Soil & Tillage Research 100 (2008) 141–153

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Soil physical responses to cattle grazing cover crops under conventional and no tillage in the Southern Piedmont USA

Alan J. Franzluebbers [*], John A. Stuedemann

USDA, Agricultural Research Service, 1420 Experiment Station Road, Watkinsville, GA 30677, United States

ARTICLE INFO

Article history:
Received 16 October 2007
Received in revised form 17 April 2008
Accepted 20 May 2008

Keywords:
Aggregation
Bulk density
Grazing
Infiltration
No tillage
Penetration resistance

ABSTRACT

Grazing of cover crops in grain cropping systems can increase economic return and diversify agricultural production systems, but the environmental consequences of this intensified management have not been well documented, especially under different tillage systems. We conducted a multiple-year investigation of how cover crop management (grazed and ungrazed) and tillage system [conventional (CT; initial moldboard plowing and thereafter disk tillage) and no tillage (NT)] affected soil physical properties (bulk density, aggregation, infiltration, and penetration resistance) on a Typic Kanhapludult in Georgia. Responses were determined in two cropping systems: summer grain/winter cover crop and winter grain/summer cover crop. Soil bulk density was reduced ($P = 0.02$) with CT compared with NT to a depth of 30 cm at the end of 0.5 year, but only to a depth of 12 cm at the end of 2, 2.5, and 4.5 years. Grazing of cover crops had little effect on soil bulk density, except eventually with 4.5 years of management. Water-stable macroaggregation was reduced ($P \leq 0.01$) with CT compared with NT to a depth of 12 cm at all sampling times during the first 2.5 years of evaluation. Stability of macroaggregates in water was unaffected by grazing of cover crops in both tillage systems. Across 7 sampling events during the first 4 years, there was a tendency ($P = 0.07$) for water infiltration rate to be lower with grazing of cover crops (5.6 mm min^{-1}) than when ungrazed (6.9 mm min^{-1}), irrespective of tillage system. Across 10 sampling events, soil penetration resistance was greater under NT than under CT at a depth of 0–10 cm ($P = 0.001$) and the difference was greater in ungrazed than in grazed systems ($P = 0.06$). Biannual CT operations may have alleviated any surface degradation with animal traffic, but the initially high level of soil organic matter following long-term pasture and conversion to cropland with NT may have buffered the soil from any detrimental effects of animal traffic. Overall, the introduction of cattle to consume the high-quality cover crop forage did not cause substantial damage to the soil.

Published by Elsevier B.V.

1. Introduction

The impact of grazing animals on the environment is generally viewed as negative. There is sufficient evidence in landscapes around the world to support this perspective (Sparrow et al., 2003; Nosetto et al., 2006; Mekuria et al., 2007; Zhao et al., 2007). Unrestricted access by large herds of cattle on rangeland can lead to streambank destabilization, trodden paths leading to water bodies, forested riparian areas denuded of soil-conserving vegetation, and high frequency of fecal deposition adjacent to and directly in water bodies (Bilotta et al., 2007). However, not all cattle management systems cause environmental degradation. The key factors in balancing cattle production with environmental quality are (1) matching stocking density with forage availability and (2) limiting access of cattle to vulnerable parts of the landscape, such as natural water sources or shaded areas that can result in heavily trafficked and damaged vegetation.

Soil organic matter is a critical component in maintaining soil quality in agricultural lands around the world. Introduction of perennial pastures on crop land is known to improve soil organic C and N, which leads to retention of organically bound nutrients and improved water relations. Cropping systems that are appropriate in the southeastern USA under conditions of high soil organic matter have not been evaluated since much of the cropland has been stripped of soil organic matter from previous tillage-intensive cropping practices.

A large portion of the agricultural land area in the southeastern USA is devoted to pasture production of cattle (USDA-NASS, 2007). Previous work has shown that grazing of perennial warm-season grasses in the summer can have positive impacts on soil organic C and N accumulation and no observable detriment to surface soil density (Franzluebbers et al., 2001). However, the role of grazing

---

[*] Corresponding author. Tel.: +1 706 769 5631; fax: +1 706 769 8962.
E-mail address: alan.franzluebbers@ars.usda.gov (A.J. Franzluebbers).

0167-1987/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.still.2008.05.011

animals in integrated crop-livestock systems does not have to be limited to the medium- or long-term pasture phase alone. Cover crops such as annual grasses, small grains, and forage legumes following grain or fiber crops can be an excellent source of high-quality forage to be utilized in integrated crop-livestock systems (Franzluebbers and Stuedemann, 2007), because of the relatively mild winter growing season throughout the southeastern USA. A potential impact of animals grazing cover crops, however, could be compaction due to trampling, as was observed in soils with relatively low organic matter (Tollner et al., 1990).

We hypothesized that surface residue cover would provide a significant buffer against animal trampling effects, such that no tillage crop production following long-term pasture could alleviate negative animal trampling effects. Our objective was to evaluate how integrated crop-livestock systems with cattle grazing of cover crops would affect soil physical properties, especially those related to soil compaction and surface soil degradation, under both conventional and no tillage management.

2. Materials and methods

2.1. Site characteristics and management

The experiment was located near Watkinsville GA (33°62′N, 83°25′W) on Cecil sandy loam and sandy clay loam soils [fine, kaolinitic, thermic Typic Kanhapludults (USDA) and Acrisols (FAO)] with 2–6% slope. Soil was moderately acidic (pH ~ 6) and contained moderate organic C (14 g kg^{-1}) and total N (1.2 g kg^{-1}) 1) in the upper 20 cm (Franzluebbers and Stuedemann, 2008). Mean annual temperature is 16.5 °C, precipitation is 1250 mm, and pan evaporation is 1560 mm.

Since 1982, a total of 18 paddocks (0.7-ha each) were managed as tall fescue [*Lolium arundinaceum* (Schreb.) S.J. Darbyshire] pastures, varying in tall fescue-endophyte association and fertilization level (Belesky et al., 1988). Pastures were grazed with Angus cattle each year, primarily in spring and autumn. All fertilization was suspended after 1997 to help avoid further accumulation of inorganic N in the soil profile below 0.3 m (Franzluebbers et al., 2000a). In May 2002, 16 of the 18 pastures were terminated either with moldboard plow or glyphosate [*N*-(phosphonomethyl) glycine] (see details below). In May 2002, a new experimental design was imposed onto this previous design by randomly allocating four primary treatments in a stratified manner across the previous treatment design to equalize any effects from previous management.

The experimental design from 2002 to 2005 consisted of a factorial arrangement of (1) tillage (conventional and no tillage) and (2) cropping system (summer grain/winter cover crop and winter grain/summer cover crop) with four replicated paddocks each, for a total of 16 main plots. Two of the original 18 pastures remained as control pastures. Main plots were split into grazed (0.5 ha) and ungrazed (0.2 ha) cover crop treatments.

Tillage systems were: (1) conventional disk tillage (CT) following harvest of each grain and cover crop and (2) no tillage (NT) with glyphosate to control weeds prior to planting. Tillage treatments were initiated in May 2002. Initial CT treatment consisted of moldboard plowing to a depth of 25–30 cm. Disk plowing only to a depth of 15–20 cm occurred in subsequent years. Pasture was terminated in the NT treatment with two applications of glyphosate (2.9 kg a.i. ha^{-1} in May and 1.2 kg a.i. ha^{-1} in June 2002).

Cropping systems were: (1) summer grain cropping with grain sorghum [*Sorghum bicolor* (L.) Moench] or corn (*Zea mays* L.) planted in April to June and harvested in September to October plus winter cover cropping of cereal rye (*Secale cereale* L.) planted in November and terminated in May and (2) winter grain cropping with wheat (*Triticum aestivum* L.) planted in November and harvested in May to June plus summer cover cropping of pearl millet [*Pennisetum glaucum* (L.) R. Br.] planted in June to July and terminated in September to October. Cultural practices were detailed in Franzluebbers and Stuedemann (2007).

Cover crop management was: (1) no grazing of cover crops and (2) grazing of cover crops with cattle to consume ~90% of available forage produced. Grazed cover crops were stocked with yearling Angus steers in the summer of 2002 and in the spring of 2003. Thereafter, cow + calf pairs were used to simulate a more typical regional management approach. Ungrazed cover crops were allowed to accumulate biomass until ~2 weeks prior to planting of the next crop and either (1) mowed prior to CT operations or (2) mechanically rolled to the ground in the NT system.

Application of N was relatively low during the first 3 years (96 ± 7 kg N ha^{-1} $year^{-1}$), but was considered adequate to assure early plant growth and development with further growth dependent upon the mineralization of stored nutrients in soil organic matter. Extractable P and K concentrations in the surface 7.5 cm of soil were ≥100 mg P kg^{-1} soil and 400 mg K kg^{-1} soil, levels considered adequate for crop production. Plant and animal production during the first 3.5 years were reported in Franzluebbers and Stuedemann (2007).

The experimental design of the cropping system component was altered in the autumn of 2005 (3.5 years after initiation) by switching to a 2-year corn–wheat/soybean rotation, with each phase of the rotation present each year. Two replications of the corn phase and two replications of the soybean phase were preceded with a cover crop of crimson clover (*Trifolium incarnatum* L.) + rye and the remaining two replications of each summer crop phase were preceded with a cover crop of rye + ryegrass (*Lolium multiflorum* L.). In subsequent years, the soybean phase was preceded by wheat harvested for grain. Tillage and cover crop management factors remained intact after the switch in cropping system practices in autumn 2005.

2.2. Soil sampling and analyses

Soil was collected 7–8 May 2002 (initiation), 16–18 December 2002 (end of 0.5 year), 3–5 March 2004 (end of 2 years), 30 November to 15 December 2004 (end of 2.5 years), and 5–13 February 2007 (end of 4.5 years). Soil sample depths were 0–3, 3–6, 6–12, and 12–20 cm in May 2002 and additionally at 20–30-cm depth thereafter. Composite samples of 8 cores in grazed plots and 5 cores in ungrazed plots were collected with a 4-cm diameter probe. At each of the soil sampling locations, surface residue was collected from a 0.04-m^2 area prior to soil coring. Surface residue was dried (55 °C, ≥3 days), ground to <1 mm, and a subsample analyzed for total C and N with dry combustion. Soil was dried at 55 °C for ≥3 days and bulk density was calculated from the total dry weight of soil and volume of coring device. For all subsequent laboratory analyses, soil was passed through a sieve with openings of 4.75 mm to remove gravel. Total organic C and total N were determined with dry combustion on subsamples ground in a ball mill for 5 min. Total C and N in surface residue and soil were reported in Franzluebbers and Stuedemann (2008).

Dry aggregate distribution was determined by placing a 50-g (0–3 and 3–6-cm depths) or 100-g (6–12, 12–20, and 20–30-cm depths) portion of soil on top of a nest of sieves (200-mm diam with openings of 1.0, 0.25, and 0.053 mm), shaking for 1 min at Level 6 (random vertical and horizontal movements of ~5 mm at ~5 Hz) on a CSC Scientific Sieve Shaker (Catalogue No. 18480, CSC Scientific Co., Fairfax VA) and weighing soil retained on the 1.0-, 0.25-, and 0.053-mm screens and that passing the 0.053-mm screen (Franzluebbers et al., 2000c). Water-stable aggregate distribution was determined from the same subsample used for dry aggregate distribution placed on top of a nest of sieves (17.5-cm diam with openings of 1.0 and 0.25 mm), which were immersed directly in city tap water that was de-ionized, and oscillated for 10 min (20-mm stroke length, 0.52 Hz). After removing the two sieves and placing them in an oven to dry, water containing soil passing the 0.25-mm sieve was poured over a 0.053-mm sieve, soil washed with a gentle stream of water, and the soil retained, transferred into a drying bottle with a small stream of water. All fractions were oven-dried at 55 °C for 3 days. Dry-stable and water-stable macroaggregates were defined by the fractions >0.25 mm (Elliott, 1986). Stability of macroaggregates was calculated as the weight of water-stable macroaggregates divided by the weight of dry-stable macroaggregates. Mean-weight diameter of both dry-stable and water-stable aggregates was calculated by summing the products of aggregate fractions and mean diameter of aggregate classes. Stability of mean-weight diameter was calculated as water-stable mean-weight diameter divided by dry-stable mean-weight diameter.

2.3. Water infiltration

Water infiltration was determined from the linear rate of water intake during 1 h within a single, 30-cm diameter steel ring inserted 2–4 cm into the ground. Water was supplied with a Mariotte system and volume of water recorded every 10 min (Bouwer, 1986). Linear regression was used to determine the rate of water infiltration. The intercept minus the estimated volume of water maintained above the soil surface was defined as apparent macropore filling. Infiltration was determined from two locations in each grazed and ungrazed plot on 15 October 2003 (end of 2nd summer cover crop), 3 May 2004 (end of 2nd winter cover crop), 27 July 2004 (prior to grazing of 3rd summer cover crop), 20 October 2004 (end of 3rd summer cover crop), 23 June 2005 (prior to grazing of 4th summer cover crop), and 5–14 June 2006 (end of 4th winter cover crop and prior to 5th summer cover crop). Soil water content at the time of infiltration measurements was determined at 0–20-cm depth with time-domain reflectrometry (Field Scout TDR-300, Spectrum Technologies Inc., Plainfield, IL) from the average of 5 measurements within a 2-m radius of each ring.

2.4. Penetration resistance

Penetration resistance was determined with an impact penetrometer (Herrick and Jones, 2002). A 2-kg hammer was dropped 0.74-m distance repeatedly onto a 2.03 cm-diameter cone with a 30° tip. The number of strikes required to reach a depth of 10, 20, and 30 cm was recorded. Each strike contained the equivalent kinetic energy of 14.5 J. Penetration resistance was determined in four locations of each grazed plot and in two locations of each ungrazed plot on 9 May 2003 (end of 1st winter cover crop), 5 August 2003 (prior to grazing of 2nd summer cover crop), 9 October 2003 (end of 2nd summer cover crop), 7 May 2004 (end of 2nd winter cover crop), 27 July 2004 (prior to grazing of 3rd summer cover crop), 22 October 2004 (end of 3rd summer cover crop), 6 April 2005 (end of 3rd winter cover crop), 29 June 2005 (prior to grazing of 4th summer cover crop), 20 October 2005 (end of 4th summer cover crop), and 24 October 2005 (end of 2-week grazing of corn stalks). Soil water content at the time of penetrometer measurements was also determined with time-domain reflectrometry as described in previous section.

2.5. Statistical analyses

The experimental design was a multiple split-block with four replications. Main plots were a factorial arrangement of tillage ($n = 2$) and cropping system ($n = 2$). Cover crop management ($n = 2$) was a split plot in horizontal space. Depth of soil sampling ($n = 4$ in May 2002 and $n = 5$ in subsequent years) was a split plot in vertical space. Sampling event ($n = 4$–10) was a split plot in time. Sampling depth and sampling event were not considered sources of variation, because response variables were analyzed within each level separately. Soil bulk density and aggregation properties within a depth increment and sampling event were analyzed for variance due to tillage, cover crop management, and their interaction using the general linear model procedure of SAS. Error terms were replication × tillage × cropping system for tillage effects and replication × tillage × cropping system × cover crop management for cover crop management and tillage × cover crop management effects. Differences among treatments were considered significant at $P \leq 0.05$. Treatment trends were considered for discussion at $P \leq 0.10$.

Multiple subsamples within an experimental unit for infiltration and penetration resistance were averaged prior to analysis of variance. Data for each experimental unit were analyzed the same as described above, except that cropping system was not a part of the model, since cropping system-specific measurements were made at different times. Significance of responses across the 7 sampling events for infiltration and across the 10 sampling events for penetration resistance was computed using mean values across replications within a sampling event as input data and sampling event as a blocking criterion. Error term was sampling event × tillage × cover crop management in this meta-analysis.

To assess the influence of antecedent soil water content on water infiltration, data for each experimental unit and sampling event were plotted using linear regression to separate the effects of tillage and cover crop management. The influence of antecedent soil water content on penetration resistance was plotted for each tillage, cover crop management, and soil depth increment using a non-linear regression equation:

$$J = J_0 + a\,\mathrm{MR}^{(-b\,\mathrm{SWC})}$$

where J is penetration resistance, J_0 is the baseline penetration resistance, MR is the maximum resistance at low soil water content (SWC), and b is the non-linear decay coefficient.

3. Results and discussion

3.1. Soil bulk density

At initiation of this study, soil bulk density averaged 1.10 Mg m^{-3} at 0–3-cm depth, 1.45 Mg m^{-3} at 3–6-cm depth, 1.54 Mg m^{-3} at 6–12-cm depth, and 1.58 Mg m^{-3} at 12–20-cm depth (Table 1). Except for an interaction at 3–6 and 0–20-cm depths, there were no differences in bulk density among prior treatment assignments. The increase in bulk density with soil depth following 20 years of perennial pasture was consistent with results from other pasture investigations in the Southern Piedmont region (Franzluebbers et al., 2000a,b).

At the end of 0.5 year in November 2002, soil bulk density was greater under CT than under NT at 0–3-cm depth, not different between tillage systems at 3–6-cm depth, and lower under CT than under NT at all lower depths (Table 1). At the end of 2 years in March 2004, similar tillage effects were observed at 0–3 and 6–12-cm depths. Additionally, there was lower bulk density under CT than under NT at 3–6-cm depth and no difference between tillage systems below 12-cm depth. Essentially, the tillage effect shifted from throughout the 30-cm profile initially to only within the

Table 1

Soil bulk density at 0–3, 3–6, 6–12, 12–20, 20–30, and 0–30-cm depths as affected by tillage, cover crop management, and their interaction when averaged across cropping systems during 5 sampling events from 2002 to 2007 near Watkinsville GA

Tillage	Cover crop	Soil bulk density (Mg m^{-3})					
		0–3	3–6	6–12	12–20	20–30	0–30
May 2002 (at initiation)							
Conventional	Ungrazed	1.12	1.48	1.57	1.60	N.D.	1.50[a]
Conventional	Grazed	1.07	1.42	1.52	1.55	N.D.	1.45[a]
No tillage	Ungrazed	1.10	1.43	1.54	1.57	N.D.	1.47[a]
No tillage	Grazed	1.10	1.46	1.53	1.58	N.D.	1.48[a]
Analysis of variance (Pr > F)							
Tillage		0.90	0.93	0.14	0.85	N.D.	0.82
Cover crop		0.27	0.63	0.06	0.33	N.D.	0.13
Tillage × cover crop		0.16	**0.05**	0.19	0.13	N.D.	**0.04**
December 2002 (at the end of 0.5 year)							
Conventional	Ungrazed	1.12	1.35	1.43	1.46	1.45	1.41
Conventional	Grazed	1.10	1.28	1.43	1.46	1.44	1.39
No tillage	Ungrazed	0.97	1.37	1.50	1.52	1.50	1.44
No tillage	Grazed	0.99	1.38	1.52	1.57	1.55	1.47
Analysis of variance (Pr > F)							
Tillage		**0.02**	0.15	**0.002**	<**0.001**	**0.02**	**0.02**
Cover crop		0.98	0.20	0.86	0.38	0.41	0.56
Tillage × cover crop		0.22	0.14	0.66	0.52	0.24	0.23
March 2004 (at the end of 2 years)							
Conventional	Ungrazed	1.16	1.31	1.40	1.56	1.52	1.45
Conventional	Grazed	1.17	1.34	1.43	1.50	1.49	1.43
No tillage	Ungrazed	0.96	1.40	1.51	1.54	1.50	1.45
No tillage	Grazed	1.04	1.40	1.54	1.54	1.54	1.48
Analysis of variance (Pr > F)							
Tillage		**0.003**	**0.04**	<**0.001**	0.53	0.59	0.26
Cover crop		0.14	0.70	0.15	0.25	0.92	0.84
Tillage × cover crop		0.26	0.61	0.85	0.29	0.25	0.21
December 2004 (at the end of 2.5 years)							
Conventional	Ungrazed	1.15	1.31	1.43	1.57	1.54	1.46
Conventional	Grazed	1.08	1.31	1.39	1.53	1.50	1.42
No tillage	Ungrazed	1.12	1.45	1.56	1.53	1.51	1.48
No tillage	Grazed	1.14	1.45	1.53	1.56	1.57	1.51
Analysis of variance (Pr > F)							
Tillage		0.77	**0.03**	**0.01**	0.91	0.40	0.08
Cover crop		0.31	0.90	0.33	0.99	0.75	0.79
Tillage × cover crop		0.06	0.97	0.81	0.25	0.17	0.15
February 2007 (at the end of 4.5 years)							
Conventional	Ungrazed	1.08	1.32	1.41	1.60	1.56	1.47
Conventional	Grazed	1.12	1.29	1.42	1.57	1.55	1.46
No tillage	Ungrazed	0.96	1.37	1.51	1.59	1.54	1.47
No tillage	Grazed	1.05	1.41	1.51	1.59	1.56	1.49
Analysis of variance (Pr > F)							
Tillage		**0.01**	<**0.001**	<**0.001**	0.59	0.83	0.23
Cover crop		**0.007**	0.89	0.91	0.14	0.85	0.80
Tillage × cover crop		0.12	**0.05**	0.64	0.29	0.61	0.27

N.D. means not determined. Bold indicates probability levels <0.05.

[a] Means represent 0–20-cm depth in May 2002.

surface 12 cm by the end of the 2nd year. Tillage effects on soil bulk density at the end of 2.5 years in December 2004 were similar to those obtained at the end of 2 years, except that no difference in bulk density was observed at 0–3-cm depth. Tillage effects on soil bulk density at the end of 4.5 years in February 2007 were similar to those at the end of 2 years. Reconsolidation of soil following CT events appeared to be relatively rapid at all depths, except in the zone of 3–12 cm, which always had lower bulk density under CT than under NT.

For a depth of 0–30 cm, soil bulk density under CT averaged 0.058 Mg m^{-3} lower ($P = 0.02$) than under NT at the end of 0.5 year, 0.024 Mg m^{-3} lower ($P = 0.26$) at the end of 2 years, and 0.050 Mg m^{-3} lower ($P = 0.08$) at the end of 2.5 years (Table 1). The effect of CT on reducing bulk density remained the strongest at a depth of 6–12-cm depth (difference of 0.11 ± 0.03 Mg m^{-3}) throughout the study. Greater bulk density with NT compared with CT has often been reported (Franzluebbers et al., 1999; Tebrügge and Düring, 1999; VandenBygaart et al., 1999; Schjønning and Rasmussen, 2000), and is a consequence of natural and management-induced consolidation processes. Although bulk density is often higher with NT than with CT, pore distribution and connectivity may become enhanced with NT due to biological activity, such that there may be no serious limitations to plant root growth or water infiltration (Kay and VandenBygaart, 2002).

The effect of cover crop management on soil bulk density when averaged across tillage systems was not significant at any soil depth, except at a depth of 0–3 cm at the end of 4.5 years (Table 1). Grazing of cover crops eventually led to an increase in soil bulk density, averaging 1.02 Mg m^{-3} when not grazed and 1.08 Mg m^{-3} when grazed. A significant interaction of cover crop management with tillage system occurred only at a depth of 3–6 cm at the end of 4.5 years, but this effect was mirrored with trends that occurred earlier. Within CT, grazing of cover crops resulted in a trend for lower bulk density at a depth of 3–6 cm at the end of 0.5 year ($P = 0.06$), lower bulk density at a depth of 0–3 cm at the end of 2.5 years ($P = 0.05$), and a trend for lower bulk density at a depth of 12–20 cm at the end of 4.5 years ($P = 0.08$). These results were contrary to the expected increase in bulk density with cattle traffic, but may have been due to the frequent disturbance of soil with CT. Within NT, grazing of cover crops resulted in a trend for greater bulk density at a depth of 0–3 cm ($P = 0.07$) at the end of 2 years and greater bulk density at a depth of 0–3 cm ($P = 0.005$) at the end of 4.5 years. Overall, introduction of cattle onto cropland caused relatively small changes in soil bulk density during the first 4.5 years of this study. The initial soil organic C concentration in the 0–3-cm depth (36 g kg^{-1}) was maintained at this high level with NT throughout the first 2.5 years of this study and this organic C-enriched surface soil may have helped mitigate the compactive force of animal traffic during grazing (Franzluebbers and Stuedemann, 2008).

The effect of animal grazing in cropping systems on soil bulk density has been investigated in a few studies. On Mollisols in Iowa, soil bulk density was not affected by winter grazing of corn stalks for 28-day periods by bred cows (3.7 head ha^{-1}), regardless of month of grazing, and therefore, amount of time when soil was frozen (Clark et al., 2004). Estimated corn residue consumption by cows was only 9%, so grazing time and trampling were minimal. On a Typic Hapludult in Georgia, soil bulk density was not different with or without grazing of a rye cover crop under CT (1.50 Mg m^{-3}), but was greater when grazed than not grazed under NT (1.60 Mg m^{-3} vs. 1.52 Mg m^{-3}) (Tollner et al., 1990). The authors attributed the difference in grazing effect to disk tillage that loosened any evidence of compaction. The surface 5 cm of a Typic Hapludoll in Argentina had greater bulk density with winter grazing of corn and soybean residues than without grazing under CT (1.34 Mg m^{-3} vs. 1.17 Mg m^{-3}), but not under NT (1.27 Mg m^{-3} vs. 1.25 Mg m^{-3}) (Diaz-Zorita et al., 2002). The diversity of results obtained with and without grazing suggests that further research will be needed to understand the factors (e.g. soil, environmental,

Table 2

Water-stable macroaggregation and its stability index at 0–3-cm, 3–6-cm, and 6–12-cm depths as affected by tillage, cover crop management, and their interaction when averaged across cropping systems during 4 sampling events from 2002 to 2004 near Watkinsville GA

Tillage	Cover crop	Water-stable macroaggregates (g macroaggregates g^{-1} soil)			Stability of macroaggregates (g wet g^{-1} dry)		
		0–3	3–6	6–12	0–3	3–6	6–12
May 2002 (at initiation)							
Conventional	Ungrazed	0.76	0.81	0.82	1.00	0.98	0.99
Conventional	Grazed	0.74	0.80	0.80	1.00	0.98	0.97
No tillage	Ungrazed	0.76	0.79	0.80	0.99	0.96	0.97
No tillage	Grazed	0.75	0.78	0.79	1.01	0.99	0.99
Analysis of variance (Pr > F)							
Tillage		0.41	0.24	0.21	0.75	0.75	0.71
Cover crop		0.18	0.68	**0.01**	0.33	0.37	0.81
Tillage × cover crop		0.67	0.83	0.91	0.25	0.39	0.24
December 2002 (at the end of 0.5 year)							
Conventional	Ungrazed	0.63	0.63	0.70	0.73	0.72	0.83
Conventional	Grazed	0.65	0.66	0.69	0.76	0.76	0.81
No tillage	Ungrazed	0.77	0.80	0.79	0.94	0.96	0.94
No tillage	Grazed	0.79	0.79	0.81	0.94	0.93	1.02
Analysis of variance (Pr > F)							
Tillage		<**0.001**	<**0.001**	**0.001**	<**0.001**	<**0.001**	<**0.001**
Cover crop		0.12	0.86	0.94	0.42	0.98	0.29
Tillage × cover crop		0.91	0.15	0.31	0.30	0.30	0.09
March 2004 (at the end of 2 years)							
Conventional	Ungrazed	0.71	0.77	0.79	0.84	0.90	0.90
Conventional	Grazed	0.69	0.75	0.79	0.82	0.89	0.91
No tillage	Ungrazed	0.79	0.83	0.83	0.96	0.99	0.98
No tillage	Grazed	0.77	0.82	0.83	0.99	1.00	0.99
Analysis of variance (Pr > F)							
Tillage		<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**
Cover crop		0.07	0.09	0.99	0.57	0.91	0.42
Tillage × cover crop		0.58	0.94	0.98	**0.04**	0.30	0.92
December 2004 (at the end of 2.5 years)							
Conventional	Ungrazed	0.66	0.75	0.73	0.84	0.86	0.88
Conventional	Grazed	0.65	0.68	0.72	0.85	0.82	0.88
No tillage	Ungrazed	0.72	0.80	0.76	0.94	0.94	0.96
No tillage	Grazed	0.70	0.75	0.76	0.98	0.98	0.99
Analysis of variance (Pr > F)							
Tillage		**0.002**	**0.008**	**0.01**	<**0.001**	<**0.001**	<**0.001**
Cover crop		0.15	<**0.001**	0.58	0.23	0.52	0.11
Tillage × cover crop		0.68	0.62	0.73	0.51	<**0.001**	**0.04**

Bold indicates probability levels <0.05.

and stocking conditions) that might contribute to differences in bulk density.

3.2. Water-stable aggregation

At initiation of this experiment, the fraction of soil as water-stable macroaggregates (>0.25 mm) was high (0.78 ± 0.03 $g\ g^{-1}$) (Table 2). In addition, the fraction of dry-stable macroaggregates was nearly the same as in water (0.99 ± 0.01 g wet g^{-1} dry). At initiation, mean-weight diameter of water-stable aggregates averaged 1.18 mm at 0–3-cm, 1.37 mm at 3–6-cm, and 1.40 mm at 6–12-cm depths (Table 3).

Initial moldboard plowing and subsequent disk tillage (CT) resulted in a significant reduction in the fraction of soil as water-stable macroaggregates and the mean-weight diameter of water-stable aggregates, as well as in the stability of these measures (i.e. wet vs. dry conditions) (Tables 2 and 3). The fraction of soil as water-stable macroaggregates during the 0.5–2.5 years of evaluation was 0.70 ± 0.05 $g\ g^{-1}$ under CT and 0.78 ± 0.04 $g\ g^{-1}$ under NT. Mean-weight diameter was 1.04 ± 0.14 mm under CT and 1.28 ± 0.15 mm under NT. In all cases presented in Tables 2 and 3, the effect was CT < NT ($P \leq 0.03$). The fraction of soil as water-stable macroaggregates and mean-weight diameter of water-stable aggregates were not affected by tillage below 12-cm depth in any year of sampling (data not shown).

Reduction in water-stable macroaggregates and mean-weight diameter as a result of inversion tillage compared with NT has been observed frequently in other studies. On a Pachic Haplustoll in Nebraska, aggregate stability index was greatly reduced under CT compared with NT and native grassland at the end of 26 years of management (Six et al., 1998). The fraction of soil as water-stable macroaggregates at a depth of 0–5 cm was always lower under CT than under NT among long-term studies in Kentucky (24 years), Michigan (9 years), Nebraska (26 years), and Ohio (33 years) (Six et al., 2000). On a Rhodic Kanhapludult in Georgia, large water-stable macroaggregates were significantly greater under NT than under CT at 0–5-cm depth, but none of the aggregate classes were different between tillage systems at 5–15-cm depth (Beare et al., 1994). Among four soils in Alberta and British Columbia, the fraction of soil as water-stable macroaggregates was greater under NT than under CT in coarse-textured soils, but not in fine-textured soils, and this effect was greatest nearest the soil surface (0–5-cm depth) and diminished with increasing soil depth (Franzluebbers

Table 3
Mean-weight diameter of water-stable aggregate distribution and its stability index relative to dry-stable aggregate distribution at 0–3, 3–6, and 6–12-cm depths as affected by tillage, cover crop management, and their interaction when averaged across cropping systems during 4 sampling events from 2002 to 2004 near Watkinsville GA

Tillage	Cover crop	Mean-weight diameter (g macroaggregates g^{-1} soil)			Stability of mean-weight diameter (g wet g^{-1} dry)		
		0–3	3–6	6–12	0–3	3–6	6–12
May 2002 (at initiation)							
Conventional	Ungrazed	1.17	1.42	1.44	1.06	1.02	0.99
Conventional	Grazed	1.12	1.38	1.44	1.07	1.03	1.00
No tillage	Ungrazed	1.24	1.36	1.42	1.02	1.00	0.98
No tillage	Grazed	1.18	1.31	1.31	1.08	1.06	1.02
Analysis of variance (Pr > F)							
Tillage		0.21	0.35	0.41	0.66	0.98	0.92
Cover crop		0.32	0.56	0.23	0.09	0.24	0.29
Tillage × cover crop		0.89	0.95	0.25	0.21	0.41	0.40
December 2002 (at the end of 0.5 year)							
Conventional	Ungrazed	0.86	0.89	1.00	0.57	0.55	0.65
Conventional	Grazed	0.90	0.99	0.97	0.61	0.63	0.62
No tillage	Ungrazed	1.28	1.40	1.35	0.90	0.93	0.86
No tillage	Grazed	1.32	1.23	1.29	0.91	0.88	0.95
Analysis of variance (Pr > F)							
Tillage		<**0.001**	<**0.001**	**0.009**	<**0.001**	<**0.001**	<**0.001**
Cover crop		0.34	0.63	0.50	0.26	0.79	0.53
Tillage × cover crop		0.99	0.06	0.83	0.51	0.23	0.25
March 2004 (at the end of 2 years)							
Conventional	Ungrazed	1.09	1.27	1.30	0.76	0.84	0.78
Conventional	Grazed	1.05	1.18	1.24	0.74	0.82	0.78
No tillage	Ungrazed	1.31	1.48	1.44	0.95	0.98	0.94
No tillage	Grazed	1.19	1.40	1.44	1.01	1.02	0.96
Analysis of variance (Pr > F)							
Tillage		**0.007**	<**0.001**	**0.004**	<**0.001**	<**0.001**	<**0.001**
Cover crop		0.13	**0.04**	0.68	0.21	0.74	0.47
Tillage × cover crop		0.43	0.98	0.63	**0.01**	0.19	0.50
December 2004 (at the end of 2.5 years)							
Conventional	Ungrazed	0.93	1.17	1.03	0.77	0.74	0.75
Conventional	Grazed	0.84	0.93	1.00	0.78	0.72	0.73
No tillage	Ungrazed	1.10	1.39	1.18	0.92	0.90	0.89
No tillage	Grazed	0.94	1.09	1.12	0.96	0.97	0.94
Analysis of variance (Pr > F)							
Tillage		**0.03**	**0.006**	**0.02**	<**0.001**	<**0.001**	<**0.001**
Cover crop		**0.03**	<**0.001**	0.28	0.25	**0.03**	0.09
Tillage × cover crop		0.49	0.59	0.64	0.55	**0.003**	**0.005**

Bold indicates probability levels <0.05.

and Arshad, 1996). On a Typic Kanhapludult in Georgia, reduced tillage type and frequency combined with winter cover cropping resulted in greater mean-weight diameter of soil aggregates compared with CT and no cover crop, suggesting that both reduced disturbance and input of C compounds from winter cover cropping contributed to improved aggregation (Franzluebbers et al., 1999). Results in this study are consistent with the literature, but also indicate that changes in aggregate distribution and stability are rapid, as a result of soil mixing with CT.

Cover crop management typically did not affect water-stable macroaggregates, except at the end of 2.5 years at 3–6-cm depth (Table 2). In this case, the fraction of soil as water-stable macroaggregates averaged 0.78 g g^{-1} when ungrazed and 0.72 g g^{-1} when grazed by cattle across tillage systems. A similar trend of lower macroaggregation with grazing occurred at the end of 2 years at 0–3-cm depth (0.75 g g^{-1} vs. 0.73 g g^{-1}; $P = 0.07$) and at 3–6-cm depth (0.80 g g^{-1} vs. 0.78 g g^{-1}; $P = 0.09$). Mean-weight diameter of water-stable aggregates was significantly lower when cover crops were grazed than ungrazed at the end of 2 years at 3–6-cm depth (1.37 mm vs. 1.29 mm), at the end of 2.5 years at 0–3-cm depth (1.01 mm vs. 0.89 mm), and at the end of 2.5 years at 3–6-cm depth (1.28 mm vs. 1.01 mm) (Table 3). The interaction between cover crop management and tillage system was not significant for either macroaggregates or mean-weight diameter.

The effect of cover crop management on stability of macroaggregates and stability of mean-weight diameter (i.e. wet/dry) was dependent upon tillage system. At the end of 2 years at 0–3-cm depth, mean-weight diameter stability was greater when cover

Table 4
Antecedent soil water content, apparent macropore filling with water (derived from intercept), and linear rate of water infiltration during 10–60 min from single-ring infiltration measurements during 5 events from 2003 to 2006 as affected by tillage, cover crop management, and their interaction in a winter grain/summer cover crop system near Watkinsville GA

Tillage	Cover crop	Soil water content (m^3 m^{-3})	Macropore filling (mm)	Infiltration rate (mm min^{-1})
15 October 2003 (end of 2nd summer cover crop)				
Conventional	Ungrazed	0.160	22	5.2
Conventional	Grazed	0.146	12	3.9
No tillage	Ungrazed	0.194	20	7.0
No tillage	Grazed	0.160	7	3.2
Analysis of variance (Pr > F)				
Tillage		0.21	0.48	0.67
Cover crop		**0.05**	0.12	**0.04**
Tillage × cover crop		0.34	0.81	0.25
27 July 2004 (prior to 3rd summer cover crop)				
Conventional	Ungrazed	0.099	13	12.8
Conventional	Grazed	0.095	32	11.6
No tillage	Ungrazed	0.098	33	7.2
No tillage	Grazed	0.099	11	9.9
Analysis of variance (Pr > F)				
Tillage		0.95	0.98	0.12
Cover crop		0.91	0.78	0.47
Tillage × cover crop		0.81	**0.04**	0.11
20 October 2004 (end of the 3rd summer cover crop)				
Conventional	Ungrazed	0.203	40	6.3
Conventional	Grazed	0.213	15	1.8
No tillage	Ungrazed	0.233	15	6.8
No tillage	Grazed	0.234	3	2.4
Analysis of variance (Pr > F)				
Tillage		0.11	0.11	0.81
Cover crop		0.56	**0.02**	**0.04**
Tillage × cover crop		0.65	0.34	0.99
23 June 2005 (prior to 4th summer cover crop)				
Conventional	Ungrazed	0.196	7	6.9
Conventional	Grazed	0.183	25	6.2
No tillage	Ungrazed	0.188	24	5.6
No tillage	Grazed	0.203	8	3.9
Analysis of variance (Pr > F)				
Tillage		0.78	0.99	0.34
Cover crop		0.96	0.90	0.17
Tillage × cover crop		0.25	0.09	0.58
5–14 June 2006 (prior to 5th summer cover crop)				
Conventional	Ungrazed	0.102	16	4.0
Conventional	Grazed	0.069	0	6.2
No tillage	Ungrazed	0.175	15	4.2
No tillage	Grazed	0.089	19	5.6
Analysis of variance (Pr > F)				
Tillage		0.17	0.62	0.78
Cover crop		**0.002**	0.41	0.21
Tillage × cover crop		0.06	0.23	0.79

Bold indicates probability levels <0.05.

crops were grazed than not grazed under NT, but not different under CT (Table 3). At the end of 2.5 years at 3–6-cm depth, macroaggregate stability was lower when cover crops were grazed than not grazed under CT, but macroaggregate stability and mean-weight diameter stability were greater when grazed than not grazed under NT. At the end of 2.5 years at 6–12-cm depth, both macroaggregate stability and mean-weight diameter stability were greater when grazed than not grazed under NT, but not different under CT. These data suggest that water-stable macroaggregates and mean-weight diameter were only marginally lower under grazed than ungrazed cover crop management. However, a part of this effect was simply smaller aggregate size prior to wet sieving since stability measurements were either equal or greater when grazed than not grazed.

Literature is scant concerning grazing impacts on aggregate distribution and stability in cropping systems. On Mollisols in Iowa, short-term winter grazing of corn stover resulted in no effect on aggregate stability compared with ungrazed corn stalks, irrespective of time that soil was frozen (Clark et al., 2004). On a Petrocalcic Calciustoll in Texas, aggregate stability of bare soil was not affected by stocking rate under dry soil conditions, but tended to decline with increasing stocking rate under moist soil conditions (Warren et al., 1986). On a Tropeptic Haplustox in Columbia, aggregate size distribution and aggregate stability were little affected by cattle grazing on improved and native savanna (Gijsman and Thomas, 1995). Our results from this study are in general agreement with the limited literature, suggesting that moderate cattle grazing of forage in cropping systems will have little impact on soil aggregate distribution and stability. In fact, presence of grass roots and accumulating debris at the soil surface (e.g. difference between CT and NT) appears to be more important for aggregation than the presence of grazing animals.

3.3. *Water infiltration*

Single-ring water infiltration was determined on 5 occasions in the summer cover crop system (Table 4) and on 2 occasions in the winter cover crop system (Table 5). Tillage system had no significant effect on infiltration rate during any of the 7 events. Therefore, it seems that the tillage effects on porosity (generally NT < CT; derived from the inverse of bulk density; Table 1) and aggregation (generally NT > CT; Tables 2 and 3) counteracted each other resulting in no difference in water infiltration between tillage systems. Macropore filling was, generally, unaffected by tillage system. At any one sampling event there was no significant difference in soil water content at the time of infiltration measurement (Tables 4 and 5), but when assessed across the 7 sampling events, soil water content was significantly greater under NT than under CT (Table 6).

Water infiltration in response to different tillage systems has not been consistent among studies. On a Typic Cryoboralf in British Columbia, infiltration rate was 0.5 mm min^{-1} under CT and 0.8 mm min^{-1} with NT for 12 years (Arshad et al., 1999). At the end of 12 years of management on a Cumulic Haplustoll in Mexico, infiltration rate (derived from a falling-head ring infiltrometer) was CT > NT in 3 of 8 comparisons and not different between tillage systems in the 5 remaining comparisons with residue retained on the field (Govaerts et al., 2007). When residue was removed from the field following harvest, infiltration rate was CT > NT in 6 of 8 comparisons and not different between tillage systems in the other 2 comparisons. Soil cover was an important factor in controlling infiltration rate. Singh and Malhi (2006) also found that removal of straw with NT management resulted in lower infiltration than retaining straw under CT or NT. At the end of 8 years of management on a Vertisol in Queensland Australia, infiltration of simulated rainfall was 1.5 mm min^{-1} under traditional tillage and 1.1 mm min^{-1} under NT with low rainfall energy, but 0.7 mm min^{-1} under traditional tillage and 1.1 mm min^{-1} under NT with high rainfall energy (McGarry et al., 2000). The results of the Australian rainfall simulation study provided compelling evidence that simulations should match environmental conditions at each particular location. The piedmont region of Georgia also experiences high-energy rainfall events. At a neighboring study in Watkinsville, 24 years of NT management of a 2.7-ha cropped watershed reduced water runoff to 22 mm year^{-1} compared with 180 mm year^{-1} under previous management with CT (Endale et al., 2000). Our measurement of ring infiltration may not have been adequate to characterize high-energy rainfall events that are more frequent in summer in Georgia, but probably was adequate to characterize low-energy

Table 5

Antecedent soil water content, apparent macropore filling with water (derived from intercept), and linear rate of water infiltration during 10–60 min from single-ring infiltration measurements during 2 events from 2004 to 2006 as affected by tillage, cover crop management, and their interaction in a summer grain/winter cover crop system near Watkinsville GA

Tillage	Cover crop	Soil water content ($\text{m}^3\ \text{m}^{-3}$)	Macropore filling (mm)	Infiltration rate (mm min^{-1})
3 May 2004 (end of the 2nd winter cover crop)				
Conventional	Ungrazed	0.141	10	10.2
Conventional	Grazed	0.151	16	7.0
No tillage	Ungrazed	0.125	43	8.0
No tillage	Grazed	0.148	25	5.6
Analysis of variance (Pr > F)				
Tillage		0.50	0.28	0.25
Cover crop		0.23	0.50	0.12
Tillage × cover crop		0.63	0.22	0.81
5–14 June 2006 (end of the 4th winter cover crop)				
Conventional	Ungrazed	0.098	39	4.8
Conventional	Grazed	0.075	17	6.0
No tillage	Ungrazed	0.125	19	7.0
No tillage	Grazed	0.088	19	5.2
Analysis of variance (Pr > F)				
Tillage		0.25	0.19	0.44
Cover crop		**0.04**	**0.05**	0.78
Tillage × cover crop		0.57	**0.05**	0.17

Bold indicates probability levels <0.05.

Table 6
Antecedent soil water content, apparent macropore filling with water (derived from intercept), and linear rate of water infiltration during 10–60 min from single-ring infiltration measurements averaged across a total of 7 events in both cropping systems from 2003 to 2006 as affected by tillage, cover crop management, and their interaction near Watkinsville GA

Tillage	Cover crop	Soil water content (m^3 m^{-3})	Macropore filling (mm)	Infiltration rate (mm min^{-1})
Conventional	Ungrazed	0.143	21	7.2
Conventional	Grazed	0.133	16	6.1
No tillage	Ungrazed	0.163	24	6.6
No tillage	Grazed	0.146	13	5.1
Analysis of variance (Pr > F)				
Tillage		**0.05**	0.99	0.23
Cover crop		0.10	0.08	0.07
Tillage × cover crop		0.64	0.48	0.79

Bold indicates probability levels <0.05.

rainfall events at other times of the year and soil-profile infiltration.

Cover crop management had a significant effect on infiltration rate only during 2 of 7 measurement events, i.e. at the end of the 2nd and 3rd summer cover crops (Table 4). Infiltration rate under grazed cover crop management was only 46 ± 20% as high as under ungrazed cover crop management during these 2 events. Across the 7 events, infiltration rate tended to be lower ($P = 0.07$) under grazed (5.6 mm min^{-1}) than under ungrazed (6.9 mm min^{-1}) conditions (Table 6). Macropore filling also tended to be lower ($P = 0.08$) under grazed than under ungrazed condition. Grazing of cover crops also led to lower soil water content than when cover crops were not grazed during 3 events, i.e. at the end of the 2nd summer cover crop, prior to the 5th summer cover crop, and at the end of the 4th winter cover crop (Tables 4 and 5). Across the 7 events, the effect of cover crop management on soil water content resulted in only a trend ($P = 0.10$), where values averaged 0.153 m^3 m^{-3} when ungrazed and 0.140 m^3 m^{-3} when grazed (Table 6).

Generally, ponded infiltration was lower with higher soil water content. However, the relationship between soil water content and infiltration rate was different between ungrazed and grazed cover crop management (Fig. 1). Across tillage systems, the common intercept was 8.9 mm min^{-1} and the slope was −0.13 mm min^{-1} per percent change in soil water content when cover crops were not grazed and −0.24 mm min^{-1} per percent change in soil water content when cover crops were grazed ($P < 0.01$). The trend for higher water infiltration rate with ungrazed than grazed cover crop management could be attributed to differences under wetter soil conditions. The data presented in Fig. 1 suggest that the negative effect of grazing cattle on water infiltration was restricted to measurement conditions of high soil water content.

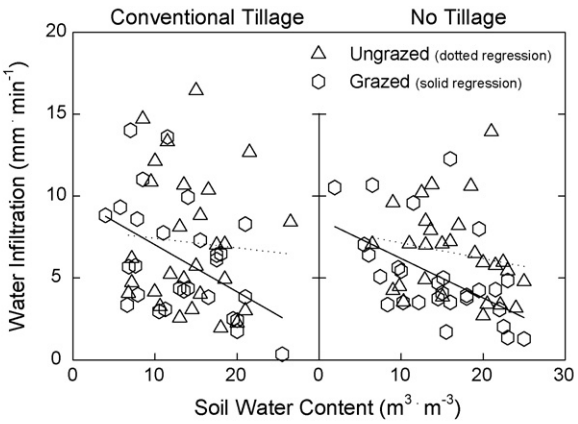


Fig. 1. Water infiltration rate from 10 to 60 min during a single-ring measurement as affected by antecedent soil water content, cover crop management (i.e. grazed or ungrazed), and tillage system near Watkinsville GA. Measurements were taken 7 times from 2003 to 2006. Regression equations were ($n = 28$): $Y = 8.0 - 0.058X$, $r^2 = 0.01$ (conventional tillage-ungrazed), $Y = 9.9 - 0.287X$, $r^2 = 0.23$ (conventional tillage-grazed), $Y = 8.1 - 0.096X$, $r^2 = 0.03$ (no tillage-ungrazed), and $Y = 8.6 - 0.240X$, $r^2 = 0.28$ (no tillage-grazed).

Literature is limited concerning grazing impacts on water infiltration in cropping systems. During the first year of oat following pasture on an Alfisol (sandy loam texture) in New South Wales Australia, hydraulic conductivity averaged 0.1 mm min^{-1} with intensive grazing by sheep and 0.2 mm min^{-1} with ungrazed oat under both shallow tillage and NT (Mead and Chan, 1992). On a Typic Cryaquept (clay texture) in Finland, ring infiltration rate averaged 0.4 mm min^{-1} in trampled pasture and 1.2 mm min^{-1} in pasture with no visible trampling (Pietola et al., 2005). In the same study on a nearby Aquic Cryorthent (sandy loam texture), ring infiltration rate averaged 0.9 mm min^{-1} in trampled pasture and 2.4 mm min^{-1} in pasture with no visible trampling. Infiltration rate averaged 0.1 mm min^{-1} and was not affected by short-term cattle stocking rate on a Typic Dystrochrept in New Zealand (Russell et al., 2001). The trend for reduced infiltration with grazing of cover crops in our study is consistent with the mixed results in the literature, i.e. reduced or no change in infiltration due to animal grazing.

3.4. Soil penetration resistance

Soil penetration resistance was determined 6 times at the beginning and end of summer cover crops (Table 7) and 4 times at the end of grazing periods with winter cover crops (Table 8). Penetration resistance was affected by tillage system mostly at a depth of 0–10 cm, in which significantly greater values occurred under NT than under CT prior to the 2nd summer cover crop, at the end of the 3rd summer cover crop, at the end of the 4th summer cover crop, at the end of the 2nd winter cover crop, and at the end of corn stalk grazing in 2005. Penetration resistance was greater under NT than under CT at a depth of 10–20 cm prior to the 2nd summer cover crop, at the end of the 1st winter cover crop, and at the end of the 3rd winter cover crop. At a depth of 20–30 cm, there were no differences in penetration resistance due to tillage system. Averaged across the 10 sampling events, penetration resistance was significantly greater under NT than under CT at 0–10-cm depth and tended to be greater ($P = 0.10$) under NT than under CT at 10–20-cm depth (Table 9). Because of the large effect at the soil surface, cumulative penetration resistance throughout the soil profile was significantly greater under NT than under CT to a depth of 30 cm.

Greater soil penetration resistance with NT compared with CT systems has often been reported (Unger and Jones, 1998; Schjǿnning and Rasmussen, 2000; Carter et al., 2002; Sharratt et al., 2006; Singh and Malhi, 2006). Soil loosening with inversion tillage reduces soil strength temporarily, but equipment traffic and natural consolidation combined with slowly declining soil organic matter content can result in soil with greater resistance in the long-term. On a Plinthic

Table 7
Antecedent soil water content and work required (penetration resistance) for a 30° steel cone with a 20.3-mm diam base to penetrate soil to 10, 20, and 30 cm depths from 6 events in 2003–2005 as affected by tillage, cover crop management, and their interaction in a winter grain/summer cover crop system near Watkinsville GA

Tillage	Cover crop	Soil water content (m^3 m^{-3})	Penetration resistance (J)				
			0–10 cm	10–20 cm	20–30 cm	0–20 cm	0–30 cm
5 August 2003 (prior to 2nd summer cover crop)							
Conventional	Ungrazed	0.210	40	94	107	134	241
Conventional	Grazed	0.204	44	82	88	126	214
No tillage	Ungrazed	0.215	82	114	131	196	326
No tillage	Grazed	0.223	72	111	112	183	296
Analysis of variance (Pr > F)							
Tillage		**0.02**	**0.001**	**0.01**	0.10	**0.003**	**0.001**
Cover crop		0.96	0.67	0.25	0.29	0.44	0.14
Tillage × cover crop		0.58	0.38	0.46	0.98	0.86	0.92
9 October 2003 (end of the 2nd summer cover crop)							
Conventional	Ungrazed	0.188	69	132	145	201	346
Conventional	Grazed	0.174	174	178	205	352	557
No tillage	Ungrazed	0.218	109	143	167	252	419
No tillage	Grazed	0.194	126	158	160	284	444
Analysis of variance (Pr > F)							
Tillage		**0.04**	0.83	0.67	0.65	0.77	0.70
Cover crop		**0.02**	**0.004**	**0.02**	0.23	**0.002**	**0.02**
Tillage × cover crop		0.42	**0.02**	0.17	0.15	**0.01**	**0.04**
27 July 2004 (prior to 3rd summer cover crop)							
Conventional	Ungrazed	0.099	82	377	448	459	907
Conventional	Grazed	0.093	86	315	486	401	887
No tillage	Ungrazed	0.098	98	343	453	441	894
No tillage	Grazed	0.102	102	279	418	381	800
Analysis of variance (Pr > F)							
Tillage		0.81	0.08	0.65	0.52	0.81	0.68
Cover crop		0.93	0.66	0.06	0.97	0.14	0.41
Tillage × cover crop		0.48	0.96	0.99	0.43	0.98	0.59
22 October 2004 (end of the 3rd summer cover crop)							
Conventional	Ungrazed	0.206	34	118	112	152	265
Conventional	Grazed	0.209	90	121	133	211	344
No tillage	Ungrazed	0.233	82	109	102	190	292
No tillage	Grazed	0.227	107	135	139	242	381
Analysis of variance (Pr > F)							
Tillage		**0.02**	**0.003**	0.70	0.81	**0.03**	0.18
Cover crop		0.85	<**0.001**	0.12	**0.05**	**0.002**	**0.004**
Tillage × cover crop		0.63	**0.05**	0.23	0.52	0.75	0.81
29 June 2005 (prior to 4th summer cover crop)							
Conventional	Ungrazed	0.174	74	131	120	205	325
Conventional	Grazed	0.155	66	104	120	170	290
No tillage	Ungrazed	0.194	73	127	158	199	317
No tillage	Grazed	0.185	88	115	114	203	325
Analysis of variance (Pr > F)							
Tillage		0.10	0.33	0.32	0.27	0.32	0.24
Cover crop		0.17	0.74	**0.01**	0.14	0.24	**0.04**
Tillage × cover crop		0.59	0.30	0.24	0.14	0.16	0.86
20 October 2005 (end of the 4th summer cover crop)							
Conventional	Ungrazed	0.120	62	154	214	216	430
Conventional	Grazed	0.109	98	187	172	285	457
No tillage	Ungrazed	0.151	118	190	189	308	497
No tillage	Grazed	0.134	141	187	187	328	515
Analysis of variance (Pr > F)							
Tillage		0.07	<**0.001**	0.34	0.70	**0.03**	0.13
Cover crop		0.21	**0.003**	0.39	0.26	**0.05**	0.50
Tillage × cover crop		0.79	0.33	0.29	0.30	0.23	0.89

Bold indicates probability levels <0.05.

Kandiudult in Alabama, penetration resistance was volatile with chisel ± disk tillage during the 2nd year of a grazed winter cover crop/cotton system, but stable with time under NT (Siri-Prieto et al., 2007). On a Typic Argiudoll in Uruguay, penetration resistance was greater under NT than under CT in the surface 10 cm of soil before winter grazing, but was not different between tillage systems in the upper 20 cm soil and was lower under NT than under CT at 20–25-cm depth (García-Préchac et al., 2004). Our results of overall greater penetration

Table 8

Antecedent soil water content and work required (penetration resistance) for a 30° steel cone with a 20.3-mm diam base to penetrate soil to 10, 20, and 30 cm depths from 4 events in 2003–005 as affected by tillage, cover crop management, and their interaction in a summer grain/winter cover crop system near Watkinsville GA

Tillage	Cover crop	Soil water content ($m^3\ m^{-3}$)	Penetration resistance (J)				
			0–10 cm	10–20 cm	20–30 cm	0–20 cm	0–30 cm
9 May 2003 (end of the 1st winter cover crop)							
Conventional	Ungrazed	0.234	58	74	102	132	234
Conventional	Grazed	0.233	111	80	88	190	278
No tillage	Ungrazed	0.264	80	114	118	194	312
No tillage	Grazed	0.250	94	131	127	225	352
Analysis of variance (Pr $>$ F)							
Tillage		0.21	0.73	**0.004**	0.11	**0.03**	**0.04**
Cover crop		0.35	**0.005**	**0.05**	0.83	**0.004**	**0.008**
Tillage × cover crop		0.44	**0.05**	0.25	0.31	0.21	0.84
7 May 2004 (end of the 2nd winter cover crop)							
Conventional	Ungrazed	0.095	89	343	515	431	946
Conventional	Grazed	0.118	160	308	354	468	822
No tillage	Ungrazed	0.090	216	555	756	771	1407
No tillage	Grazed	0.099	186	334	393	520	913
Analysis of variance (Pr $>$ F)							
Tillage		0.42	**0.01**	0.11	0.11	**0.04**	0.07
Cover crop		0.31	0.36	**0.04**	**0.03**	0.17	**0.03**
Tillage × cover crop		0.67	**0.05**	0.11	0.30	0.08	0.15
6 April 2005 (end of the 3rd winter cover crop)							
Conventional	Ungrazed	0.165	94	118	121	212	334
Conventional	Grazed	0.204	137	127	107	264	371
No tillage	Ungrazed	0.190	112	181	143	294	437
No tillage	Grazed	0.208	124	146	144	270	414
Analysis of variance (Pr $>$ F)							
Tillage		0.49	0.65	**0.03**	0.33	**0.03**	**0.04**
Cover crop		0.15	0.09	0.61	0.35	0.69	0.82
Tillage × cover crop		0.55	0.29	0.40	0.29	0.30	0.36
24 October 2005 (end of the 2-week grazing of corn stalks)							
Conventional	Ungrazed	0.138	102	170	170	272	442
Conventional	Grazed	0.145	131	175	146	306	453
No tillage	Ungrazed	0.158	123	165	178	288	466
No tillage	Grazed	0.149	176	191	185	367	552
Analysis of variance (Pr $>$ F)							
Tillage		0.08	**0.001**	0.55	0.36	**0.007**	0.08
Cover crop		0.98	0.06	0.35	0.72	0.11	0.26
Tillage × cover crop		0.49	0.55	0.50	0.50	0.49	0.37

Bold indicates probability levels <0.05.

resistance with NT than with CT within the upper 20 cm of soil are consistent with previous research. However, it should be noted that there were no significant differences in penetration resistance between tillage systems during 3 of 10 sampling events.

Cover crop management had a significant effect on soil penetration resistance on several occasions. At a depth of 0–10 cm, penetration resistance was greater under grazed than ungrazed condition at the end of the 2nd, 3rd, and 4th summer cover crops (Table 7), as well as at the end of the 1st winter cover crop (Table 8). At a depth of 10–20 cm, penetration resistance was greater under grazed than ungrazed condition at the end of the 2nd summer cover crop and at the end of the 1st winter cover crop, but lower under grazed than ungrazed condition at the end of the 2nd winter cover crop and prior to the 4th summer cover crop. At a

Table 9

Antecedent soil water content and work required (penetration resistance) for a 30° steel cone with a 20.3-mm diam base to penetrate soil to 10, 20, and 30 cm depths averaged across a total of 10 events in both cropping systems from 2003 to 2005 as affected by tillage, cover crop management, and their interaction near Watkinsville GA

Tillage	Cover crop	Soil water content ($m^3\ m^{-3}$)	Penetration resistance (J)				
			0–10 cm	10–20 cm	20–30 cm	0–20 cm	0–30 cm
Conventional	Ungrazed	0.163	70	171	205	241	447
Conventional	Grazed	0.164	110	168	190	277	467
No tillage	Ungrazed	0.181	109	204	240	313	541
No tillage	Grazed	0.177	122	179	198	300	498
Analysis of variance (Pr $>$ F)							
Tillage		$<$**0.001**	**0.001**	0.10	0.27	**0.01**	**0.04**
Cover crop		0.73	**0.001**	0.27	0.14	0.53	0.71
Tillage × cover crop		0.46	0.06	0.40	0.49	0.18	0.29

Bold indicates probability levels <0.05.

depth of 20–30 cm, penetration resistance was greater under grazed than ungrazed condition at the end of the 3rd summer cover crop, but lower under grazed than ungrazed condition at the end of the 2nd winter cover crop. Averaged across the 10 sampling events, penetration resistance was greater under grazed than ungrazed cover crops, but only at a depth of 0–10 cm (Table 9).

There were several significant interactions between tillage and cover crop management on soil penetration resistance. On 3 occasions (end of the 2nd summer cover crop and end of the 1st and 2nd winter cover crop), penetration resistance was greater with than without grazing under CT, but not different between cover crop systems under NT. At the end of the 3rd summer cover crop, penetration resistance was greater with grazing than without grazing under both tillage systems, but the effect was greater under CT than under NT. Averaged across the 10 sampling events, there was a trend ($P = 0.06$) for an interaction of tillage and cover crop management at a depth of 0–10 cm (Table 9); significantly greater penetration resistance with grazed than ungrazed condition under CT, but no difference between grazed and ungrazed condition under NT.

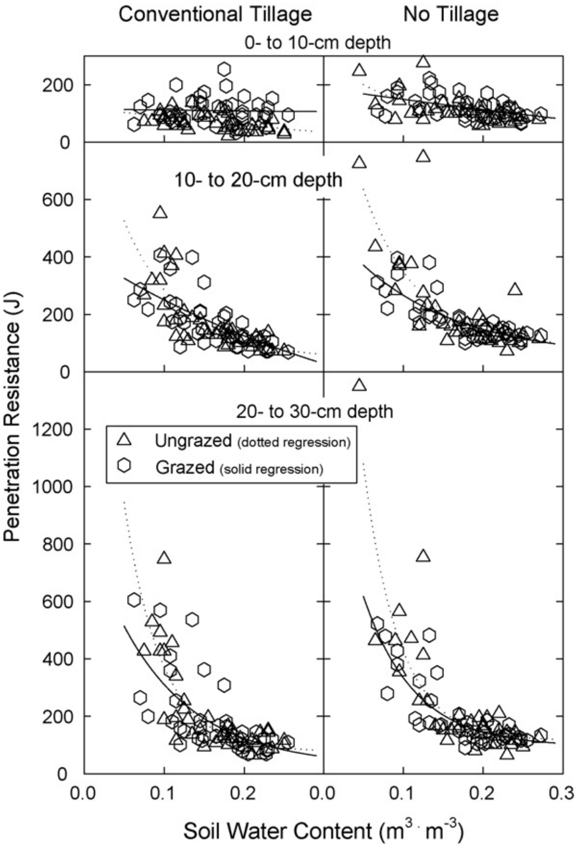


Fig. 2. Soil penetration resistance at 0–10-cm, 10–20-cm, and 20–30-cm depths as affected by antecedent soil water content, cover crop management (i.e. grazed or ungrazed), and tillage system near Watkinsville GA. Measurements were taken 10 times from 2003 to 2005. Regression equations were ($n = 40$): $Y = -226 + 346e^{-1.0X}$, $r^2 = 0.25$ (conventional tillage, ungrazed, 0–10 cm depth), $Y = 101 + 15e^{-3.4X}$, $r^2 = 0.00$ (conventional tillage, grazed, 0–10 cm depth), $Y = 77 + 228e^{-12.3X}$, $r^2 = 0.36$ (no tillage, ungrazed, 0–10 cm depth), $Y = -350 + 538e^{-0.7X}$, $r^2 = 0.23$ (no tillage, grazed, 0–10 cm depth), $Y = 45 + 960e^{-13.9X}$, $r^2 = 0.58$ (conventional tillage, ungrazed, 10–20 cm depth), $Y = -312 + 724e^{-2.5X}$, $r^2 = 0.49$ (conventional tillage, grazed, 10–20 cm depth), $Y = 87 + 1149e^{-14.8X}$, $r^2 = 0.64$ (no tillage, ungrazed, 10–20 cm depth), $Y = 49 + 479e^{-7.9X}$, $r^2 = 0.62$ (no tillage, grazed, 10–20 cm depth), $Y = 78 + 2541e^{-21.5X}$, $r^2 = 0.67$ (conventional tillage, ungrazed, 20–30 cm depth), $Y = 26 + 837e^{-10.8X}$, $r^2 = 0.45$ (conventional tillage, grazed, 20–30 cm depth), $Y = 116 + 2974e^{-22.6X}$, $r^2 = 0.79$ (no tillage, ungrazed, 20–30 cm depth), and $Y = 95 + 1143e^{-15.6X}$, $r^2 = 0.70$ (no tillage, grazed, 20–30 cm depth).

Literature is sparse comparing soil penetration resistance in grazed and ungrazed cropping systems. On a Mollisol in Iowa, soil penetration resistance was 31 ± 9% ($n = 6$) greater following 28-d grazing events in winter than under ungrazed corn stalks when soil was frozen for only 22 ± 33% of the time and only 13 ± 6% greater (not significant) ($n = 9$) when soil was frozen for longer periods of time (72 ± 41%) (Clark et al., 2004). Hamza and Anderson (2005) reviewed the literature and showed evidence of greater penetration resistance in the upper 20 cm of soil with grazing than without, but suggested the difference was below the threshold to affect plant growth. On an Ultisol in Brazil, short-duration grazing during the first year of guineagrass (*Panicum maximum*) resulted in greater penetration resistance of the surface 5 cm of soil with 5.7 animal units ha^{-1} than with 4.4 or 3.5 animal units ha^{-1} (da Silva et al., 2003). Our results of greater penetration resistance for grazed compared with ungrazed cover crops under CT, but few differences under NT, are consistent with previous studies conducted mostly with inversion tillage.

Penetration resistance at 0–10-cm depth was little affected by soil water content under any of the four management conditions (Fig. 2). However with increasing soil depth, soil penetration resistance became increasingly dependent upon soil water content condition. The negative, non-linear relationship suggested a strong influence of soil water content below approximately 0.15 m^3 m^{-3} (equivalent to 33% water-filled pore space assuming an average bulk density of 1.46 Mg m^{-3} and total porosity of 0.45 m^3 m^{-3}). At soil water content >0.15 m^3 m^{-3}, there was much less effect of soil water content on penetration resistance, irrespective of soil depth. Wet soil is known to minimize soil strength (Busscher et al., 1997; Dexter et al., 2007). Tillage and cover crop management systems did not greatly affect the relationship between penetration resistance and soil water content, despite differences in depth distribution of soil organic C and clay content (Franzluebbers and Stuedemann, 2008), depth distribution of bulk density (Table 1), and soil water content (Tables 4–9). It is possible that these factors influencing penetration resistance interacted to nullify relational changes or that the range of difference in factors influencing penetration resistance was simply too small to affect the relationship.

4. Summary and conclusions

Conversion of long-term perennial pasture to cropland resulted in changes in soil physical properties that were dependent upon subsequent tillage system. Initial moldboard plowing followed by disk tillage (CT) resulted in lower soil bulk density to a depth of 0–30 cm than undisturbed soil managed with no tillage (NT) at the end of 0.5 year. Thereafter, differences in bulk density between tillage systems disappeared below a depth of 12 cm with disk tillage only to 15–20 cm. Grazing of cover crops had little effect on soil bulk density, perhaps because of the high surface-soil organic C concentration following perennial pasture that mitigated compaction. Soil aggregation was degraded with CT compared with NT management. Stability of aggregates was unaffected by grazing of cover crops in both tillage systems. Water infiltration was variably affected by tillage and cover crop management, but was reduced with grazing of cover crops compared with ungrazed cover crops when soil water content was high at the time of measurement. Soil penetration resistance was often greater under NT than under CT, despite soil under NT was generally wetter than under CT. Soil penetration resistance was greater under grazed than ungrazed cover crops with CT, but not different between cover crop systems with NT. Overall, the introduction of cattle to consume the high-quality cover crop forages (*Secale cereale* and *Pennisetum glaucum*) did not cause substantial physical damage to the soil. Additional long-term research is warranted to verify these short-term (initial 2.5 years) results, especially since integrated crop-livestock systems with conservation tillage could increase farm production and protect environmental services.

Acknowledgements

We gratefully acknowledge the excellent technical contributions of Steve Knapp, Eric Elsner, Devin Berry, Stephanie Steed, Kim Lyness, Robert Martin, and Dwight Seman. Financial support was provided in part by the USDA–National Research Initiative Competitive Grants Program (Agr. No. 2001-35107-11126) and the Georgia Agricultural Commodity Commission for Corn.

References

Arshad, M.A., Franzluebbers, A.J., Azooz, R.H., 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada. Soil Till. Res. 53, 41–47.

Beare, M.H., Hendrix, P.F., Coleman, D.C., 1994. Water-stable aggregates and organic matter fractions in conventional- and no-tillage soils. Soil Sci. Soc. Am. J. 58, 777–786.

Belesky, D.P., Stuedemann, J.A., Plattner, R.D., Wilkinson, S.R., 1988. Ergopeptine alkaloids in grazed tall fescue. Agron. J. 80, 209–212.

Bilotta, G.S., Brazier, R.E., Haygarth, P.M., 2007. The impacts of grazing animals on the quality of soils, vegetation, and surface waters in intensively managed grasslands. Adv. Agron. 94, 237–280.

Bouwer, H., 1986. Intake rate: cylinder infiltrometer. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, Second Ed., Agronomy Series 9, Am. Soc. Agron., Soil Sci. Soc. Am., Madison, WI, pp. 825–844.

Busscher, W.J., Bauer, P.J., Camp, C.R., Sojka, R.E., 1997. Correction of cone index for soil water content differences in a coastal plain soil. Soil Till. Res. 43, 205–217.

Carter, M.R., Sanderson, J.B., Ivany, J.A., White, R.P., 2002. Influence of rotation and tillage on forage maize productivity, weed species, and soil quality of a fine sandy loam in the cool-humid climate of Atlantic Canada. Soil Till. Res. 67, 85–98.

Clark, J.T., Russell, J.R., Karlen, D.L., Singleton, P.L., Busby, W.D., Peterson, B.C., 2004. Soil surface property and soybean yield response to corn stover grazing. Agron. J. 96, 1364–1371.

da Silva, A.P., Imhoff, S., Corsi, M., 2003. Evaluation of soil compaction in an irrigated short-duration grazing system. Soil Till. Res. 70, 83–90.

Dexter, A.R., Czyz, E.A., Gate, O.P., 2007. A method for prediction of soil penetration resistance. Soil Till. Res. 93, 412–419.

Diaz-Zorita, M., Duarte, G.A., Grove, J.H., 2002. A review of no-till systems and soil management for sustainable productino in the subhumid and semiarid Pampas of Argentina. Soil Till. Res. 65, 1–18.

Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50, 627–633.

Endale, D.M., Schomberg, H.H., Steiner, J.L., 2000. Long term sediment yield and mitigation in a small Southern Piedmont watershed. Int. J. Sediment Res. 14, 60–68.

Franzluebbers, A.J., Arshad, M.A., 1996. Water-stable aggregation and organic matter in four soils under conventional and zero tillage. Can. J. Soil Sci. 76, 387–393.

Franzluebbers, A.J., Langdale, G.W., Schomberg, H.H., 1999. Soil carbon, nitrogen, and aggregation in response to type and frequency of tillage. Soil Sci. Soc. Am. J. 63, 349–355.

Franzluebbers, A.J., Stuedemann, J.A., 2007. Crop and cattle responses to tillage systems for integrated crop-livestock production in the Southern Piedmont, USA. Renewable Agric. Food Syst. 22, 168–180.

Franzluebbers, A.J., Stuedemann, J.A., 2008. Early changes in soil organic carbon and nitrogen fractions in response to tillage and integrated crop/livestock production. Soil Sci. Soc. Am. J. 72, 613–625.

Franzluebbers, A.J., Stuedemann, J.A., Schomberg, H.H., 2000a. Spatial distribution of soil carbon and nitrogen pools under grazed tall fescue. Soil Sci. Soc. Am. J. 64, 635–639.

Franzluebbers, A.J., Stuedemann, J.A., Schomberg, H.H., Wilkinson, S.R., 2000b. Soil Biol. Biochem. and N pools under long-term pasture management in the Southern Piedmont USA. 32, 469–478.

Franzluebbers, A.J., Stuedemann, J.A., Wilkinson, S.R., 2001. Bermudagrass management in the Southern Piedmont USA. I. Soil and surface residue carbon and sulphur. Soil Sci. Soc. Am. J. 65, 834–841.

Franzluebbers, A.J., Wright, S.F., Stuedemann, J.A., 2000c. Soil aggregation and glomalin under pastures in the Southern Piedmont USA. Soil Sci. Soc. Am. J. 64, 1018–1026.

García-Préchac, F., Ernst, O., Siri-Prieto, G., Terra, J.A., 2004. Integrating no-till into crop-pasture rotations in Uruguay. Soil Till. Res. 77, 1–13.

Gijsman, A.J., Thomas, R.J., 1995. Aggregate size distribution and stability of an Oxisol under legume-based and pure grass pastures in the eastern Columbian savannas. Aust. J. Soil Res. 33, 153–165.

Govaerts, B., Fuentes, M., Mezzalama, M., Nicol, J.M., Deckers, J., Etchevers, J.D., Figueroa-Sandoval, B., Sayre, K.D., 2007. Infiltration, soil moisture, root rot and nematode populations after 12 years of different tillage, residue and crop rotation managements. Soil Till. Res. 94, 209–219.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Till. Res. 82, 121–145.

Herrick, J.E., Jones, T.L., 2002. A dynamic cone penetrometer for measuring soil penetration resistance. Soil Sci. Soc. Am. J. 66, 1320–1324.

Kay, B.D., VandenBygaart, A.J., 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil Till. Res. 66, 107–118.

McGarry, D., Bridge, B.J., Radford, B.J., 2000. Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. Soil Till. Res. 53, 105–115.

Mead, J.A., Chan, K.Y., 1992. Cultivation techniques and grazing affect surface structure of an Australian hardsetting soil. Soil Till. Res. 25, 217–230.

Mekuria, W., Veldkamp, E., Haile, M., Nyssen, J., Muys, B., Gebrehiwot, K., 2007. Effectiveness of exclosures to restore degraded soils as a result of overgrazing in Tigray. Ethiopia. J. Arid Environ. 69, 270–284.

Nosetto, M.D., Jobbágy, E.G., Paruelo, J.M., 2006. Carbon sequestration in semi-arid rangelands: Comparison of *Pinus ponderosa* plantations and grazing exclusion in NW Patagonia. J. Arid Environ. 67, 142–156.

Pietola, L., Horn, R., Yli-Halla, M., 2005. Effects of trampling by cattle on the hydraulic and mechanical properties of soil. Soil Till. Res. 82, 99–108.

Russell, J.R., Betteridge, K., Costall, D.A., Mackay, A.D., 2001. Cattle treading effects on sediment loss and water infiltration. J. Range Manage. 54, 184–190.

Schjønning, P., Rasmussen, K.J., 2000. Soil strength and soil pore characteristics for direct drilled and ploughed soils. Soil Till. Res. 57, 69–82.

Sharratt, B., Zhang, M., Sparrow, S., 2006. Twenty years of tillage research in subarctic Alaska. I. Impact on soil strength, aggregation, roughness, and residue cover. Soil Till. Res. 91, 75–81.

Singh, B., Malhi, S.S., 2006. Response of soil physical properties to tillage and residue management on two soils in a cool temperate environment. Soil Till. Res. 85, 143–153.

Siri-Prieto, G., Reeves, D.W., Raper, R.L., 2007. Tillage systems for a cotton-peanut rotation with winter-annual grazing: impacts on soil carbon, nitrogen and physical properties. Soil Till. Res. 96, 260–268.

Six, J., Elliott, E.T., Paustian, K., Doran, J.W., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62, 1367–1377.

Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000. Soil structure and organic matter. I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64, 681–689.

Sparrow, A.D., Friedel, M.H., Tongway, D.J., 2003. Degradation and recovery processes in arid grazing lands of central Australia. Part 3. Implications at landscape scale. J. Arid Environ. 55, 349–360.

Tebrűgge, F., Dűring, R.-A., 1999. Reducing tillage intensity: a review of results from a long-term study in Germany. Soil Till. Res. 53, 15–28.

Tollner, E.W., Calvert, G.V., Langdale, G., 1990. Animal trampling effects on soil physical properties of two Southeastern U.S. ultisols. Agric. Ecosyst. Environ. 33, 75–87.

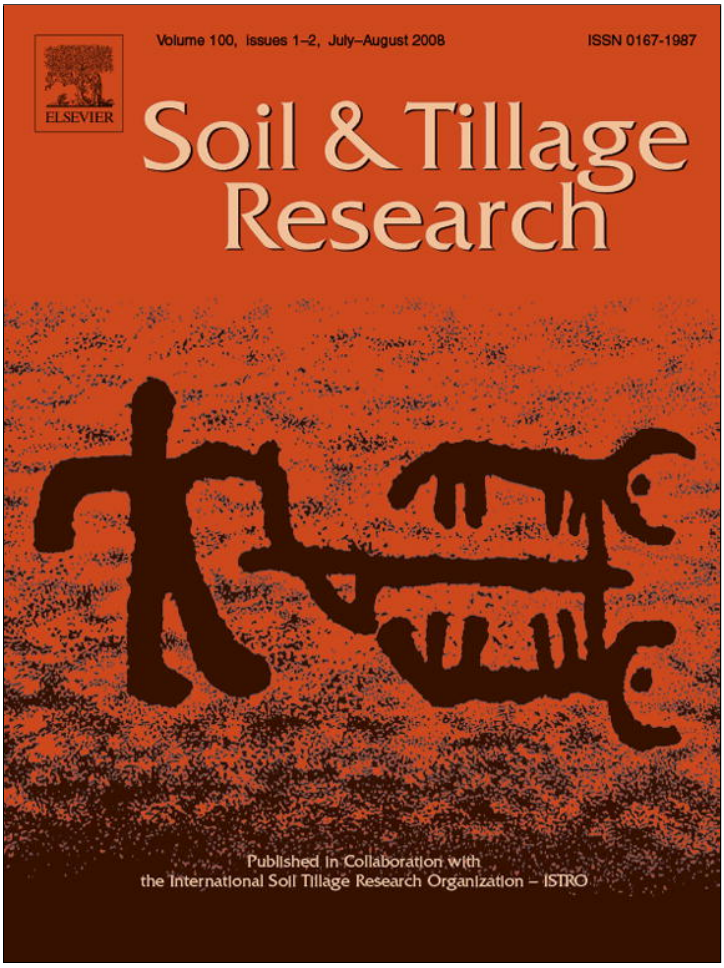
Unger, P.W., Jones, O.R., 1998. Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum. Soil Till. Res. 45, 39–57.

USDA-NASS, 2007. 2002 Census of Agriculture, Volume 1, Geographic Area Series Census, U.S. State Data, USDA–National Agricultural Statistics Service, Accessed at: www.nass.usda.gov/Census/Create_Census_US.jsp, Verified: 21 September 2007.

VandenBygaart, A.J., Protz, R., Tomlin, A.D., 1999. Changes in pore structure in a no-till chronosequence of silt loam soils, southern Ontario. Can. J. Soil Sci. 79, 149–160.

Warren, S.D., Nevill, M.B., Blackburn, W.H., Garza, N.E., 1986. Soil response to trampling under intensive rotation grazing. Soil Sci. Soc. Am. J. 50, 1336–1341.

Zhao, W.Y., Li, J.L., Qi, J.G., 2007. Changes in vegetation diversity and structure in response to heavy grazing pressure in the northern Tianshan Mountains, China. J. Arid Environ. 68, 465–479.



Volume 100, Issues 1–2, July–August 2008 ISSN 0167-1987

Soil & Tillage Research

Published in Collaboration with
the International Soil Tillage Research Organization – ISTRO