co-variables. The *post-hoc* Tukey Honest Test for unequal variance was used to test for differences among nutrient stocks of different land uses. In order to determine whether changes in soil nutrient stocks between current land use and native vegetation were statistically significant, we used a one-sample t-test, where the null hypothesis was that the population mean was equal to zero.

All tests were reported as significant at a level of 10%. Statistical tests were performed using a STATISTICA12 package.

3. Results

3.1 Paired study sites

3.1.1. Soil carbon, nitrogen, and phosphorus concentrations and related ratios

Carbon, nitrogen, and phosphorus concentrations decreased with soil depth (Figure 2). The average carbon concentration was higher in the topsoil (0-5 and 5-10 cm) of native vegetation soils compared with pasture and CPS soils ($p = 0.05$). However, in deeper soil layers, there was no statistically significant difference between native vegetation, pasture and CPS soils (Figure 2a). The average soil nitrogen concentration followed the same pattern as carbon (Figure 2b). However, differences between forest, and pasture and CPS soils were significant down to the 10-20 cm soil layer. The P_{ME} concentrations in the soil profiles showed a different pattern than carbon and nitrogen. P_{ME} were higher in the CPS and pasture soils than in forest soils in the topsoil and also in the soil depth layer of 10-20 cm (Figure 2c). The C:N ratios of pasture and CPS soils were higher than the native vegetation soils in all soil depths; however, this difference was not statistically significant for any particular depth (Figure 3a). There was a difference in the $C:P_{ME}$ ratio between forest, pasture and CPS soils, this ratio was higher in the forest soils, intermediate in the pasture, and lower in the CPS soils (Figure 3b). Due to the wide variability of the data, differences were only significant in the first three soil depth intervals: 0-5 cm ($p < 0.01$); 5-10 cm ($p < 0.01$); and 10-20 cm ($p = 0.03$). Finally, the $N:P_{ME}$ showed a similar trend than $C:P_{ME}$, with higher ratios in native vegetation soils, decreasing in the pasture and reaching the lowest values in the CPS soils (Figure 3c). Again, values were only different at the same soil depth intervals observed for $C:P_{ME}$, with all of them at a probability ratio lower than 0.01.

3.1.2. Soil nitrogen and phosphorus stocks

The average nitrogen stock of the native vegetation soils in the topsoil was 2.27 Mg ha^{-1} decreasing significantly to 1.72 Mg ha^{-1} in the CPS ($p = 0.05$) and to 1.54 Mg ha^{-1} in pasture soils ($p < 0.01$) (Table 2). In the next soil layer (0 - 30 cm), the same tendency was observed. The average nitrogen stock was equal to 5.12 Mg ha^{-1}, decreasing significantly to 3.94 Mg ha^{-1} in the CPS ($p = 0.04$), and to 3.84 Mg ha^{-1} in pasture soils ($p = 0.03$) (Table 2). On the other hand, differences in soil nitrogen stocks among different land uses were not significant at the 0 – 60 cm of the soil layer; the nitrogen soil stock was 7.30 Mg ha^{-1} in the native vegetation, and 5.93 Mg ha^{-1} and 6.16 Mg ha^{-1} in the CPS and pasture soils, respectively (Table 2).

In general, there was a net loss of nitrogen stocks between native vegetation and current land uses in the soil (Table 2). In the forest-CPS pairs for the topsoil the $\Delta N_{abs} = -0.64$ Mg ha^{-1}, and a $\Delta N_{rel} = -22\%$, both differences were significant at 1% level (Table 2). The same pattern was observed for the 0 – 30 cm soil interval, where $\Delta N_{abs} = -1.28$ Mg ha^{-1}, and the $\Delta N_{rel} = -20\%$ (Table 2). In the forest-pasture paired sites, the $\Delta N_{abs} = -0.63$ Mg ha^{-1}, and the $\Delta N_{rel} = -28\%$ found in the topsoil were both statistically significant at 1% (Table 2). The same was true for the 0 – 30 cm soil layer, where the $\Delta N_{abs} = -1.10$ Mg ha^{-1}, which was equivalent to a loss of -22‰ (Table 2).

On the other hand, a net gain of phosphorus was observed between native vegetation and current land uses in the soil. The phosphorus soil stock in the topsoil of native vegetation areas was equal to 11.27 kg ha^{-1}, increasing significantly to 30.06 kg ha^{-1} ($p < 0.01$) in the CPS soil and to 21.6 kg ha_{-1} ($p < 0.01$) in the pasture soils (Table 3). Considering the 0 – 30 cm soil layer, the phosphorus stock in the native vegetation soils was 21.74 kg ha^{-1}, also significantly increasing in the CPS soils to 49.50 kg ha^{-1} ($p = 0.02$), and to 47.60 kg ha^{-1} in the pasture soils (Table 3). Finally, in the 0 – 60 cm soil layer, the phosphorus stock in the native vegetation soils was 42.70 kg ha^{-1}, which was not significantly lower than the phosphorus soil stock in the CPS soils, which was equal to 62.90 kg ha^{-1}. On the other hand, the soil phosphorus stock in the pasture soils was 68.33 kg ha^{-1}, which is significantly different ($p = 0.02$) than the soil phosphorus stock of the native vegetation soils (Table 3).

In relative terms, in the topsoil, for the native vegetation-CPS paired sites an overall phosphorus gain was observed, the $\Delta P_{abs} = 20.56$ kg ha^{-1}, and the $\Delta P_{rel} = 325\%$, both significant at 1% level (Table 3). The same pattern was observed at the 0 – 30 cm soil layer, where the $\Delta P_{abs} = 27.03$ kg

ha^{-1}, and the ΔP_{rel} = 205%, and at the 0 – 60 cm soil layer, where the ΔP_{abs} = 25.64 kg ha^{-1}, and the ΔP_{rel} = 145% (Table 3). In the native vegetation-pasture pair sites, the same increase in phosphorus stocks was also observed in the pasture soils. In the topsoil, the ΔP_{abs} = 10.06 kg ha^{-1} ($p < 0.01$), and the ΔP_{rel} = 52% ($p < 0.01$) were statistically significant (Table 3). The same was true for the 0 – 30 cm soil layer, in this case the ΔP_{abs} = 25.70 kg ha^{-1} ($p < 0.01$) and the ΔP_{rel} = 220% ($p < 0.01$); and for the 0 – 60 cm soil layer, where the ΔP_{abs} = 25.42 kg ha^{-1} ($p < 0.01$), and the ΔP_{rel} = 172% ($p < 0.01$) (Table 3).

3.2 Regional survey of pasture soils

3.2.1. Soil carbon, nitrogen, and phosphorus concentrations and related ratios

We compared element concentrations and ratios of the regional survey pasture soils with the native vegetation soil site of the paired sites (Figures 2 and 3). Carbon, nitrogen and phosphorus concentrations decreased with soil depth, and were significantly lower ($p < 0.01$) in the pasture soils than in the native vegetation soils (Figure 2). The C:N ratio of the regional pasture survey was higher than the native vegetation soil (Figure 3). The $C:P_{ME}$ and $N:P_{ME}$ ratios were much higher in the pasture soils of the regional survey compared with forest soils, and in these cases, there was a sharp increase with soil depth (Figure 3).

3.2.2. Soil nitrogen and phosphorus stocks

At the 0 - 10 cm soil layer the average total soil nitrogen stock was equal to 1.66±0.87 Mg ha^{-1} (Table 4), and at 0 – 30 cm the average soil stock was 3.91±1.90 Mg ha^{-1}. At the 0 – 10 cm and 0 – 30 cm soil layers, the average phosphorus stock was 8.50 kg ha^{-1}, and 14.71 kg ha^{-1}, respectively (Table 4). The average nitrogen stock in the pasture soils of the regional survey at both depth layers (0 -1 0 cm and 0 – 30 cm) was very similar to the stocks found in the pasture and CPS of the paired sites survey, and, therefore, also lower than the soil stocks found in the native vegetation areas (Table 4). On the other hand, the average phosphorus stock in the pasture soils of the regional survey was much lower than the soil stocks of pasture and CPS of the pair-site surveys, being even smaller than the soil stocks of native vegetation areas (Table 4).

4. Discussion

4.1. Sources of uncertainty

Due to time and financial constraints, we were unable to sample soil from native vegetation near each pasture site in the regional survey. This poses a challenge because it is important to compare changes in the soil nitrogen and phosphorus stocks with the native vegetation as done in the paired study sites. In order to overcome the lack of original nutrient soil stocks, we used estimates of native vegetation obtained in the paired sites. Another difficulty is the lack of reliable information on the land-use history; we cannot guarantee that differences among land uses already existed or were due to the replacement of the native vegetation (Braz et al., 2012; Assad et al., 2013). In addition, we only have a point-in-time measurement; we did not follow temporal changes in nitrogen and phosphorus soil stocks. Therefore, it is not possible to know if the soil organic matter achieved a new steady-state equilibrium; as a consequence our results should be interpreted with caution (Sanderman and Baldock, 2010).

4.2. C:N:P_{ME} soil stoichiometry

Overall, the C:N ratio was lower in the native vegetation soils compared with pasture and CPS soils (Figure 3a); however, such differences were only statistically significant at the soil surface. These differences are probably explained by a nitrogen loss and not a carbon gain, since soil carbon stocks in pasture and CPS soils were lower than in native vegetation soils (Assad et al., 2013). The reasons for preferential nitrogen loss in these systems in relation to the forest soil are discussed in the next section.

Different soil C:N ratios as observed in the native vegetation, could influence nitrogen dynamics, favoring faster organic matter decomposition and nitrogen mineralization in native vegetation soils due to lower soil C:N ratios (Mooshammer et al., 2014b). However, it is difficult to conclude whether a small difference between native vegetation soils and the others would be enough to trigger such changes. According to Mooshammer et al. (2014a), the threshold value of the C:N ratio required to change the status of nitrogen to be mineralized or immobilized by the soil biota is around 20. Soil C:N ratios, even in the pasture and CPS soils are well below this value (Figure 3a).

Another important trend was the lower depth variability of C:N ratios compared with the concentrations of carbon and nitrogen with depth (Figure 2a and 2b). This trend is consistent with the initial hypothesis of Tian et al. (2010) who hypothesized that the C:N ratio would not vary with depth because of the coupling of carbon and nitrogen in the soil. According to Tischer et al. (2014) such constancy is a consequence of similar inputs of organic matter by primary producers to the soils, and also due to the fact that N immobilization or mineralization as the organic matter (carbon) to which N is linked is converted in CO_2 by heterotroph microbial soil population (McGill et al., 1975; McGill and Cole, 1981).

Among different land uses, the elements: P_{ME} were also distinct (Figure 3b and 3c). As the carbon concentration and stock decreased in pasture and CPS soils compared to native vegetation soils (Assad et al., 2013), it is likely that the C:P_{ME} decreased in the pasture soils and in the CPS soils due to a combination of C loss with an increase in P_{ME} caused by the use of P-fertilizers (Figure 2c). The same trend was observed with N:P_{ME}, and probable is also a combination of N loss and P enrichment in pasture and CPS soils compared with native vegetation soils.

As P_{ME} generally decreases with soil depth (Figure 2c), we expected an increase of C: P_{ME} and N: P_{ME} with depth. Such increase was particularly observed between 5 to 10 cm depth; after that depth, ratios were approximately constant, decreasing between 40 to 60 cm (Figure 3b and 3c). One reason for this decrease in the deepest soil layer could be the contribution of inorganic P through weathering (Tian et al., 2010), as attested to by an increase of P_{ME} in the deepest soil layer in soils under native vegetation (Figure 2c). Another possibility in agricultural soils is that cultivation itself can promote mobilization of this phosphate fraction by addition of phosphorus fertilization and changes in soil physical properties by cultivation itself or by grazing (see discussion below, Conte et al., 2002; Costa et al., 2014; Fonte et al., 2014).

4.3. Land-use changes alter nitrogen and phosphorus stocks

In most of the plot-level paired sites and in most of the regional soil survey, we found a loss of nitrogen compared to the native vegetation. It seems that this is a common pattern observed for different crops and different types of land management in several regions of Brazil; like in the Northeast (Lima et al., 2011; Fracetto et al., 2012; Barros et al., 2013; Sacramento et al., 2013); in Central Brazil (Cardoso et al., 2010; Silva et al., 2011; Guareschi et al., 2012) and in the South (Sisti et al., 2004; Sá et al., 2013; Santana et al., 2013). Sá et al. (2013) found lower soil nitrogen stocks in several farms located in southern Brazil (Paraná State) that have adopted no-till and crop rotation systems for at least ten years compared with the native vegetation of the region. On the other hand, the adoption of no-till systems tends to increase soil nitrogen stocks compared to conventional tillage (Sisti et al., 2004; Sá et al., 2013). In this respect, it is interesting to note that the only three sites (SL, PG, AP) where the soil nitrogen stocks were higher in the agriculture field than in the native vegetation, were CPS sites, where no-till was practiced and there was a system of crop rotation, with soybean in the summer, and oat or wheat in the winter (Table 1).

We found a positive and significant ($p < 0.01$) correlation between soil carbon stock losses found by Assad et al. (2013) and the soil nitrogen stock losses found in this study. Such correlations were especially significant in the CPS systems, where more than 70% of the variance in the nitrogen losses were explained by carbon losses (Figures 4 and 5). These correlations are an indication that whatever mechanisms are leading to such losses, they are simultaneously affecting carbon and nitrogen (McGill et al., 1975). There are several studies at the plot level showing that changes in soil properties is one of the leading causes affecting losses of organic matter with soil cultivation (e.g. Mikhailova et al., 2000; Kucharik et al., 2001). In addition, findings of several regional and global surveys also pointed in the same direction (e.g. Davidson and Ackerman, 1993; Amundson 2001; Guo and Gifford, 2002; Zinn et al., 2005; Ogle et al., 2005; Don et al., 2011; Eclesia et al. 2012). It seems that a combination of decreasing organic matter inputs, in cases where crops replaced native forests, with an increase in soil organic matter decomposition leads to a decrease in the long run. This decrease seems to especially be fostered in annual crops by exposing bare soil between harvests, leading to higher temperatures (Baker et al., 2007; Coutinho et al., 2010; Salimon et al., 2004), which in turn leads to higher decomposition rates (e.g. Davidson and Janssens, 2006; Dorrepaal et al., 2009). For instance, Carmo et al. (2012) found higher soil temperature and high CO_2 emissions in pasture soil compared with the forest soil nearby, with both sites located in the southeast region of Brazil (State of São Paulo).

Nitrogen dynamics is regulated by a balance between inputs, losses and transformations between different forms of nitrogen (Drinkwater et al, 2000). Generally, land-use changes tend to disrupt the nitrogen cycle of the native vegetation. The main natural nitrogen input is via biological nitrogen fixation (BNF), and the main anthropogenic addition is via N-mineral fertilizer inputs. In tropical forests, BNF is considered one of the main inputs of nitrogen (Vitousek et al., 2002). In crops like soybean, BNF is also important as a source of new nitrogen to the system, especially in Brazil where soybean may fix higher amounts of nitrogen (Alves et al., 2003). Several of the CPS systems evaluated in this study involve the use of soybean under crop rotation systems (Table 1). However, decreases of soil nitrogen stocks of these CPS were observed, compared with soils of the native vegetation (Figures 6a and 6b). The same was observed by Boddey et al. (2010) comparing soil carbon and nitrogen stocks of no-till and conventional tillage systems involving a crop rotation with soybean in farms located in the State of Rio Grande do Sul (southern Brazil). According to these authors, the nitrogen export by grain harvesting is high enough to prevent a build-up of this nutrient in the soil (Boddey et al., 2010).

Most pastures in Brazil are not fertilized, so over time, a decrease in nitrogen inputs coupled with an increase of nitrogen outputs is generally observed, leading to lower mineralization and nitrification rates (Verchot et al., 1999; Melillo et al., 2002 Garcia-Montiel et al., 2000; Wick al., 2005; Neill et al., 2005; Carmo et al., 2012). According to Boddey et al. (2004), not even the return of nitrogen to soil pasture via urine and dung is sufficient to compensate for other nitrogen losses. As a consequence the continuous use of unfertilized pastures leads to overall N-impoverishment in the system, leading to lower soil nitrogen stocks, as observed in this study.

On the other hand, we observed a general increase in soil phosphorus stocks of pasture and CPS-paired sites compared with soil stocks of the native vegetation (Figures 7a and 7b). The higher soil phosphorus stocks in the CPS could be explained by the addition of phosphorus fertilizer to the fields (Aguiar et al. 2013; Messsiga et al., 2013; Costa et al., 2014). Generally, an increase of soil phosphorus is observed after use of P-fertilizers in the topsoil due to the low mobility of phosphorus, especially in no-till systems (Costa et al., 2007; Pavinatto et al., 2009; Messiga et al., 2010). In several of the CPS sites, there are crop rotations between maize, rice and soybean, and all these crops are fertilized with phosphorus, especially soybean, because phosphorus is an important nutrient in the biological nitrogen fixation process (Divito and Sadras, 2014). The variation of phosphorus concentration with soil depth provides indirect support for this hypothesis. In the majority of the CPS sites and even pasture soils of the paired sites there is a gradient in phosphorus concentration with much higher concentrations near the soil surface (Figure 2c).

The soil phosphorus stocks of pastures located in the paired sites were higher than soil phosphorus stocks of the regional pasture survey. For instance, at the 0-10 cm soil layer, the average P_{stock} of pasture soil at the paired sites was equal to 22 $kg.ha^{-1}$ (Table 3), which is significantly higher than the average P_{stock} of pasture soil sampled in the regional level survey (9 $kg.ha^{-1}$, Table 4). This latter average is similar to the average P_{stock} of the native vegetation sampled in the paired study sites, which was equal to 12 $kg.ha^{-1}$ (Table 3). As we mentioned earlier, we do not have accurate information on pasture management and grazing conditions. However, as the pasture-paired sites were located in research stations and well-managed farms, we believe that overall, the pasture in these areas is in better condition compared with pasture included in the regional survey. As already mentioned, in some pasture of the paired sites, a steep decrease in phosphorus content with soil depth was observed, being indirect evidence that these pastures received some kind of phosphorus amendment or lime application that raised the pH and made phosphorus available to plants (Uehara and Gillman, 1981). If this is the case, these differences in pasture management will probably explain differences observed in soil phosphorus stocks between pastures of the paired sites and regional survey. This is because Fonte et al. (2014) found that soils of well-managed pastures located on poor tropical soils had great differences in soil aggregation, which in turn influence the soil phosphorus level, favoring a higher phosphorus content in well-managed pastures compared to degraded pastures. On the other hand, Garcia-Montiel et al. (2000) and Hamer et al. (2013) found an increase in soil phosphorus stocks for several years after the conversion of Amazonian forests to unfertilized pastures. The main cause of this increase seems to be soil fertilization promoted by ash of forest fires, coupled with root decomposition of the original vegetation. However, it seems that with pasture aging, there is a decrease in available phosphorus mainly in strongly weathered tropical soils (Townsend et al., 2002; Numata et al., 2007).

In an earlier paper Assad et al. (2013) have shown a decrease in soil carbon stock in relation to the original vegetation either for pasture and CPS soils. In this paper we found that nitrogen stocks also decrease considerably with land-use changes, even in well managed CPS systems, and especially in pastures of the regional survey that reflect better the reality of pasture management in Brazil. These findings have important policy implications because Brazil recently implemented a program (Low Carbon Agriculture) devoted to increasing carbon and nitrogen concentration in soils by a series of techniques, especially no-till, crop-livestock systems (CPS), and improvement of degraded pastures. Therefore, the findings of this paper set a baseline of soil nutrients stocks and stoichiometry for future comparisons.

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References

Aguiar, A.C.F., Cândido, C.S.C., Carvalho, C.S., Monroe, P.H.M., and Moura, E.G.: Organic matter fraction and pools of phosphorus as indicators of the impact of land use in the Amazonian periphery. **Ecological Indicators** 30, 158–164, 2013.

Allison, S. D., Wallenstein, M. D. and Bradford, M. a.: Soil-carbon response to warming dependent on microbial physiology, **Nat. Geosci.,** 3(5), 336–340, doi:10.1038/ngeo846, 2010.

Alves, B.J.R., Boddey, R.M., and Urquiaga, S.: The success of BNF in soybean in Brazil. **Plant Soil** 252, 1–9, 2003.

Amundson, R.: The Carbon Budget in Soils, **Annual Review of Earth and Planetary Sciences**, 29, 535–562, 2001.

Assad, E. D., Pinto, H. S., Martins, S. C., Groppo, J. D., Salgado, P. R., Evangelista, B., Vasconcellos, E., Sano, E. E., Pavão, E., Luna, R., Camargo, P. B., and Martinelli, L. A.: Changes in soil carbon stocks in Brazil due to land use: paired site comparisons and a regional pasture soil survey, **Biogeosciences**, 10, 6141-6160, 2013.

Baker, J. M., Ochsner T. E., Ventera, R. T., and Giffis, T. J.: Tillage and soil carbon sequestration: What do we really know? **Agriculture, Ecosystems & Environment**, 118, 1-5, 2007.

Ball-Coelho, B. Salcedo, I. H. Tiessen, H. and Stewart, W. B.: Short- and long-term phosphorus dynamics in fertilized ultisol under sugarcane. **Soil Sci. Soc. Am.,** 57: 1027-1034, 1993.

Barros, J.D.S., Chaves, L.H.G., Chaves, I.B., Farias, C.H.A. and Pereira, W.E.: Estoque de carbono e nitrogênio em sistemas de manejo do solo, nos tabuleiros costeiros paraibanos. **Revista Caatinga**, Mossoró, 26, 1, 35-42, 2013.

Bayer, C., Martin-Neto, L., Mielniczuk, J., Pavinato, A., and Dieckow, J.: Carbon Sequestration in Two Brazilian Cerrado Soils Under No-till, **Soil and Tillage Research**, 86, 237–245, 2006.

Boddey, R. M., Jantalia, C. P., Conceição, P. C., Zanata, J. A., Cimélio, B., Mielniczuk, J., Dieckow, J., Santos, H. P., Denardins, J. E., Aita, C., Giacomini, S. J., Alves, B. J. R., and Urquiaga, S.: Carbon accumulation at depth in Ferralsols under zero-till subtropical agriculture, **Global Change Biology**, 16, 784–795, 2010.

Boddey, R.M., Macedo, R., Tarré, R.M, Ferreira, E., Oliveira O.C., Rezende, C.P., Cantarutti, R.B., Pereira J.M., Alves, B.J.R. and Urquiaga, S.: Nitrogen cycling in *Brachiaria* pastures: the key to understanding the process of pasture decline. **Agriculture, Ecosystems & Environment** 103, 389–403, 2004.

Braz, S. P., Urquiaga, S., Alves, B. J. R., Jantalia, C. P., Guimarães, A. P., dos Santos, C. A., dos Santos, S. C., Pinheiro, E. F. M., and Boddey, R. M.: Soil Carbon Stocks under Productive and Degraded Brachiaria Pastures in the Brazilian Cerrado, **Soil Science Society of America**, 77, 914–928, 2012.

Bustamante, M. M. C., Nobre, C. A., Smeraldi, R., Aguiar, A. P. D., Barioni, L. G., Ferreira, L. G., Longo, K., May, P.,Pinto, A. S. , and Ometto, J. P. H. B.: Estimating greenhouse gas emissions fom cattle raising in Brasil. **Climatic Change**, 115: 559–577, 2012.

Cardoso, E.L., Silva, M.L.N., Silva, C.A., Curi, N. and Freitas, D.A.F.: Estoques de carbono e nitrogênio em solo sob florestas nativas e pastagens no bioma Pantanal. **Pesquisa Agropecuária Brasileira**, 45, n.9, p.1028-1035, 2010.

Carmo, J.B., Sousa Neto, E.R., Duarte-Neto, P.J., Ometto, J.P.H.B. and Martinelli, L.A.: Conversion of the coastal Atlantic forest to pasture: Consequences for the nitrogen cycle and soil greenhouse gas emissions. **Agriculture Ecosystems and Environment**. 148. 37-43, 2012.

Cerri, C.E.P., Piccolo, M.C., Feigl, B.J., Paustian, K., Cerri, C.C., Victoria, R.L. and Melillo, J.M.: Interrelationships among soil total C and N, microbial biomass, trace gas fluxes, and internal N-cycling in soil under pasture of the Amazon region. **Journal of Sustainable Agriculture,** 25. 45-69, 2006.

Cleveland, C. C. and Liptzin, D.: C:N:P stoichiometry in soil: is there a “Redfield ratio” for the microbial biomass? **Biogeochemistry**, 85(3), 235–252, doi:10.1007/s10533-007-9132-0, 2007.

Conte, E., Anghinoni, I., and Rheinheimer, D. S.: Fósforo da biomassa microbiana e atividade de fosfatase ácida após aplicação de fosfato em solo no sistema plantio direto. **Revista Brasileira de Ciência do Solo**, 26: 925-930, 2002.

Costa, M. H., Yanagi, S. N. M., Souza, P. J. O. P., Ribeiro, A. & Rocha, E. J. P. Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. *Geophys. Res. Lett.* **34**, L07706 (2007).

Costa, S.E.V.G.A., Souza, E. D., Anghinoni, I., Carvalho, P. C. F., Martins, A. P., Kunrath, T. R., Cecagno, D., and Balerini, F.: Impact of an integrated no-till crop–livestock system on phosphorus distribution, availability and stock. **Agriculture, Ecosystems and Environment**, 190: 43–51, 2014.

Coutinho, R.P., Urquiaga S., Boddey, R.M., Alves, B.J.R., Torres, A.Q.A. and Jantalia, C.P.: Estoque de carbono e nitrogênio e emissão de N_2O em diferentes usos do solo na Mata Atlântica. **Pesquisa Agropecuária Brasileira**., Brasília, v.45, n.2, p.195-203, 2010.

Davidson, E. A. and Ackerman, I. L.: Changes in soil carbon inventories following cultivation of previously untilled soils, **Biogeochemistry**, 20, 161-193, 1993.

Davidson, E. A. and Janssens, I.A.: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. **Nature** 440, 165-173, 2006.

Davidson, E.A., Keller, M., Erickson, H.E., Verchot, L.V. and Veldkamp, E.: Testing a conceptual model of soil emissions of nitrous and nitric oxides. **BioScience** 50**:** 667-680, 2000.

Ding, F., Hu, Y.-L., Li, L.-J., Li, A., Shi, S., Lian, P.-Y. and Zeng, D.-H.: Changes in soil organic carbon and total nitrogen stocks after conversion of meadow to cropland in Northeast China, **Plant Soil**, 373(1-2), 659–672, doi:10.1007/s11104-013-1827-5, 2013.

Divito, G.A. and Sadras, V.O.: How do phosphorus, potassium and sulphur affect plant growth and biological nitrogen fixation in crop and pasture legumes? A meta-analysis. **Field Crops Research** 156 161–171, 2014.

Don, A., Schumacher, J. and Freibauer, A.: Impact of Tropical Land-use Change on Soil Organic Carbon Stocks - a Meta-analysis. **Global Change Biology**, 17, 1658–1670, 2011.

Dorrepaal, E., Toet, S., Van Logtestijn, R.S.P., Swart, E., Van De Weg, M.J., Callaghan, T.V. and Aerts, R.: Carbon Respiration from Subsurface Peat Accelerated by Climate Warming in the Subarctic. **Nature**, 460, 616–619, 2009.

Drinkwater, L.E., Janke, R.R. and Rossoni-Longnecker, L.: Effects of tillage intensity on nitrogen dynamics and productivity in legume-based grain systems. **Plant and Soil** 227: 99–113, 2000.

Eclesia, R.P., Jobbagy, E.G., Jackson, R.B., Biganzoli, F., Piñeiro, G.: Shifts in soil organic carbon for plantation and pasture establishment in native forests and grasslands of South America. **Global Change Biology**, 18, 3237–3251, 2012.

Ellert, B. H., Janzen, H. H., Van den Bygaart, A. J., and Bremer, E.: Measuring change in soil organic carbon storage, in: Soil Sampling and Methods of Analysis, Chapter 3, edited by: Carter, M. R. and Gregorich, E. G., CRC Press, Boca Raton, USA, 25-38, 2008.

Erickson, H., Keller, M. and Davidson, E.A.: Nitrogen Oxide Fluxes and Nitrogen Cycling during Post-agricultural Succession and Forest Fertilization in the Humid Tropics. **Ecosystems** 4: 67-84, 2001.

Fonte, S.J., Nesper, M., Hegglin, D., Velásquez, J.E., Ramirez, B., Rao, I.M., Bernasconi, S.M., Bünemann, E.K., Frossard, E. and Oberson, A.: Pasture degradation impacts soil phosphorus storage via changes to aggregate-associated soil organic matter in highly weathered tropical soils. **Soil Biology & Biochemistry** 68,150-157, 2014.

Fracetto, F.J.C., Fracetto, G.G.M., Cerri, C.C., Feigl, B.J. and Siqueira Neto, M.: Estoques de carbono e nitrogênio no solo cultivado com mamona na caatinga. **Revista Brasileira de Ciência do Solo**, 36:1545-1552, 2012.

Fujii, K.: Soil acidification and adaptations of plants and microorganisms in Bornean tropical forests. **Ecological Research,** 29: 371–381, 2014.

Gama-Rodrigues, A.C., Sales, M.V.S., Silva, P.S.D., Comerford, N.B. and Cropper, W.P.: Gama-Rodrigues, E.F. An exploratory analysis of phosphorus transformations in tropical soils using structural equation modeling. **Biogeochemistry** 118:453–469, 2014.

Garcia-Montiel, D.C., Neill, C, Melillo, J., Thomas, S., Steudler, P.A. and Cerri, C.C.: Soil Phosphorus Transformations Following Forest Clearing for Pasture in the Brazilian Amazon. **Soil Science Society of America Journal.** 64:1792–1804, 2000.

Gatiboni, L. C., Kaminski, J., and Santos, D. R.: Modificações nas formas de fósforo do solo após extrações sucessivas com Mehlich-1, Mehlich-3 e resina trocadora de ânions. **Revista Brasileira de Ciência do Solo**, 29: 363-371, 2005.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., and Toulmin, C.: Food security: The challenge of feeding 9 billion people. **Science** 327: 812-818, 2010.

Guareschi, R.F., Pereira, M.G. and Perin, A.: Deposição de resíduos vegetais, matéria orgânica leve, estoques de carbono e nitrogênio e fósforo remanescente sob diferentes sistemas de manejo no cerrado Goiano. **Revista Brasileira de Ciência do Solo**, 36. 909-920, 2012.

Guo, L.B. and Gifford, R. M.: Soil Carbon Stocks and Land Use Change: a Meta Analysis, **Global Change Biology**, 8, 345–360, 2002.

Hamer, U., Potthast, K., Burneo, J.I. and Makeschin, F.: Nutrient stocks and phosphorus fractions in mountain soils of Southern Ecuador after conversion of forest to pasture. **Biogeochemistry** 112:495–510, 2013.

Hättenschwiler, S., Coq, S., Barantal, S., and Handa, I. T.: Leaf traits and decomposition in tropical 5 rainforests: revisiting some commonly held views and towards a new hypothesis, New Phytol., 189: 950–965, doi:10.1111/j.1469-8137.2010.03483.x, 2011.

Hedley, M.J., Stewart, J.W.B., and Chauhan, B.S.: Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. **Soil Sci. Soc. Am. J.**, 46,970-976, 1982.

Hessen, D. O., Ågren, G. I., Anderson, T. R., Elser, J. J., Peter, C., Hessen, D. A. G. O., Agren, G. I., Anderson, T. R., Elser, J. J. and Ruiter, P. C. D. E.: Carbon Sequestration in Ecosystems : The Role of Stoichiometry CARBON SEQUESTRATION IN ECOSYSTEMS : THE ROLE OF STOICHIOMETRY, **Ecology**, 85(5), 1179–1192, 2004.

Jiao, F., Wen, Z.-M., An, S.-S. and Yuan, Z.: Successional changes in soil stoichiometry after land abandonment in Loess Plateau, China, **Ecol. Eng.**, 58, 249–254, doi:10.1016/j.ecoleng.2013.06.036, 2013.

Keathing, B. A., Carberry, P. S., Bindraban, P. S., Asseng, S., Meinke, H., and Dixon, J.: Eco-efficient agriculture: concepts, challenges, and opportunities. **Crop Science** 50, 109-119, 2010.

Kucharik,C.J., Brye, K.R., Norman, J.M., Foley, J.A., Gower, S.T. and Bundy, L.G.: Measurements and Modeling of Carbon and Nitrogen Cycling in Agroecosystems of

Southern Wisconsin: Potential for SOC Sequestration during the Next 50 Years. **Ecosystems** 4: 237–258, 2001.

Lapola, D. M., Martinelli, L.A., Peres, C.A., Ometto, J.P.H.B., Ferreira, M.E., Nobre, C.A., Aguiar, A.P.D., Bustamante, M.M.C., Cardoso, M.F., Costa, M.H., Joly, C.A., Leite, C.C., Moutinho, P., Sampaio, G., Strassburg, B.B.N. and Vieira, I.C.G.: Pervasive transition of the Brazilian land-use system. **Nature Climate Change** 4. 27-35, 2014.

Lima, S.S., Carvalho Leite, L.F., Oliveira, F.C. and Costa, D.B.: Atributos químicos e estoques de carbono e nitrogênio em argissolo vermelho-amarelo sob sistemas agroflorestais e agricultura de corte e queima no norte do Piauí. **Revista Árvore,** v.35, n.1, p.51-60, 2011.

Machado, L. A. Z., Balbino, L. C., and Ceccon, G.: **Integração lavoura-pecuária-floresta - Estruturação dos sistemas de integração lavoura-pecuária**. Embrapa Agropecuária Oeste, Dourados-MS, 46p. 2011.

Maia, S., Ogle, S. and Cerri, C.: Effect of grassland management on soil carbon sequestration in Rondônia and Mato Grosso states, Brazil, **Geoderma**, 149, 84–91, 2009.

Marchão, R.L., Becquer T., Brunet, D., Balbino, L.C., Vilela, L. and Brossard, M.: Carbon and nitrogen stocks in a Brazilian clayey Oxisol: 13-year effects of integrated crop–livestock management systems. **Soil & Tillage Research** 103, 442–450, 2009.

Martinelli, L.A., Naylor, R., Vitousek, P.M. and Moutinho, P.: Agriculture in Brazil: impacts, costs, and opportunities for a sustainable future. **Environmental Sustainability**, 2, 431–438, 2010.

McGill, W. B., Shields, J. A., and Paul, E. A.: Relation between carbon and nitrogen turnover in soil organic fractions of microbial origin. **Soil Biol. Biochem**. 7, 57-63, 1975.

McGill, W.B., and Cole, C.V.: Comparative aspects of cycling of organic C, N, S and P through soil organic matter. **Geoderma**, 26, 267-286, 1981.

Mehlic, A.: Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant, Commun. Soil Sci. Plan., 15, 1409-1416; DOI: 10.1080/00103628409367568, 1984.

Melillo, J.M., Steudler, P.A., Aber, J.D., Newkirk, K., Lux, H., Bowles, F.P., Catricala, C., Magill, A., Ahrens, T. and Morrisseau, S.: Soil warming and carbon-cycle feedbacks to the climate systems. **Science** 298, 2173–2176, 2002.

Mello, F. F. C., Cerri, C. E. P., Holbrook, H. M., Paustian, K., Maia, S. M. F., Galdos, M. V., Bernoux, M., and Cerri, C. C.: Payback time for soil carbon and sugar-cane ethanol, **Nat. Clim. Change**. 4, 605-609, doi: 10.1038/NCLIMATE2239, 2014.

Messiga, A. J., Ziadi, N., Bélanger, G., and Morel, C.: Soil nutrientes and other major properties in grassland fertilized with nitrogen and phosphurus. **Soil Sci. Soc. of Am.** 18, 643-652, 2013.

Messiga, A. J., Ziadi, N., Morel, C. and Parent L.E.E.: Soil phosphorus availability in no-till versus conventional tillage following freezing and thawing cycles. **Can. J. Soil Sci**. 90: 419-428. 2010.

Mikhailova, E.A., Bryant, R.B., Vassenev, I.I., Schwager, S.J. and Post, C.J.: Cultivation Effects on Soil Carbon and Nitrogen Contents at Depth in the Russian Chernozem. **Soil Science Society of America Journal** 64:738–745, 2000.

Mooshammer, M., Wanek, W., Hämmerle, I., Fuchslueger, L., Hofhansl, F., Knoltsch, A., Schnecker, J., Takriti, M., Watzka, M., Wild, B., Keiblinger, K. M., Zechmeister-Boltenstern, S. and Richter, A.: Adjustment of microbial nitrogen use efficiency to carbon:nitrogen imbalances regulates soil nitrogen cycling., **Nat. Commun**., 5, 3694, doi:10.1038/ncomms4694, 2014a.

Mooshammer, M., Wanek, W., Zechmeister-Boltenstern, S., and Richter, A.: Stoichiometric imbalances between terrestrial decomposer communities and their resources: mechanisms and implications of microbial adaptations to their resources, **Front. Microbiol**. 5: article 22, doi:10.3389/fmicb.2014.00022, 2014b.

Neill, C., Steudler, P.A., Garcia-Montiel, D.C., Melillo, J.M., Feigl, B.J., Piccolo, M.C. and Cerri, C.C.: Rates and controls of nitrous oxide and nitric oxide emissions following of forest to pasture in Rondônia. **Nutrient Cycling in Agroecosystems** 71, 1-15, 2005.

Numata, I., Chadwick O.A., Roberts D.A., Schimel J.P., Sampaio F.F., Leonidas F.C. and Soares J.V.: Temporal nutrient variation in soil and vegetation of post-forest pastures as a function of soil order, pasture age, and management, Rondonia, Brazil. **Agriculture, Ecosystems & EnvironmentAgric Ecosyst Environ** 118:159–172, 2007.

Oberson, A, Friesen, D.K., Rao, I.M., Bühler, S. and Frossard, E.: Phosphorus Transformations in an Oxisol under contrasting land-use systems: The role of the soil microbial biomass. **Plant and Soil 237:** 197–210, 2001.

Ogle, S.M., Breidt F.J. and Paustian, K.: Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions, **Biogeochemistry**, 72, 87–121, 2005.

Pavinato, P.S., Merlin, A., Rosolem, C.A.: Phosphorus fractions in Brazilian Cerrado soils as affected by tillage. **Soil & Tillage Research** 105, 149–155, 2009.

Sá, J.C.M., Cerri, C.C., Dick, W.A., Lal, R., Venske Filho, S.P., Piccolo, M.P. and Feigl, B.E.: Organic Matter Dynamics and Carbon Sequestration Rates for a Tillage Chronosequence in a Brazilian Oxisol, **Soil Science Society of America Journal**, 65, 1486–1499, 2001.

Sá, J.C.M., Santos, J.B., Lal, R., Moraes, A., Tivet, F., Sá, M.F.M., Briedis, C., Ferreira, A.O., Eurich, G., Farias, A. and Friedrich, T.: Soil-Specific Inventories of Landscape Carbon and Nitrogen Stocks under No-Till and Native Vegetation to Estimate Carbon Offset in a Subtropical Ecosystem. **Soil Science Society of America Journal** 77:2094–2110, 2013.

Sacramento, J.A.A.S., Araújo, A.C.M., Escobar, M.E.O., Xavier, F.A.S., Cavalcante, A.C.R. and Oliveira, T.S.: Soil carbon and nitrogen stocks in traditional agricultural and agroforestry systems in the semiarid region of Brazil. **Revista Brasileira de Ciência do Solo**, 37:784-795, 2013.

Salimon, C.I., Victoria, R.L., Davidson, E.A., and Melo, A.W.F.: CO2 flux from soil in pastures and forests in southwestern Amazonia. **Global Change Biology**, 10, p. 833-843, 2004.

Sanchez, P.A., Couto, W. and Buol, S.W.: The fertility capability soil classification system: interpretation, applicability and modification. **Geoderma** 27, 283 – 309, 1982.

Sanderman, J. and Baldock, J.A.: Accounting for soil carbon sequestration in national inventories: a soil scientist's perspective, **Environment Research Letter**, 5, 1 – 6, 2010.

Santana, G.S., Dick, D.P., Tomazi, M., Bayer, C. and Jacquest, V.A.: Chemical Composition and Stocks of Soil Organic Matter in a South Brazilian Oxisol under Pasture. **Journal of the Brazilian Chemical Society**, Vol. 24, 5, 821-829, 2013.

Sartori, F., Markewitz, D. and Borders, B. E.: Soil carbon storage and nitrogen and phosphorous availability in loblolly pine plantations over 4 to16 years of herbicide and fertilizer treatments, **Biogeochemistry**, 84(1), 13–30, doi:10.1007/s10533-007-9072-8, 2007.

Schrumpf, M., Kaiser, K. and Schulze, E.-D.: Soil organic carbon and total nitrogen gains in an old growth deciduous forest in Germany., **PLoS One**, 9(2), e89364, doi:10.1371/journal.pone.0089364, 2014.

Silva, E.F., Lourente, E.P.R., Marchetti, M.E., Mercante, F.M., Ferreira, A.K.T., Fujii, G.C.: Frações lábeis e recalcitrantes da matéria orgânica em solos sob integração lavoura‑pecuaria.**Pesquisa Agropecuária Brasileira**46, 10, p.1321-1331, 2011.

Sisti, C.P.J., Santos, H.P., Kohhann, R. Alves, B.J.R., Urquiaga, S., Boddey, R.M.: Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. **Soil & Tillage Research** 76, 39–58, 2004.

Stewart, J. W. B., and Tiessen, H.: Dynamics of soil organic phosphorus. **Biogeochemistry** 4, 41–60. 1987.

Tian, H., Chen, G., Zhang, C., Melillo, J.M. and Hall, C.S.H.: Pattern and variation of C:N:P ratios in China's soils: a synthesis of observational data. **Biogeochemistry** 98, 139-151, 2010.

Tiessen, H., and Stewart, J. W. B.: Particle-size Fractions and their Use in Studies of Soil Organic Matter: II. Cultivation Effects on Organic Matter Composition in Size Fractions. **Soil Sci. Soc. of Am.**, 47,,509-514, 1983.

Tiessen, H., Stewart, J. W. B., and Bettany, J. R.: Cultivation effects on the amounts and concentration of carbon, nitrogen, and phosphorus in grassland soils. **Agronomy Journal**, 74, 831-835, 1982.

Tilman, D., Balzer, C., Hill, J., and Befort, B. L.: Global food demand and the sustainable intensification of agricukture. **PNAS**, 108, 20260–20264, 2011.

Tischer, A., Potthast, K. and Hamer, U.: Land-use and soil depth affect resource and microbial stoichiometry in a tropical mountain rainforest region of southern Ecuador., **Oecologia**, 175(1), 375–93, doi:10.1007/s00442-014-2894-x, 2014.

Townsend, A. R., Asner, G. P., Cleveland, C. C., Lefer, M. E., and Bustamante, M. M. C.: Unexpected changes in soil phosphorus dynamics along pasture chronosequences in the humid tropics, **J. Geophys. Res**., 107: article 34, doi:10.1029/2001JD000650, 2002.

Uehara G., Gillman G.P.: The mineralogy, chemistry, and physics of tropical soils with variable charge clays. **Westview Press**, Inc.: Boulder, Colorado, 1981.

Verchot, L. V., Davidson, E. A., Cattanio, J. H., Ackerman, I. L., Erickson, W. E., Keller, M.: Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia. **Global Biochemical Cycles** 13, 31-46, 1999.

Vitousek, P.M., Cassman, K., Cleveland, C., Crews, T., Field, C.B., Grimm, N.B., Howarth, R.W., Marino, R., Martinelli, L.A., Rastetter, E.B.: Sprent, J.I. Towards an ecological understanding of biological N fixation. **Biogeochemistry** 57: 1–45, 2002.

Walker, T. W., and Syers, J. K.: The fate of phosphorus during pedogenesis. **Geoderma**, 15, 1-19, 1976.

Walker, T.W., and Adams, A.F.R.: Studies on soil organic matter. **Soil Sci.**, 85, 307-318, 1958.

Wendt, J. W. and Hauser, S: An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers, **Eur. J. Soil Sci**., 64, 58–65, DOI: 10.1111/ejss.12002, 2013.

Wick, B., Veldkamp, E., Mello, W.Z., Keller, M., Crill, P.: Nitrous oxide fluxes and nitrogen cycling along a pasture chronosequence in Central Amazonia, Brazil. **Biogeosciences,** 2: 499-535, 2005.

Zinn, Y.L., Lal, R., Resck, D.V.S.: Changes in Soil Organic Carbon Stocks Under Agriculture in Brazil. **Soil and Tillage Research**, 84, 28–40, 2005.

Table 1. Characterization of sampled sites: native vegetation (NV), pastures (P), crop-livestock systems (CPS).

City (Code)-Region	Point	Latitude	Longitude	Land-use system	Established	Biome
Sete Lagoas (SL) – Southeast	**1**	19º29’57”	44º11’03”	Pasture	-	Cerrado
	2	19º29’24”	44º10’48”	CPS (1 year of pasture followed by 2 years of corn)	-	Cerrado
	3	19º29’11”	44º11’19”	CPS (corn, pasture and eucalyptus)	2009	Cerrado
	4	19º29’37”	44º11’09”	Forest	-	Cerrado
	5	19º29’28”	44º11’08”	CPS (1 year of pasture followed by 2 years of soybean)	-	Cerrado
Coronel Xavier (CX) – Southeast	**6**	21º01’06”	44º12’53”	Native Vegetation	-	Atlantic Forest
	7	21º01’13”	44º12’56”	Pasture	-	Atlantic Forest
	8	21º01’12”	44º12’53”	CPS (corn, pasture and eucalyptus)	2009	Atlantic Forest
	9	20º59’35”	44º10’18”	Pasture	-	Atlantic Forest
	10	20º59’36”	44º10’18”	Forest	-	Atlantic Forest
	11	20º59’40”	44º10’20”	CPS (corn, pasture and eucalyptus)	2009	Atlantic Forest
São Carlos (SC)-Southeast	**15**	21º58’49”	47º51’10”	Pasture	-	Cerrado
	16	21º58’27”	47º51’10”	CPS (pasture and eucalyptus)	2010	Cerrado
	17	21º58’38”	47º51’17”	Forest	-	Cerrado
	18	21º57’47”	47º51’00”	CPS (pasture and eucalyptus)	2007	Cerrado
Cafeara (CS)-Southeast	**19**	22º50’38”	51º42’28”	CPS (pasture and soybean)	2003	Atlantic Forest
	20	22º50’02”	51º42’52”	Forest	-	Atlantic Forest
	21	22º52’12”	51º43’37”	Pasture	-	Atlantic Forest
Iporã (IP)-Southeast	**22**	24º00’26”	53º45’01”	CPS (1 year of pasture and 3 years of soybean)	-	Atlantic Forest
	23	24º00’06”	53º45’32”	Pasture	-	Atlantic Forest
	24	24º01’20”	53º45’38”	Forest	-	Atlantic Forest
Xambrê (XA)-Southeast	**25**	23º47’34”	53º36’20”	Pasture	-	Atlantic Forest

	26	23º47’14”	53º36’10”	CPS (pasture and soybean)	2000	Atlantic Forest
	27	23º47’23”	53º36’31”	CPS (soybean and eucalyptus)	2010	Atlantic Forest
	28	23º48’29”	53º35’25”	Forest	-	Atlantic Forest
Campo Mourão (CM)-Southeast	**29**	24º06’25”	52º21’40”	Pasture	-	Atlantic Forest
	30	24º06’21”	52º21’34”	CPS (corn and pasture)	2001	Atlantic Forest
	31	24º06’18”	52º21’34”	Forest	-	Atlantic Forest
Juranda (JU)-Southeast	**32**	24º18’21”	52º42’17”	CPS (rotation soybean or corn and pasture)	2006	Atlantic Forest
	33	24º18’34”	52º42’16”	Pasture	-	Atlantic Forest
	34	24º18’10”	52º42’18”	Forest	-	Atlantic Forest
Ponta Grossa (PG)-Southeast	**35**	25º06’37”	50º03’04”	CPS (soybean, pasture and eucalyptus)	2006	Atlantic Forest
	36	25º06’32”	50º03’26”	CPS (soy in summer and oats in winter)	2010	Atlantic Forest
	37	25º06’43”	50º03’49”	Forest	-	Atlantic Forest
	38	25º06’54”	50º03’49”	Pasture	-	Atlantic Forest
Arroio dos Ratos (AR)-South	**39**	30º06’14”	51º41’32”	CPS (soy in summer and *L. multiflorum* in winter)	2002	Pampa
	40	30º06’12”	51º41’33”	CPS (corn or soy in summer and *L. multiflorum* in the winter)	2002	Pampa
	41	30º06’06”	51º41’58”	*Campos*	-	Pampa
	42	30º06’06”	51º41’31”	Pasture	-	Pampa
Tuparecetã (TU)-South	**43**	28º56’34”	54º21’35”	CPS (soy in summer and *L. multiflorum* in winter)	2001	Pampa
	44	28º56’11”	54º21’25”	CPS (soy in summer and *L. multiflorum* in winter)	2001	Pampa
	45	28º56’31”	54º20’02”	Pasture	-	Pampa
	46	28º55’48”	54º20’29”	*Campos*	-	Pampa
Nova Esperança do Sul (NS)-South	**47**	29º27’12”	54º48’40”	CPS (sorghum, pasture and eucalyptus)	2007	Atlantic Forest
	48	29º27’33”	54º49’17”	Pasture	-	Atlantic Forest
	49	29º27’31”	54º49’18”	Forest	-	Atlantic Forest
Bagé (BA)-South	**50**	31º22’11”	54º00’11”	CPS (rice in summer and *L. multiflorum* in winter)	2007	Pampa
	51	31º22’01”	54º00’28”	*Campos*	-	Pampa

	52	31º28’30”	53º58’15”	CPS (sorghum, pasture and eucalyptus)	2005	Pampa
	53	31º19’17”	54º00’12”	CPS (soy in summer and *L. multiflorum* in winter)	2007	Pampa
Capão do Leão (CL)-South	**54**	31º49’57”	52º28º28”	*Campos*	-	Pampa
	55	31º49’19”	52º28’40”	CPS (soy in summer and *L. multiflorum* in winter)	2007	Pampa
	56	31º49’19”	52º28’11”	CPS (soy or rice in summer and *L. multiflorum* in winter)	2007	Pampa
Passo Fundo (PF)-South	**57**	28º13’32”	52º24’30”	CPS (soy or corn in summer and *L. multiflorum* or oats in the winter)	1996	Atlantic Forest
	58	28º13’31”	52º24’28”	CPS (soy or corn in summer and *L. multiflorum* or oats in winter)	1996	Atlantic Forest
	59	28º13’30”	52º24’24”	Forest	-	Atlantic Forest

Table 2. Mean, standard-deviation (Std.Dev.), minimum and maximum of soil nitrogen stocks (N_{stock}, expressed as Mg ha^{-1}) at 0 – 10 cm, 0 – 30 cm, and 0 -60 cm soil depth layer for forest, crop-livestock systems and pasture soils at the paired study sites. ΔN_{abs} is the difference between the soil nitrogen stock of native vegetation and crop livestock systems and pasture soils obtained in the paired study sites (expressed as Mg ha^{-1}) . ΔN_{rel} is the same difference expressed as percentage. Nitrogen losses are indicated by a minus sign (-).

			Native vegetation (0-10cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
N_{stock}	16	2.27	1.04	0.97	4.64
			CPS (0-10cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
N_{stock}	27	1.72	0.72	0.52	2.80
ΔN_{abs}	27	-0.64	0.76	-2.54	0.52
ΔN_{rel}	27	-21.81	30.63	-71.37	42.93
			Pasture (0-10cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
N_{stock}	13	1.54	0.89	0.55	2.82
ΔN_{abs}	13	-0.63	0.70	-2.02	0.43
ΔN_{rel}	13	-27.89	27.53	-70.77	18.71
			Native vegetation (0-30cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
N_{stock}	16	5.12	2.12	2.20	9.01
			CPS (0-30cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
N_{stock}	27	3.94	1.65	1.45	7.65
ΔN_{abs}	27	-1.28	1.70	-4.89	1.60
ΔN_{rel}	27	-19.81	29.19	-65.14	45.81
			Pasture (0-30cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
N_{stock}	13	3.84	1.85	1.52	6.49
ΔN_{abs}	13	-1.10	1.14	-3.20	0.80
ΔN_{rel}	13	-21.84	18.95	-63.63	14.06

			Native vegetation (0-60cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
N_{stoc}	16	7.30	3.28	2.68	12.00
			CPS (0-60cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
N_{stock}	27	5.93	2.51	2.12	11.68
ΔN_{abs}	27	-1.48	2.37	-5.12	2.82
ΔN_{rel}	27	-13.41	31.47	-59.97	41.42
			Pasture (0-60cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
N_{stock}	13	6.16	2.79	2.80	10.19
ΔN_{abs}	13	-1.54	1.47	-3.89	1.05
ΔN_{rel}	13	-17.67	20.20	-47.21	20.62

Table 3. Mean, standard-deviation (Std.Dev.), minimum and maximum of soil phosphorus stocks (P_{stock}, expressed as kg ha^{-1}) at 0 – 10 cm, 0 – 30 cm, and 0 - 60 cm soil depth layer for forest, crop-livestock systems and pasture soils at the paired study sites. ΔP_{abs} is the difference between the soil phosphorus stock of native vegetation and crop livestock systems and pasture soils obtained in the paired study sites (expressed as kg ha^{-1}). ΔP_{rel} is the same difference expressed as a percentage. Phosphorus losses are indicated by a minus sign (-).

			Native vegetation (0-10cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
P_{stock}	16	11.27	14.26	0.80	60.50
			CPS (0-10cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
P_{stock}	27	30.06	25.63	1.60	95.50
ΔP_{abs}	27	20.56	23.91	-14.50	78.50
ΔP_{rel}	27	324.96	381.11	-23.97	1650.11
			Pasture (0-10cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
P_{stock}	13	21.63	22.35	0.60	78.10
ΔP_{abs}	13	10.06	26.78	-50.50	62.05
ΔP_{rel}	13	52.14	813.43	-83.47	2818.72
			Native vegetation (0-30cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
P_{stock}	16	21.74	24.49	3.10	105.50
			CPS (0-30cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
P_{stock}	27	49.50	37.11	3.20	137.50
ΔP_{abs}	27	27.03	41.48	-79.01	102.50
ΔP_{rel}	27	205.05	245.34	-74.18	900.08
			Pasture (0-30cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
P_{stock}	13	47.60	60.77	2.30	218.00
ΔP_{abs}	13	25.70	64.17	-83.51	191.35
ΔP_{rel}	13	218.59	324.31	-79.16	937.76

			Native vegetation (0-60cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
P_{stock}	16	42.70	53.92	6.40	216.50
			CPS (0-60cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
P_{stock}	27	62.90	39.75	6.90	155.49
ΔP_{abs}	27	25.64	62.51	-175.00	107.49
ΔP_{rel}	27	145.54	178.00	-100.00	535.23
			Pasture (0-60cm)		
	N	Mean	Std.Dev.	Minimum	Maximum
P_{stock}	13	68.33	72.12	11.90	241.40
ΔP_{abs}	13	25.42	89.37	-184.52	201.16
ΔP_{rel}	13	171.92	285.12	-100.00	850.26

Table 4. Mean, standard-deviation (Std.Dev.), median minimum, and maximum, standard-deviation (Std.Dev.) Soil nitrogen (N_{stocks}, express as Mg ha^{-1}) and phosphorus (P_{stocks}, kg ha^{-1}) at 0-10 and 0 – 30 cm soil depth layers for pasture soils included in the regional survey.

	Depth (cm)	N	Mean	Std.Dev.	Median	Minimum	Maximum
N_{stocks}	10	115	1.66	0.87	1.49	0.40	4.20
N_{stocks}	30	115	3.91	1.90	3.61	1.01	8.90
P_{stocks}	10	115	8.50	14.60	3.08	0.50	89.50
P_{stocks}	30	115	14.71	26.90	5.72	1.01	179.50

Figures Legends

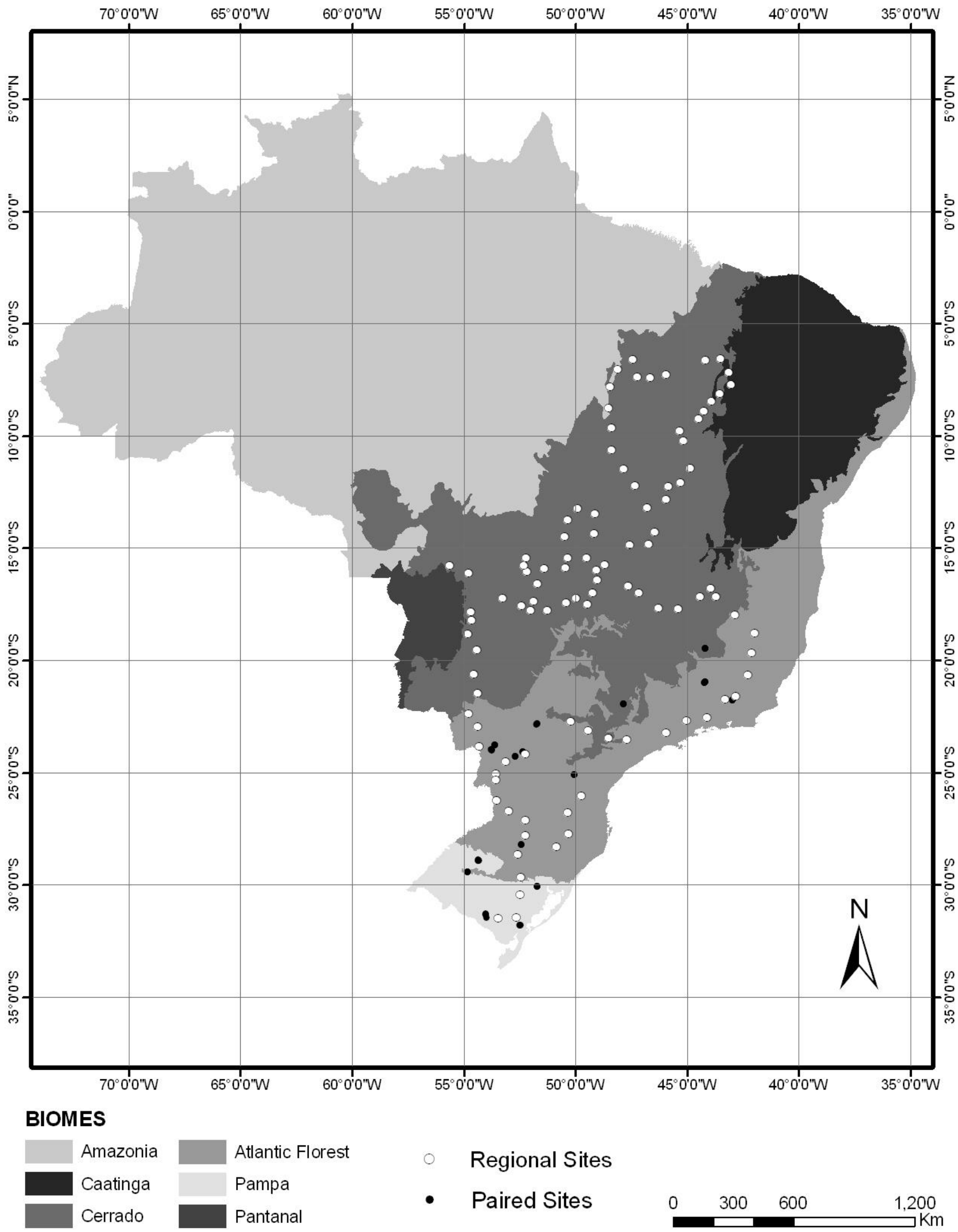

Figure 1. Sampling sites located throughout Brazil. White circles indicate pasture sites of the regional survey; black circles indicate paired study sites, and various shaded areas indicate Brazilian biomes.

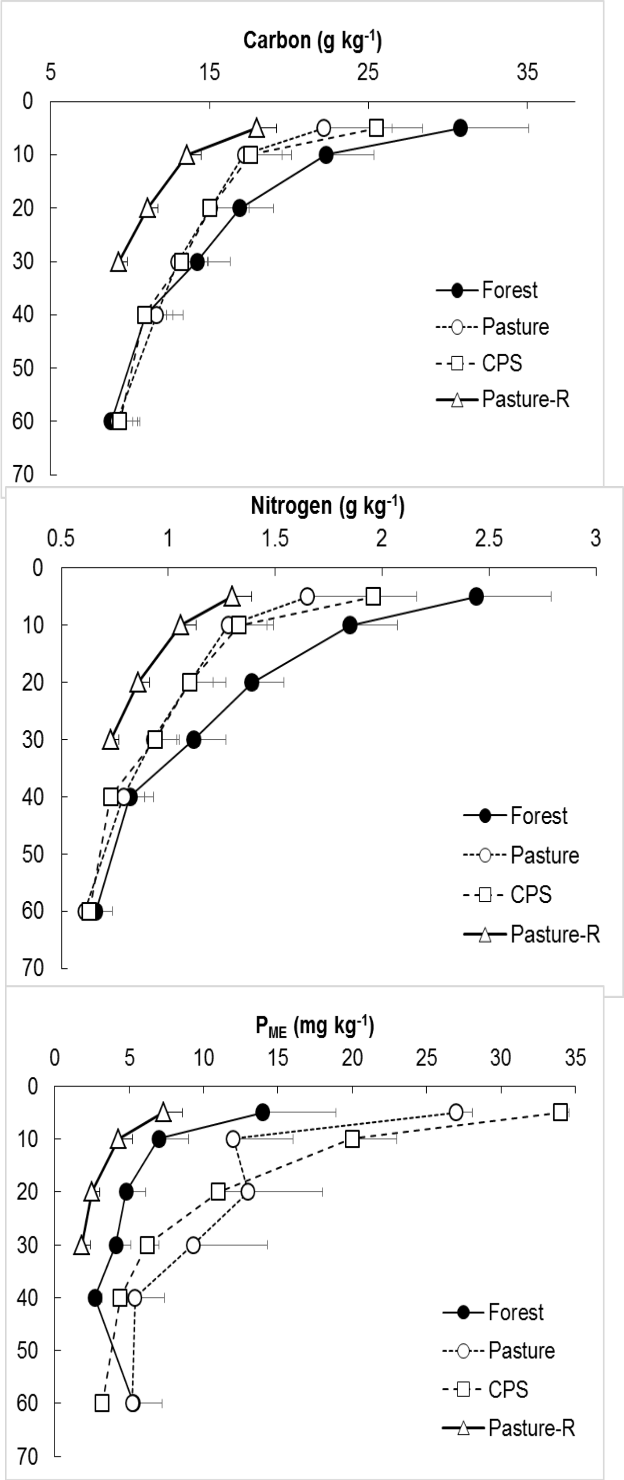

Figure 2. Soil depth variability of (a) carbon, (b) nitrogen and (c) and Mehlic-3 extracted phosphorus (P_{ME}) in forest, pasture and CPS soils of the paired study sites and of the regional pasture survey (Pasture-R). Points represent the means by soil depth and the horizontal bars are standard errors.

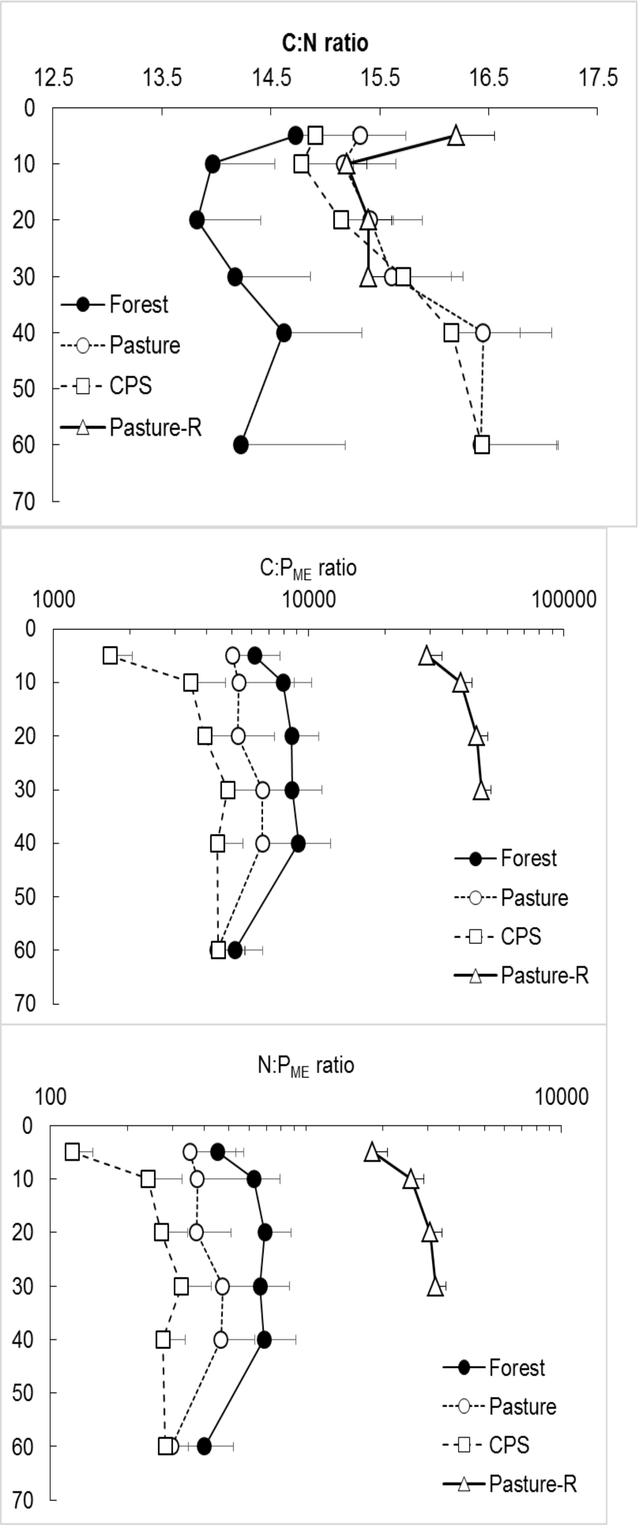

Figure 3. Soil depth variability of (a) C:N ratios, (b) C:P$_{ME}$ and (c) N:P$_{ME}$ in forest, pasture and CPS soils of the paired study sites, and of the regional pasture survey (Pasture-R). Points represent the means by soil depth and the horizontal bars are standard errors.

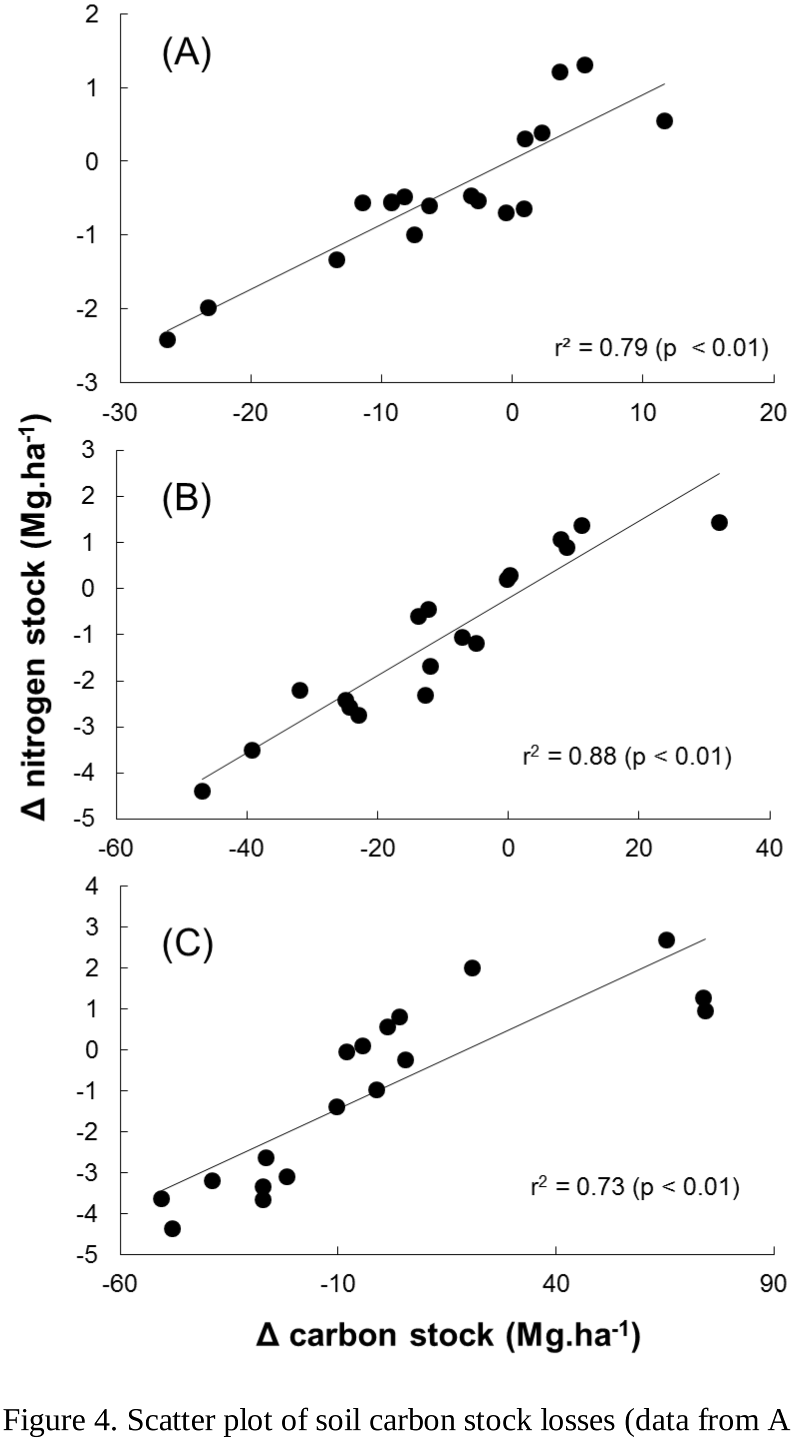

Figure 4. Scatter plot of soil carbon stock losses (data from Assad et al. 2013), and soil nitrogen stock losses found in this study between CPS and native vegetation in the paired-study sites (A) 0-10 cm (B) 0 – 30 cm (C) 0 – 60 cm depth intervals

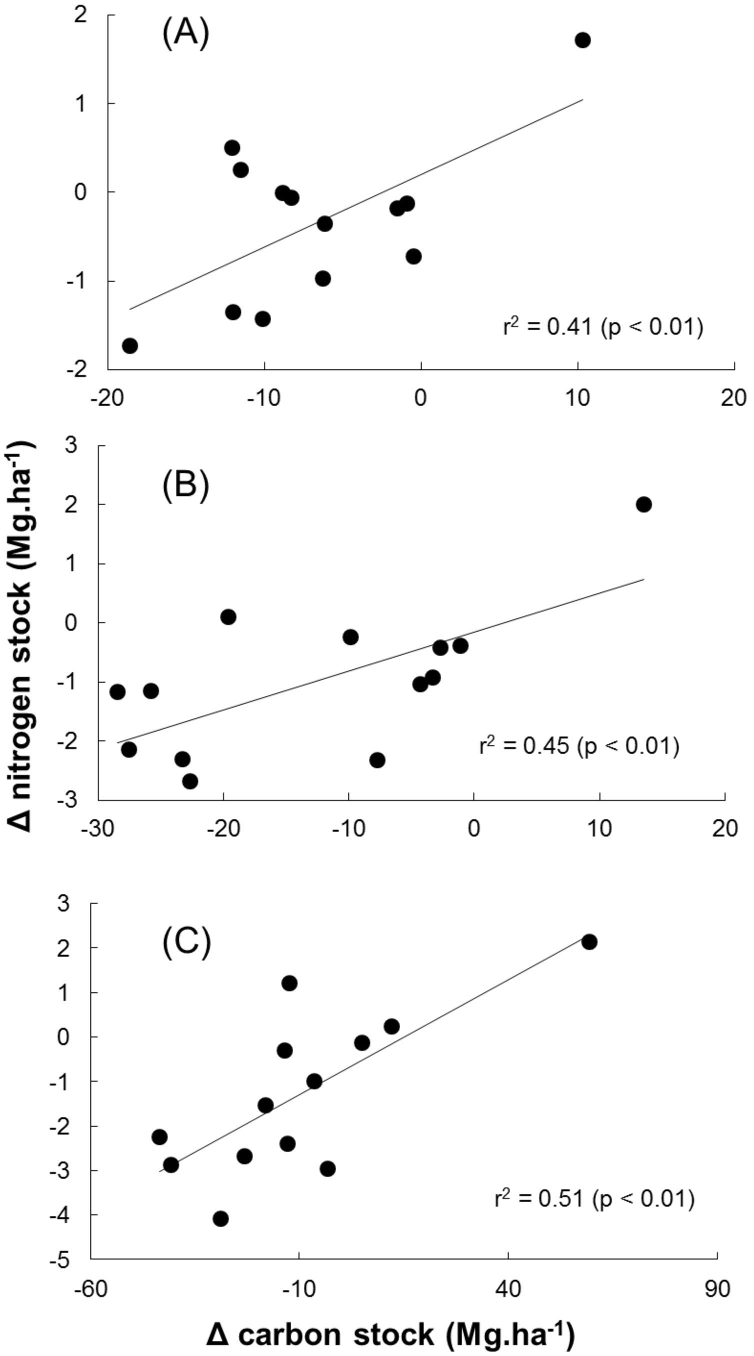

Figure 5. Scatter plot of soil carbon stock losses (data from Assad et al. 2013), and soil nitrogen stock losses found in our study between pasture and native vegetation in the paired-study sites (A) 0 – 10 cm (B) 0 – 30 cm (C) 0 – 60 cm depth intervals.

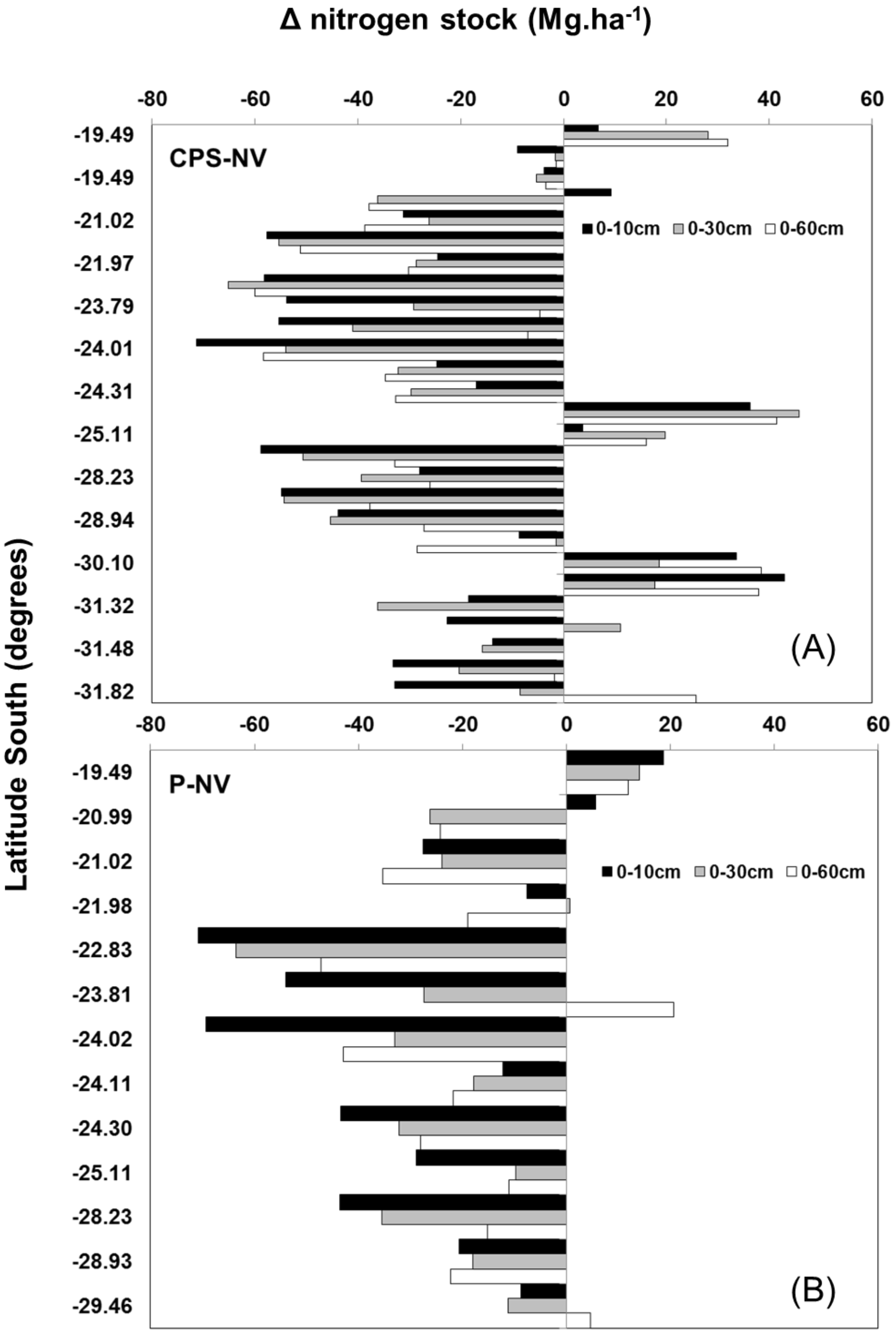

Figure 6. Absolute difference of soil nitrogen stocks between different depth intervals: (A) crop-livestock systems (CPS) and native vegetation (NV); and (B) pasture (P) and native vegetation (NV) at different paired study sites. Each paired-site study area is indicated by its latitude. Losses are indicated by a minus sign (-).

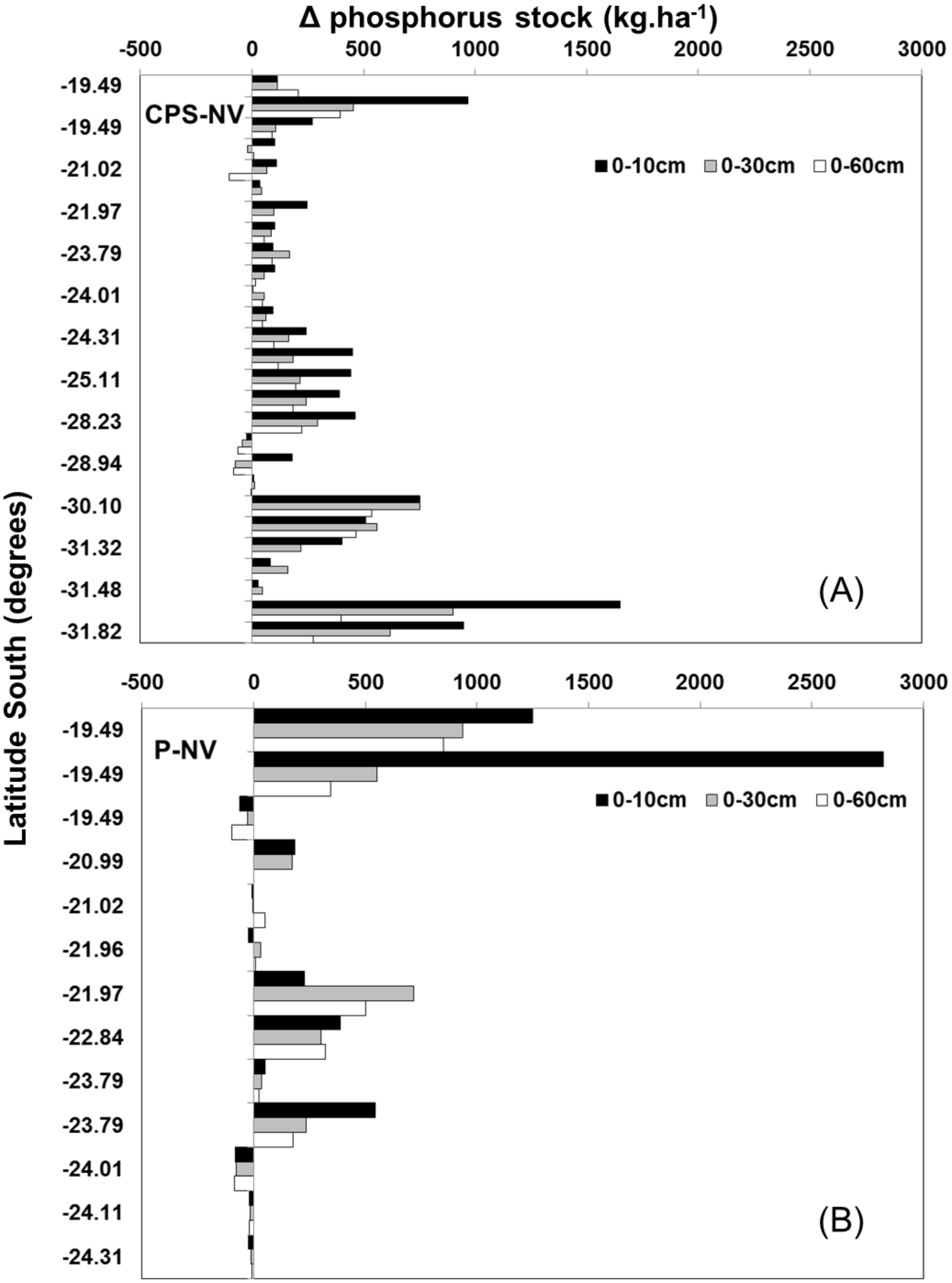

Figure 7. Absolute difference of soil phosphorus stocks between different depth intervals: (A) crop-livestock systems (CPS) and native vegetation (NV); and (B) pasture (P) and native vegetation (NV) at different paired study sites. Each paired-site study area is indicated by its latitude. Losses are indicated by a minus sign (-).