# Soil Physical Aspects of Integrated Crop-Livestock Systems

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## ABSTRACT

Integrated crop-livestock systems are inherently more complex than the current model of specialized agricultural production in industrialized countries with clear separation of crops and animals. A movement towards integrating crops and livestock will have impacts on soils and the environment; the key is to understand whether those impacts will be negative or positive. Literature is reviewed on the soil physical responses to various components of integrated crop-livestock systems. Response categories were separated into effects on (1) rooting environment (soil aggregation, bulk density, and penetration resistance), (2) water availability (soil water content and water infiltration), and (3) nutrient availability (soil organic matter and soili-profile stratification of organic matter and nutrients). Both negative and positive effects of introducing animals onto cropland are possible. With high soil moisture and high stocking rate, animal trampling can compact soil and disrupt the soil surface sufficiently to cause a reduction in subsequent plant growth and contribute to increased water runoff and nutrient loss during intense rainfall events. However, well-managed, integrated crop-livestock systems should create opportunities to avoid continuous stocking of animals on perennial pasture, thereby distributing the stress of animal traffic onto a greater land area and across different times of the year. More research is needed to understand whole-system interactions in integrated crop-livestock systems, not just direct effects of isolated components, such as (a) forage-crop rotations without animals or (b) animal treading effects in isolation of long-term cropping system evaluation.

## INTRODUCTION

Soil, without question, is the terrestrial foundation that supports human inhabitation of the Earth through the production of food, feed, and fiber. Mismanagement of the soil resource can result in soil being a source of environmental degradation, thereby threatening air and water quality, as well as a source of human health and nutrition.

Robust cropping systems are needed to buffer production outcomes against weather variations, limit negative environmental impacts of farming systems, and create agroecologically-sensitive opportunities to build long-term sustainability and maintain profit. In terms of environmental quality in general and soil quality in specific, diversified cropping systems are needed to replenish soil organic matter and build soil structure so that:

- Rainfall infiltrates soil to improve water availability to crops;
- Water runoff is minimized to avoid (a) soil erosion and (b) pollution of water bodies;
- Roots adequately penetrate the soil profile for more complete extraction of water and nutrients;
- Soil microorganisms proliferate to provide biotic diversity, healthy communities of organisms surrounding roots, and actively cycle nutrients for plant availability; and

- Crop production is optimized under the given environmental conditions of a particular farm setting.

Integrated crop-livestock systems have the potential to contribute to these agroecological outcomes by diversifying cropping systems with annual and perennial crops, providing animal manures directly on land to enhance soil fertility, and keeping soil covered more continuously to avoid soil erosion and prevent a decline in soil quality. How integrated crop-livestock systems specifically affect soil physical properties is the focus of this manuscript. Literature is reviewed from three primary themes of soil physical aspects of integrated crop-livestock systems: (1) rooting environment, (2) water transport and availability, and (3) nutrient distribution and availability.

Perennial forages are a key component of ruminant livestock grazing systems. As a phase in a diversified crop rotation, perennial forages offer clear benefits to soil, including soil erosion control. From the Sanborn Field in Missouri, topsoil thickness at the end of 100 years of management averaged 20 cm under continuous corn (*Zea mays*), 31 cm under a 6-yr rotation of corn-oat (*Avena sativa*)-wheat (*Triticum aestivum*)-red clover (*Trifolium pratense*)-timothy (*Phleum pratense*)-timothy, and 44 cm under continuous timothy (Gantzer et al., 1990). Soil erosion rates predicted from USLE in this study averaged 19, 2.5, and 0.3 Mg ha$^{-1}$ yr$^{-1}$ for the three management systems, respectively. The loss of nutrient-rich topsoil by soil erosion can have damaging effects on many soil properties, including bulk density, available water-holding capacity, and soil pH, as well as on crop productivity even with high-fertility management (Gantzer and McCarty, 1987; Bauer and Black, 1994). Along with the abatement of soil erosion, perennial forages often improve soil organic matter (Magdoff and Weil, 2004) and link surface and subsurface soil rooting profiles through the development of undisturbed and continuous biopores as a result of root channels (Elkins et al., 1977) and faunal activity (Shipitalo et al., 2000).

Of key importance in the sustainable development of integrated crop-livestock systems is assessing the positive and negative impacts of livestock on various components of the farming system, including how livestock affect soil physical quality. Livestock can exert a significant mechanical load on the soil surface, especially considering the small footprint of large animals, such as mature dairy cows. An adult Friesian cow was determined to exert a pressure of 220 kPa on the soil (Scholefield and Hall, 1986). However, even for cattle, the pressure can vary significantly depending upon type and age of animal, land slope, and extent of movement. The range of hoof pressures reported in the literature has been 130 to 350 kPa for cattle (Willatt and Pullar, 1983; Scholefield and Hall, 1986; Nie et al., 1997), 331 kPa for horses (Cohron, 1971), 83 to 124 kPa for sheep (Cohron, 1971; Willatt and Pullar, 1983), and 60 kPa for goats (Willatt and Pullar, 1983). This compares to a contemporary tractor tire exerting a pressure of 100 to 200 kPa (Schjønning et al., 2006).

When grazing animals congregate and frequently tread land, typically at drinking and feeding stations, they poach the land, denuding it of vegetation and making it susceptible to erosive forces and unbalanced in nutrient loading. This visual consequence of animal behavior on perennial pastures has been typically the focus of most research documenting the impacts of grazing animals on soil and water quality. The consequences on soil in these heavy-use areas, however, are not typical of what is envisioned for integrated crop-livestock systems. This review addresses research from animal trampling across a gradient of stocking rates, although integrated crop-livestock systems will typically have relatively low stocking rate on a yearly basis, considering that cropland will not always have a forage crop available for grazing, unlike perennial pastures.

## ROOTING ENVIRONMENT

### Soil aggregation

Soil aggregation is important for stabilizing the soil surface against erosion, creating sufficient porosity for retention and transport of water, and protecting soil organisms from predation and rapid decomposition of organic matter. Stability of aggregates to disruption can be used to measure the soil's ability to resist erosion (Kemper and Koch, 1966). Aggregate size distribution from micro- (<0.25 mm) to macro-aggregates (>0.25 mm) following both dry- and wet-sieving can provide a measure of structural stability and types of pores present (Franzluebbers et al., 2000b). Protection of organic matter and microbial communities within macro-aggregates can facilitate soil C sequestration and enhance soil biodiversity (Elliott, 1986; Rutherford and Juma, 1992; Beare et al., 1994).

Forage crops offer an excellent opportunity to build soil structure, because of limited soil disturbance and extensive rooting. On a Typic Humaquept in Quebec Canada, mean-weight diameter of water-stable aggregates increased during the first five years under alfalfa (*Medicago sativa*), but did not change with time under corn cropping or fallow management with conventional tillage (Angers, 1992). On a Typic Humaquept and a Typic Fragiaquept in Quebec Canada, mean-weight diameter of water-stable aggregates decreased following moldboard plowing of timothy meadow and declined even further with increasing number of years of corn and barley (*Hordeum vulgare*) cropping (Angers et al., 1992). On a Mollic Cryoboralf in Alberta Canada, mean-weight diameter of water-stable aggregates at a depth of 0-10 cm was affected by forage and cropping management under no tillage: 2.1 mm under smooth brome (*Bromus inermis*) = 2.2 mm under red fescue (*Festuca rubra*) > 1.8 mm under continuous wheat = 1.5 mm under wheat-wheat-canola (*Brassica campestris*) (Arshad et al., 2004). Similarly on a Typic Kanhapludult in Georgia, mean-weight diameter of water-stable aggregates at a depth of 0-20 cm was greater under tall fescue (*Lolium arundinaceum*)-bermudagrass (*Cynodon dactylon*) pasture (1.2 mm) than under long-term conservation-tillage cropland (1.0 mm) (Franzluebbers et al., 2000b). On a similar Typic Kanhapludult, mean-weight diameter was greater under conservation tillage than under conventional tillage (Franzluebbers et al., 1999).

From 15- to 19-year-old grazed and hayed pastures in Georgia, stability of aggregation (mean-weight diameter with wet sieving divided by that with dry sieving) was not affected by cattle traffic (0.74 mm $mm^{-1}$ when grazed *vs* 0.72 mm $mm^{-1}$ when hayed) nor was soil glomalin content (a biologically produced glue) at a depth of 0-20 cm (Franzluebbers et al., 2000b). During the first four years of Coastal bermudagrass establishment, stability of aggregation at a depth of 0-2 cm increased from 0.69 to 0.85 mm $mm^{-1}$, but was not significantly affected whether pasture was grazed by stocker cattle in the summer or not grazed (Franzluebbers et al., 2000b). On a silty clay soil (Petrocalcic Calciustoll) in Texas, soil aggregate stability was not affected by cattle grazing (weaned heifers, 240 kg $head^{-1}$) compared to without grazing when the soil was dry, but was lower when the soil was wet and the stocking rate exceeded 0.24 animal units ha$^{-1}$ (Warren et al., 1986). On a silty clay loam (Tropeptic Haplustox) in Columbia, aggregate size distribution and aggregate stability were little affected by stocking rate on improved and native savanna (Gijsman and Thomas, 1995).

On silt loam and silty clay loam soils in Iowa (Mollisols), soil aggregate stability was not affected by winter grazing of corn stalks during 28-day periods by bred cows (average of 606 kg head$^{-1}$, 3.7 head ha$^{-1}$) during 3 years of measurement (Clark et al., 2004). At the end of 3 years of cropping system evaluation on a Typic Kanhapludult in Georgia, stability of aggregation was similar whether cover crops were grazed by cow-calf pairs (average of 2.43 Mg ha$^{-1}$ for 47 days) or not at a depth of 0-3 cm (0.88 *vs* 0.84 mm mm$^{-1}$, $p = 0.16$) and at a depth of 3-6 cm (0.84 *vs* 0.82 mm, $p = 0.19$) (A.J. Franzluebbers, unpublished data).

These data from long-term pastures and short-term cover crops suggest that grazing cattle under normal stocking conditions have little impact on stability of soil aggregation. Presence of grass roots and detrital debris at the soil surface appears to be more important for aggregation than the presence of grazing animals. In a review of stocking rate effects on aggregate size and stability, Greenwood and McKenzie (2001) reported that most of the cited studies (n = 8) found a generally negative response to animal grazing, but most responses were weak or related to intense treading.

## Bulk density

Soil compaction reduces porosity, thereby limiting air and water storage and transport, which alters nutrient cycling and exploration potential of roots. Bulk density is a commonly used measure of soil compaction. Bulk density of uncompacted soil is a function of texture, aggregation, and organic matter content. Coarse-textured soils tend to have greater inherent bulk density than fine-textured soils (Table 1), partly because of the greater propensity of fine-textured soils to be more highly aggregated (Franzluebbers et al., 2000b). Soils with high organic matter content have low bulk density, as a result of the low particle density of organic matter and the positive influence of organic matter on aggregation (Fig. 1).

*Table 1. Soil bulk density as affected by soil texture and extent of cattle trampling in Finland. Data from Pietola et al. (2005).*

| *Soil depth (cm)* | *Clay* | | | *Sandy loam* | | |
|---|---|---|---|---|---|---|
| | *Grazed, but no visible trampling* | | *Poached* | *Grazed, but no visible trampling* | | *Poached* |
| | ---------------------------------- | | *Mg m$^{-3}$* | ---------------------------------- | | |
| *0-5* | *0.90* | | *0.88* | *1.30* | < | *1.39* |
| *10-15* | *1.06* | < | *1.14* | *1.41* | | *1.45* |
| *20-25* | *1.08* | < | *1.16* | *1.41* | | *1.40* |
| *30-35* | *1.13* | | *1.09* | *1.49* | | *1.46* |

Pastures and forage cropping systems can result in higher bulk density than conventional cropping systems, because of traffic combined with general lack of tillage, but can also result in lower bulk density due to soil organic matter accumulation, vigorous rooting, and soil faunal activity. On a Typic Kanhapludult in Georgia, soil bulk density at a depth of 0-20 cm was 1.48 Mg m$^{-3}$ under 20-year-old tall fescue-common bermudagrass pasture and 1.57 Mg m$^{-3}$ under 24-year-old conservation-tillage cropland (Franzluebbers et al., 2000b).

On a Mollic Cryoboralf in Alberta Canada, soil bulk density at a depth of 0-10 cm was not different among forage and no-tillage cropping systems managed continuously for 10 years (Arshad et al., 2004).

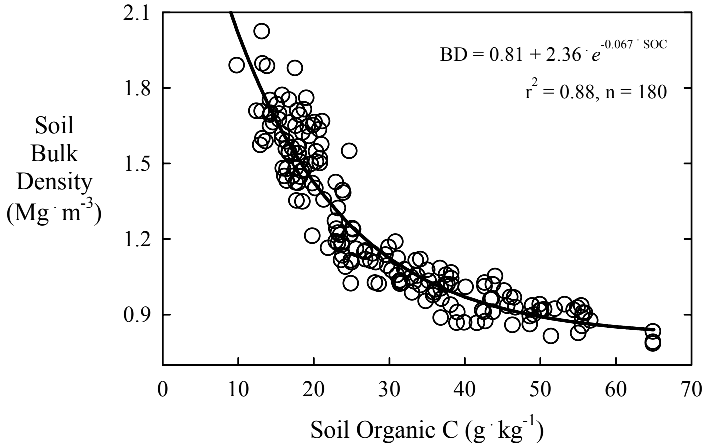

*Figure 1. Relationship of soil bulk density with soil organic carbon concentration at a depth of 0-2 cm in a Typic Kanhapludult in Georgia. Data from Franzluebbers et al. (2001).*

Poached soil from cow trampling around drinking stations in Finland had greater bulk density than in grazed pasture with no visible trampling, but the effect was depth and soil-texture dependent (Table 1). On a silty clay soil (Petrocalcic Calciustoll) in Texas, bulk density at a depth of 0-5 cm was greater with cattle grazing (weaned heifers, 240 kg head$^{-1}$) than without and the effect increased with increasing stocking rate (Warren et al., 1986). Soil bulk density averaged 0.91 Mg m$^{-3}$ without grazing, 1.00 Mg m$^{-3}$ with 0.12 animal units ha$^{-1}$ and 1.04 Mg m$^{-3}$ with 0.24 animal units ha$^{-1}$. Increasing sheep stocking rate from 0 to 22 head ha$^{-1}$ on a silty loam soil in Victoria Australia resulted in an increase in soil bulk density from 0.89 to 1.05 Mg m$^{-3}$ (Willatt and Pullar, 1983). These cited studies demonstrated increases in bulk density with animal treading, which may have been important to disruption of aggregation and surface sealing, but none of which should have been debilitating to root growth and/or air and water storage and transport since values were still <1.3 Mg m$^{-3}$.

On a Typic Hapludult in Georgia, stocker cattle (70-350 kg head$^{-1}$) managed for three years with a near-continuous grazing system (January to October) on Tift-44 bermudagrass pasture overseeded with rye (*Secale cereale*) resulted in greater bulk density (1.63 Mg m$^{-3}$) than under pasture excluded from cattle grazing (1.50 Mg m$^{-3}$) (Tollner et al., 1990). On a Typic Kanpludult under Coastal bermudagrass in Georgia, soil bulk density at a depth of 0-6 cm declined with time from 1.53 Mg m$^{-3}$ to 1.26 Mg m$^{-3}$ due to accumulation of surface soil organic matter, tended to be greater at the end of summer than prior to summer, and was not significantly affected by grazing with stocker cattle (271 kg head$^{-1}$) as compared to ungrazed plots during the first 5 years of management (Franzluebbers et al., 2001). These results suggest that cattle trampling could have both negative and neutral effects on soil compaction, likely depending upon soil water content, vigor of plant growth recovery following grazing, stocking rate, and/or landscape features.

On silt loam and silty clay loam soils in Iowa (Mollisols), 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, winter grazing (December to April) by stocker cattle (200-350 kg head$^{-1}$, 4 head ha$^{-1}$) of a rye cover crop following soybean (*Glycine max*) grain harvest for three years resulted in bulk density at a depth of 0-

20 cm that was not different from the same cropping system that was not grazed when managed with conventional disk tillage (1.50 Mg $m^{-3}$), but was greater than when not grazed with no-tillage management (1.60 vs. 1.52 Mg $m^{-3}$) (Tollner et al., 1980). The authors attributed the difference in grazing effect to disk tillage that loosened any evidence of compaction. In contrast to this earlier study in Georgia, grazing of winter and summer cover crops by cow-calf pairs in Georgia did not significantly alter surface bulk density under either conventional tillage or no tillage (Table 2). This later study was conducted following long-term pasture, and therefore, surface soil organic matter was high relative to that of conventional tillage, which probably mitigated the compactive impact of grazing cattle (Franzluebbers and Stuedemann, 2005). 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 conventional tillage (1.34 *vs* 1.17 Mg $m^{-3}$), but not under no tillage (1.27 *vs* 1.25 Mg $m^{-3}$) (Diaz-Zorita et al., 2002).

*Table 2. Soil bulk density at a depth of 0-3 cm as affected by tillage and cover crop management, as well as number of years of integrated crop-livestock management in Georgia. Data from Franzluebbers and Stuedemann (2005).*

| *Years of management* | *Conventional tillage* | | *No tillage* | |
|---|---|---|---|---|
| | *Ungrazed* | *Grazed* | *Ungrazed* | *Grazed* |
| | *-------------------------------- Mg $m^{-3}$ --------------------------------* | | | |
| *0* | *1.12* | *1.07* | *1.10* | *1.10* |
| *1* | *1.12* | *1.10* | *0.97* | *0.99* |
| *2* | *1.16* | *1.17* | *0.96* | *1.04* |
| *3* | *1.15* | *1.08* | *1.12* | *1.14* |

*Differences between cover crop management systems (ungrazed vs grazed) within a tillage system and year were not significant at $p \leq 0.05$.*

In a review of grazing effects on soil bulk density, Greenwood and McKenzie (2001) cited 22 studies, most of which found an increase in bulk density with increased treading. The change in bulk density between the extremes of grazing treatments was 0.12 ± 0.12 Mg $m^{-3}$ (n = 46). Taking all of the results on bulk density into consideration, animal grazing generally compacts soil but the extent of this compaction may be mitigated by controlling the timing and extent of grazing and whether the soil surface is firm enough to withstand the traffic (such as with conservation-tillage cropland under long-term pasture with reasonable stocking rate).

## Penetration resistance

Resistance of soil to root exploration can be a limitation to crop productivity. The resistance threshold at which root elongation is significantly hindered varies with plant species, but usually is between 2.0 and 3.0 MPa (Atwell, 1993). Soil penetration resistance is a function of bulk density and soil water content, i.e. as bulk density increases and soil water content decreases, penetration resistance increases (Taylor and Gardner, 1962). Soil penetration resistance is typically measured with a cone-tipped rod using either a dynamic or static driving mechanism. Point measurements of penetration resistance should be considered an index of soil resistance to root penetration only, since roots explore soil intraaggregate pores of least resistance while mechanical devices must penetrate whatever solids and voids are encountered in the insertion path.

On a Typic Hapludult in Georgia, stocker cattle managed for three years with a near-continuous grazing system on bermudagrass/rye pasture resulted in greater penetration resistance (1.5 MPa) than under pasture excluded from cattle (1.1 MPa), but this difference may have been partly due to the indirect effect of greater soil water content (13.4% without cattle and 12.0% with cattle) (Tollner et al., 1990). On an Ultisol (Dark Red Podzolic) in Brazil, guineagrass (*Panicum maximum*) was sown, managed with irrigation, and grazed by cows using a short-duration grazing system at three stocking densities (5.7, 4.4, and 3.5 animal units $ha^{-1}$) resulting in three forage mass levels (1, 2.5, and 4 Mg $ha^{-1}$) (da Silva et al., 2003). Penetration resistance of the surface 5 cm of soil was measured one year after grazing started and was greater with the lowest forage mass level (5.6 MPa) than with the medium (3.5 MPa) and high forage mass levels (3.4 MPa). Da Silva et al. (2003) cautioned that longer term studies would be needed to strengthen conclusions that high grazing intensity was detrimental to the soil surface.

Soil penetration resistance at a depth of 0-10 cm was occasionally greater with winter grazing of corn stalks by bred cows (3.7 head $ha^{-1}$) in Iowa (Clark et al., 2004). Soil penetration resistance was 31 ± 9% (n = 6) greater following 28-day 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). On a Typic Kanhapludult in Georgia, the energy required to penetrate the surface 10 cm of soil following the second year of grazing a rye cover crop was 107 ± 37 and 94 ± 12 J under conventional and no tillage, which tended to be greater than when the cover crop was not grazed (58 ± 27 and 80 ± 19 J, respectively) (A.J. Franzluebbers, unpublished data).

It appears that penetration resistance is a more discerning response variable to the impact of animal treading than soil aggregation and bulk density. However, since water content is a significant variable affecting penetration resistance, it must be accounted and appropriate adjustments made to penetration resistance measurements, which could confound interpretations. Long-term studies are needed with measurements of soil penetration resistance, bulk density, and aggregation at different times of the year and at different lengths of implementation of integrated crop-livestock systems.

## WATER AVAILABILITY

### Soil water content

On a Rhodic Paleudult in Georgia, stocker cattle managed with a rotational grazing system on alfalfa pasture had little impact on soil water retention characteristics compared with pasture excluded from cattle for one year (Tollner et al., 1990). On a Typic Kanhapludult in Georgia, soil water content was little affected by cattle grazing of summer and winter cover crops compared with ungrazed cover crops when managed under conventional tillage, but tended to be lower with grazing than without grazing under no tillage, except when the soil was very dry (Fig. 2). A beneficial effect of no tillage compared with conventional tillage on soil water content was observed at all but the driest conditions.

In a review of stocking rate effects on soil water, Greenwood and McKenzie (2001) cited 15 studies, 10 of which found a negative relationship with stocking rate. Four studies reported variable or no effect of stocking rate on soil water content and one study reported that ungrazed pasture had lower soil water content from greater water uptake at the end of the growing season. Soil water content is dynamic, depending upon weather conditions (temperature and precipitation), soil texture, drainage, and rate and extent of plant uptake. The key concern in integrated crop-livestock systems is to maximize water-use efficiency by avoiding water runoff and allowing precipitation to infiltrate soil.

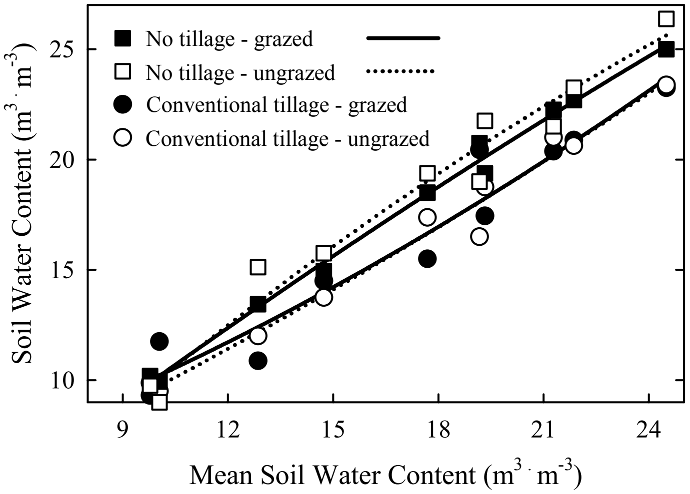

*Figure 2. Soil water content (0-20 cm) under cropping systems with and without cattle grazing of cover crops in Georgia. Data are from 10 sampling periods during the first two years of experimentation with and without grazing of cover crops (A.J. Franzluebbers, unpublished data).*

## Water infiltration

Perennial grasses and legumes can be effective at increasing water infiltration from precipitation and decreasing soil loss, especially from the severe high-intensity thunderstorms that occur during the summer in the southeastern USA and other parts of the world. Hendrickson et al. (1963a) wrote "The most promising single answer to the persistent row-crop erosion hazard on sloping land has been the increasing use of the highly protective grass-based crop rotations". In their research on Piedmont soils in the southeastern USA, runoff from pastures averaged 10% of precipitation compared with 20% for continuous cotton (*Gossypium hirsutum*) and soil loss from pastures averaged <1 Mg ha$^{-1}$ compared with 45 Mg ha$^{-1}$ for continuous cotton with conventional tillage (Hendrickson et al., 1963b).

On a Typic Hapludult in Georgia, stocker cattle managed for three years with a near-continuous grazing system on bermudagrass/rye pasture had no significant impact on steady-state water infiltration, which averaged 2.6 cm hr$^{-1}$ (Tollner et al., 1990). Saturated hydraulic conductivity of surface soil (4-8 cm) of Mollisols in Inner Mongolia China was greater in ungrazed grasslands (130-165 cm d$^{-1}$) than in winter-grazed grasslands (46 cm d$^{-1}$) and overgrazed grasslands (99 cm d$^{-1}$) (Krűmmelbein et al., 2006).

On a hill country pasture in New Zealand, water infiltration rate was not affected by short-term (40 min) treading from cows on pasture with prior sheep grazing, averaging 5.9 mm hr$^{-1}$ without cows, 5.6 mm hr$^{-1}$ with 296 cows ha$^{-1}$, and 5.5 mm hr$^{-1}$ with 592 cows ha$^{-1}$ (Russell et al., 2001). Sediment loss from this simulated rainfall study (72 mm hr$^{-1}$) was also not affected by cow treading, despite the proportion of bare ground increased with cow treading. Hoof imprints into the soil created small areas for water to pond (detention volume averaged 0.3, 6.9, and 8.2 m$^3$ ha$^{-1}$ with 0, 296, and 592 cows ha$^{-1}$, respectively), and therefore, may have mitigated the movement of sediment across the soil surface (Russell et al., 2001).

On a Typic Cryaquept with >70% clay in Finland, steady-state water infiltration was greater in a 3.5-yr-old pasture [timothy and cock's-foot grass (*Dactylis glomerata*)] with no visible trampling (7.2 cm $hr^{-1}$) compared with pasture with some trampling (2.9 cm $hr^{-1}$), pasture in the vicinity of a drinking site with some signs of penetrated hooves (1.7 cm $hr^{-1}$), and pasture at drinking sites with destroyed vegetation (1.0 cm $hr^{-1}$) (Pietola et al., 2005). On a nearby coarser-textured soil (Aquic Cryorthent with 6% clay), steady-state water infiltration was also greater in a pasture [timothy and meadow fescue (*Festuca pratensis*)] grazed by cows for one year with no visible trampling (13.2 cm $hr^{-1}$) than in pasture at drinking sites with destroyed vegetation (2.4 cm $hr^{-1}$). Reduced water infiltration by cattle trampling in the clay soil was attributed to low mechanical strength and kneading effects in combination with high water content during stressing, as well as reduced porosity of surface soil in the sandy loam (Pietola et al., 2005). Deep hoofprints associated with poached pasture are not produced immediately upon treading wet soil, but only after a progressive loss of soil strength due to repeated treading (Scholefield and Hall, 1986).

## NUTRIENT AVAILABILITY

### Soil organic matter

Several well-described management strategies are available to increase and maintain soil organic matter in integrated crop-livestock systems, at least compared with conventionally farmed systems with intensive tillage and simple rotations. Sod-based crop rotations are valuable in restoring soil fertility, interrupting disease and pest cycles, and improving soil physical characteristics. Conservation-tillage systems (including reduced tillage, strip tillage, ridge tillage, and no tillage) can maintain high surface residue cover and soil organic matter to improve water infiltration, allow development of continuous biopores throughout the soil profile, and create more opportunities for traffic throughout the year. Cover crops and forage crops in rotation with grain and fiber crops can provide a diversity of organic matter inputs and keep the soil covered for longer periods of time.

In a survey of 50 farm fields in Argentina, soil organic C of the surface 20 cm was greater under pastures (11.3 g $kg^{-1}$) than under annual crops, which was also affected by whether tillage was conventional (8.5 g $kg^{-1}$) or conservation (10.3 g $kg^{-1}$) (Diaz-Zorita et al., 2002). In a survey of 87 farm fields in the southeastern USA, soil organic C of the surface 20 cm was greater under pastures (39 Mg $ha^{-1}$) than under conservation-tillage cropland (28 Mg $ha^{-1}$) and conventional-tillage cropland (22 Mg $ha^{-1}$) (Causarano-Medina, 2006). Soil organic C in a long-term pasture-crop rotation in Argentina increased with increasing number of years of pasture and decreased following pasture termination and subsequent cropping with inversion tillage (Studdert et al., 1997). Similar temporal changes occurred for light fraction C and microbial biomass N. In this conventionally tilled experiment, aggregate stability and soil organic C were positively correlated, indicating that perennial pasture was important to total soil organic matter accumulation, as well as the biologically active fractions that assist in the formation of water-stable aggregates. From a long-term cropping system on a Typic Argiudoll in Uruguay, oscillating soil organic C was observed in response to pasture and crop phases, in which soil organic C of the 0-20-cm depth averaged 15.0 g $kg^{-1}$ at the end of pasture phases and 12.2 g $kg^{-1}$ at the end of cropping phases (García-Préchac et al., 2004). In this same study, 28 years of continuous cropping resulted in soil organic C of 10.2 g $kg^{-1}$. Following pasture phases, organically bound nutrients in soil organic matter were released to subsequent crops and reduced the need for N fertilizer.

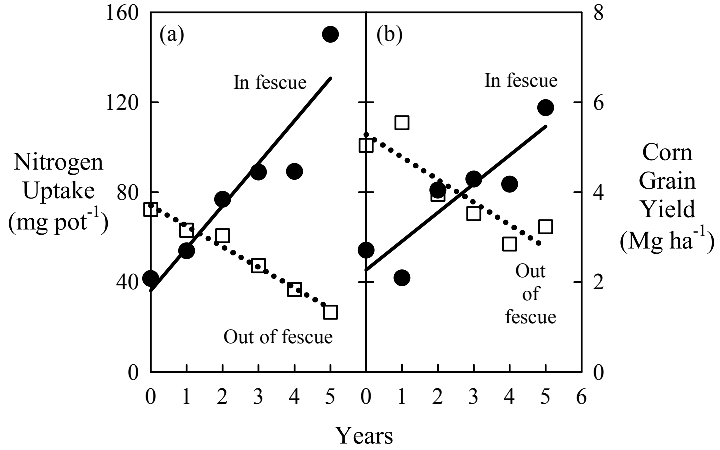

*Figure 3. Nitrogen uptake by sorghum-sudangrass grown in the greenhouse (a) and corn grain yield in the field (b) as affected by number of years previously in tall fescue (in fescue) and number of years since tall fescue terminated (out of fescue). Data collected near Watkinsville Georgia (Giddens et al., 1971a, b).*

On a Typic Kanhapludult in Georgia, conversion of cropland to bermudagrass pasture resulted in soil organic C accumulation in the surface 6 cm at the rate of 0.3 Mg $ha^{-1}$ $yr^{-1}$ when hayed, 0.6 Mg $ha^{-1}$ $yr^{-1}$ when left unharvested, and 1.4 Mg $ha^{-1}$ $yr^{-1}$ when grazed by cattle (Franzluebbers et al., 2001). On a similar soil in Georgia, total N within the surface 20 cm accumulated at a rate of 73 kg $ha^{-1}$ $yr^{-1}$ during the first 10 years of grazed tall fescue pasture in a long-term chronosequence evaluation (Franzluebbers et al., 2000a). The organic N that accumulated during tall fescue pasture development was subsequently released to cereal crops, which was demonstrated both in greenhouse and field studies (Fig. 3).

Crop rotations including one to several years of forage crops often result in an increase in soil organic matter. On a Gray Luvisol in Alberta Canada, soil organic C was initially 13.3 g $kg^{-1}$ at a depth of 0-15 cm and increased to 15.9 g $kg^{-1}$ with 50 years of a 5-year rotation (wheat-oat-barley-alfalfa-alfalfa) and declined to 10.3 g $kg^{-1}$ in a fallow-wheat rotation (Janzen et al., 1998). In the 5-year rotation with forages, soil organic C further increased to 21.7 g $kg^{-1}$ with application of animal manure. With 100 years of cropping at the Morrow Plots in Illinois, soil organic C at a depth of 0-20 cm was 18.8 g $kg^{-1}$ with continuous corn, 21.4 g $kg^{-1}$ with corn-oat rotation, and 28.9 g $kg^{-1}$ with corn-oat-red clover rotation (Huggins et al., 1998). At the end of 30 years of management on a Typic Fragiudalf in Ohio, soil organic C at a depth of 0-30 cm was 18.4 g $kg^{-1}$ with a corn-soybean rotation, 21.5 g $kg^{-1}$ with continuous corn, and 21.9 g $kg^{-1}$ with a corn-oat-hay rotation (Dick et al., 1998). The lack of soil disturbance during forage growth, longer growing season, and more continuous input of residues from forage crops all contribute to the accumulation of soil organic matter in complex crop rotations.

With the expected soil-surface trampling by grazing animals in integrated crop-livestock system, management of crops with conservation tillage should be viewed positively, because of the greater load-bearing capacity of undisturbed soil. Any subsoil compaction could still be alleviated with a non-inversion tillage implement, such as paraplow or subsoiler (Siri-Prieto et al., 2007). On a Typic Kanhapludult in Georgia following long-term tall fescue pasture termination, the difference in total soil N between no tillage and conventional tillage became progressively greater with time at a depth of 0-20 cm (A.J. Franzluebbers, unpublished data). The observed difference of 179 kg N $ha^{-1}$ $yr^{-1}$ suggests that substantial organic N was mineralized following conventional tillage and that N was being redistributed from deeper in the profile to the surface with no tillage.

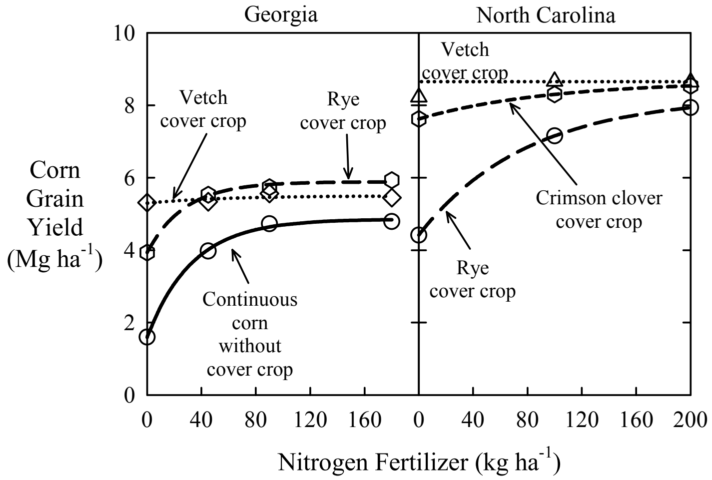

*Figure 4. Corn grain yield response to N fertilizer as affected by cover crop management. Georgia data from 1958 to 1964 near Watkinsville (Adams et al., 1970). North Carolina data from 1984 (McLeansville) and 1985 (Reidsville) (Wagger, 1989).*

Cover crops can provide a viable short-rotation opportunity to build soil organic matter, while at the same time providing high-quality forage in integrated crop-livestock systems. Legume cover crops can supply sufficient N for succeeding crops to achieve maximum yield with little or no additional N fertilizer (Fig. 4). In a review of soil organic C changes with agricultural management in the southeastern USA, Franzluebbers (2005) observed that no-tillage cropping systems with cover crops sequestered soil organic C at a rate of 0.53 Mg $ha^{-1}$ $yr^{-1}$ compared with 0.28 Mg $ha^{-1}$ $yr^{-1}$ in no-tillage systems without cover crops. On a Typic Kanhapludult in Georgia, surface residue N plus total soil N at a depth of 0-6 cm during the first three years of an integrated crop-livestock study was not affected whether cover crops were grazed or not (0.70 *vs* 0.73 Mg $ha^{-1}$ under conventional tillage and 1.67 *vs* 1.72 Mg $ha^{-1}$ under no tillage) (A.J. Franzluebbers, unpublished data).

## Soil-profile stratification of organic matter and nutrients

Stratification of organic matter with soil depth is common in many natural ecosystems and managed grasslands and forests (Franzluebbers et al., 2000a), as well as cropland under long-term conservation tillage (Dick et al., 1998). The soil surface is the vital interface that (1) receives much of the fertilizers and pesticides applied to cropland and grassland, (2) receives the intense impact of rainfall, and (3) partitions the flux of gases into and out of soil. Franzluebbers (2002a) suggested that the degree of stratification can be used as an indicator of soil quality or soil ecosystem functioning, because surface organic matter is essential to erosion control, water infiltration, and conservation of nutrients. Stratification ratio of soil organic C, as well as from other soil C and N fractions, can be calculated by dividing the concentration in the surface (i.e., a depth increment within the 0-10 cm zone) by the concentration near the bottom of a typically tilled layer (i.e., a depth increment within the 15-30 cm zone). As an example, stratification ratio was calculated from soil C and N concentrations at depths of 0-6 and 12-20 cm on a Typic Kanhapludult in North Carolina, in which higher residue input with less intensive silage harvesting led to increasingly greater stratification ratio of soil organic C (Franzluebbers and Brock, 2007).

On a Typic Kanhapludult in Georgia, undisturbed soil cores with different soil organic C content resulting from long-term management were evaluated for structural and hydrologic characteristics (Franzluebbers, 2002b). When soil from a depth of 0-12 cm was sieved to homogenize its contents, greater total organic C content (18.9 Mg ha$^{-1}$ under long-term no-tillage cropping vs 9.4 Mg ha$^{-1}$ under long-term conventional-tillage cropping) reduced soil bulk density by 12% and improved water infiltration by 27%. However when soil was left undisturbed, greater stratification of soil organic C reduced soil bulk density by 10% and improved water infiltration nearly threefold.

On a Typic Argiudoll in Wisconsin, mean soil P losses during 1-hr rainfall simulation events in summer and autumn were lower under no tillage than under conventional tillage (Table 3). Loss of P in runoff was statistically lower under no tillage than under conventional tillage in (a) 6 of 6 events for total P, (b) 2 of 6 events for dissolved P, and (c) 5 of 6 events for bioavailable P (Andraski et al., 1985). Despite extractable soil P was greater under no tillage than under conventional tillage, especially near the soil surface, runoff loss of P fractions was mitigated by the presence of surface residue and high surface soil organic C.

*Table 3. Mean loss of P in runoff during six rainfall simulation events (73 to 136 mm h$^{-1}$) on a silt loam under conventional tillage (moldboard plow) and no tillage in a corn cropping system in Wisconsin. Data from Andraski et al. (1985).*

| *Tillage system* | *Soil organic C*[a] | *Extractable soil P*[a] | *Phosphorus loss*<br>*Total* | <br>*Dissolved* | <br>*Bioavailable* |
|---|---|---|---|---|---|
| | *Mg ha$^{-1}$* | *mg kg$^{-1}$* | ------------ *kg ha$^{-1}$ event$^{-1}$* | | ------------ |
| *Conventional* | *32.5* | *39* | *1.31* | *0.02* | *0.21* |
| *No tillage* | *38.3* | *62* | *0.18* | *0.01* | *0.03* |

*[a] Soil properties at a depth of 0 to 2.5 cm.*

*Table 4. Mean watershed runoff volume (% of rainfall), soil loss, and P during 5 years under conventional tillage and no tillage at 3 locations in Oklahoma and Texas. Data from Sharpley et al. (1992).*

| *Tillage* | *Runoff* | *Soil loss* | *P in runoff*<br>*Particulate* | <br>*Bioavailable* | <br>*Total* |
|---|---|---|---|---|---|
| | *%* | *Mg ha$^{-1}$* | ------------- *kg ha$^{-1}$ yr$^{-1}$* | | ------------- |
| | *Bushland TX, Torrertic Paleustoll (54 cm rainfall)* | | | | |
| *Stubble mulch* | *5* | *0.9* | *0.5* | *0.1* | *0.5* |
| *No tillage* | *8* | *0.5* | *0.3* | *0.2* | *0.4* |
| | *Woodward OK, Typic Ustochrept (60 cm rainfall)* | | | | |
| *Disk tillage* | *17* | *39.6* | *14.4* | *0.9* | *14.9* |
| *No tillage* | *23* | *1.9* | *1.8* | *1.5* | *2.9* |
| | *El Reno OK, Udertic Paleustoll (74 cm rainfall)* | | | | |
| *Plow tillage* | *20* | *12.8* | *5.7* | *1.2* | *5.9* |
| *No tillage* | *24* | *0.4* | *0.5* | *1.4* | *1.7* |

From paired watersheds in the Southern Plains USA, mean soil loss and P in runoff were lower under no tillage than under conventional tillage (Table 4). Soil organic matter was not reported in this study, but was expected to be higher under no tillage than under conventional tillage. Despite water runoff volume was greater under no tillage than under conventional tillage, nutrient runoff concentration was reduced with no tillage (Sharpley et al., 1992). However, runoff loss of bioavailable P tended to be greater with no tillage than with conventional tillage, suggesting that overland flow of water without sediment transport was still carrying dissolved nutrients.

On a Typic Kanhapludult in Georgia, stratification ratio of soil microbial biomass C (0-6 cm / 12-20 cm) was greater when winter cover crops were grazed than ungrazed, but lower when summer cover crops were grazed than ungrazed (A.J. Franzluebbers, unpublished data). Differences in stratification ratio between cover crop management treatments may have been due to differences in quality of cover crops. Larger differences in stratification ratio were observed between conventional tillage (1.9 ± 0.3) and no tillage (5.6 ± 0.8) in this study. Allowing soil organic matter to accumulate at the soil surface will help slow mineralization of organic nutrients, buffer the soil surface from the compactive effects of animal and machinery traffic, and protect the soil from erosion and nutrient loss via runoff.

## IMPLICATIONS

The impacts of integrated crop-livestock systems on soil physical properties and processes can be summarized in the following:

1. *Rooting environment* under integrated crop-livestock systems may be both negatively and positively affected when animals are introduced into cropping systems. With high soil moisture and high stocking rate, animal trampling can compact soil and disrupt the soil surface sufficiently to cause a reduction in subsequent plant growth and contribute to increased water runoff during intense rainfall events. However, these negative impacts of animal trampling are not universal. Long-term cropping systems with perennial grass as part of the rotation sequence will have high surface soil organic matter, good soil structure, and continuous biopores due to undisturbed soil and high biological activity. Managing cropland with conservation tillage following pasture phases can preserve these positive grass-phase benefits and lead to enhanced production and environmental outcomes.
2. *Water availability* under integrated crop-livestock systems may also be both negatively and positively affected when animals are introduced into cropping systems. With an increase in soil organic matter, especially at the soil surface, soil water retention, water infiltration, and water availability for crops will increase. High animal traffic can poach vegetation and subsequently reduce water infiltration and availability. Most of the literature on animal traffic effects on soil physical properties has focused on extreme stocking rates that often lead to long-term damaged conditions. However, well-managed, integrated crop-livestock systems should create opportunities to avoid continuous stocking of animals on perennial pasture only, thereby distributing the stress of animal traffic onto a greater land area and across different times of the year.
3. *Nutrient availability* under integrated crop-livestock systems will certainly be altered compared with conventional cropping systems due to the processing of crop biomass through the animal digestive system. Direct physical impacts of grazing animals could reduce nutrient availability if losses of nutrients were exacerbated, such as through increased volatilization of ammonia, denitrification, and runoff losses of N, P, and other nutrients. However, with enhanced soil organic matter and a concomitant improvement in water infiltration and nutrient retention near the soil surface, nutrient availability could increase with integrated crop-livestock

systems. Certainly, more research is needed to understand all of the possible implications of various integrated crop-livestock systems on the soil physical environment.

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