INFLUENCES OF AGRICULTURAL PRACTICE AND SUMMER GRAZING ON SOIL COMPACTION IN WHEAT PADDOKS

B. K. Northup, J. A. Daniel, W. A. Phillips

ABSTRACT. Agriculture in the Southern Great Plains (SGP) relies on production systems that combine yearling cattle and grazing of winter wheat. Incorporating summer legumes into the fallow period of wheat would allow longer grazing seasons and potential improvements in livestock gain, but may adversely affect soil conditions. This study examined the impacts of additional grazing during summer on soil compaction within paddocks of grazed wheat. Four 1.6 ha paddocks were used to study two systems of producing forage by conservation tillage during 1999 and 2000. Both systems combined winter and spring grazing of wheat with either grazing of an annual legume during summer (SL) or chemical fallow during summer (SCF). Enclosures (n = 2) were established in each paddock to serve as ungrazed controls. Soil compaction was measured by resistance to a cone penetrometer to 300 mm soil depth on three dates (May and December 1999, June 2000), and measures of bulk density and soil moisture were collected. Regression analyses showed a significant relationship between resistance and bulk density across agricultural practices, and separate relationships for grazing treatments. The SL agricultural practice produced greater compaction of soil than SCF below 75 mm depth, with gradual increases over the last two sampling dates. In contrast, grazing generated increases in compaction at all depths on all dates, with the largest increases noted between 50 and 100 mm. Results suggest that combining grazing of wheat with grazing legumes during the summer, under conservation tillage, may not represent sustainable management in the short term.

Keywords. Compaction, Grazing, Summer fallow, Summer legumes, Winter wheat.

A primary component of agriculture in the Southern Great Plains (SGP) is production of weight gains by stocker cattle. Most calves in the U.S. are born in the spring, sold in early fall as weaned calves, and then shipped to feedlots in the Central Great Plains for finishing (fig. 1). While en route to feedlots, these growing animals, known as stocker cattle, spend time in the SGP grazing cost-efficient paddocks of grass, where they serve as a pool that feedlots utilize to fill feeder space as it becomes available (Peel, 2003). The primary forage resource in the SGP for grazing stockers is paddocks of winter wheat (*Triticum aestivum*). Stocker cattle may be grazed from November through April to harvest beef (graze-out), or they can be removed in early March to allow grain harvest in June (graze-grain). Therefore, production systems applied to wheat paddocks are dynamic and variable. Length of grazing season and numbers of animals grazed are defined by weather, paddock productivity (Hossain et al., 2004), production costs, and the market values of animal gain and wheat grain (Peel, 2003). Surveys showed that 58% (±18%) of the 2.6 × 10^6 ha of wheat planted annually during 1996 to 2002 in Oklahoma were grazed, mostly in a dual-purpose role, by 1.1 (±0.3) × 10^6 stockers (Hossain et al., 2004; True et al., 2001). Nationally, about 4.5 (±0.7) × 10^6 (~30%) of all stockers annually available in the U.S. during the 1990s were...
located in the SGP (Peel, 2003). The economy of the SGP, and the nation’s beef industry, are therefore dependent on winter wheat as forage.

The reliance of agriculture in the SGP on grazing wheat paddocks means that management must be balanced and not adversely affect soil properties, to ensure long-term sustainability. Both tillage and grazing have the potential to reduce soil productivity if applied incorrectly. Tillage has the capacity to increase turnover of organic matter, and its constituent chemicals, via improved conditions for microbial decomposition (Oades, 1993; Lal et al., 1998), which contributes to increased soil bulk density. Changes in management practices applied to croplands, with or without grazing, can also influence soil properties, particularly during transitions among tillage systems (Wilkins et al., 2002; Sidhu and Duiker, 2006; Blanco-Canqui et al., 2009).

Greater bulk densities of soils were reported with increasing levels of grazing pressure applied to native rangeland (van Haveren, 1983; Daniel et al., 2002). Similar effects have been reported for paddocks of annual forages. Mulholland and Fullen (1991) demonstrated that cattle grazing paddocks on loamy sand generated higher bulk densities in the 70 to 105 mm increment of soil. In response to grazing of wheat paddocks, bulk density of soils increased, infiltration rates were reduced, and surface runoff increased regardless of the management system applied to the crop (Daniel et al., 2006; Daniel, 2007). Soil compaction caused by grazing (Worrell et al., 1992; Winter and Unger, 2001) may therefore be similar to the effects of vehicular traffic, which can reduce future grain production by crops (Reyes et al., 2005; Sidhu and Duiker, 2006). However, reports of the speed with which grazing affects soil properties, and the duration of such effects, have been variable (Wheeler et al., 2002; Siri-Prieto et al., 2007).

The majority of precipitation received in the SGP normally occurs during the fall through spring of most calendar years (Garbrecht et al., 2000). As such, the management of winter wheat is naturally synchronized to make optimum use of the precipitation received during the fall through spring (Redmon et al., 1995). Wheat paddocks are typically left fallow during the summer to allow soil water to accumulate for the next fall planting (Hossain et al., 2004). Producers in the SGP could extend the grazing season of stockers by incorporating summer legumes into wheat-based systems (Daniel et al., 2006; Rao and Northup, 2009). An extended grazing season associated with such a change in land use may improve returns from animal gains. The inclusion of grazed winter annuals into cotton-based agriculture in Alabama allowed large improvements in net returns, but with a range of positive and negative effects on cotton yields related to tillage (Siri-Prieto et al., 2007). While lengthening the grazing season is an appealing tactic, it may have adverse effects and risks when applied to wheat paddocks in the SGP. Summer legumes utilize soil water needed for the establishment of wheat (Nielsen and Vigil, 2005) and the production of forage in the fall (Vigil and Nielsen, 1998; Rao and Northup, 2009). Further, including a summer grazed season in systems of continuous graze-out wheat might further increase soil compaction, and affect other soil processes (Daniel, 2007).

The effects of grazing on soils in conventional systems of cereal production have been documented in many areas (Worrell et al., 1992; Solie et al., 1993; Winter and Unger, 2001). There is less information on how the combination of winter wheat and double-cropped summer forages will affect soil properties in the SGP when managed by conservation tillage. Double-cropping a summer legume with wheat was shown to increase surface runoff and sediment yields (Daniel et al., 2006) in Oklahoma, indicating the presence of more compacted surface soils. Further, double-cropping summer legumes with wheat under conservation tillage in the SGP reduced available soil moisture within the profile over four years (Rao and Northup, 2009). However, the influence of such changes in management on the physical properties of soils has not been well documented. The objective of this study was to characterize the short-term impacts of double-cropping a summer legume with wheat on soil compaction, and related properties. Our working hypothesis was that double-cropping a grazed summer legume in rotation with graze-out wheat has similar effects on soil compaction as the traditional grazed wheat-summer fallow system.

**Materials and Methods**

**Site Description**

This study was conducted during 1998 through 2000 at the USDA-ARS Grazinglands Research Laboratory (35° 33’ 29” N, 98° 150” W) near El Reno, Oklahoma (Daniel, 2001). The site is within the Red Prairies region of southern Kansas, Oklahoma, and northern Texas (fig. 1) where production of winter wheat coupled with summer fallow is the most common agricultural practice (Hossain et al., 2004). Experiments were conducted on 1.6 ha cultivated paddocks (n = 4) constructed as experimental watersheds in 1976 (Daniel, 2001). The paddocks were managed during 1977 to 1998 by conventional tillage (plowing, disking, and surface harrowing) and were used in systems of continuous winter wheat/summer fallow that produced forage grazed by stocker cattle. The paddocks were situated across a common slope (3% to 5%) and aspect (westerly). Dominant soils were Renfrow and Kirkland (fine, mixed, thermic Udertic Paleustolls) that developed on parent material defined as Permian-aged Dog Creek shale consisting of reddish-brown shale with thin inter-bedding of reddish-brown siltstone (Daniel, 2002). The Renfrow soils developed on residuum formed from the underlying calcareous shale parent material and were found on crests and sideslopes (Fisher and Swafford, 1976; USDA-NRCS, 1999). Kirkland soil series were found on crests and formed from the underlying shale. Both soils series have relatively fine texture (28% sand, 49% silt, 23% clay) and low permeability. Climate at the study site was an unstable mix of the sub-humid eastern and semiarid western regions of Oklahoma, with large oscillations between wet and dry periods (Garbrecht et al., 2000).

Precipitation at the study site averaged (±SD) 837 (±142) mm during 1976 through 2000, with minima and maxima in 1980 (605 mm) and 1986 (1107 mm). Seasonal distribution of annual rainfall during the period was 11%, 32%, 32%, and 26%, respectively, in the winter, spring, summer, and fall.

**Applied Treatments**

All four paddocks were initially prepared by moldboard plow (300 mm depth) and repeated disking (200 mm depth) during August to September 1998 to provide uniform starting conditions. Experimental systems of management were...
initiated in October 1998 with conservation tillage (no-till) applied to all paddocks to measure cumulative effects of management on near-surface properties of soils. Winter wheat (cultivar 2163, 112 kg ha\(^{-1}\)) was planted in all paddocks each fall with a no-till drill, and two fertilizer applications of 45 kg N ha\(^{-1}\) (98 kg ha\(^{-1}\) broadcast urea) were undertaken: one in October and the second in March. Two subsets of management were then applied to the paddocks: agricultural practice, and grazing. Two agricultural practices were applied to replicate paddocks (\(n = 2\)) as main effects during the summer of the traditional system of managing graze-out wheat: (1) summer chemical fallow (SCF) as a control, and (2) summer legume (SL). Paddocks managed by SCF were sprayed with Glyphosate (Roundup; 1.1 kg ha\(^{-1}\)) to control, and (2) summer legume (SL). Paddocks managed by SCF were sprayed with Glyphosate (Roundup; 1.1 kg ha\(^{-1}\)) to kill remaining vegetation after wheat graze-out (early May), and residues (<1000 kg ha\(^{-1}\) biomass) were mown to 15 cm and left on the soil surface. Fallow conditions were maintained by herbicide applications until wheat was planted in late September to early October for the next cycle of grazing. Management applied to the SL treatment included Korean lespedeza (Lespedeza stipulacea) as a summer forage. Lespedeza seed was broadcast (35 kg ha\(^{-1}\)) into two paddocks in early March, incorporated into the soil by hoof action of the cattle, and allowed to grow through July. Cattle were then reintroduced to the SL paddocks for summer grazing (mid-July to mid-September). The paddocks were sprayed with Glyphosate to prepare for the next cycle of planting wheat after removal of cattle in September.

Two grazing practices were incorporated into the agricultural practices applied to paddocks as split-plots: grazed during summer, and not grazed. Two randomly located enclosures (5 5 m) were established in each paddock to serve as the ungrazed treatment and retained for the duration of the experiment. Enclosures were not grazed during both the wheat and SL phases of the year. All biomass >15 cm height above the soil surface was clipped by forage harvester at maturity of the planted forages (May for wheat, September for lespedeza) and removed from the enclosures. Ungrazed enclosures therefore represented methods of producing hay crops rather than as grazed resources. Stocking densities applied to the grazed treatment during winter, spring, and summer were dictated by available forage at the start of grazing and by projection of amounts of biomass expected for the remainder of the given period. All paddocks were grazed at low stocking rates during December and at higher rates during March through April to utilize the rapid growth of wheat as it matured (table 1). Summer grazing of lespedeza provided a 138 animal unit day (AUD) ha\(^{-1}\) increase in grazing applied to SL paddocks, compared to grazing only wheat. Average body weights of stocker cattle that grazed wheat and the summer legume were 230 and 295 kg, respectively.

**Compaction Measurements**

**Resistance to Penetration**

Resistance to penetration was measured with a hand-held digital cone penetrometer (Rimik CP40, Agridry-RIMIK Pty., Ltd., Toowoomba, Queensland, Australia) that conformed to accepted standards for the technique (ASAE Standards, 1996). The penetrrometer consisted of a 30° circular, 12.6 mm diameter (125 mm\(^2\) surface area) stainless steel conical tip attached to a stainless steel shaft. The shaft and tip were inserted into the soil to a 300 mm depth at speeds of 0.0014 m s\(^{-1}\) (ASAE Standards, 1996; Lowery and Morrison, 2002). Data were collected in May 1999 (end of first wheat cycle), December 1999 (mid-study), and June 2000 (end of second wheat cycle) at times when the soil profile was moist and conditions approximated field capacity. May and June readings were collected after graze-out of wheat, and readings in December were collected at the start of winter grazing. Resistance measurements were collected from randomly chosen 0.5 m\(^2\) locations (\(n = 4\)) in the grazed portions of paddocks (fig. 2) and from random locations (\(n = 2\)) in each ungrazed enclosure (\(n = 2\)). In cases where chosen locations were situated in areas affected by overly high animal traffic, or the presence of recent vehicular traffic, a

<table>
<thead>
<tr>
<th>Year</th>
<th>Season[a]</th>
<th>SCF</th>
<th>SL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>Winter</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>176</td>
<td>209</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>--</td>
<td>138</td>
</tr>
<tr>
<td>2000</td>
<td>Winter</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>147</td>
<td>78</td>
</tr>
<tr>
<td>Mean (±SD)</td>
<td>Winter</td>
<td>24 (±2)</td>
<td>20 (±7)</td>
</tr>
<tr>
<td></td>
<td>Spring</td>
<td>162 (±21)</td>
<td>144 (±239)</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>--</td>
<td>138</td>
</tr>
<tr>
<td>Total Annual</td>
<td></td>
<td>186</td>
<td>302</td>
</tr>
</tbody>
</table>

[a] Grazing during winter, spring, and summer was applied in December, March through April, and July through September, respectively.

[b] SCF and SL, respectively, represent summer chemical fallow and summer legume practices applied to paddocks. One animal unit day (AUD) of grazing by stocker cattle is presented as the equivalent of one animal unit. One AUD represents the amount of biomass required to support one 454 kg cow and one 136 kg suckling calf each day (12.7 kg dry matter of forage).

![Figure 2. Illustrations of 1.6 ha wheat paddocks, ungrazed enclosures, and sampling sites used to define soil compaction in response to grazing and agricultural practices during summer.](image)

<30 mm s\(^{-1}\) (ASAE Standards, 1996; Lowery and Morrison, 2002). Data were collected in May 1999 (end of first wheat cycle), December 1999 (mid-study), and June 2000 (end of second wheat cycle) at times when the soil profile was moist and conditions approximated field capacity. May and June readings were collected after graze-out of wheat, and readings in December were collected at the start of winter grazing. Resistance measurements were collected from randomly chosen 0.5 m\(^2\) locations (\(n = 4\)) in the grazed portions of paddocks (fig. 2) and from random locations (\(n = 2\)) in each ungrazed enclosure (\(n = 2\)). In cases where chosen locations were situated in areas affected by overly high animal traffic, or the presence of recent vehicular traffic, a
different random location was chosen for sampling. The cone penetrometer was inserted into the soil (in 15 mm increments) ten times per site, and penetration readings (cone index values) were expressed by averages per 15 mm soil increment. Amounts of water in the different increments of soil were also described at each sampling date with time domain reflectometry (model 6050X Trase System 1, Soil Moisture Equipment Corp., Santa Barbara, Cal.) using 150 mm attenuation probes (Ferré and Topp, 2002).

**Bulk Density**

Soil cores were collected in May 1999 to calculate bulk densities and soil textures as in aid in interpreting soil resistance to the cone penetrometer. Cores were collected in 50 mm dia. × 150 mm plastic liners with a hand-held sampler (AMS core sampler, Art’s Manufacturing and Supply, American Falls, Ida.). Each core was capped and labeled in the field, and transported to the laboratory. The cores were then sawn into 50 mm increments, weighed, dried at 105°C for 24 h, and re-weighed to describe dry soil mass and gravimetric soil moisture. Lengths of the plastic liners of each increment and the cutting tip of the sampler were measured by vernier scale and used to calculate sample volume. Volume of increments and their corresponding dry weight were used to calculate bulk density (Grossman and Reinsch, 2002). Soil textural classes were determined by hydrometer methods outlined by Gee and Bauder (1986).

**Statistical Analyses**

Resistance to cone penetrometer, bulk density, and moisture of samples collected in May 1999 were analyzed by regression techniques to determine if definable relationships existed between cone resistance and bulk density or soil moisture. The best-fit non-linear functions (Statsoft, 1995) describing relationships, as related to agricultural practice and grazing treatments, were defined. Measurements of resistance to cone penetrometer were analyzed by double repeated measures (cross-sectional) analysis in a mixed model (Littel et al., 1996; Patetta, 2005). Agricultural practice (n = 2) and grazing (n = 2) served as fixed effects, while soil depth (n = 20) and sampling date (n = 3) were repeated elements. Unstructured variance/covariance matrices were used in the model to accommodate changes in level of covariance and form of autocorrelation among individual depths and sample periods, and to account for some missing observations during the sampling periods. Individual paddocks were used as local subjects in ordering data for the analysis. The analysis was restricted to main, two-way, and three-way interactions among fixed and cross-sectional effects due to a lack of d.f. required to develop stable statistical models for other interactions. Level of significance in tests of mean differences was set at p = 0.05.

**Results and Discussion**

**Soil Property-Resistance Relationships**

Texture of soils in the paddocks under SCF and SL management in May 1999 were relatively uniform across agricultural practice and grazing management. Mean (±SD) particle fractions were 26% (±2%) sand, 49% (±1%) silt, and 25% (±2%) clay, which was similar to previously reported values for the upper 30 cm of Renfrow and Kirkland soils (USDA-NRCS, 1999). Bulk density of the upper 50 mm of soil in ungrazed enclosures of both agricultural practices was less dense than grazed areas in May 1999 (table 2). The largest difference in bulk density related to grazing was noted under the SL treatment. In contrast to soil texture, the bulk densities reported here for the grazed portions of paddocks were higher than those normally recorded for Renfrow and Kirkland soils (USDA-NRCS, 1999). The high densities recorded in May 1999 gave some indication of cumulative impacts of past management. These paddocks were planted to wheat under conventional tillage and grazed 21 years prior to this experiment. As such, bulk density at the end of the first grazing season showed the influence of accumulated cultivation and grazing. Soil organic matter in these paddocks was 25% lower than in neighboring paddocks of native prairie at this site (B. Northup, unpublished data). Organic matter acts as a shock absorber for the soil system and serves as the source of compounds required for development of soil structure (Oades, 1993). However, cultivation effectively mines organic matter from agricultural soils by improving conditions for increased microbial decomposition (Lal et al., 1998). Soils of cultivated paddocks on this site can therefore be defined as compacted at the start of the experiment. Water content of soils in May 1999 also differed slightly. Ungrazed enclosures had more soil water across agricultural practices in the upper 150 mm of soil than the grazed parts of paddocks, and paddocks planted to summer legumes had amounts of soil water similar to fallowed (SCF) paddocks.

Bulk density of soils under agricultural management and grazing treatments showed distinct non-linear relationships with resistance to cone penetrometer. There was no statistical difference (p > 0.65) between type of equation (second-order logarithmic) or their coefficients under the two agricultural practices (fig. 3a). Therefore, the relationship between bulk density and resistance was not a function of agricultural practice after the first year of producing wheat forage. This was not an unexpected result, as the SL treatment was not yet applied. Penetrometer readings of resistance therefore had relatively uniform relationships with bulk density across a broad range of soils on this site. The relationship between resistance and bulk density (adjusted R² = 0.76; p < 0.01) displayed large increases in bulk density per unit of resistance.

**Table 2. Mean (±SD) soil water and bulk density of the top 150 mm of soil in May 1999 of wheat paddocks and ungrazed enclosures used in defining regression relationships between soil characteristics and resistance to cone penetrometer.**

<table>
<thead>
<tr>
<th>Agricultural Practice[a]</th>
<th>Grazing Management</th>
<th>Soil Depth (mm)</th>
<th>Bulk density (Mg m⁻³)[b]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCF</td>
<td>Grazed</td>
<td>0-50</td>
<td>1.69 (0.16)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50-100</td>
<td>1.80 (0.11)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-150</td>
<td>1.82 (0.07)</td>
</tr>
<tr>
<td>Ungrazed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SL</td>
<td>Grazed</td>
<td>0-50</td>
<td>1.59 (0.22)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50-100</td>
<td>1.71 (0.22)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-150</td>
<td>1.78 (0.08)</td>
</tr>
<tr>
<td>Ungrazed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[a] SCF and SL, respectively, represent summer chemical fallow and summer legume practices applied to paddocks (n = 2 per practice).

[b] Bulk density calculated with volumes and dry mass of samples (Grossman and Reinsch, 2002).

[c] Gravimetric soil moisture expressed as percent soil mass.
through ~1100 kPa, when the relationship changed to a flatter rate of increase. In contrast, the two forms of grazing generated different non-linear relationships (fig. 3b). A first-order logarithmic function defined a significant ($p < 0.05$) relationship between resistance and bulk density of soil under grazing, although the fit ($R^2_{adj} = 0.34$) was low, and a high degree of variance was recorded in the relationship. Alternatively, the relationship between resistance and bulk density of soils in the ungrazed enclosures displayed a second-order logarithmic relationship with a better fit ($R^2_{adj} = 0.65$). The ranges of values covered by these two equations also differed, with the relationship in ungrazed enclosures restricted between 250 and 1750 kPa, while grazed parts of paddocks produced a range of observations with higher resistance (750 to 3000 kPa). No definable relationship ($p > 0.35$) could be developed between water content of soil and resistance measurements in response to agricultural practice ($0.14 < R^2 < 0.24$) or grazing ($0.05 < R^2 < 0.20$). Only one sampling date was included in the analysis, so the available range of relationships between soil moisture and resistance was limited.

**MANAGEMENT EFFECTS ON RESISTANCE**

The cross-sectional analysis of variance applied to soil resistance to cone penetrometer produced significant effects ($p < 0.05$) related to agricultural practice and grazing. Two significant three-way interactions were recorded in the analysis: agricultural practice $\times$ depth $\times$ date ($F_{1,123} = 22.1; p < 0.01$), and grazing treatment $\times$ depth $\times$ date ($F_{1,123} = 76.0; p < 0.01$). All other two- and three-way interactions were not significant ($0.13 < R^2 < 0.68$). In the agricultural practice $\times$ soil depth $\times$ date interaction, across grazing management, the lowest levels of resistance recorded ($<1100$ kPa) occurred in the upper 75 mm of the profile (fig. 4). Resistance was higher and relatively constant below 75 mm, and resistance of soils in the paddocks that incorporated summer legumes increased over the last two sampling dates. A pronounced bulge was initially recorded in the 125 to 200 mm increment in December 1999, and resistance of soils in the SL treatment exceeded the fallow treatment at depths below 150 mm in June 2000. In contrast, the resistance of soils under summer fallow was more consistent across dates, with a slight increase in the upper 100 mm in December 1999, although this increase did not persist into June 2000. These results indicate that influences of the applied agricultural practices were not uniform throughout the soil profile. Results also showed the speed with which effects of agricultural practices applied to wheat paddocks can accumulate. Observations in May 1999 represented conditions at the end of first season of practices applied to wheat (December to April) under conservation tillage. At that time, paddocks planted to legumes during the summer period were less compacted than paddocks under summer fallow. Thereafter, compaction of subsurface soil in SL paddocks gradually increased, indicating that the influence of agricultural practices had subtle effects on soil compaction. Changes in resistance required time, and impacts were not immediately uniform across the entire measured profile.

The eventual result of incorporating a summer legume into a system of continuous graze-out wheat was greater compaction in subsurface layers (below 100 mm) within two years. Some of the compaction recorded in near-surface soils on our site was likely related to the transition of cropland from conventional tillage to no-till. Wilkins et al. (2002) reported high levels of compaction after one year of no-till, but significantly lower compaction levels in the long term (17 years). Such long-term reductions in compaction have been related to the accumulation of soil organic matter and organic carbon under no-till (Blanco-Canqui et al., 2009), which requires time to accrue (Oades, 1993). Our results therefore indicate that the short-term impacts of agricultural practices applied by conservation tillage in the SGP may not be positive.

As with agricultural practices, the lowest levels of resistance ($<1100$ kPa) in the grazing management $\times$ depth $\times$ date interactions, across agricultural practice, were recorded.
near the surface soil (fig. 5). Grazing produced a distinct bulge in compaction, although at a different depth than was recorded for agricultural practices. The increase in resistance was noted in the surface layers (upper 65 mm) after only one year of grazing applied to wheat, and was consistent throughout the profile on all sampling dates. Soils in the ungrazed enclosures showed a smaller and more general increase in resistance with depth across all dates, and were slightly denser over the two later observations. Resistances of soil to the cone penetrometer under the two grazing treatments converged at depths below 200 mm in December 1999. Although the enclosures were not grazed during the experiment, and movement of equipment across the areas was limited, this response indicated that growing wheat or legumes as hay crops may also result in compaction of near-surface soil.

A contributing factor to the increased resistance over time may be slightly dryer soils during the latter sample periods (table 3). Unfortunately, identical soil conditions across dates, which would improve interpretations of our results (Lowery and Morrison, 2002), could not be attained due to variability in amounts and timing of precipitation. Soils under SCF were 11% to 22% drier under grazing, and 16% to 29% dryer under no grazing, during the December 1999 and June 2000 samplings than in May 1999. Soils under the SL practice were also slightly dryer in June 2000. However, resistance measurements were collected at times when soils were fully moist, with estimates ranging from 14% to 24% moisture content. The average (±SD) moisture content reported for the A horizon (upper 200 to 300 mm) of these soils at field capacity was 20% (±5%) (USDA-NRCS, 1999). The influence of dryer soils on resistance measurements in December 1999 and June 2000 may be relatively small compared to the applied treatments.

Resistance measurements (and hence compaction) recorded in the grazed and ungrazed portions of the paddocks showed that grazing affected the soil profile differently from the applied agricultural practices. The primary influences of grazing would be the effects of trampling by cattle, which can lead to puddled surface soils of wheat paddocks, particularly during winter and spring when the soils tend to be wettest (Daniel, 2007). Krzic et al., (2000) also reported such effects on tame cool-season perennial paddocks that were grazed when soils were wet. Results reported in studies on grazed croplands found that the level of compaction within the soil profile was variable in response to grazing. Mulholland and Fullen (1991) found resistance to a soil penetrometer was greater in the 70 to 105 mm depth of grazed paddocks than in soil above or below this layer. Our study noted effects similar to the above study, with grazing affecting compaction in the entire upper 300 mm of soil, but mostly in the 50 to 100 mm section. Grazing may also have a cumulative effect on compaction of grazed wheat paddocks, although this effect was difficult to define, given the high levels of resistance recorded in May 1999. Such a response indicates that grazing of no-till planted wheat may require only one year to achieve high levels of compaction.

Changes in physical properties of soil related to management can be significant and problematic. The extended grazing season we report here from including a grazed summer legume in a system of continuous graze-out wheat under conservation tillage over two years increased soil compaction, although the results were confounded with agricultural practice. Some reports of changes in soil properties related to agricultural practice or grazing showed that such effects were a temporary phenomena. Wheeler et al. (2002) reported increased bulk density in soils of cool-season perennial swards in Colorado in response to one grazing season, but the increase disappeared one year after cessation of grazing. Similar effects in croplands were reported for responses to vehicle traffic (Wood et al., 1993; Reyes et al., 2005; Gelder et al., 2007), which can generate some of the impacts found under high-density grazing. This impermanence was related to remediation treatments (cultivation, sub-soiling) that eliminated dense layers near the soil surface (Sidhu and Duiker, 2006). Longer and more detailed studies are required to define the effects of double-cropping graze-out wheat with a grazed summer legume on compaction of soils under conservation tillage.

**Table 3. Mean (±SD) amounts of water in the top 150 mm of the soil profile in wheat paddocks receiving different agricultural practices and grazing management during 1999 and 2000.**

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>SCF</td>
<td>Grazed</td>
<td>18 (1)</td>
<td>14 (3)</td>
<td>16 (5)</td>
</tr>
<tr>
<td>Ungrazed</td>
<td>24 (3)</td>
<td>17 (5)</td>
<td>20 (2)</td>
<td></td>
</tr>
<tr>
<td>SL</td>
<td>Grazed</td>
<td>16 (1)</td>
<td>17 (1)</td>
<td>15 (6)</td>
</tr>
<tr>
<td>Ungrazed</td>
<td>21 (1)</td>
<td>21 (3)</td>
<td>19 (5)</td>
<td></td>
</tr>
</tbody>
</table>

[a] SCF and SL, respectively, represent summer chemical fallow and summer legume practices applied to paddocks (n = 2 per practice).

[b] Amounts of soil water as described by time domain reflectometry (Ferre and Topp, 2002).

**CONCLUSION**

Agriculture in the SGP is reliant on grazing stocker cattle on wheat, and this reliance is dependent on productive croplands. As such, management systems applied to wheat paddocks should not adversely affect soil properties and should allow sustainable agronomic activities. Our results indicate that both agricultural practice and grazing applied to conservation-tilled wheat paddocks in central Oklahoma may increase compaction of near-surface soils within two years.

Figure 5. Interactions in relationships between grazing, sampling date, and soil depth in resistance of soil to a cone penetrometer averaged across agricultural practices. Horizontal bars represent 1 SD, and Diff is the contrast (581 kPa) used in determining significant differences among means.
years, although within different sections of the profile. Conservation tillage, with or without inclusion of a summer legume in a dual-crop system, did not limit compaction in the short term, and may result in higher bulk density of soils for several years before soil improvement occurs. Producers in the SGP should consider double-cropping a forage legume during the fallow period of winter wheat as a short-term tactical tool, to be applied over a limited series of years. Alternatively, a multi-crop rotation, including wheat (fall through spring), summer legume, winter fallow, and short-season spring forage or grain crops, could be developed to conserve moisture, improve soil condition, and diversify farming operations.

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