PERSISTENCE OF SOIL STRUCTURAL MODIFICATIONS ALONG A HISTORIC WAGON TRAIL

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Abstract

Wagon wheel ruts are still visible along pioneer trails in the USA, which suggests that vehicular traffic can modify soil properties for a century. We compared physical properties of a Barnes loam (fine-loamy, mixed Udic Haploboroll) across three transects of the 1864 to 1871 Wadsworth Trail. Compaction was evident within wheel ruts of the trail, as penetration resistance and bulk density were 10% greater and water infiltration and air permeability were 50% lower within the wheel ruts than outside the trail. Erosion was also apparent within the wheel ruts, as the greater density could not fully account for the thinner A horizon (60 mm). Our investigation suggests that degradation of soil properties caused by compaction or erosion from wagon wheel or animal traffic may persist for >100 yr. This information underscores the importance that agricultural practices must minimize soil loss or compaction.

The advent of large tractors and implements bolstered the efficiency of farming operations during the twentieth century. Fewer transverses across fields during planting and harvesting are required today compared with yesteryear owing to wider implements and the greater horsepower of the tractor. Improved efficiency in field operations, however, may not always be beneficial to long-term soil productivity, as soil deformation or compaction may occur as equipment is driven across fields (Hakansson et al., 1988).

Adverse effects of compaction on plant growth can be ameliorated near the soil surface by tillage and, to some extent, by the natural forces associated with soil wetting and drying and freezing and thawing. Voorhees (1983) found that the natural forces occurring during one winter in Minnesota resulted in a 7% reduction in bulk density in the surface 75 mm of a silty clay loam. Contrary to this finding, Kay et al. (1985) observed no net change in near-surface bulk density of a silt loam and a clay loam from fall to spring in Ontario due to the instability of the soil matrix during thaw consolidation.

Subsoil compaction may persist for a decade or longer in cold regions despite the importance of freezing and thawing in the development of soil structure (Van Vliet-Lanoe et al., 1984). For example, Etana and Hakansson (1994) found little change in soil density below the depth of tillage 11 yr after compacting soils in Sweden even though soils froze to 0.4 m. Similarly, Blake et al. (1976) observed no change in soil density below the tillage depth 9 yr after compacting a clay loam in Minnesota, where freezing occurred to 0.9 m. Schjonning and Rasmussen (1994) also reported that compaction of a coarse sand persisted for at least 6 yr in Denmark.

We present experimental evidence that suggests soil structural modifications caused by vehicular traffic may persist for longer than a century.

Methods and Materials

Wagon wheel ruts are evident along the Mormon and Oregon Trails in the mid-continental USA and suggest that soil structural modifications caused by compaction can persist for more than a century. We examined soil physical properties along a portion of the historic Wadsworth Trail in Stevens County, Minnesota. This trail was developed in 1864 to carry military supplies from St. Cloud, MN, to Fort Wadsworth, Dakota Territory (now Fort Sisseton, SD). In 1871, the westward extension of the railroad into Stevens County greatly diminished travel along the trail. The authenticity of the Wadsworth Trail at the study site was confirmed by the original 1868 survey of Stevens County, from maps and memoirs contained in the collections of the Stevens County Historical Museum, and by current and previous landowners.

Wagon wheel ruts along the Wadsworth Trail are apparent for a distance of 40 m on the crest of a glacial till ridge about 5 km north of Morris, MN (45°39′N, 96°54′W). The ruts were largely created by oxen and horses pulling wagons that could carry as much as 4 Mg in freight (Wheeling, 1992). We presume that traffic ceased along this portion of the trail between 1883 and 1889 when private and county roads were established nearby. The small tract of prairie where the ruts are located was in pasture until 1963 and has thereafter remained idle.

The trail has been overgrown with native grasses such as big bluestem (*Andropogon furcatus* Muhl.), little bluestem (*Schizachyrium scoparium* Michx.), side-oats grama (*Atheropogon curtipendulus* Michx.), and switchgrass (*Panicum virgatum* L.). Bluegrass (*Poa annua* L.), goldenrod (*Solidago rigida* L.) and Bur oak (*Quercus macrocarpa* Michx.) are also apparent along the ridge.

Three transects, which perpendicularly bisected the trail, were established where the terrain varies in slope from 0.5 to 5%. Elevation along these transects is illustrated in Fig. 1. At 11 equidistant locations along a 6-m-long portion of each transect, vegetation from a 0.35-m^2 area was cleared to expose the soil surface. Within these cleared areas, the following soil properties were measured on 17 to 19 Sept. 1996: soil water content, thermal conductivity, penetration resistance, air permeability, and water infiltration. In addition, core samples were taken to determine bulk density, particle size, and depth of soil horizons. Soil water content was measured by time domain reflectometry with 0.3-m-long probes inserted vertically into the soil. Thermal conductivity was determined by inserting a 125-mm-long probe vertically into the soil and monitoring the temperature rise and heat pulse of the probe with a data logger. Penetration resistance was measured using a 30° cone with a 19-mm base. The maximum resistance was determined at 50-mm depth increments to 0.3 m. Air permeability was measured using an air permeameter. Air from the permeameter was constrained to flow into the soil using a 125-mm-diam. plastic pipe, which was driven into the soil at the center of the cleared area to a depth of 0.1 m. A double-

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ring infiltrometer, consisting of a 0.3-m o.d. plastic pipe centered over the 125-mm pipe, was used to measure water infiltration for 0.75 h.

At 24 h after ponded infiltration, air permeability was again determined at each location along the transect. Measurements were also repeated to assess water content, thermal conductivity, and penetration resistance near the center of the cleared area. Duplicate 30-mm-diam. soil cores were then taken to a 1-m depth at each location. One set of core samples was used to differentiate soil horizons by color, structure, and presence of carbonates. The other set of core samples was used to determine particle size by the hydrometer method and bulk density.

Analysis of variance was used to evaluate spatial differences ($P = 0.05$) in soil properties at four positions across the trail. Those positions were: (i) midway between wheel ruts, (ii) wheel ruts, (iii) shoulder of trail (0.6 m outward from each wheel rut), and (iv) outside of trail (1.2 m or more outward from each wheel rut).

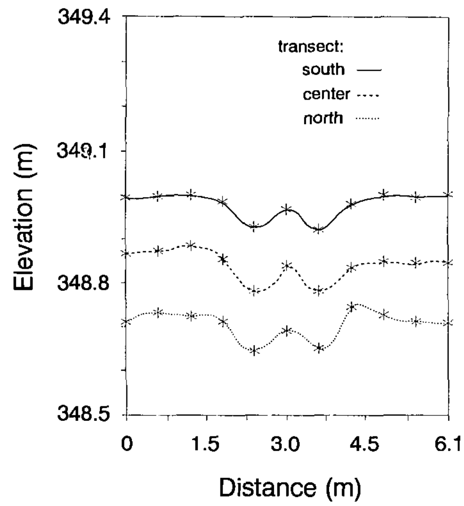

Fig. 1. Elevation (above mean sea level) along three transects of the historic Wadsworth Trail located near Morris, MN. Soil physical properties along each transect were measured at distances denoted by asterisks.

Results and Discussion

Soil water content at the initiation of this study (17 September) varied from 0.10 to 0.14 $m^3\ m^{-3}$ whereas water content 24 h after ponded infiltration (19 September) varied from 0.26 to 0.34 $m^3\ m^{-3}$ across all transects and locations. Spatial differences in soil water content across the trail were apparent on 17 September when water content was 10% greater within the wheel ruts than outside the trail (Table 1). This may suggest that the soil within the wheel ruts had a smaller and more uniform pore-size distribution than the soil outside the trail. Generally, soils with smaller and more uniform pore sizes tend to retain more water (greater water content) with a decline in water potential (Gupta et al., 1989). No differences in soil water content across the trail were found 24 h after ponded infiltration.

Thermal conductivity across all locations and transects averaged 1.0 W m^{-1} C^{-1} on 17 September and 1.82 W m^{-1} C^{-1} on 19 September. Conductivity on 17 September was 65% greater within the wheel rut than outside of the trail (Table 1), possibly as a result of the greater bulk density (Table 2) and soil water content within the wheel rut. Differences in thermal conductivity caused by variations in bulk density are small for dry soils, but differences may be accentuated by an accompanying increase in soil water content. For example, the empirical equations of Campbell (1985) indicated a difference in thermal conductivity of 0.05 W m^{-1} C^{-1} for a dry loam (15% clay content, water content of 0.1 $m^3\ m^{-3}$) between densities of 1.2 and 1.0 Mg m^{-3}. This difference in thermal conductivity, however, would be 0.3 W m^{-1} C^{-1} if the water content of the dense soil was 0.15 $m^3\ m^{-3}$. On 19 September, conductivity within the wheel rut was 55% greater than outside the trail (Table 1), which may be due solely to variations in bulk density because water content was similar at all positions across the trail. This difference in thermal conductivity (0.8 W m^{-1} C^{-1}) is larger than the 0.2 W m^{-1} C^{-1} estimated by Campbell (1985) for a wet loam (water content of 0.3 $m^3\ m^{-3}$) at densities of 1.0 and 1.2 Mg m^{-3}. Perhaps other soil physical factors, such as structure, not accounted for in the empirical derivation may have affected the measured thermal conductivity (Farouki, 1986).

Penetration resistance did not vary across the trail at the initiation of this study (Fig. 2), but increased from 1.4 MPa near the soil surface to 2.2 MPa at the 275-mm depth. After ponded infiltration, penetration resistance varied across the trail and was nearly constant with

Table 1. Soil properties in proximity to the historic Wadsworth Trail in west-central Minnesota. Properties were examined before (17 September) and after (19 September) water infiltration.

Date	Position across trail†	Water content	Thermal conductivity	Water infiltration‡ Cumulative	Water infiltration‡ Near steady state	Air permeability
		$m^3\ m^{-3}$	W m^{-1} °C^{-1}	m	mm s^{-1}	mm^2
Sept. 17	outside	0.11a§	0.84a	0.92b	0.25b	>1.2
	wheel rut	0.13c	1.37b	0.53a	0.13a	>1.2
	between ruts	0.11a	1.77c	0.89b	0.22b	>1.2
	shoulder	0.12b	0.97a	0.47a	0.12a	>1.2
Sept. 19	outside	0.31	1.52a	–	–	0.37b
	wheel rut	0.30	2.34b	–	–	0.11a
	between ruts	0.29	2.41b	–	–	0.40b
	shoulder	0.30	2.08ab	–	–	0.16a

† Properties were examined outside the trail (1.2 m or more outward from the wheel ruts), in the center of the wheel ruts, midway between wheel ruts, and at the shoulder of the trail (0.6 m outward from the wheel rut).
‡ Cumulative infiltration for 0.75 h; near-steady-state infiltration measured 0.75 h after start of infiltration.
§ Means followed by the same letter are not significantly different at the 0.05 probability level.

Table 2. Bulk density in the upper 0.3 m of the soil profile at various positions across the historic Wadsworth Trail in west-central Minnesota.

Position across trail†	Bulk density at depth					
	0–0.05 m	0.05–0.10 m	0.10–0.15 m	0.15–0.20 m	0.20–0.25 m	0.25–0.30 m
	Mg m^{-3}					
Outside	0.95	1.03a‡	1.11	1.14a	1.11a	1.11
Wheel rut	1.01	1.13c	1.21	1.23b	1.23b	1.17
Between ruts	0.99	1.12bc	1.15	1.16a	1.09a	1.11
Shoulder	0.94	1.05ab	1.13	1.20b	1.12a	1.14

† Properties were examined outside the trail (1.2 m or more outward from the wheel ruts), in the center of the wheel ruts, midway between wheel ruts, and at the shoulder of the trail (0.6 m outward from the wheel rut).
‡ Means within a column followed by the same letter are not significantly different at the 0.05 probability level.

depth. Differences in penetration resistance across locations after ponded infiltration were apparent at the 0.10 probability level to a depth of 175 mm. Penetration resistance was greater either within or between the wheel ruts than outside the trail. For example, penetration resistance at 50-mm increments from 25 to 175 mm was, respectively, 0.71, 0.58, 0.52, and 0.47 MPa within the wheel ruts and 0.51, 0.48, 0.45, and 0.41 MPa outside the trail. Resistance to penetration is influenced to a greater extent by changes in soil water potential than by changes in soil density (Taylor and Gardner, 1962). Since soil water content was similar on 19 September, the greater resistance within the wheel rut was probably due to greater soil density within the wheel rut than outside the trail (Table 2).

Cumulative infiltration was 0.4 m greater outside the trail than within the wheel rut (Table 1) and varied across all locations and transects from 0.20 to 1.17 m. Near-steady-state infiltration was also greater outside the trail than within the wheel ruts (Table 1) and ranged from 0.05 to 0.37 mm s^{-1} across all locations and transects. Infiltration outside the trail (0.25 mm s^{-1}) was 25% greater than steady-state water flow through similar soils used for agriculture within the region (Logsdon et al., 1990) and may be due to larger or more abundant biopores created by the native prairie grass or fauna. Differences in infiltration across the trail suggest that the soil outside the trail or between the wheel ruts differed in pore structure and continuity compared with the soil within the wheel ruts or on the shoulder of the trail. Generally, infiltration is enhanced in soils with larger pores, better pore continuity, and smaller pore tortuosity (Horton et al., 1994), and in soils that are less dense (Akram and Kemper, 1979). Differences in infiltration found in this study may be due to differences not only in pore geometry but also in soil density.

Air permeability could not be assessed at the initiation of this study due to limitations of our permeameter system and the porous structure of the dry soil. However, permeabilities 24 h after ponded infiltration confirmed the results obtained from measurements of water infiltration. Permeabilities outside the trail were about 230% or 0.25 mm^2 greater than within the wheel rut. Air permeability is influenced in part by pore diameter, but also by water potential, bulk density, and soil structure (Stepniewski et al., 1994).

Soil density was 10% (0.1 Mg m^{-3}) greater within the wheel rut than outside the trail (Table 2) and appeared

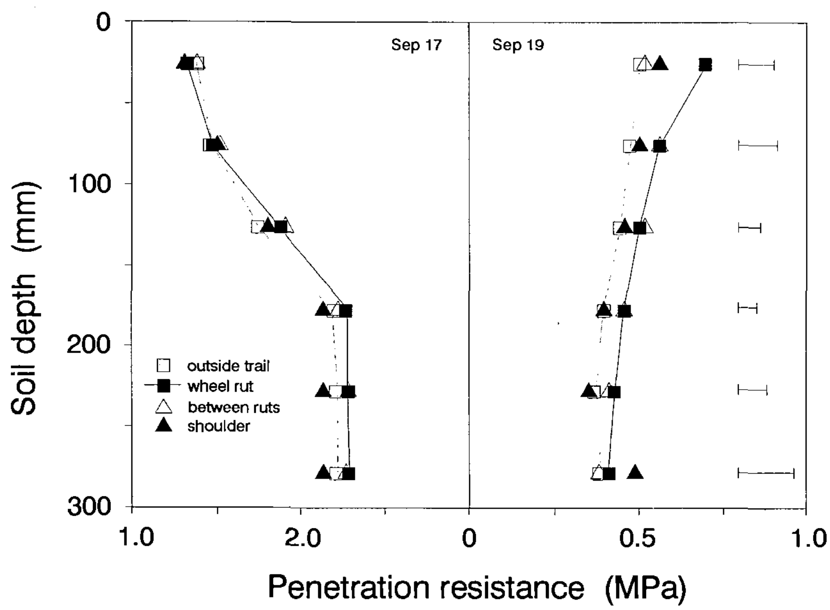

Fig. 2. Penetration resistance at various positions across the historic Wadsworth Trail. Resistance as a function of depth was measured outside the trail, in the wheels ruts, between wheel ruts, and on the shoulder of the Trail before (17 September) and 24 h after (19 September) ponded infiltration. Error bars denote least significant difference (P = 0.10).

to influence water content, thermal conductivity, penetration resistance, infiltration, and air permeability. Soil or pore structure may impact heat and water flow and mechanical impedance, but the macrostructure (medium granular) and texture (39% sand and 13% clay) of the A horizon was the same at all locations. The depth of the A horizon, however, was 0.16 m within the wheel rut and 0.22 m outside the trail (least significant difference = 0.04 m) while carbonates were detected at 0.22 m within the wheel rut and at 0.29 m outside the trail (least significant difference = 0.03 m). The greater density cannot fully account for the thinner A horizon and shallower depth to carbonates within the wheel rut than outside the trail. Thus, differences in soil properties across the trail may be due in part to soil loss within the wheel rut during the past 110 yr.

Conclusions

There is evidence from both previous studies and this study that soil structural modifications caused by traffic can persist from a decade to more than a century. Differences in physical properties across the historic Wadsworth Trail were, in part, caused by compaction from animal and wheel traffic. In addition, soil displacement by erosion or traffic within the ruts contributed to the measured differences in soil properties. Nevertheless, soil removal or compaction caused by vehicular traffic may persist for a century. Therefore, to preserve the integrity of our soils for future generations, practices must be implemented to minimize soil loss or compaction by vehicular traffic on agricultural soils subject to no tillage.

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