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Land use effects on subtropical, sandy soil under sandyzation/desertification processes

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ABSTRACT

Very fragile sandy soils have high erosion susceptibility, low water retention, and low nutrient and carbon storage. In southern Brazil, substitution of native grassland by grain production in conventional tillage has caused severe degradation, even reaching an extreme state of "sandyzation" or non-vegetated sand. We measured indicators to assess soil quality in a Quartzipsamment ("Neossolo Quartzarênico") under different uses and also in extreme state of "sandyzation" or non-vegetated sand, where annual average rainfall is 1511 mm with regular distribution throughout the year. Four land uses/conditions were evaluated: (i) native grassland (NG) (4% clay); (ii) nine years-old eucalyptus forest (EF) (4% clay); (iii) corn production in conventional tillage (CT) (3% clay); and (iv) extreme state of "sandyzation" or non-vegetated sand (NVS) (2% clay). Measured soil chemical properties were soil organic carbon (SOC) in 0–2.5, 2.5–5, 5–7.5, 7.5–10 and 10–20 cm soil layers, Ca, Mg, K, Al saturation, and effective cation exchange capacity (CEC) in 0–2.5 cm layer. Measured soil physical properties were soil bulk density (BD), total porosity (TP), macroporosity (Macro), microporosity (Micro), water retention, and saturated hydraulic conductivity (Ks) in 0–3, 5–8, and 10–13 cm soil layers, whereas aggregate stability in water was measured in 0–5 cm soil layer. Soil chemical and physical properties indicate an extreme state of degradation of NVS, which had significantly lowest SOC and thus low CEC, associated to leaching of exchangeable bases and high aluminum saturation. CT also provided a significant decrease in SOC in all soil layers, and other in chemical properties in the 0–2.5 cm layer, whilst EF was the most efficient system to build up SOC compared to NG in surface layers (0–2.5 and 2.5–5 cm) and presented better chemical conditions. In general, soil physical quality was degraded in NVS and improved in EF, whilst there were no significant differences in CT compared to NG for most soil physical properties. Soil physical properties were closely related to surface SOC of the different land uses. NVS provided a significant decrease in Micro, whilst EF provided a significant increase in TP and Macro in 0–3 and 5–8 cm soil layers. High TP and Macro, low Micro, and very high Ks were observed in NVS. The CT provided significant decrease in water aggregate stability compared to NG and the water aggregate stability rank was EF > NG > CT, whereas NVS soil was completely devoid of aggregation. NVS restricts plant growth, root development, plant nutrient uptake and soil cover, thus creating an environment prone to wind erosion and soil degradation. Management practices that include permanent soil cover, restore SOC, improve soil aggregation and create pores for water retention and availability, increase base saturation and promote nutrient cycling are necessary to preserve these fragile lands.

1. Introduction

Parent material and climate conditions in the Holocene Epoch – Cenozoic Era (Bombin and Klamt, 1974) – resulted in the genesis of sandy sediments in the southernmost Brazilian state (Fig. 1), bordering with Uruguay and Argentina, where sandy areas lacking vegetation are found (Suertegaray, 1995). Under currently more humid weather conditions, these sediments led to the formation of

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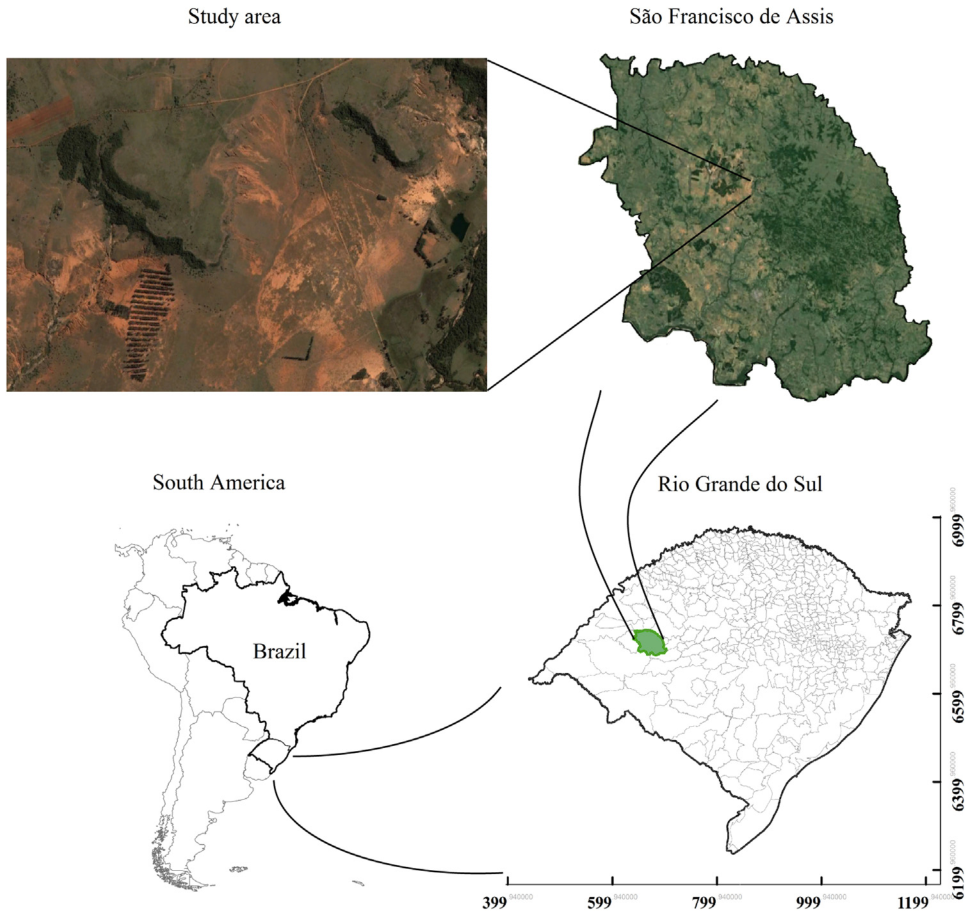

Fig. 1. Study area with sandyzation sites, in São Francisco de Assis municipality, in the southwestern region ("Campanha") of Rio Grande do Sul State, Southern Brazil.

sandy-textured soils, highly susceptible to degradation by water and wind erosion to such an extent that desertification is possible. However, these areas are of relatively high rainfall (over 1300 mm per year), and have edaphological and geobotanic properties distinctive from deserts.

Although associated to desertification since the 1970′s, sandyzation is a single phenomenon associated to hydrological and eolian processes, and to climate regimes that are different from those that characterize desertification (Suertegaray and Verdu, 2008). In humid climate there is the formation of "islands" or patches of exposed, loose sand ("areais" or sandynized soil), thus erroneously called areas of desertification (Suertegaray, 1995), especially on slopes and valleys with sandstone rocks prone to water erosion, with potential subsequent wind activity (Suertegaray, 1987).

Sediments are mobilized by water during rainy days and by wind on dry, windy days, hindering vegetation establishment. Reworking of these quaternary deposits resulted from morphogenetic dynamics, where surface runoff, particularly concentrated flow in gullies, expose, transport and deposit sand particles, further enhanced by wind erosion processes. There are indications that the sandynized areas are formed by natural or geological erosion (Marchiori, 1995; Bellanca and Suertegaray, 2003; Suertegaray et al., 2005) and accelerated erosion by anthropic effects (Cordeiro and Soares, 1975; Souto, 1984; Verdum, 1997).

These "sandynized" or "non-vegetated sand" areas occupy an estimated area of 3000 ha in ten municipalities in the Rio Grande do Sul state, with some of them having up to 229 patches of sand (Andrades et al., 2005), in much larger area of sandy soils highly susceptible to erosion (around 250 thousand ha).

Prevailing agroecosystems in the region include the use of extensive, low productivity livestock and agriculture, and minor presence of forestry. Regional climate and sandy soils of low natural fertility, undulated relief, with natural vegetation of grasses and with low winter growth characterize the agroecosystem as naturally fragile and even more when in agriculture or animal husbandry (Souto, 1984). In the 1970's and 80's there was intense agricultural use of sandy soils, where native grasslands were replaced by conventional tillage for soybean and wheat cropping, resulting in severe soil and ecosystem degradation.

Loss of vegetative cover, exposing sandy material to erosive agents, is the main factor encouraging soil degradation (Souto, 1984). In a sandynized area, sand movement by wind from September to December of 2001 was 5.05 Mg ha^{-1}, while in the whole year of 2002 this movement was 11.08 Mg ha^{-1}. With the use of cover plants, sand movement was, respectively, only 0.36 and 0.77 Mg ha^{-1}, which corresponds to a decrease of around 93% (Rovedder and Eltz, 2008a). High rainfall intensity associated to high wind intensity favors the movement of soil particles, but high precipitation and low wind intensity may result in less sand movement and erosion (Rovedder and Eltz, 2008a). Local rainfall average is highest (153.6 mm) in September and October (Souto, 1984), and greatest average wind speed of 2.89 m s^{-1} is in September to November (Instituto Nacional de Meteorologia (INMET), 2012).

Sandy soils are characterized by weak aggregation (Capurro et al., 2002; Wohlenberg et al., 2004; Reichert et al., 2009a), poor water retention properties (Tomasella and Hodnett, 1998; Reichert et al., 2009b, 2015b; Fidalski et al., 2013), high permeability (Bruand et al., 2005), water infiltration (Reichert and Norton, 1995, 1996), and susceptibility to compaction (Ramos et al., 2014). Sandy soils retain little water at high water potentials and water content decreases rapidly with decrease in water potential (Panayiotopoulos and Mullins, 1985), and the volumetric water content retained at given matric potentials may be greatly overestimate by pedotransfer functions developed from temperate soils database, as observed for sandy soils of Brazilian Amazonia (Tomasella and Hodnett, 1998). Soil saturated hydraulic conductivity (Ks) of sandy soils in the tropics varies within a range of values covering several orders of magnitude ($10^{-7} < Ks < 10^{-3}\,m\,s^{-1}$) (Bruand et al., 2005).

Tropical sandy soils, more than other soils, require careful management. Even if most physical degradation processes are more easily reversible in tropical sandy soils than in other soils, the physical fertility of these soils is low (Bruand et al., 2005). Soils occurring in areas under 'sandyzation' have natural low agricultural and ecosystem production potential, because of the great physical limitations to water storage and plant nutrient availability (Azevedo and Kaminski, 1995). Vegetation is savanna-woody-grassy steppe vegetation with abundance of shrubs and undergrowth (Marchiori, 1995), resulting in poor forage with low nutritional value and deficient mineral composition (Agostini and Kaminski, 1976) and species of vegetation distributed following soil fertility levels (Soares et al., 2015). Agricultural use in these areas is risky because of limiting soil conditions, frequent summer drought and occurrence of wind erosion (Scopel et al., 2013). Nevertheless, soil quality in properly managed sandy soils may potentially improve faster than in clayey soils (Reinert, 1998) due to lower resilience of the latter. Although the problem is easily identified, solutions are complex. If the aim is using marginal, fragile, and low-productivity soils in productive system, especial land use and management systems are required. Degradation of fragile ecosystems is triggered when system resistance to anthropic disturbance is surpassed. Our objective was to assess the effect of traditional use of natural grassland, conventional-tillage corn, and eucalyptus forest on soil physical and chemical properties in an area with fragile sandy soil prone to sandyzation.

2. Material and methods

2.1. Study area

The study was carried out on a farm in São Francisco de Assis municipality in southern Brazil (Figs. 1 and 2), in "sandynized" (6747921.30 m S, 679445.54 m W). The soil was classified as Quartzipsament by Soil Taxonomy (Soil Survey Staff, 2014) and "Neossolo Quartzarênico" by the Brazilian Soil Classification System (Embrapa, 2006) (Fig. 2a). The soil is derived from sandstone parent material (Fig. 2b) with very high sand content (>95%) and very low clay content, weak soil structure, and rolling landscape. Annual rainfall is about 1511 mm, with monthly rainfall over 95 mm, and annual evapotranspiration of about 903 mm, i.e., 60% of total rainfall (Álvares et al., 2013).

The experiment consisted of four land uses and four replications. The studied land uses, all located on similar landscape position and in close proximity among them, were native grassland (NG) (4% clay); nine years-old eucalyptus forest (EF) (4% clay); non-vegetated sand (NVS) (high degraded) (2% clay); and soil under five years of corn cropping with conventional tillage (CT) (3% clay).

2.2. Soil sampling and laboratory analysis

Disturbed soil samples were taken from 0 to 2.5, 2.5–5, 5–7.5, 7.5–10, and 10–20 cm soil layers to evaluate soil organic carbon (SOC), from 0 to 2.5 cm soil layer to determine soil exchangeable bases (K, Ca, Mg), aluminum saturation, and effective cation exchange capacity (CEC). When soil is not tilled as in most of our land uses, there is a clear gradient in SOM, which calls for sampling of smaller depth increments (Bayer et al., 2002).

Soil organic carbon (SOC), exchangeable bases K, Ca and Mg, and Al contents were determined following methods described in Tedesco et al. (1985). SOC was analyzed by wet combustion method (Nelson and Sommers, 1982) and then soil organic matter was calculated (SOM = 1.724 SOC); available soil K was extracted with Mehlich-I solution ($0.05\,mol\,L^{-1}$ HCl + $0.0125\,mol\,L^{-1}$ H_2SO_4) and measured by flame photometry; and Ca, Mg and Al were extracted by KCl 1N and measured with an atomic absorption

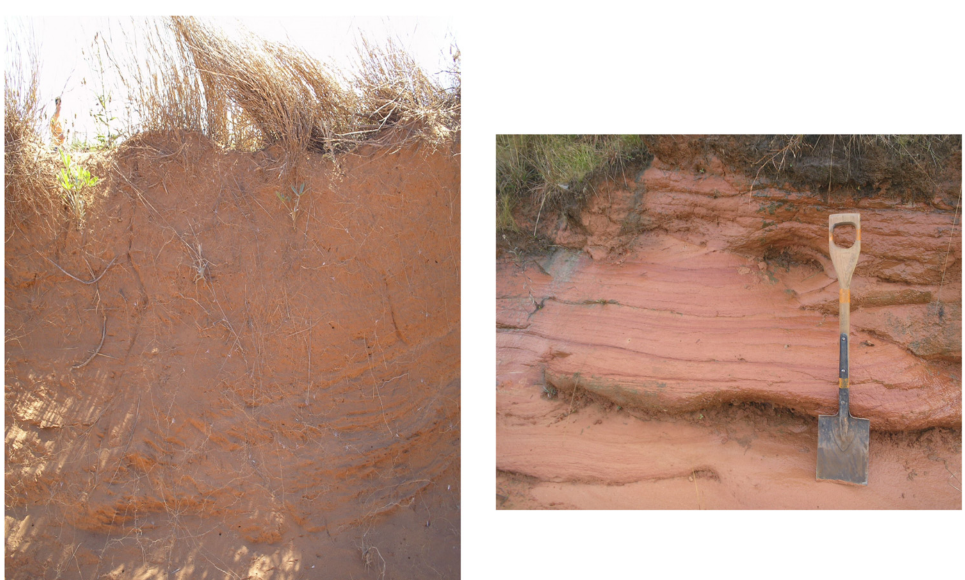

Fig. 2. Soil profile of the studied Quartzipsament (a) and sandstone parent material (b).
Source: pictures taken by L.E.A. Suzuki.

spectrophotometer (Tedesco et al., 1985). Aluminum saturation, sum of the bases (SB) and effective cation exchange capacity were calculated from the different exchangeable cations.

Undisturbed soil samples were taken from 0 to 3, 5–8, and 10–13 cm soil layers using soil cores (5.3 cm diameter by 3 cm height), with four sample replications per layer, to evaluate total porosity (TP), macroporosity (Macro), microporosity (Micro), bulk density (BD), water retention and saturated hydraulic conductivity (Ks) (Klute, 1986). These three layers were sampled since they are the most affected when soil is not tilled (Genro Júnior et al., 2009; Reichert et al., 2009c). Disturbed soil samples were taken from the same soil layers to evaluate soil particle density (PD) (Gubiani et al., 2006).

The undisturbed soil samples were capillary saturated (0 kPa) for 48 h, and hydraulic conductivity was measured with a constant-head permeameter (Klute, 1986). Afterwards, samples were again capillary saturated, and then subjected to tensions of 1 and 6 kPa on a tension table (Klute, 1986). Subsequently, samples were subjected to tensions of 33, 100, and 500 kPa in Richards pressure plates apparatus (Klute, 1986) to determine soil water retention. Finally, samples were oven-dried at 105 °C to determine soil bulk density (Klute, 1986). Soil total porosity was calculated from soil bulk (BD) and particle density (PD) values (TP = 1- (BD/PD)). Microporosity was calculated based on volumetric water retention at 6 kPa, while macroporosity is the difference between total porosity and microporosity.

Soil samples with partially disturbed structure were taken from 0 to 5 cm layer to evaluate aggregate stability using two strategies: (i) aggregate stability in water using the method by Kemper and Chepil (1965) with initial aggregate sizes between 8 and 4.7 mm and 25 g sample amount, and (ii) aggregate stability in water using a modified method using 50 g passed through an 8 mm sieve. The aggregate classes were 8.00–4.76; 4.76–2.00; 2.00–1.00; 1.00–0.21 and <0.21 mm. Geometric mean diameter (GMD) and mean weight diameter (MWD) of water stable aggregates were calculated.

2.3. Statistical analysis

Soil properties data were analyzed comparing the NVS, CT and EF with the control NG by the Dunnett test ($p < 0.05$), whilst the relationship between SOM and CEC was evaluate using linear regression analysis.

The Dunnett test is well suited for this type of experiment since it is similar to a contrast analysis, where a Student's *t*-statistic is computed for each treatment and the statistic compares the treatment to a single control.

We chose the native grassland land use as control, since this is the traditional land use in the region and our aim was to compare it with alternative uses which could potentially improve (eucalyptus forest), reduce (conventional tillage for crop production), or present intense damage (sandynized areas) soil quality.

3. Results

3.1. Soil chemical properties

Soil organic carbon (SOC) was low, and changes with soil depth were small in all land uses except for soil with eucalyptus (Fig. 3). The SOC was statistically lower in NVS and CT and higher in EF than in NG for 0–2.5 and 2.5–5 cm soil layers, compared to the control NG. In the 5–7.5 and 7.5–10 cm soil layers, EF was not statistically different from NG, while NVS and CT had significantly lower SOC than NG. For 10–20 cm soil layer, SOC was higher in NG then in NVS, CT and EF.

The NVS had the lowest SOC in all five studied soil layers in the four land uses. SOC for NVS, NG and CT was quasi constant from the soil surface to 20 cm depth. The EF had the highest SOC in the surface layer, and the SOC abruptly decreased from the 0–2.5 cm to 2.5–5 cm soil layers and then gradually decreased until 20 cm soil depth.

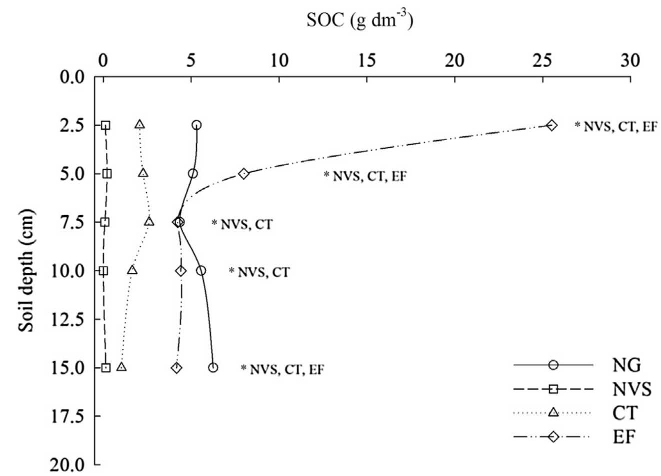

Fig. 3. Soil organic carbon in 0-2.5, 2.5-5, 5-7.5, 7.5-10, and 10–20 cm soil layers of a Quartzipsamment soil under four different land uses.
[1]NG: native grassland; NVS: extreme state of "sandyzation" or non-vegetated sand; CT: grain production in conventional tillage; EF: nine years-old eucalyptus forest.
[2]Means compared to the control NG by Dunnett test ($p < 0.05$): "*": means differ significantly from the control NG; ns: not significant.

A close relationship between soil organic matter (SOM) and CEC was observed ($R^2 = 0.96$) (Fig. 4), as for most sandy soils a great proportion of CEC originates from SOM. The remarkable low SOM stock for NVS is associated with low CEC and low cation retention. The greatest numeric difference of CEC was observed between NVS and EF, whilst for NG and CT the CEC was similar with intermediary values among the four land uses. The lowest CEC was observed for NVS, followed by NG, CT and EF, respectively.

Soil exchangeable bases had similar behavior as CEC, as expected (Fig. 5). NVS provided significant decrease in Mg, K and CEC, whilst the decrease in Ca, Al and SB was not statistically different from the control NG. Aluminum saturation increased significantly for NVS than NG. CT was statistically different from NG only for K and aluminum saturation. EF provided significant

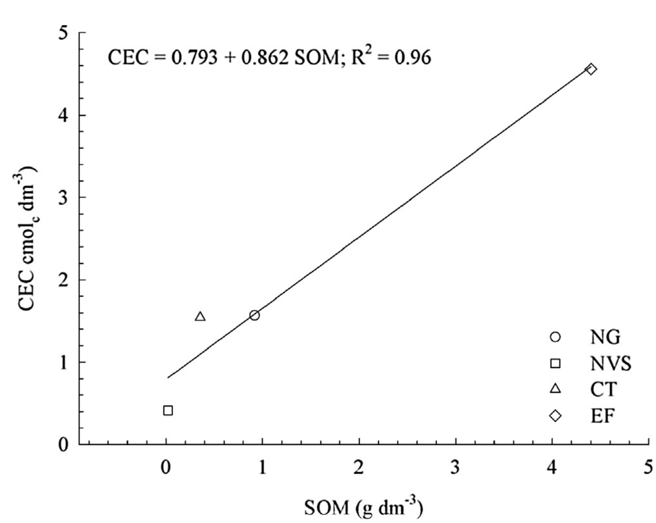

Fig. 4. Soil organic carbon (SOC) and effective cation exchange capacity (CEC) in 0–10 cm soil layer of a Quartzipsamment soil under four different land uses.
[1]NG: native grassland; NVS: extreme state of "sandyzation" or non-vegetated sand; CT: grain production in conventional tillage; EF: nine years-old eucalyptus forest.

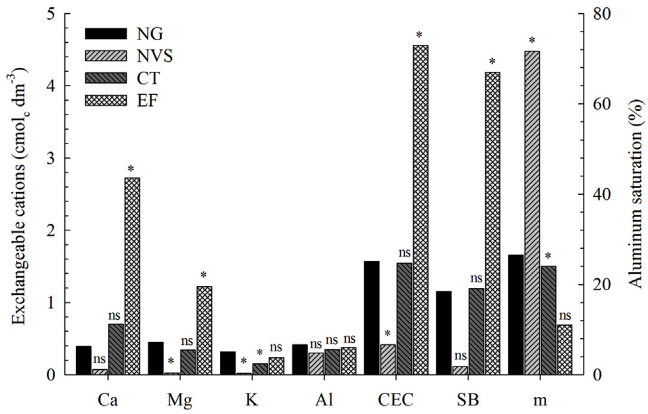

Fig. 5. Soil exchangeable cations (Ca, Mg, K, Al), effective cation exchange capacity (CEC), sum of the bases (SB) and aluminum saturation (m) in 0–2.5 cm soil layer of a Quartzipsamment soil under four different land uses.
[1]NG: native grassland; NVS: extreme state of "sandyzation" or non-vegetated sand; CT: grain production in conventional tillage; EF: nine years-old eucalyptus forest.
[2]Means compared to the control NG by Dunnett test ($p < 0.05$): "*": means differ significantly from the control NG; ns: not significant.

increase in Ca, Mg, CEC, and SB compared to NG, whilst the increase in K and Al and the decrease in aluminum saturation were not statistically different from NG.

The EF provided remarkable high Ca, Mg, CEC and SB values. Aluminum saturation was inversely proportional of exchangeable bases, as the highest value was observed for NVS, and the lowest for EF (Fig. 5).

3.2. Soil physical properties

The NVS provided significant increase in soil bulk density (BD), with the highest BD (1.52 g cm^{-3}) in the 0–3 cm layer, whilst CT were not statistically different in this layer, compared to the control NG. The EF provided significant decrease in soil BD where the lowest BD (1.09 g cm^{-3}) was observed in the 0–3 cm soil layer (Table 1). In the 5–8 cm soil layer, the EF also provided significant decrease in soil BD, whilst BD was similar and not statistically different for CT and NVS (Table 1). In the 10–13 cm soil layer, the BD was not statistically different for NVS, CT and EF, when compared to the control NG.

Soil physical indicators of NVS also reflect the degree of soil degradation, based on soil water content extremely and significantly low (Fig. 6) and significantly low microporosity in all soil layers (Table 1). Macro and TP were not statistically different for NVS compared to NG in all soil layers. Micro, Macro and TP were not statistically different in the CT compared to NG in all soil layers. The EF provided significant increase in Macro and TP in the 0–3 and 5–8 cm soil layers, whilst Micro was not statistically different compared to NG. In the 10–13 cm soil layer, whilst Micro, Macro and TP were not statistically different in EF compared to NG (Table 1).

Table 1
Soil bulk density (BD), macro, micro and total porosity (TP) of a Quartzipsamment soil, in three layers, under four different land uses.

Land use[a]	BD[b] (g cm^{-3})	Micro (cm^3 cm^{-3})	Macro	TP
0–3 cm				
NG	1.40	0.175	0.461	0.462
NVS	1.52*	0.078*	0.421^{ns}	0.422^{ns}
CT	1.40^{ns}	0.143^{ns}	0.459^{ns}	0.460^{ns}
EF	1.09*	0.209^{ns}	0.570*	0.572*
5–8 cm				
NG	1.54	0.163	0.407	0.409
NVS	1.55^{ns}	0.073*	0.409^{ns}	0.410^{ns}
CT	1.56^{ns}	0.155^{ns}	0.398^{ns}	0.399^{ns}
EF	1.44*	0.169^{ns}	0.443*	0.445*
10–13 cm				
NG	1.54	0.162	0.408	0.410
NVS	1.54^{ns}	0.077*	0.414^{ns}	0.414^{ns}
CT	1.51^{ns}	0.156^{ns}	0.418^{ns}	0.419^{ns}
EF	1.47^{ns}	0.156^{ns}	0.432^{ns}	0.433^{ns}

[a] NG: native grassland; NVS: extreme state of "sandyzation" or non-vegetated sand; CT: grain production in conventional tillage; EF: nine years-old eucalyptus forest.
[b] Means compared to the control NG by Dunnett test ($p < 0.05$): "*" means differ significantly from the control NG; ns: not significant.

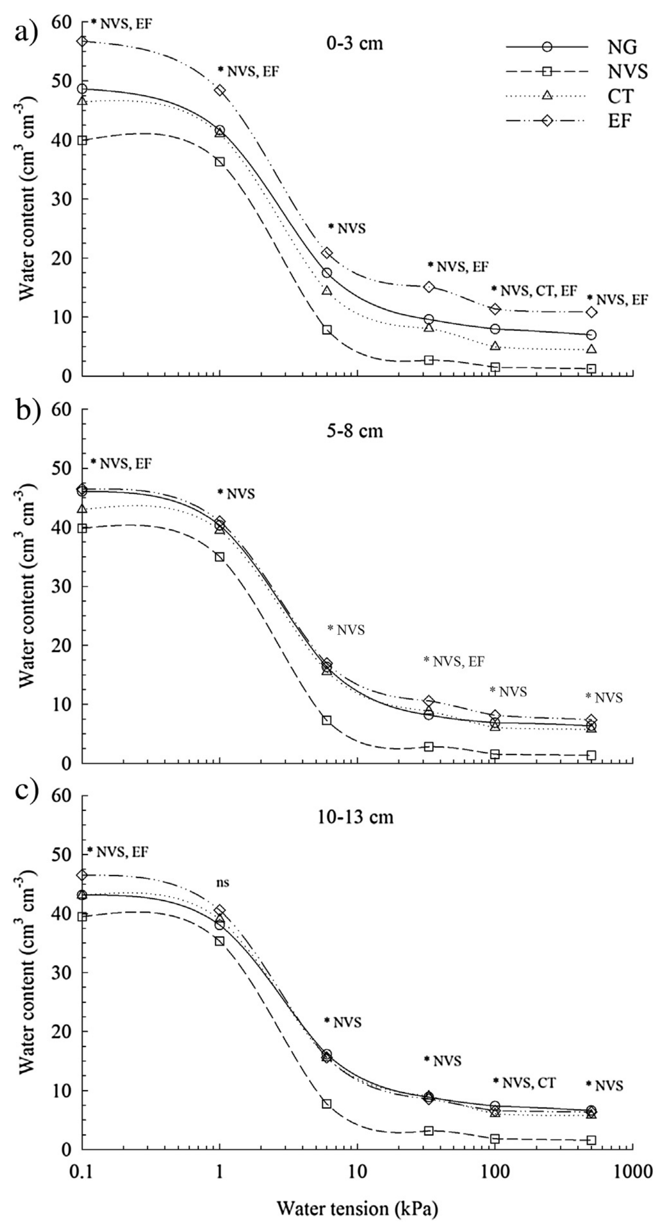

Fig. 6. Soil water retention in 0–3, 5–8 and 10–13 cm soil layers of a Quartzipsamment soil under four different land uses.
[1]NG: native grassland; NVS: extreme state of "sandyzation" or non-vegetated sand; CT: grain production in conventional tillage; EF: nine years-old eucalyptus forest.
[2]Means compared to the control NG by Dunnett test ($p < 0.05$): "*": means differ significantly from the control NG; ns: not significant.

Land uses caused differences in microporosity, as NVS had lowest microporosity: approximately 50% lower compared to the other land uses in all soil layers (Table 1). Greatest microporosity was observed for land uses with higher SOC content, namely EF. Hence, patterns in microporosity were very similar to the behavior of the SOC content, where the EF had higher microporosity in soil surface and decreased with increasing soil depth. Microporosity was higher in NG than in CT, where both land uses had similar behavior with depth. Furthermore, microporosity in CT was greater than in NVS.

Sharp reduction in water retained by soil pores from saturation to tension of 33 kPa was observed in all soil layers (0–3, 5–8 and 10–13 cm) for all land uses (Fig. 6). The proportion of the various soil pore classes were similar for all land uses, where the pores between 288 μm (1 kPa) and 48 μm (6 kPa) were responsible for most soil water storage (Fig. 6).

Greatest differences in water retention among land uses were observed in the 0–3 cm soil layer, where EF had highest and NVS had lowest water retention for all water tensions. NVS showed always significantly lowest water retention in all soil layers and water tensions compared to the control NG, except for 1 kPa in the 10–13 cm soil layer.

Water retention was statistically different between CT and NG only at 100 kPa in the 0–3 and 10–13 cm soil layers (Fig. 6). The EF provided significant increase in water retention in the 0–3 cm soil layer for most water tensions, except at 6 kPa. In the 5–8 and 10–13 cm soil layers, EF significantly increased water retention at saturation condition (Fig. 6).

High soil macroporosity (Table 1) was associated with high saturated hydraulic conductivity (Ks) (Fig. 7), which was always greater than 75 cm h^{-1} in all land uses. The NVS provided significant increase in Ks in all soil layers compared to Ks in NG. Even though Ks was high, the CT provided no significant differences in Ks compared to NG in all soil layers (Fig. 7). Soil Ks was high in the 0–3 cm soil layer for EF and decreased with increase in soil depth, where significant differences were observed in the 0–3 and 5–8 cm soil layers compared to NG (Fig. 7).

Water-stable soil aggregates were absent in NVS, where the soil solid mass was formed by single grains coated with some clay and iron oxides (visual observation). For other land uses, soil aggregation based on GMD and MWD decreased from EF to NG and to CT, where the decrease in CT was statistically different from NG (Table 2).

Proportion of aggregates from 8.00 to 4.76 and 4.76 to 2.00 mm decreased, whilst aggregates 2.00–1.00, 1.00–0.21 and <0.21 mm

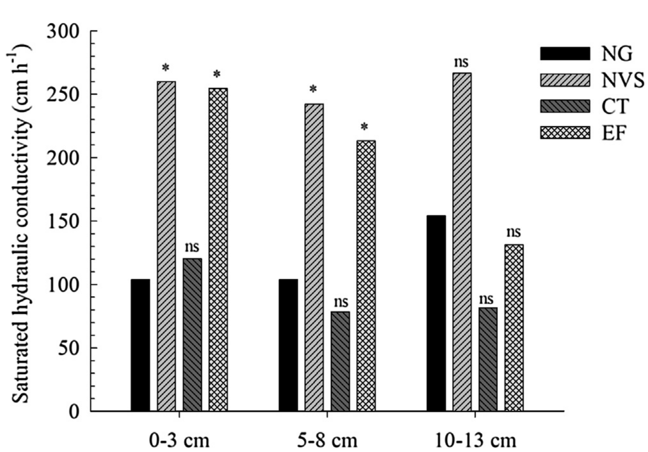

Fig. 7. Soil saturated hydraulic conductivity in 0–3, 5–8 and 10–13 cm soil layers of a Quartzipsamment soil under four different land uses.
[1]NG: native grassland; NVS: extreme state of "sandyzation" or non-vegetated sand; CT: grain production in conventional tillage; EF: nine years-old eucalyptus forest.

significantly increased in CT compared to NG when using the original analysis method (Table 2).

The EF provided increase in proportion of aggregate between 8.00 to 4.76 mm, and decrease in all other aggregate classes compared to NG when using the original analysis method, but significant difference was observed only for aggregate class between 4.76 and 2.00 mm (Table 2).

When using the modified analysis method, CT provided significant decrease in proportion of aggregates from 8.00 to 1.00 mm, and increase in proportion of aggregates < 0.21 mm (Table 2). However, EF had significant increase in proportion of aggregates from 8.00 to 4.76 mm, and increase in proportion of aggregates from 2.00 to 1.00 mm (Table 2).

For the samples sieved to only 8.00 mm diameter, the land use effect was more pronounced compared to those samples with aggregates only of 4.76–8.00 mm diameter.

4. Discussion

4.1. Soil organic carbon, cation exchange capacity, and exchangeable cations

Lowest soil organic carbon and consequently organic matter in NVS is partially due to the low clay content that provides little physical protection for organic matter against microbial decomposition, and high temperatures contribute further to high rates of biological oxidation of soil organic carbon (Bayer et al., 2000). Less protection of organic matter from microbial breakdown results in lower soil organic matter build up (McDonough and Vadakattu, 2010). These soils strive to increase soil organic matter content because of the sandy nature and high temperature. Rovedder (2003) observed temperatures of up to 49 °C at 3 cm depth at exposed soil in a sandynized area, but when area was revegetated with cover crops the soil temperature reduced by 18.6%.

Organic matter accumulation in soils with high sand content is more important than in clayey soils, due the fragile nature and difficulty in increasing organic matter in sandy soils. Debarba and Amado (1997) studied a shallow sandy-textured Alfisol with 9% clay and 73% sand, and observed that when the same soil was maintained bare the whole year the total annual loss of organic matter of the arable layer was equivalent to 10% of the total, so that only after a few years farming is not sustained economically anymore because of the reduced soil fertility and overall low soil quality.

In conventional tillage of non-sandynized soil, SOC was lower than in NG because of low biomass production, high biomass exportation by crops, and intense tillage. Continuous monocropping may cause decline in soil organic carbon, and the rate of decline depends on climate, soil and cropping systems and rotations (Reeves, 1997). Capurro et al. (2002) did not observe increment in organic carbon and aggregate stability in a study of a native pasture system substituted by oats in a sandy soil with 80% sand, although oat provided greater shoot biomass production.

In EF, the greatest accumulation of SOC compared to other land uses, mainly at the surface but also in deeper layers, shows the beneficial effect of implementation of forest systems in areas with potential occurrence of sandyzation. The greater SOC under eucalyptus forest is associated to high residue input, soil protection, and well developed root system, conditions that may, in addition to increasing the SOM, improve the physical quality and resistance to degradation of this type of soil that is fragile by nature and degraded by intense use and improper management. Twenty-nine-years of *Pinus elliottii* growth increased soil fertility of a sandynized soil by means of increased soil organic matter (Elesbão, 2011). Similarly to our study, the author observed increase in organic matter content three times greater than the

Table 2
Soil aggregate stability of a Quartzipsamment soil under three different land uses.

Aggregates classes and indexes	Method of Kemper & Chepil (25 g of aggregates from 4.76 to 8 mm)			Modified method of Kemper & Chepil (50 g of aggregates smaller than 8 mm)		
(mm)	NG[b,c]	CT	EF	NG	CT	EF
(%)						
8.00–4.76	32.5	12.0*	36.6ns	12.1	6.3*	21.4*
4.76–2.00	10.2	7.8*	7.0*	12.1	6.2*	11.7ns
2.00–1.00	0.9	2.4*	1.3ns	6.1	4.6*	4.9*
1.00–0.21	3.4	15.3*	2.8ns	12.0	14.7ns	7.0ns
<0.21	53.0	62.5*	52.4ns	57.6	68.3*	55.1ns
(mm)						
GMD[a] wet	0.6	0.3*	0.7ns	0.5	0.3*	0.5*
MWD wet	2.5	1.2*	2.7ns	1.4	0.8*	1.9*

Method of Kemper & Chepil (25 g of aggregates from 4.76 to 8 mm); Modified method of Kemper & Chepil (50 g of aggregates smaller than 8 mm).
[a] GMD: geometric mean diameter; MWD: mean weight diameter.
[b] NG: native grassland; CT: grain production in conventional tillage; EF: nine years-old eucalyptus forest.
[c] Means compared to the control NG by Dunnett test ($p < 0.05$): "*": means differ significantly from the control NG; ns: not significant.

initial value observed prior to the implementation of pines. Neufeldt et al. (2002) also observed higher SOC in eucalyptus forest than in grassland areas. Despite the poor soil, forest can be established to control and to reduce the sandyzation process as fast-growing (Rovedder and Eltz, 2008b).

In sandy soils, in addition to the organic carbon accumulation and the promotion of greater aggregate stability, organic matter is the main determinant of soil fertility, nutrient storage, and microbial and enzymatic activities (Neufeldt et al., 2002; Blanchart et al., 2004; Ashagrie et al., 2005). Low soil fertility of sandy soils may be minimized with cover plants, crop rotation, direct seeding systems, rotational grazing, soil mulch maintenance, split fertilization and liming, and addition of organic matter (Azevedo and Kaminski, 1995).

Any nutrient-holding capacity they may have come from coating of clay and organic matter on sand particles. Soil organic matter has specific surface area varying between 800 and 900 $m^2 g^{-1}$ (Meurer et al., 2006), and cation exchange capacity that can reach 1400 $cmol_c kg^{-1}$ (Canellas et al., 1999), with water- and nutrients-holding capacity much larger than sand, whose specific surface area is less than 0.10 $m^2 g^{-1}$ and cation exchange capacity is practically null. Thus, the lower CEC in NVS is mostly due to the lack of SOC, not only due to a lack of clay.

Soil nutrients, SOC and CEC had similar behavior, where the contents of exchangeable bases were higher for EF than NG and lower for NVS than NG. The higher concentration of nutrients in the EF in relation to NG is presumably a consequence of the greater accumulation of biomass, increase in SOC content and the slow release of nutrients to the soil by the slow decomposition of SOC. Nutrients contained in residues from secondary forest vegetation are slowly released to soil as observed for sandy Amazon soils (Denich et al., 2005; Reichert et al., 2015a).

Nutrient leaching in sandy soils is high, and most cations in colloid exchange sites are occupied by aluminum, resulting in high Al saturation, as observed in NVS. Soils in tropical regions have low nutrient reserve, and strong acidity and aluminum toxicity (Sanchez and Logan, 1992). Soil Al saturation is an indicator of poor environment for plant growth, resulting in low soil surface protection against climatic factors (wind and rain) which accelerate land degradation. In a review on aluminum toxicity in plants, Gupta et al. (2013) state that about 50% of the arable lands in the world are acid ($pH < 5.5$), in which absorbed aluminum inhibits root elongation and affects plant growth. Aluminum toxicity affects physical and cellular processes, inhibiting root growth and functioning. Root damage results in a reduced and damaged root system, thus limiting water and mineral nutrient uptake. Capurro et al. (2002) observed partial desiccation of native grassland in sandy soils decreased organic carbon and soil aggregation, and increased exchangeable Al.

4.2. Soil bulk density, porosity and aggregation

Spatial arrangement of particles and pore space defines the soil ecological environment, assessed by properties as soil density, geometry, size and continuity of pores, infiltration and water retention and aeration (Reichert et al., 2016). In our study, all bulk density values were less than 1.75 $g cm^{-3}$, the value which is considered critical for agricultural crops in sandy and sandy loam soils (Reichert et al., 2009c).

Eucalyptus forest had lower soil BD than NG in the surface layer (0–3 cm) and even in sub-surface layers (5–8 cm and 10–13 cm) possibly due the effect of organic matter accumulated on the surface during the eucalyptus growing period. The low density of the organic materials and the soil organic matter content, associated to their high elasticity (Braida et al., 2008), contribute to the formation of more stable, lower density aggregates, resulting in lower soil bulk density. The lower soil BD for EF compared to NG is related to more organic matter accumulated during the growing period in surface layers (0–3 cm and 5–8 cm), while in the sub-surface layer (10–13 cm) the SOM was less and, consequently, soil BD was higher. The EF and CT had similar soil bulk density and total porosity compared to NG in deepest soil layer (10–13 cm), clearly showing the effects of SOM accumulated mainly in the surface-most soil layer. Similarly to our study, John et al. (2005) observed lower BD in eucalyptus forest than in grassland and crop areas, and the BD behavior was related to SOC. John et al. (2005) and Zinn et al. (2011) observed lower BD in surface than in sub-surface layer for eucalyptus forest related to SOC. In sandy Amazon soils under secondary forest vegetation, the amplitude of soil BD was similar to the range of our study, namely from 1.24 to 1.46 $g cm^{-3}$ (Reichert et al., 2015a).

The increase in total porosity was not because of increased macroporosity, as noted by Reichert et al. (2015a), but due to combined changes in macro and soil microporosity. Microporosity is influenced by soil texture and organic carbon (Guedes et al., 2012). Soil macroporosity was greater than critical limit for plant growth of 0.10 $cm^3 cm^{-3}$, in all soil layers and land uses, which maintains adequate levels of soil aeration and gas exchange (Drewry et al., 2008). A very low degree of compactness may be an indication of very loose soil that affects water retention and soil-seed contact (Reynolds et al., 2007) and reduces crop yield, just as does high degree of compactness (Reichert et al., 2009c).

Nevertheless, soil gas and water flow depends upon soil pore-size distribution and pore continuity (Mentges et al., 2016), which affect root growth, water retention and availability and temperature amplitude.

The size distribution of the aggregates was not evaluated in NVS due to lack of soil structure, caused by the high content of sand particles in the absence of SOC, which reduces bonds between particles and thus has high effect on soil aggregation. Sandy soils are characterized by weak structure or no structure (Lima et al., 2006). This behavior shows the high natural soil fragility and the need for strategies to increase the content of soil organic matter, structure and aggregate stability. For other land uses, despite of some differences, all aggregation indicators showed similar trend and had close association with SOC stock.

Conventional soil tillage reduced larger aggregates (8.00–4.76 mm) by decreasing their stability, and increased the amount of small aggregates (<2.00 mm). Aggregate stability decreases in bare soil (Wohlenberg et al., 2004; Torres et al., 2015), in tilled soil compared to no-till (Reinert et al., 1984; Campos et al., 1995; Loss et al., 2015), and with increase in frequency and intensity of tillage (Da Ros et al., 1997). Even if the organic carbon content is higher in the conventional system compared to NVS, soil tillage ruptures soil aggregates and stimulates microbial decomposition of soil organic matter, reducing aggregating substances and aggregate stability (Flores et al., 2008). When compared to clay soils situated in colder climate, organic matter decomposition rate is intensified in sandy texture soils in warm climate regions (Six et al., 2002), as is the case in our study especially for CT and NVS land uses. Since the main aggregating agents iron and aluminum oxides and organic matter are scarce in sandy soils (Reichert and Norton, 1994), conservational agriculture such as direct seeding and forest systems must be adopted to improve soil structure.

Due to maintenance of organic material and soil moisture and environmental conditions favorable to the development of microorganisms and plants, direct seeding or maintenance of natural vegetation may promote microbial activity that results in water stable aggregates (Campos et al., 1995). This behavior can be demonstrated by comparing the stability of CT and NG aggregates, in which similar SOC provided differences in aggregate stability. Organic matter in various stages of decomposition, activity and nature of microorganisms, and action of plant rooting system is highly variable considering the various possibilities of organic matter sources, variation of microorganisms, types of rooting systems, and local soil and climate conditions. Hence, soil structure is highly dynamic in the various agricultural environments and in time (Wohlenberg et al., 2004), thus requiring continuous addition of organic material to maintain adequate soil structure for crop development (Campos et al., 1995). Roots of plants, although only a small fraction of the organic constituents of soil, exert great influence on the formation and stability of soil aggregates (Silva and Mielniczuk, 1997). In our study, organic matter and, possibly, roots had a significant effect on aggregate stability in EF and NG land uses.

Although advantageous for all soils, the positive effects of organic matter are more pronounced in sandy soils. These soils are more susceptible to changes in soil structure, although their recovery is also faster compared to clay soils. Choosing crops with large amount of biomass production and displaying vigorous root system well distributed throughout the soil profile is critical to maintaining soil structural quality and organic matter increase with depth (Reichert et al., 2007).

Soil quickly reconsolidates with the lack or reduced effect of organic matter on soil structure and system equilibrium. Further, leaving plant residues from mulching secondary vegetation on the soil is not, by itself, an effective practice for maintaining structural soil quality in the short term (Reichert et al., 2014), highlighting the importance of the introduction and maintenance of forest components to increase soil aggregation, as observed for SOC that provided stability of larger aggregates. Flores et al. (2008) observed that conventional soil tillage compared to native forests reduced the abundance of larger aggregates by decreasing their stability and organic matter content by 60%, in a sandy loam soil.

4.3. Soil hydraulic properties: water retention and hydraulic conductivity

Land uses provided differences in soil capacity properties (Reichert et al., 2016) such pore size distribution and the amount of water retention, and in soil intensity properties like water conductivity. As organic matter has higher cation exchange capacity than mineral fractions, organic matter retains a larger amount of water than sand (Braida et al., 2008). Furthermore, organic matter has higher specific surface and the ability to create micropores and to bind other particles to create finer, thus better retaining, pores. Thus, in land use EF with greatest SOC content, the combined effect of organic matter in improving soil structure, aggregate stability and increased CEC provided greater soil water retention in all studied tensions. The major difference between land uses in soil water retention was observed in the surface layer (0–3 cm) and decreased with depth, which is consistent with changes in SOC.

Similarly to our study, sandy texture and high macroporosity of a sandy Amazonian soil were responsible for high amount of drainable water, sharp reduction in the volume of water retained in the pores from saturation to field capacity, from soil saturation until field capacity, down to 0.20 m depth in all systems (Reichert et al., 2015b). Using a literature database for Rio Grande do Sul soils, Reichert et al. (2009b) quantified less water retention at 10 kPa tension (field capacity) and 1500 kPa (permanent wilting point), and water availability to plants for sandy classes because of their low specific surface area, as observed in our study, especially for NVS. Furthermore, soil pores had greater diameter and that water availability was low in sandy soil (Fidalski et al., 2013), and, combined with low unsaturated hydraulic conductivity, thus posing high risk also of water stress

Since pore size distribution and texture influence water retention, the soil's permeability for water was different among the land uses (Fig. 7). In a sandy soil with a clay content of only 0.25% in the whole profile, Prevedello et al. (1995) measured saturated hydraulic conductivity (Ks) values from 1.1×10^{-6} to 7.5×10^{-5} m s^{-1}, compared to our slightly lower Ks values ranging from about 2.8×10^{-5} to 7×10^{-5} m s^{-1}. Eucalyptus forest, which had highest SOC, aggregation and possibly greater amount of bioporos, i. e. vertical pores, and NVS showed comparable results for Ks, which suggests high water fluxes in this soil for both land conditions, i. e., degraded and improved state compared to the original condition (NG). High Ks was observed for NVS in all soil layers due to the absence of soil structure, whilst for EF soil Ks was higher in surface layer and reduces with soil depth. This behavior was related to soil structure provided by SOC.

Our results showed that land use with higher SOC had greater water retention and saturated hydraulic conductivity, with agrees with Rawls et al. (2003). For low soil carbon contents, they observed that an increase in organic matter augmented water retention only in sandy soils; for high soil carbon content, organic matter increase increased water retention in all soils, independently of granulometry. Although in surfacemost layers (0–3 cm and 5–8 cm) the improved (EF) and the highly degraded (NVS) soil condition had greater Ks than the control NG. There are two different reasons for this behavior: for EF conductivity increased due to soil structure improvement, whereas for NVS this increase is probably associated to highly sandy nature of the degraded land.

Higher Ks is not necessarily equal to an “improved” Ks. Heavy rainfall events are surely well absorbed by a higher Ks but it means also that water infiltrates fast into deeper layers, where it is possible unavailable for the plant (roots). Conservation systems, forest plantation or native vegetation should be adopted in an attempt to maintain or improve soil quality, especially for intensity properties as soil hydraulic conductivity, which is considered a dynamic property and exhibits variations in time and space (Reichert et al., 2016).

5. Implications of the present study on the prevention of sandyzation

Although many conditions contribute to desertification, these can be determined either by climate change, mainly characterized by an increasing deficiency of rainfall, and by anthropic interventions (Nimer, 1980, 1988) or by a combination of both. In Southern Brazil, the desertification processes are not observed, but sandyzation process occurs in the southwestern sector of the State, especially in the sub-region known as Campanha Gaúcha (Suertgaray and Verdum, 2008), where sandyzation is a result from the reworking of non-consolidated surface sands that are constantly mobilized, which in turn hinder the vegetation from fixing itself (Suertegaray, 1987). For these surface formations, probably quaternary, reworking of sandy deposits resulted from morphogenetic dynamics, where surface runoff expose, transport, and deposit sand, particularly the concentrated flows in gullies. The resulting sand formations tend to be constantly moved by winds. Nutrient loss and mobilization make it difficult for pedogenesis and vegetation growth to progress. Sand deposits are the final result, locally known as “areais” (sand deposits with no vegetation cover).

Earlier hypotheses link the origin of this soil degradation process to anthropogenic causes. For instance, Souto (1984) proposed that the origins of these sands are mostly linked to grassland overgrazing and soil mismanagement. Although acknowledging the soil as fragile, Souto (1984) considered the phenomenon to be caused by anthropic soil misuse, proposing soil recovery by planting exotic forests, mainly eucalyptus.

Climatic risks for agriculture in these regions are high, making farming a high-risk activity. The “Agricultural Zoning of Climatic Risk” (MAPA, 2015) has the goal of minimizing the climate-related crop losses. Since clay content is usually less than 10%, most sandy soils present are not suitable to grow most crops of economic interest, or have a very-short period for planting, especially annual crops like soybeans, corn and beans.

Many soils used for crop production during the summer become bare soils in the winter. Besides the use of cover plants, crop-livestock integration is an interesting alternative (Costa et al., 2015; Fidalski and Alves, 2015; Cecagno et al., 2016). However, intense care must be practiced to reduced soil structure degradation because of greater intensity of land use in crop-livestock integration system.

Direct seeding with crop rotation and mulch supply arises as an alternative to minimizing losses and improving the soil environment. For instance, a sandy-loam soil under direct seeding for 15 years presented the best physico-hydraulic conditions and remained longer within the range of optimal moisture for the growth and development of common bean and soybean, compared to chiseling and conventional tillage (Lima et al., 2006). Direct seeding presented the lowest maximum temperature and lower variation of daily soil temperature, increased moisture in the surface layer, remaining longer in the range of water available for plants in function of soil cover, which reduced evaporation losses when compared to conventional tillage and reduced tillage (Salton and Mielniczuk, 1995).

For erosive processes control in sandy soils in the Campanha region, Klamt and Schneider (1995) recommend, in addition to the maintenance of plant cover and their establishment in NVS, the construction of divergent channels and waterways and placement of fences to avoid grazing and trampling by animals, one of the causes of accelerated erosive processes. Areas already affected by water or wind erosion must be fenced and natural vegetation restored or forested with species adapted to conditions of soil instability and low nutrient availability. Further, Rovedder and Eltz (2008b) indicate the use of eucalyptus to contain the sandyzation process, but in consortium with cover plants of fast growth to reduce the abrasive effects of sediments in suspension due to wind erosion and the exposure of the roots.

6. Conclusions

Eucalyptus forest was the most efficient system to retain soil total organic carbon, after the conversion of native grassland to conventional tillage, planted forest and non-vegetated sand.

Most cation exchange capacity of the investigated sandy soils is due to total organic carbon, thus low organic carbon of non-vegetated sand area represented a significant loss in soil cation exchange capacity, leaching of exchangeable bases, and high aluminum saturation. The later restricts plant growth and reduces soil cover, thus contributing to an environment prone to wind erosion.

Greater soil physical changes are observed at the soil surface, and are closely related to soil organic matter, which in turn affects aggregate formation and stability, pore size distribution, and soil permeability, and seems to be the driving force to resist soil degradation. Water aggregate stability rank was eucalyptus forest > native grassland > conventional tillage. Soil physical properties indicate an extreme state of degradation of non-vegetated sand area with 98% of sand, where complete absence of aggregation is observed and with very-high saturated hydraulic conductivity.

Careful management of these sandy soils is needed and could be met well by implementing forest stands, to avoid the devastating effect of sandyzation.While the focus of our study was on sandy soil from southern Brazil, similar consideration are valid for the Cerrado region where, for instance, the Botucatu (sandstone) formation is present, particularly for highly erodible soils such as Quartzipsamment (“Neossolos Quartzarênicos”), with long, low slopes, and improper land use and soil management.

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References

Álvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Z. 22, 711–728. doi: http://dx.doi.org/10.1127/0941-2948/2013/0507.
Agostini, J.H.E., Kaminski, J., 1976. Estudo preliminar das concentrações de nutrientes em solos e pastagens naturais ocorrentes em diferentes regiões do Rio Grande do Sul. Rev. Centro Cienc. Rurais 6, 385–406.
Andrades, C.O., Suertegaray, D.M.A., Guasselli, L.A., 2005. Atualização do mapeamento e quantificação dos areais do sudoeste do RS através de imagens LANDSAT TM. 17. Salão de Iniciação Científica da UFRGS.
Ashagrie, Y., Zech, W., Guggenberger, G., 2005. Transformation of a Podocarpus falcatus dominated natural forest into a monoculture Eucalyptus globulus plantation at Munesa, Ethiopia: soil organic C, N and S dynamics in primary particle and aggregate-size fractions. Agric. Ecosyst. Environ. 106, 89–98. doi: http://dx.doi.org/10.1016/j.agee.2004.07.015.
Azevedo, A.C., Kaminski, J., 1995. Considerações sobre os solos dos campos de areia no Rio Grande do Sul. Ciênc. Ambiente 11, 65–70.
Bayer, C., Mielniczuk, J., Martin-Neto, L., 2000. Efeitos de sistemas de preparo e de cultura na dinâmica da matéria orgânica e na mitigação das emissões de CO_2.

Rev. Bras. Cienc. Solo 24, 599–607. doi:http://dx.doi.org/10.1590/S0100-06832000000300013.
Bayer, C., Dick, D.P., Ribeiro, G.M., Scheuermann, K.K., 2002. Carbon stocks in organic matter fractions as affected by land use and soil management, with emphasis on no-tillage effect. Cienc. Rural 32, 401–406. doi:http://dx.doi.org/10.1590/S0103-84782002000300006.
Bellanca, E.T., Suertegaray, D.M.A., 2003. Sítios arqueológicos e areais no sudoeste do Rio Grande do Sul. Mercator. Rev. Geogr. UFC 4, 99–114.
Blanchart E., Albrecht A., Bernoux M., Brauman A., Chotte J.L., Feller C., Ganry F., Hien E., Manlay R., Mase D., Sall S., Villenave C., 2004. Organic matter and biofunctioning in tropical sandy soils and implications for its management. In: FAO Corporate Document Repository. Regional Office for Asia and the Pacific. Management of tropical Sandy soils for sustainable agriculture. 1–33. Available in http://www.fao.org/docrep/010/ag125e/AG125E19.htm#TopOfPage (accessed 19.07.15.).
Bombin, M., Klamt, E., 1974. Evidências paleoclimáticas em solos do Rio Grande do Sul. Comun. Museu Ciênc. PUCRS 13, 183–193.
Braida, J.A., Reichert, J.M., Reinert, D.J., Sequinatto, L., 2008. Elasticidade do solo em função da umidade e do teor de carbono orgânico. Rev. Bras. Cienc. Solo 32, 477–485. doi:http://dx.doi.org/10.1590/S0100-06832008000200002.
Bruand A., Hartmann C., Lesturgez G., 2005. Physical properties of tropical sandy soils: A large range of behaviors. In: Management of Tropical Sandy Soils for Sustainable Agriculture: A holistic approach for sustainable development of problem soils in the tropics. Khon Kaen, Thailand. 2005, 27.11.2005 au 2.12.2005. Proceedings 148–158.
Campos, B.C., Reinert, D.J., Nicolodi, R., Ruedel, J., Petrere, C., 1995. Estabilidade estrutural de um Latossolo vermelho-escuro distrófico após sete anos de rotação de culturas e sistemas de manejo de solo. Rev. Bras. Cienc. Solo 19, 121–126.
Canellas, L.P., Santos, G.A., Amaral, N.B.M., 1999. Reações da matéria orgânica. In: Santos, G.A., Camargo, F.A.O. (Eds.), Fundamentos da matéria orgânica do solo: ecossistemas tropicais e subtropicais. Gênesis, Porto Alegre (508 p).
Capurro, E.P.G., Reichert, J.M., Reinert, D.J., García, F., 2002. Atributos do solo e biomassa radicular após quatro anos de semeadura direta de forrageiras de estação fria em campo natural dessecado com herbicidas. Rev. Bras. Cienc. Solo 26, 211–223. doi:http://dx.doi.org/10.1590/S0100-06832002000100022.
Cecagno, D., De Andrade Costa, S.E.V.G., Anghinoni, I., Kunrath, T.R., Martins, A.P., Reichert, J.M., Gubiani, P.I., Balerini, F., Fink, J.R., De Faccio Carvalho, P.C., 2016. Least limiting water range and soybean yield in a long-term, no-till, integrated crop-livestock system under different grazing intensities. Soil Tillage Res. 156, 54–62. doi:http://dx.doi.org/10.1016/j.still.2015.10.005.
Cordeiro, C.A., Soares, L.C., 1975. A erosão nos solos arenosos da região sudoeste do Rio Grande do Sul. Revista Brasileira de Geografia 4, 32–50.
Costa, N.R., Andreotti, M., Lopes, K.S.M., Yokobatake, K.L., Ferreira, J.P., Pariz, C.M., Bonini, C.S.B., Longhini, V.Z., 2015. Atributos do solo e acúmulo de carbono na integração lavoura-pecuária em sistema plantio direto. Rev. Bras. Cienc. Solo 39, 852–863. doi:http://dx.doi.org/10.1590/01000683rbcs20140269.
Da Ros, C.O., Secco, D., Fiorin, J.E., Petrere, C., Cadore, M.A., Pasa, L., 1997. Manejo do solo a partir de campo nativo: efeito sobre a forma e estabilidade da estrutura ao final de cinco anos. Rev. Bras. Cienc. Solo 21, 241–247.
Debarba, L., Amado, T.J.C., 1997. Desenvolvimento de sistemas de produção de milho no sul do Brasil com características de sustentabilidade. Rev. Bras. Cienc. Solo 21, 473–480. doi:http://dx.doi.org/10.1590/S0100-06831997000300017.
Denich, M., Vlek, P.L.G., Sá, T.D.A., Vielhauer, K., Lucke, W.G., 2005. A concept for the development of fire-free fallow management in the Eastern Amazon. Braz. Agric. Ecosyst. Environ. 110, 43–58. doi:http://dx.doi.org/10.1016/j.agee.2005.05.005.
Drewry, J.J., Cameron, K.C., Buchan, G.D., 2008. Pasture yield and soil physical property responses to soil compaction from treading and grazing- a review. Soil Res. 46, 237–256. doi:http://dx.doi.org/10.1071/SR07125.
Elesbão, L.E.G., 2011. Performance do *Pinus elliottii* Engelm. E *Pinus taeda* L. em áreas arenizadas e degradadas no oeste do Rio Grande do Sul. 155f. Tese (Doutorado em Engenharia Florestal). Universidade Federal de Santa Maria.
Embrapa, 2006. Empresa Brasileira de Pesquisa Agropecuária. Sistema Brasileiro de Classificação de Solos. Embrapa, Brasília 306 p.
Fidalski, J., Alves, S.J., 2015. Altura de pastejo de braquiária e carga animal limitada pelos atributos físicos do solo em sistema integração lavoura-pecuária com soja. Rev. Bras. Cienc. Solo 39, 864–870. doi:http://dx.doi.org/10.1590/01000683rbcs20140667.
Fidalski, J., Tormena, C.A., Alves, S.J., Auler, P.A.M., 2013. Influência das frações de areia na retenção e disponibilidade de água em solos das formações Caiuá e Paranavaí. Rev. Bras. Cienc. Solo 37, 613–621. doi:http://dx.doi.org/10.1590/S0100-06832013000300007.
Flores, C.A., Reinert, D.J., Reichert, J.M., Albuquerque, J.A., Pauletto, E.A., 2008. Recuperação da qualidade estrutural, pelo sistema plantio direto, de um Argissolo Vermelho. Cienc. Rural 38, 2164–2172. doi:http://dx.doi.org/10.1590/S0103-84782008000800012.
Genro Júnior, S.A., Reinert, D.J., Reichert, J.M., Albuquerque, J.A., 2009. Atributos físicos de um Latossolo Vermelho e produtividade de culturas cultivadas em sucessão e rotação. Cienc. Rural 39, 65–73. doi:http://dx.doi.org/10.1590/S0103-84782009000100011.
Gubiani, P.I., Reinert, D.J., Reichert, J.M., 2006. Método alternativo para a determinação da densidade de partículas do solo: exatidão, precisão e tempo de processamento. Cienc. Rural 36, 664–668. doi:http://dx.doi.org/10.1590/S0103-84782006000200049.
Guedes, E.M.S., Fernandes, A.R., Lima, H.V., Serra, A.P., Costa, J.R., Guedes, R.S., 2012. Impacts of different management systems on the physical quality of an Amazonian Oxisol. Rev. Bras. Cienc. Solo 36, 1269–1277. doi:http://dx.doi.org/10.1590/S0100-06832012000400021.
Gupta, N., Gaurav, S.S., Kumar, A., 2013. Molecular basis of aluminium toxicity in plants: a review. Am. J. Plant Sci. 4, 21–37. doi:http://dx.doi.org/10.4236/ajps.2013.412A3004.
Instituto Nacional de Meteorologia (INMET), 2012. Estações Automáticas: Estação: Alegrete-A826. Dados. Available at: http://www.inmet.gov.br (accessed 09.08.16.).
John, B., Yamashita, T., Ludwig, B., Flessa, H., 2005. Storage of organic carbon in aggregate and density fractions of silty soils under different types of land use. Geoderma 128, 63–79. doi:http://dx.doi.org/10.1016/j.geoderma.2004.12.013.
Kemper, W.D., Chepil, W.S., 1965. Size distribution of aggregates. In: Black, C.A., Evans, D.D., White, J.L., Eniminger, L.E., Clark, F.E. (Eds.), Methods of soil analysis: physical and mineralogical properties, including statistics of measurement and sampling. Part 1. ASA, Madison, pp. 499–510.
Klamt, E., Schneider, P., 1995. Solos suscetíveis à erosão eólica e hídrica na região da campanha do Rio Grande do Sul. Ciênc. Ambiente 11, 71–80.
Klute, A., 1986. Methods of Soil Analysis: Physical and Mineralogical Methods, 2nd. American Society of Agronomy, Soil Science Society of America, Madison.
Lima, C.L.R., Reinert, D.J., Reichert, J.M., Suzuki, L.E.A.S., Gubiani, P.I., 2006. Qualidade físico-hídrica e rendimento de soja (*Glycine Max* L.) e feijão (*Phaseolus vulgaris* L.) de um Argissolo Vermelho distrófico sob diferentes sistemas de manejo. Cienc. Rural 36, 1172–1178. doi:http://dx.doi.org/10.1590/S0103-84782006000400020.
Loss, A., Basso, A., Oliveira, B.S., Koucher, L.P., Oliveira, R.A., Kurtz, C., Lovato, P.E., Curmi, P., Brunetto, G., Comin, J.J., 2015. Carbono orgânico total e agregação do solo em sistema de plantio direto agroecológico e convencional de cebola. Rev. Bras. Cienc. Solo 39, 1212–1224. http://dx.doi.org/10.1590/01000683rbcs20140718.
MAPA, 2015. Ministério da Agricultura, Pecuária e Abastecimento. Zoneamento agrícola de riso climático. Available at: http://www.agricultura.gov.br/politica-agricola/zoneamento-agricola (accessed 16.05.15.).
Marchiori, J.N.C., 1995. Vegetação e Areais no Sudoeste do Rio Grande do Sul. Rev. Ciênc. Ambiente 11, 81–92.
McDonough, C., Vadakattu, G., 2010. Success with Sandy Soils. Farm Talk 2p.
Mentges, M.I., Reichert, J.M., Rodrigues, M.F., Awe, G.O., Mentges, L.R., 2016. Capacity and intensity soil aeration properties affected by granulometry, moisture, and structure in no-tillage soils. Geoderma 263, 47–59. doi:http://dx.doi.org/10.1016/j.geoderma.2015.08.042.
Meurer, E.J., Rhenheimer, D., Bissani, C.A., 2006. Fenômeno de sorção em solos, In: Meurer, E.J. (Ed.), Fundamentos de química do solo. 3 ed. revisada e ampliada Evangraf, Porto Alegre, pp. 117–162.
Nelson, E.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter, In: Page, A.L. (Ed.), Methods of Soil Analysis. Part 2. 2nd ed. Agronomy Monograph 9. ASA and SSSA, Madison, pp. 539–579.
Neufeldt, H., Resck, D.V.S., Ayarza, M.A., 2002. Texture and land-use effects on soil organic matter in Cerrado Oxisols, Central Brazil. Geoderma 107, 151–164. doi:http://dx.doi.org/10.1016/S0016-7061(01)00145-8.
Nimer, E., 1980. Subsídio ao plano de ação mundial para combater a desertificação—Programa das Nações Unidas para o Meio Ambiente. Rev. Bras. Geogr. 42, 612–627.
Nimer, E., 1988. Desertificação: realidade ou mito? Rev. Bras. Geogr. 50, 7–39.
Panayiotopoulos, K.P., Mullins, C.E., 1985. Packing of sands. J. Soil Sci. 36, 129–139.
Prevedello, C.L., Kobiyama, M., Jacobs, G.A., Divardin, C.R., 1995. Comparação dos métodos do perfil instantâneo e de van Genuchten na obtenção da condutividade hidráulica de uma areia marinha. Rev. Bras. Cienc. Solo 19, 1–5.
Ramos, M.F., Strieder, G., Lima, L.S.C., Pedron, F.A., Suzuki, L.E.A.S., 2014. Grau de compactação de solos arenosos altamente suscetíveis à erosão. In: Reunião Sul-Brasileira de Ciência do Solo, 10, Pelotas, 2014. Anais . . . Pelotas. 3p.
Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil organic carbon on soil retention. Geoderma 116, 61–76. doi:http://dx.doi.org/10.1016/S0016-7061(03)00094-6.
Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res. 43, 131–167. doi:http://dx.doi.org/10.1016/S0167-1987(97)00038-X.
Reichert, J.M., Norton, L.D., 1994. Aggregate stability and rain-impacted sheet erosion of air-dried and prewetted clayey surface soils under intense rain. Soil Sci. 158, 159–169. doi:http://dx.doi.org/10.1097/00010694-199409000-00001.
Reichert, J.M., Norton, L.D., 1995. Surface seal morphology as affected by fluidized bed combustion bottom-ash. Soil Technol. 7, 303–317. doi:http://dx.doi.org/10.1016/0933-3630(94)00015-V.
Reichert, J.M., Norton, L.D., 1996. Fluidized bed combustion bottom-ash effects on infiltration and erosion of variable charge soil. Soil Sci. Soc. Am. J. 60, 275–282. doi:http://dx.doi.org/10.2136/sssaj1996.03615995006000010042x.
Reichert, J.M., Suzuki, L.E.A.S., Reinert, D.J., 2007. Compactação do solo em sistemas agropecuários e florestais: identificação, efeitos, limites críticos e mitigação. Tópicos Ciência Solo 5, 49–134.
Reichert, J.M., Albuquerque, J.A., Kaiser, D.R., Reinert, D.J., Urach, F.L., Carlesso, R., 2009a. Estimation of water retention and availability in soils of Rio Grande do Sul. Rev. Bras. Cienc. Solo 33, 1547–1560. doi:http://dx.doi.org/10.1590/S0100-06832009000600004.
Reichert, J.M., Norton, L.D., Favaretto, N., Huang, C., Blume, E., 2009b. Settling velocity, aggregate stability, and interrill erodibility of soils varying in clay

mineralogy. Soil Sci. Soc. Am. J. 73, 1369–1377. doi:http://dx.doi.org/10.2136/sssaj2007.0067.
Reichert, J.M., Suzuki, L.E.A.S., Reinert, D.J., Horn, R., Håkansson, I., 2009c. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Tillage Res. 102, 242–254. doi:http://dx.doi.org/10.1016/j.still.2008.07.002.
Reichert, J.M., Bervald, C.M.P., Rodrigues, M.F., Kato, O.R., Reinert, D.J., 2014. Mechanized land preparation in eastern Amazon in fire-free forest-based fallow systems as alternatives to slash-and-burn practices: hydraulic and mechanical soil properties. Agric. Ecosyst. Environ. 192, 47–60. doi:http://dx.doi.org/10.1016/j.agee.2014.03.046.
Reichert, J.M., Rodrigues, M.F., Bervald, C.M.P., Brunetto, G., Kato, O.R., Schumacher, M.V., 2015a. Fragmentation, fiber separation, decomposition, and nutrient release of secondary-forest biomass, mechanically chopped-and-mulched, and cassava production in the Amazon. Agric. Ecosyst. Environ. 204, 8–16. doi:http://dx.doi.org/10.1016/j.agee.2015.02.005.
Reichert, J.M., Rodrigues, M.F., Bervald, C.M.P., Kato, O.R., 2015b. Fire-free fallow management by mechanized chopping of biomass for sustainable agriculture in eastern Amazon: effects on soil compactness, porosity, and water retention and availability. Land Degrad. Dev. 27 doi:http://dx.doi.org/10.1002/ldr.2395.
Reichert, J.M., Rosa, V.T., Vogelmann, E.S., Rosa, D.P., Horn, R., Reinert, D.J., Sattler, A., Denardin, J.E., 2016. Conceptual framework for capacity and intensity physical soil properties affected by short and long-term (14 years) continuous no-tillage and controlled traffic. Soil Tillage Res. 158, 123–136. doi:http://dx.doi.org/10.1016/j.still.2015.11.010.
Reinert, D.J., Mutti, L.S.M., Zago, A., Azolin, M.A.D., Hoffmann, C.L., 1984. Efeito de diferentes métodos de preparo do solo sobre a estabilidade de agregados em Solo Podzólico Vermelho-Amarelo. Rev. Centro Ciênc. Rurais 14, 19–25.
Reinert, D.J., 1998. Recuperação de solos em sistemas agropastoris. In: Dias, L.E., Mello, J.W.V. (ed.) Recuperação de áreas degradadas. p. 163–176. Sociedade Brasileira de Recuperação de Áreas Degradadas. Viçosa.
Reynolds, W.D., Drury, C.F., Yang, X.M., Fox, C.A., Tan, C.S., Zhang, T.Q., 2007. Land management effects on the nearsurface physical quality of a clay loam soil. Soil Tillage Res. 96, 316–330. doi:http://dx.doi.org/10.1016/j.still.2007.07.003.
Rovedder, A.P.M., Eltz, F.L.F., 2008a. Revegetação com plantas de cobertura em solos arenizados sob erosão eólica no Rio Grande do Sul. Rev. Bras. Cienc. Solo 32, 315–321. doi:http://dx.doi.org/10.1590/S0100-06832008000100029.
Rovedder, A.P.M., Eltz, F.L.F., 2008b. Desenvolvimento de *Pinus elliottii* e do *Eucalyptus tereticornis* consorciado com plantas de cobertura, em solos degradados por arenização. Cienc. Rural 38, 84–89. doi:http://dx.doi.org/10.1590/S0103-84782008000100014.
Rovedder, 2003. Revegetação com culturas de cobertura e espécies florestais para contenção do processo de arenização em solos areníticos no sudoeste do Rio Grande do Sul. Universidade Federal de Santa Maria, Mestrado (Ciência do Solo).
Salton, J.C., Mielniczuk, J., 1995. Relações entre sistemas de preparo, temperatura e umidade de um podzólico vermelho-escuro de Eldorado do Sul (RS). Rev. Bras. Cienc. Solo 19, 313–319.
Sanchez P.A., Logan T.J., 1992. Myths and science about the chemistry and fertility of soils in the tropics. In: Lal, R., Sanchez, P.A. Myths and science about the chemistry and fertility of soils in the tropics. Madison: Soil Science Society of America and American Society of Agronomy. p. 35–46. (SSSA Special Publication 29).
Scopel, I., Sousa, M.S., Peixinho, D.M., Martins, A.P., 2013. Levantamento de áreas sob arenização e relações com o uso da terra no sudoeste de Goiás e no Sudoeste do Rio Grande do Sul—Brasil. Observat. Rev. Eletrôn. Geogr. 5, 24–47.
Silva, I.F., Mielniczuk, J., 1997. Ação do sistema radicular de plantas na formação e estabilização de agregados do solo. Rev. Bras. Cienc. Solo 21, 113–117.
Six, J., Feller, C., Denef, K., Ogle, S.M., Sá, J.C.M., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soilsáeffects of no-tillage. Agronomie 22, 755–775. doi:http://dx.doi.org/10.1051/agro:2002043.
Soares, M.P., Reys, P., Pifano, D.S., Sá, J.L., de Silva, P.O., da Santos, T.M., Silva, F.G., 2015. Relationship between edaphic factors and vegetation in savannas of the Brazilian Midwest region. Rev. Bras. Cienc. Solo 39, 821–829. doi:http://dx.doi.org/10.1590/01000683rbcs20130726.
Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.
Souto, J.J.P., 1984. Deserto, uma ameaça? Estudos dos núcleos de desertificação na fronteira sudoeste do RS. Secretaria da Agricultura. Porto Alegre, p. 172.
Suertegaray, D.M.A., Verdum. R., 2008. Desertification in the Tropics. In Encyclopedia of Life Support Systems (EOLSS) [Eds. Del Claro, K., Oliveira, P.S., Rico-Gray, V., Ramirez, A., Barbosa, A.A.A., Bonet, A., Scarano, F.R., Consoli, F.L., Garzon, F.J.M., Nakajima, J.N., Costello, J.A., Sampaio, M.V., Quesada, M., Morris, M.R., Rios, M.P., Ramirez, N., Marçal Junior, O., Macedo, R.H.F., Marquis, R.J., Martins, R.P., Rodrigues, S.C., Luttge, U.]. Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford,UK [http://www.eolss.net].
Suertegaray, D.M.A., Verdum, R., Bellanca, E.T., Uagoda, R.S., 2005. Sobre a gênese da arenização no sudoeste do Rio Grande do Sul. Rev. Terra Livre 1, 135–150.
Suertegaray, D.M.A., 1987. A trajetória da natureza: um estudo geomorfológico sobre os areais de Quaraí-RS. 243f. Tese (Doutorado—Faculdade de Filosofia, Letras e Ciências Humanas), Universidade de São Paulo, 243 p.
Suertegaray, D.M.A., 1995. O Rio Grande do Sul descobre os seus desertos. Ciênc. Ambiente 11, 33–352.
Tedesco, M.J., Volkweiss, S.J., Bohnen, H., 1985, Análises de solo, plantas e outros materiais. Porto Alegre, Faculdade de Agronomia, UFRGS. 188 p (Boletim Técnico de Solos, 5).
Tomasella, J., Hodnett, M.G., 1998. Estimating soil water retention characteristics from limited data in Brazilian Amazonia. Soil Sci. 163, 190–200. doi:http://dx.doi.org/10.1097/00010694-199803000-00003.
Verdum, R., 1997. Approche géographique des deserts dans lês communes de São Francisco de Assis et Manuel Viana – Etat do Rio Grande do Sul – Brésil. 211f. Tese (Doutorado), Université de Toulouse II (Le Mirai), U.T.H, França.
Wohlenberg, E.V., Reichert, J.M., Reinert, D.J., Blume, E., 2004. Dinâmica da agregação de um solo franco-arenoso em cinco sistemas de culturas em rotação e em sucessão. Rev. Bras. Cienc. Solo 28, 891–900. doi:http://dx.doi.org/10.1590/S0100-06832004000500011.
Zinn, Y.L., Lal, R., Resck, D.V.S., 2011. Eucalypt plantation effects on organic carbon and aggregation of three different-textured soils in Brazil. Soil Res. 49, 614–624. doi:http://dx.doi.org/10.1071/SR11264.