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Changes in topsoil bulk density after grazing crop residues under no-till farming

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ABSTRACT

The grazing of crop residues during the winter in integrated crop–livestock systems can either increase soil bulk density (BD) by compaction or decrease BD by swelling, as a function of gravimetric soil water content (GW) during grazing. A field experiment was conducted from 2005 to 2008 to evaluate the BD response to grazing in a no-till silty loam soil (Typic Argiudoll) of the Pampas region of Argentina. Soil BD (core method), GW data and the calculated air volume (AV) were obtained from the 0–50 mm and 50–100 mm layers at different sampling times from ungrazed and grazed treatments. Over most of the study period (2006 through 2008) soil BD showed little impact from grazing, with minimal temporal variation (1.32–1.46 Mg m^{-3}). This stable behavior was ascribed to low rainfall and relatively low GW values at the time when soil was trampled by livestock and routinely trafficked by machinery. Soil BD in the upper (0–50 mm) layer was significantly ($p<0.001$) lower at the beginning of the study (2005 to early 2006), when the rainfall was higher (as was soil GW) during transit periods. Lower BD was not due to soil swelling but to air that was trapped by kneading in response to transit of livestock and machinery. Fitted straight lines indicated that this process became particularly prominent when GW was >330 g kg^{-1} in the ungrazed treatment and GW was >240 g kg^{-1} in the grazed treatments. Grazing accentuated the soil kneading process that promoted air entrapment. Our results suggest in this no-tilled silt loam soil that winter grazing of crop residues caused no deterioration of topsoil porosity in the no-tilled silty loam soil.

1. Introduction

While integrated crop–livestock systems allow the diversification of agricultural production (Franzluebbers and Stuedemann, 2008), the introduction of livestock in croplands can lead to the compaction of shallow soil. Compaction is caused by the collapse of macropores and the deformation of soil structure (Chanasyk and Naeth, 1995; Greenwood et al., 1997, 1998; Drewry et al., 2000; Singleton et al., 2000). The degree of compaction can be easily assessed by measuring bulk density (BD) (Chanasyk and Naeth, 1995; Greenwood and McKenzie, 2001). The extent to which livestock grazing affects BD is primarily controlled by the water content of the soil when animals are present. When soil is wet or very wet and livestock trampled an area, compaction is likely. The magnitude of compaction often increases when stocking rate is greater and decreases during grazing exclusion periods (Drewry and Paton, 2000; Greenwood and McKenzie, 2001; Drewry, 2006). The probability that compaction will occur decreases in integrated crop–livestock systems when no-till farming is utilized. The presence of crop stubble and debris in no-till fields protects the surface from damage and increases the soil's load-bearing capacity (Franzluebbers and Stuedemann, 2008).

Variability in soil BD is not only due to management factors, but also to natural soil characteristics (Berndt and Coughlan, 1976; Voorhees and Lindstrom, 1984; Franzluebbers et al., 1995). Soil water content is the primary natural factor in fine-textured soils, where volume changes substantially by swelling and shrinking (Jayawardane and Greacen, 1987; Oades, 1993; Logsdon and Karlen, 2004). The degree to which BD changes with water content depends largely on the percentage of clay and the proportion of expansible minerals (e.g. smectite type of clay) (Parker et al., 1982). Changes in soil volume also occur, although to a lesser magnitude, in soils with a minimum amount of clay (i.e. >8% by weight) (Dexter, 1988). This is the case for many loamy and silty loamy soils found in many fertile plains around the world. The Pampas region of Argentina is one such region, where significant volume changes in water content were found in silty, and silty clay, loams (Taboada et al., 2004; 2008). Soil water content may be an important BD covariable that should be considered for these types of soil when studying management impacts on topsoil porosity. Silty and silty clay loams have been cultivated in the Pampas for about a century, but only in recent years has the grazing of crop residues from the previous year become more common. The impact of grazing on the BD of these soils is poorly understood, as is the interaction with water content.

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Soil BD is usually increased by grazing, as shown in the occurrence of classical, shallow compaction processes (Willatt and Pullar, 1983; Greenwood and McKenzie, 2001; Drewry, 2006). Grazing-induced declines in BD are less common and, when they do occur, are not easily explained. They have been ascribed to the intensive transit of animals on saturated soil. Drewry (2006) distinguished poaching or puddling from pugging or shearing processes. Poaching or puddling can be regarded as the opposite of soil compaction, as it can lead to lower BD through swelling (Mullins and Fraser, 1980). Pugging or shearing have been related to fingerprint marks and are associated with pasture damage. Pietola et al. (2005) observed that the trampling by livestock when soil water content was high causes kneading and homogenization of soil. As a consequence, soil BD decreases and total porosity increases in the most trampled sites. The aim of the present work was to assess, *in situ*, the influence of winter grazing of crop residues by livestock on the relationship between BD and soil water content in silty loam soils that are managed with no-till farming. The *a priori* hypothesis was that soil BD declines as a result of soil swelling during wet periods and that the process is intensified by livestock trampling.

2. Materials and methods

2.1. Site characteristics

The study was conducted from September 2005 to September 2008 at a farm managed with an integrated crop–livestock production system under no-till farming. The farm is located in the northern Pampean Region, called Rolling Pampa (33º 18′ 23.3″ S; 61º 58′ 2.3″ W). This region has a temperate (mean annual temperature: 17.5 ºC) and humid (mean annual precipitation: 1044 mm) climate. Most rainfall occurs in the spring and summer (September–March) and is often low during the winter. The whole study area is covered by a fine silty, thermic Typic Argiudoll (Soil Taxonomy); Luvic Phaeozem (FAO Soil Classification).

The production farm was managed with a crop (8 years)–pasture (4 years) rotation scheme, always no-till. Soils were alternatively cropped to maize (*Zea mays* L.) from mid-October until the end of March, and soybean (*Glycine max* L., Merrill) from mid-November until the end of April. Crop residues and winter weeds (*Stellaria media* L. and *Bowlesia incana*) were yearly grazed during the winter at a nearly constant stocking rate (1.1 cow ha^{-1}). When the winter weeds had substantially diminished, livestock was moved to a nearby pasture field to preserve the agricultural residue ground cover. Herbicides (glyphosate and atrazine) were not applied during winter. After the cropping phase, composite pastures (grass-alfalfa (*Medicago sativa* L.)) were sown using no-till systems. The pasture was grazed under a rotational scheme at stocking rates as high as 30–40 animals ha^{-1}.

2.2. Field treatments and soil sampling

The experiment began 4 years after the end of the pasture period. The study area covered 45 ha of the farm, where two treatments were installed: a) grazed: livestock grazing of winter weeds and crop residues, as usual; b) ungrazed: a fenced area which prevented grazing during the winter. This fenced treatment was considered a control. The experimental design was completely randomized ($n = 3$).

Soil samples were collected during the study period on three sampling dates: a) before livestock grazing (BGZ), which usually occurs after harvesting of summer crops in autumn; b) after livestock grazing (AGZ) that usually occurs at the end of winter; and c) before maize or soybean harvesting (HAR).

2.3. Analyses

Soil samples were collected at study initiation to determine: a) soil textural class (particle size analysis using the pipette method); b) clay mineralogy (X-ray diffraction); c) soil pH (1:2.5 distilled water suspension); d) total organic carbon (wet combustion analysis) (Nelson and Sommers, 1996). During the study, rainfall was measured in pluviometers placed near the experiment area.

Soil bulk density (BD) was determined by the core method. During the study, at the BGZ, AGZ and HAR sampling times, three soil cores (5 cm height, 100 cm^3 each) were randomly taken from each treatment and each plot from the 0–50 mm and 50–100 mm layers. Soil gravimetric water content (GW) was determined by oven drying the soil sample at 105 ºC to constant weight. Soil air volume (AV) was calculated using the following equation:

$$AV\,(\%) = 100 - (BD\,/\,PD^{*}100) - VW \tag{1}$$

where VW is the volumetric water content of the sample and PD is the soil particle density (2.65 Mg m^{-3}).

Two undisturbed samples of about 8000 cm^3 (10 cm height) were collected with a spade at the beginning of the study (initial) and on the AGZ sampling date in 2005 and 2006 in both ungrazed and grazed treatments. After air drying in the laboratory under constant temperature conditions (25 ºC), soil samples were initially dry-sieved by vibration (4.8, 3.4 and 2 mm screen-opening sieves) and the mean weight diameter of dry-sieved aggregates was calculated. Dry-sieved aggregates were moistened to field capacity and wet-sieved (4.8, 3.4, 2, 1, 0.5, 0.3 mm screen-opening sieves) using a Yoder apparatus; the mean weight diameter was calculated. The change in mean weight diameter between dry-sieved and wet-sieved aggregates (CMWD) represents an index of soil structural instability (Burke et al., 1986).

2.4. Soil kneaded experiment

A field experiment was conducted to simulate the remolding action of cattle hooves on wet soil. Eight large cores (15 cm diameter × 15 cm height) were inserted into the soil to a depth of up to 50 mm in the grazed treatment. These cores were located as proximal pairs, one was used as a control and the other was kneaded by hand. All cores were previously wetted with distilled water and allowed to reach soil–water saturation. Once saturated, the soil of one core per pair was gently kneaded by hand for 2 min, to simulate the action of livestock trampling on wet soil. Therefore, there were two experimental treatments: control (not kneaded) and kneaded. A soil core (100 cm^3) was extracted from the center of each large core to determine soil BD, GW, VW and VA after the treatments were applied.

2.5. Statistical analysis

Trends in BD in the ungrazed and grazed treatments were analyzed as repeated measures over time. We tested three different covariance structures (VC, CSH and ARH(1)) (Littell et al., 1998). The covariance structure VC resulted in the best agreement with the Akaike information criterion (AIC; Akaike, 1974).

Different models were adjusted to describe the BD–GW and the AV–GW relationships. The similarity of models fitted for each treatment was tested through the comparison between: i) a basic model, that describes the BD–GW relationship using one function per treatment (six parameters, three per function) and ii) a restricted model, that describes the BD–GW relationship using only one function for both treatments (three parameters). Differences between the fitted basic and restricted models were analyzed using an f-test (Mead et al., 1993). The calculated parameters of each function were compared using the Student's t, which was computed as:

$$t = \left[(p_1 - p_2)\,/\,(s_{p1} - s_{p2})\right] \tag{2}$$

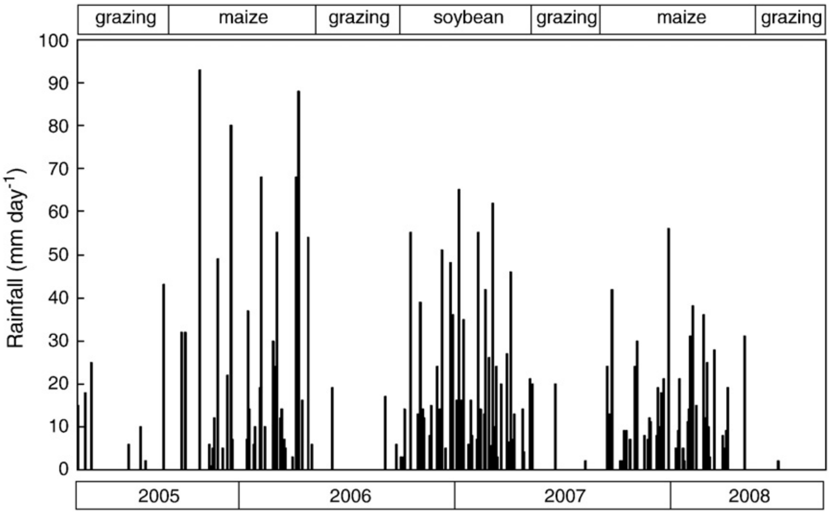

Fig. 1. Daily rainfall during the study. Periods under winter grazing and the maize and soybean growing cycles are indicated.

where: p is the parameter value, and s is the standard error value of the parameter in the treatment to be compared. The degrees of freedom were calculated as (N − 4) (Neter and Wasserman, 1974).

Data from the kneaded experiment were analyzed by ANOVA. When a significant effect was found, the least significant difference (LSD) test was used to compare the means of the different treatments (P<0.05).

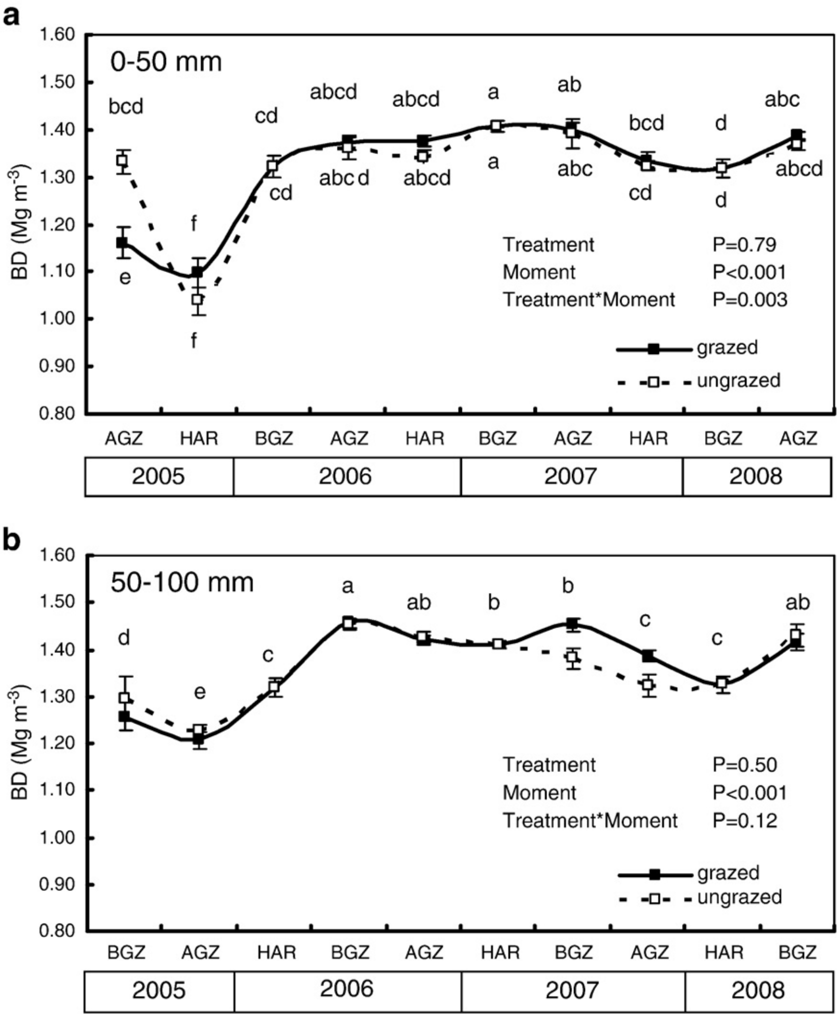

Fig. 2. Mean (±1 S.E.) bulk density of soil in the grazed and ungrazed treatments at 0–50 mm (a) and 50–100 mm (b) over the experimental period. Different letters indicated statistically significant differences between treatment*moment for 0–50 mm; and between moment for 50–100 mm. BGZ: before grazing; AGZ: after grazing; and HAR: crop harvest.

3. Results

3.1. Soil properties and rainfall

The soil at the experimental site was classified as silty loam, corresponding to a particle size distribution as follow: clay 250 g kg^{-1}, silt 614 g kg^{-1}, sand 136 g kg^{-1}. X-ray diffraction analysis of the clay fraction indicated a prevalence of pure illite in the 0–50 mm and 50–100 mm layers, with a minor amount of quartz and plagioclase. Hematite was also found in the 50–100 mm layer. Organic matter content in the first 50 mm was 42.7 g kg^{-1}, and 31.3 g kg^{-1} in the 50–100 mm layer. Soil was moderately acid in the first 100 mm. Rainfall differed greatly among the different winter grazing periods, which usually ran from about April to September (Fig. 1). Total rainfall during this period was as high as 126 mm in 2005, but only 45 mm, 22 mm and 2 mm in 2006, 2007 and 2008, respectively.

3.2. Temporal variations in soil BD

Temporal variations in BD were different for the 0–50 mm and 50–100 mm layers (Fig. 2). In the 0–50 mm layer there was a highly significant "moment × treatment" interaction (Fig. 2a). Soil BD remained quite stable (1.32 to 1.41 Mg m^{-3}) and was similar between treatments during most of the study period (beginning of 2006 to 2008). However, early in the study (2005 to the beginning of 2006) BD behaved quite differently and was more variable. In AGZ in 2005, soil BD was significantly ($P<0.05$) higher in the ungrazed (1.32 Mg m^{-3}) than in the grazed (1.16 Mg m^{-3}) treatment. Some months later, in the 2005 HAR sampling, BD decreased in both the ungrazed and grazed treatments (mean BD = 1.06 Mg ha^{-1}). Soil BD increased again at the 2006 BGZ sampling and remained relatively stable for the remainder of the study. This different BD behavior also occurred in the 50–100 mm layer (Fig. 2b), although BD fluctuations over time were less striking. In the deeper soil layer there was no interaction between time and treatment effects. Soil BD showed significant changes only in relation to sampling date.

3.3. Soil BD–GW and VA–GW relationships

Soil BD–GW relationships were different in the upper and lower soil layers (Fig. 3). In the 0–50 mm layer soil BD was highly variable (0.90–1.50 Mg m^{-3}). Two straight lines were fitted to the ungrazed (Fig. 3a) and grazed (Fig. 3c) data sets. In each case the first portion (to the left in each figure) of the best-fit line was essentially horizontal, showing little change in BD as GW increased. In each treatment, however, there was a sudden and sharp decline in soil BD when GW reached a certain critical threshold (c-parameter). This parameter was significantly higher in the ungrazed treatment (300.7 g kg^{-1}) than in the grazed treatment (189.7 g kg^{-1}). Above this threshold, soil BD declined with GW. The linear slope (b-parameter) was significantly higher ($p = 0.002$) in the ungrazed ($r^2 = 0.72$) than in the grazed ($r^2 = 0.47$) treatment. In the BD–GW plots there were several distinct data points below the fitted line (Fig. 3c). It is likely that factors other than water content were causing changes in BD in these samples. In the 50–100 mm soil layer of the ungrazed treatment there was no discernable BD–GW relationship (Fig. 3b). A single straight line proved to be the best fit for the grazed

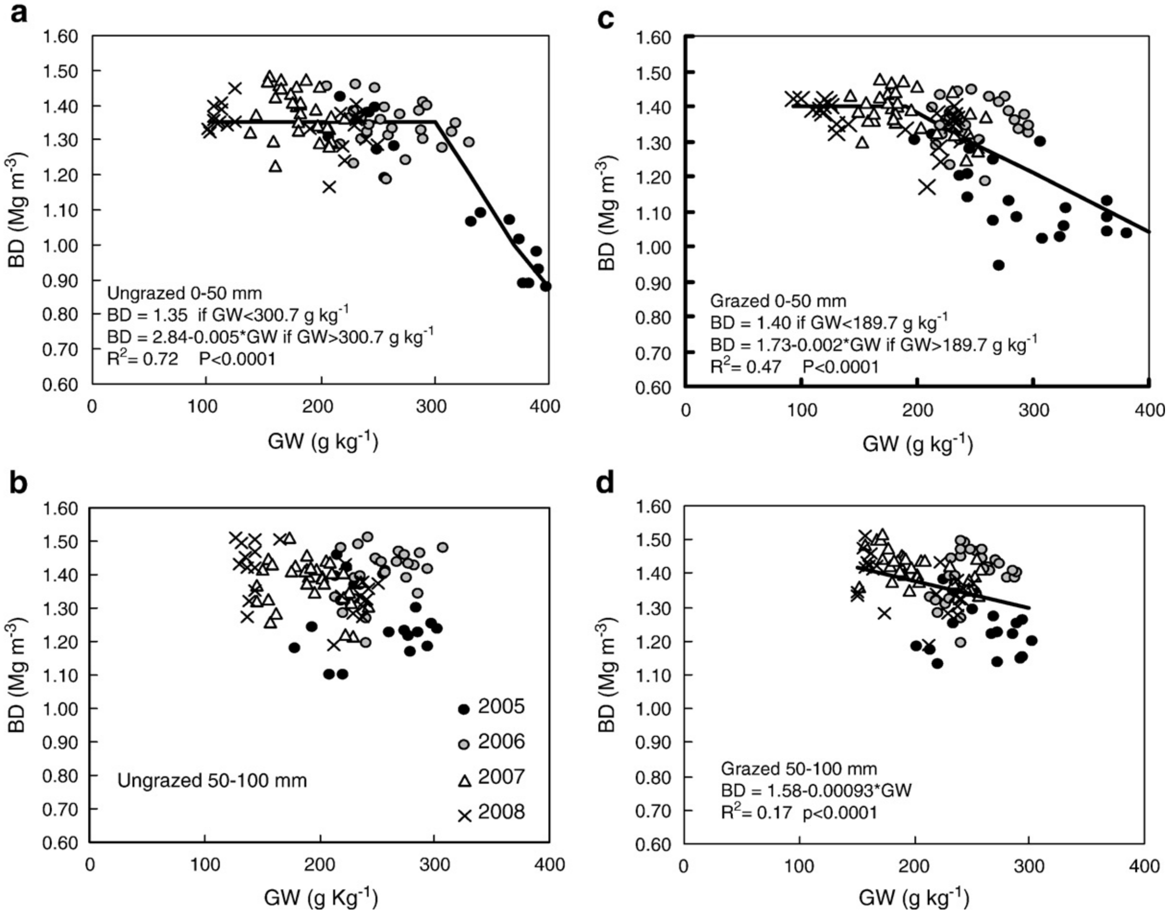

Fig. 3. Relationship between bulk density and water content in ungrazed 0–50 mm (a), ungrazed 50–100 mm (b), grazed 0–50 mm (c) and grazed 50–100 mm (d) sample. Solid lines represent the best-fit model for a particular set of data. There was no noticeable trend in the ungrazed 50–100 mm sample.

treatment at 50–100 mm, although the linear model accounted for only a small fraction of the data variability ($r^2 = 0.17$) (Fig. 3d).

Soil AV varied negatively with GW in the ungrazed and grazed treatments of the 0–50 mm layer (Fig. 4a, c), and 50–100 mm layer (Fig. 4b, d). In the surface layer a group of points departed from the fitted line (circled points in Fig. 4a and c). These points corresponded to sampling dates from September 2005 and March 2006. If these points were excluded from analysis there was a high correlation between AV and GW in the ungrazed ($r^2 = 0.76$) and grazed treatments ($r^2 = 0.74$). These departing points suggest the occurrence of trapped air in soil pores, which occurred at GW > 330 g kg^{-1} in the ungrazed treatments and at GW > 240 g kg^{-1} in the grazed treatment.

3.4. Soil structural instability

The lowest CMWD (0.489 mm ± 0.055) was found in the initial soil condition, before treatments were imposed. Some months later, in the "after grazing" 2005 sample, soil CMWD remained similar (to the initial) in the ungrazed treatment (0.620 mm ± 0.034) but increased significantly in the grazed treatment (0.989 mm ± 0.078). This period was the wettest winter in the experiment. This caused soil structural instability to be significantly higher when grazing occurred. In AGZ 2006 soil CMWD did not statically differ between grazed (0.69 mm) and ungrazed (0.59 mm) treatments.

3.5. Soil kneading experiment

Soil BD was significantly ($P = 0.02$) higher and AV significantly lower ($P = 0.007$) in the unkneaded soil, relative to the kneaded soil (Fig. 5a, b). Kneading, therefore, caused soil BD to decrease by 0.09 Mg m^{-3} and the AV to increase by 4% (v/v).

4. Discussion

In the present study, changes in BD did not follow the generally-reported trend of soil BD increases in the first few centimeters, because of compaction by the mechanical impact of animal hooves (Chanasyk and Naeth, 1995; Greenwood et al., 1997, 1998; Greenwood and McKenzie, 2001). Only in the first sampling date variations in soil BD were due to grazing (Fig. 2). The time period in which soil BD was substantially different (in 2005) was characterized by high rainfall (Fig. 1), causing the soil to be wetter than occurred for the remainder of the study. During this wet period, soil BD varied negatively with GW in the ungrazed and grazed treatments (Fig. 2a, b). This relationship was notably different for the rest of the study when BD remained quite stable.

Similar variability in BD in fine-textured soils with swelling clays has been reported (Parker et al., 1982; Jayawardane and Greacen, 1987; McGarry and Daniells, 1987; Oades, 1993). In those studies, the decline in BD along with GW is generally attributed to swelling. Only a small amount of swelling of the clay fraction will cause a measurable change in soil volume (Dexter, 1988; Oades, 1993; Taboada et al., 2008). Swelling was also observed in medium-textured soils in which changes in soil volume were only moderate (Jayawardane and Greacen, 1987; McGarry and Daniells, 1987; Oades, 1993). In the Argiudoll studied here, clay content was substantial (250 g kg^{-1} of clay content) and was due mainly to pure illite, a mineral displaying minimal expansibility. This clay mineralogy is similar to that found in other Mollisols of the Pampas region (Camilión, 1993; Taboada et al., 2008). Therefore, one or more factors other than swelling could cause the variations in BD observed in the current investigation.

A second factor that can cause a decrease in BD is the transit of animals when soil is saturated, causing poaching or puddling damage

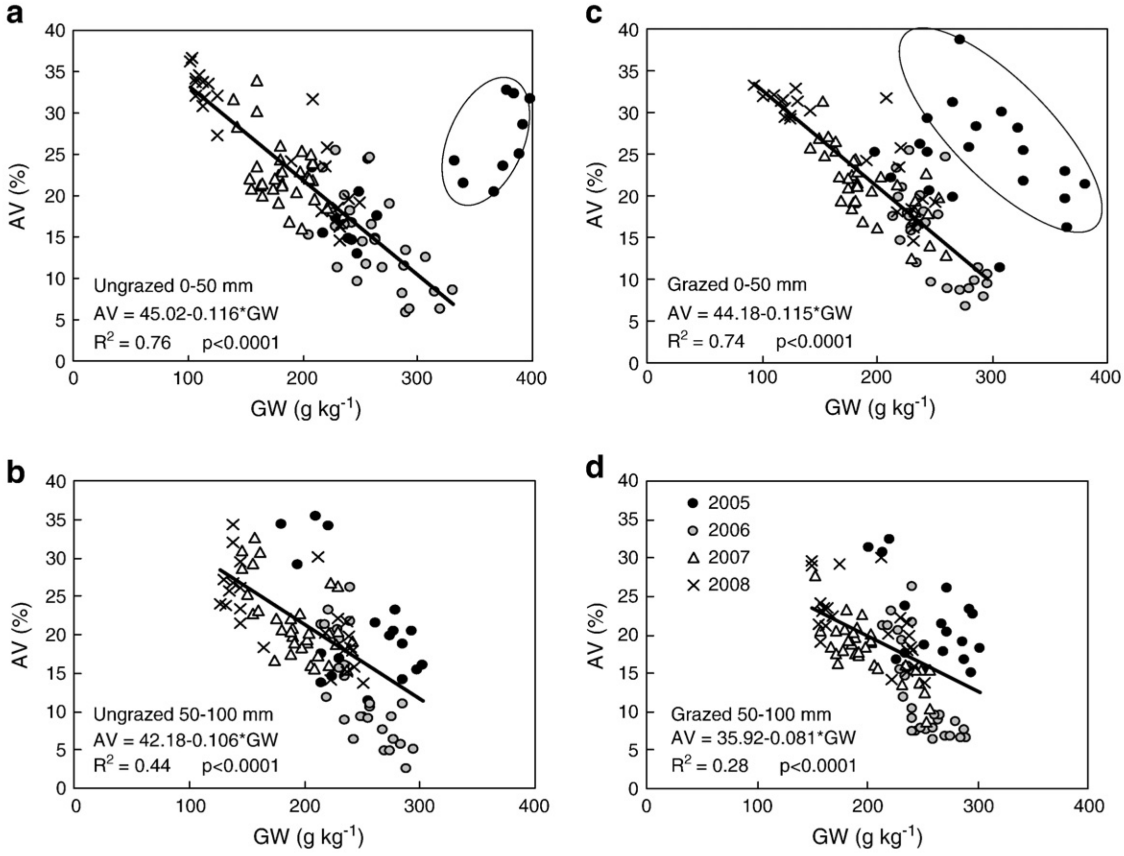

Fig. 4. Relationship between air volume and gravimetric water content for ungrazed and grazed treatments in ungrazed 0–50 mm (a), ungrazed 50–100 mm (b), grazed 0–50 mm (c) and grazed 50–100 mm (d) samples. Solid lines represent the best-fit model for a particular set of data. Circled points were considered departing dataset and were excluded from the fitted functions.

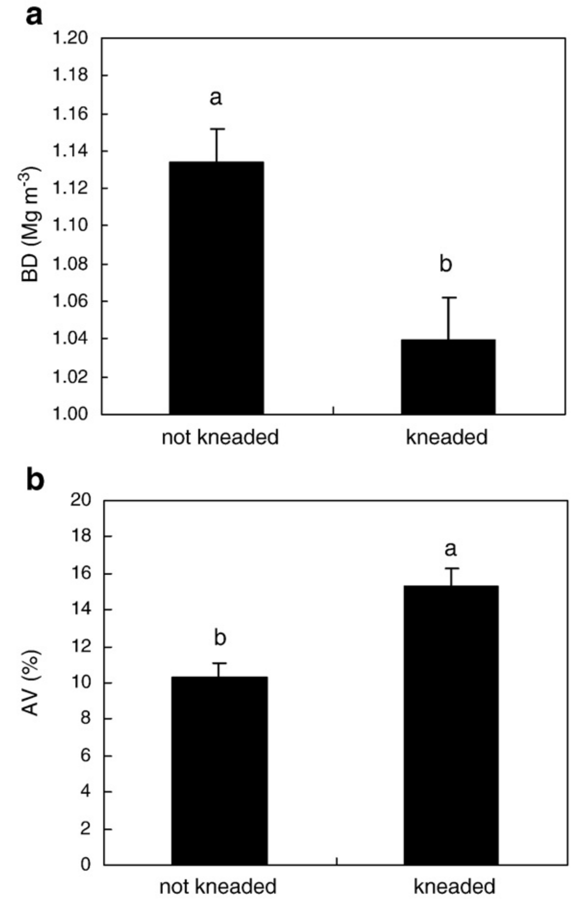

Fig. 5. Mean (±1 S.E.) bulk density (a) and air volume (b) of unkneaded and kneaded soil treatments. Different letters indicate statically significant differences between treatments.

to the soil (Greenwood and McKenzie, 2001; Drewry, 2006). This results in soil swelling because of the remolding action of cattle hooves in saturated soil (Mullins and Fraser, 1980; Scholefield and Hall, 1986; Greenwood and McKenzie, 2001). Poaching damages can lead to dense, unstable clods in the soil (Mullins and Fraser, 1980). The high rains that occurred early in the study allowed poaching to occur (Fig. 1). In addition the higher soil structural instability during grazing 2005 correlated well with the remolding process caused by cattle hooves. However, the substantial decreases in BD with increasing GW (Fig. 3a, c) during this period were not due to swelling but to air entrapment under wet soil conditions (Fig. 4a, c). The trapped air caused BD to decline and the resulting data points to deviate from the fitted AV–GW straight lines. These points did not fit the typical straight lines of rigid soils, in which AV decreases during wetting. Such processes of air entrapment are due to the impossibility of air bubbling from wet soil to the atmosphere. As a result, soil swells by inflation because of the development of trapped air pressures (Gäth and Frede, 1995; Wang et al., 1998). Similar processes of inflation were found in Pampas soils under ponded conditions (Taboada et al., 2001). The high level of precipitation did not occur again during the study and, hence, it is likely that soil was not molded again by trampling. Similar soil behavior was reproduced in the kneading experiment, showing significantly higher AV and lower BD values in the kneaded than in the non kneaded treatment (Fig. 5).

It should be noted that the higher AV at high GW contents were also found, albeit to a lesser extent, in soil of the ungrazed treatment (Fig. 4a). This suggests that other factors than grazing could also contribute to explain this process. For instance, the frequent passage of machinery could also cause BD to decrease by kneading, particularly when the soil is wet. Air entrapment could also occur from the impact of heavy rain over bare ground, as usual at the time of maize sowing. This leads to the formation of vesicular voids under surface microcrusts (Collins et al., 1986). Decreases in BD are not only caused by air entrapment. Soil BD can also decline because of the creation of new pores by growing roots of maize (Gibbs and Reid, 1988), as could happen from the first to the second sampling date in both ungrazed and grazed treatments (Fig. 2a).

Trapped air disappeared in autumn 2006 when maize was harvested. This caused soil BD to increase again and the soil to acquire a quasi-rigid character. It is possible that this new behavior was related to the subsequent prevailing dry soil conditions, especially during grazing periods. The resulting high soil bearing capacity protected the soil against transit loading effects during the rest of the study. Regardless, from the comparison of the fitted lines of the BD–GW relationship in ungrazed and grazed treatments, it is apparent that grazing altered the threshold below which variability in soil BD was dependant on GW (Fig. 3a, c).

Results showed that kneading the soil led to decreases in BD that were similar to those caused by grazing at the beginning of the study. The process could be regarded as the sealing of topsoil by trampling and kneading, thus impeding release of air to the atmosphere. As a result of air entrapment, the soil becomes inflated and its BD decreases when GW is high.

5. Conclusions

Soil BD decreased in the top 50 mm when the wet soil was treaded on in winter. However, soil BD decreases were not caused by soil swelling, as hypothesized, but by trapping of air and a concomitant increase in air volume. The process was also observed, albeit to a lesser extent, in the ungrazed treatment.

A stable behavior of BD related to livestock trampling and machinery traffic was found during periods of low rainfall. Grazing crop residues during winter under no-till farming caused no deterioration of topsoil porosity in the studied silty loam soil.

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