Georgia Journal of Science

Volume 63 *No. 2 Scholarly Contributions from the Membership and Others*

Article 4

2005

The Influence of Long-Term Anthropogenically-Induced Compaction on Select Properties of Soils in the Midwestern United States

Eric C. Brevik
ecbrevik@valdosta.edu

Recommended Citation

Brevik, Eric C. (2005) "The Influence of Long-Term Anthropogenically-Induced Compaction on Select Properties of Soils in the Midwestern United States," *Georgia Journal of Science*, Vol. 63, No. 2, Article 4.
Available at: http://digitalcommons.gaacademy.org/gjs/vol63/iss2/4

THE INFLUENCE OF LONG-TERM ANTHROPOGENICALLY-INDUCED COMPACTION ON SELECT PROPERTIES OF SOILS IN THE MIDWESTERN UNITED STATES

Eric C. Brevik
Department of Physics, Astronomy, and Geosciences
Valdosta State University
Valdosta, GA, 31698-0055
ecbrevik@valdosta.edu

ABSTRACT

Soil compaction by heavy equipment has become one of the most important problems in modern large-scale plant production, but one area that has not received much attention is the effect of soil compaction on prairie soils over time periods in excess of about 10 years. This study addresses this issue by comparing properties in compacted to non-compacted soils in an abandoned farmyard and along a preserved stretch of the Mormon Trail. Properties compared include soil morphology, bulk density, carbon, C/N ratio, and apparent electrical conductivity (EC_a). Bulk density, organic carbon, and EC_a values were consistently different in the compacted versus non-compacted soils. Darker soil colors were consistently found at greater depths and roots were more abundant in the non-compacted soils. Some changes in C/N ratios were observed and a zone of platy structure was found in the abandoned farmyard.

Keywords: soil compaction, Iowa, North Dakota

INTRODUCTION

The frequent crossing of soil by heavy equipment in modern agricultural and forestry operations has made soil compaction one of the most important issues these industries face today (1, 2). Soil compaction has many negative influences on the soil system, including: reduced agricultural yields (3, 4, 5, 6), forage production (7, 8, 9), and tree growth (10); reduced numbers and diversity of soil fauna (11, 12, 13); restricted root development (5, 14); restricted air and water movement through the soil (1, 15); and reduced additions of organic matter to compacted areas (9). At one time it was widely believed within the soil science community that natural forces such as annual freeze-thaw cycles and wetting-drying cycles of shrink-swell clays would alleviate compaction problems in soils that were located in the appropriate climates and/or contained shrink-swell clays (16) and that tillage would address the problem in tilled soils (17). However, research over the last 20 years has disproved this belief (9, 17, 18, 19, 20, 21, 22, 23).

Most of the studies that address soil compaction issues address time periods of less than 20 years (i.e., 17, 19, 22, 24) and/or address soil compaction in forested ecosystems (i.e., 10, 18, 20, 21, 25). Longer-term studies on grassland soils are largely absent, with the notable exceptions of 9 and 23. This is probably because much of the land in grassland regions has been tilled for agricultural purposes, leaving little in the way of relatively undisturbed compacted study sites. By contrast, it is much easier to find areas in forests undisturbed for 20 plus years due to the long growth period of the crop and lack of tilling operations. There are, however, sites in grassland areas of the United States that have undergone compaction and then been undisturbed by tillage for long periods of time, including the abandoned farmyards found throughout the American Midwest and the occasional preserved portions of wagon trails. While these sites usually have not been used for production agriculture, they often include soils used for such purposes in adjoining fields. Two such sites were utilized for this study.

Study Sites

The sites chosen for this study are an abandoned farmyard near the town of Linton in south-central North Dakota and a preserved portion of the Mormon Trail near Murray in south-central Iowa. Compaction at the North Dakota site was by farm traffic such as tractors and heavy trucks, while compaction at the Iowa site was caused by covered wagon traffic. The North Dakota farmstead was established in the 1930s (A. Amundson, verbal communication, 5/14/2000) and abandoned in 1973 (P. Wagner, verbal communication, 9/1998). P. Wagner, now retired in Linton, is the wife of the farmer who worked this site until 1973, and A. Amundson is a long-time neighbor who saw the farmstead constructed when he was a young man. The Iowa site was compacted when the portion of the Mormon Trail that ran through southern Iowa was used from 1846 until approximately 1853 (26). Sampling at the two sites was done between 1998 and 2000; therefore soils had been compacted for 60-70 years at the North Dakota site and about 150 years at the Iowa site at the time of sampling. As well as can be determined, neither site has been tilled since the compacting events took place (P. Wagner, verbal communication, 9/1998, and R. Jackson, verbal communication, 7/1998). R. Jackson is a rancher who's family has owned the Iowa site for several generations.

The soil at the North Dakota site is mapped as the Bryant series (Fine-silty, mixed, superactive, frigid Typic Haplustolls), which are deep, well-drained, moderately permeable soils on loess covered uplands (27). The average summer temperature in Emmons County is 21°C (69°F) and the average winter temperature is -11°C (13°F) (27). The average annual precipitation is 43.9 cm (17.3 inches), with about 70% of the precipitation occurring from April through August (27). This area averages between 100 and 120 days a year that the high is above and the low below freezing (i.e. freeze-thaw cycles) (28). While the depth the soil freezes is not represented by these values, there are significant freeze-thaw processes occurring at this site. The geology of the study area is characterized by an undulating till surface of low to moderate relief that is veneered by loess (29). The youngest till at this site is Early Wisconsinan to possibly pre-Wisconsinan in age (29). Loess deposition began in this area during the Late Wisconsinan and continued off and on through the late Holocene (29). From about 13,000 until 10,000 years BP, soils in this area developed under a spruce woodland in a climate that was cooler and moister than current (29). However, due to erosion and deposition, this geomorphic surface is not necessarily present at the modern surface or even still in existence in all parts of Emmons County (29). Since about 10,000 years BP the climate has fluctuated, leading to changes in native vegetation between long, medium, and short grasses (29).

The soil at the Iowa study site is Sharpsburg with 2-5% slopes. The Sharpsburg is classified as Fine, montmorillonitic, mesic Typic Argiudolls. Sharpsburg soils are moderately well drained and formed in loess on narrow convex ridgetops and sideslopes on uplands with a native vegetation of tall prairie grass (30). The Clarke County climate includes an average summer temperature of 24°C (75.4°F) with an average winter temperature of -6°C (20.5°F) and an average of 88.5 cm (34.9 inches) of annual precipitation with about 60% falling between April and August (30). This area averages between 100 and 120 days a year that the high is above and the low below freezing (28). The geology is characterized by thick loess over till with the Yarmouth-Sangamon paleosol marking the boundary between the loess and till (30). Between 30,000 and 11,000 years BP Clarke County had a cool moist climate and coniferous forest vegetation, but the climate became warmer and drier between 11,000 and 9,000 years BP, and since 9,000 BP has been similar to that of today (30).

The North Dakota site was used as a farmstead (site for the farm buildings) between the 1930s and 1973; the Iowa site has been used as pasture ever since it was fenced in the late 1800s (P. Wagner, verbal communication, 9/1998, and R. Jackson, verbal communication, 7/1998). Both sites contain "native" grassland communities. While each has undoubtedly been impacted by the uses they have been placed under and do not have a true, full suite of native plants, neither was ever tilled or planted and the plants that are present are native species that survived human uses or exotics that have come in on their own. Therefore, these are seen as reasonable sites to study the impact of compaction on selected grassland soil properties.

MATERIALS AND METHODS

The top 20 cm of twelve pedons were sampled for bulk density, total carbon, nitrogen, and particle size analyses. A shallow pit was dug at each pedon and the pit wall described using standard soil survey methods (31). Six pedons were sampled at the North Dakota site and six at the Iowa site. In each case, three pedons came from the compacted areas at the site and three alongside the compacted areas, with each compacted pedon being paired with one control (or non-compacted) pedon located approximately 3 m off the area of compaction. Bulk density samples were collected in 5 cm depth increments in each of the twelve sampled pedons, with two bulk density samples being taken from each 5 cm increment. Bulk soil samples were then collected from each 5 cm increment for laboratory analysis and stored in sealed and labeled plastic bags.

Bulk density was determined at the North Dakota site using the paraffin-coated clod method (32) and at the Iowa site using rings of known volume (each ring is approximately 60 cm^3) to collect soil cores which were then dried at 105°C for 24 hours (31). The bulk density methods differ because data was originally collected from these sites as a part of two separate studies. However, the different methods are not a problem, because bulk density values are not being compared between the two sites. Total soil carbon and nitrogen content were determined with a LECO CHN-600 using the total combustion technique (31). Two C and N samples were analyzed for each depth increment in each pedon. The Sharpsburg soils sampled for this study have been leached free of carbonates (pH is about 6.0) (30); therefore total carbon is assumed to also represent total soil organic carbon (SOC). Inorganic carbon content at the North Dakota site was determined using the Chittick method (33) and SOC was calculated by subtracting inorganic carbon from total carbon. The C/N ratio was determined by dividing SOC by total nitrogen. Bulk density values were multiplied by the percent SOC, determined from the corresponding pedon and depth increments, to obtain the mass of SOC per unit volume of soil.

An electromagnetic induction survey was also run at each site using a Geonics EM-38 in the vertical dipole. When used in the vertical dipole, the EM-38 integrates soil properties to a depth of about 1.5 m to obtain an apparent soil electrical conductivity (EC_a) value (34). Soil EC_a is controlled by a combination of soluble salts, clay content and mineralogy, soil water content, and soil temperature (35, 36). Research has shown that changes in bulk density can alter soil electrical properties (37, 38). For this study, EC_a data was collected in the compacted soils and to each side of the area of compaction.

Mean values of the various soil properties investigated in the compacted versus non-compacted areas were compared using a t-test for paired two sample means with the statistical package embedded in Microsoft Excel (Redmond, WA).

RESULTS AND DISCUSSION

Soil EC_a was higher in the compacted soils at both the North Dakota and Iowa sites than in the non-compacted soils (Tables I, II). In addition, there was no significant difference in soil EC_a measurements made on opposite sides of the compacted soils (Table II); this indicates that the compaction was causing the differences in soil EC_a as opposed to other possible explanations. Changes in bulk density may change soil EC_a because more clay is packed into a unit volume of soil and the contact between soil particles is increased (38). Changes in bulk density can also alter water relations in the soil; it takes less water to saturate a compacted soil as opposed to a relatively uncompacted soil, assuming the soils are otherwise similar, because there is less pore space in the compacted soil (39). These altered water relations may, in turn, influence soil EC_a (40). In this particular study, the EC_a survey does not establish exactly what pedologic changes have taken place in the compacted soils, but it provides evidence that there are differences in soil properties between the compacted and non-compacted soils.

Table I. Results of the electromagnetic induction surveys at each study site. Non-compacted 1 and non-compacted 2 refer to measurements made on either side of the compacted soils.

Site	Compacted	Non-Compacted 1	Non-Compacted 2
North Dakota	55.6	46.3	45.6
Iowa	53.8	46.6	46.1

Table II. P-values from the statistical comparisons of the electromagnetic induction surveys. Non-compacted 1 and non-compacted 2 refer to measurements made on either side of the compacted soils.

North Dakota		
Site	Non-Compacted 1	Non-Compacted 2
Compacted	0.0014	<0.0001
Non-Compacted 1		0.7522
Iowa		
Site	Non-Compacted 1	Non-Compacted 2
Compacted	<0.0001	0.0001
Non-Compacted 1		0.4841

Comparison of the field observations shows some definite differences in soil morphologic properties. The pedons in the compacted areas have lighter surface colors than in the non-compacted pedons, for example, 10YR 4/2 in the compacted pedons versus 10YR 3/2 in the non-compacted pedons at the North Dakota site. With the exception of the absence of the dark surface layer in the compacted pedons, the same colors tend to occur in both the compacted and non-compacted pedons. However, changes routinely occur about 10 cm deeper in the non-compacted pedons than in the compacted pedons (i.e., pedons from both compacted and non-compacted areas shift from 10YR 4/2 to 10YR 5/2 at the North Dakota site, but this shift occurs at about 15 cm in the control pedons and 5 cm in the compacted pedons).

There are considerably more roots in the upper few centimeters of the control pedons than in the corresponding portion of the compacted pedons. There is also a distinct zone of platy structure in the compacted pedons at the North Dakota site from about 5 to 10 cm that is not present in any of the control pedons or in the compacted pedons at the Iowa site. Intense compaction may cause platy structure (41), and the absence of platy structure in the compacted pedons at the Iowa site may indicate that the compaction in North Dakota was more intense than the compaction in Iowa.

Mean bulk density values are higher in the compacted than in the non-compacted pedons at all depths studied; these differences are statistically significant in the upper two depth intervals at the North Dakota site and the lower three depth intervals at the Iowa site (Table III). This finding is significant, because both these study sites are in areas that have strong potential for freeze-thaw activity (28) and the soils at both sites contain significant quantities of smectite clays (27, 30). Freeze-thaw processes and the wetting and drying of smectite clays can lead to considerable volume changes within the soil (42). Some researchers have theorized that these volume changes would act to alleviate soil compaction (16), but that does not appear to be the case at either of these two long-term compaction sites. There is also a consistent trend of higher carbon values in the non-compacted pedons than in the compacted pedons when measured as both percent carbon (Table IV) and as mass of carbon per unit volume of soil (Table V) with the exception of the surface layers at the Iowa site. These differences in carbon content likely explain the color trends with depth in these profiles (43, 44), as discussed above.

Table III. Mean bulk density values and statistics for the four depth intervals sampled in this study and the P values for the statistical comparison of compacted to non-compacted values by depth.

Depth Interval (cm)	Mean bulk Density Non-compacted Pedons (g/cm^3)	Standard Deviation	Mean bulk Density Compacted Pedons (g/cm^3)	Standard Deviation	P Value
North Dakota Site					
0-5	0.82	0.124	1.09	0.201	0.016
5-10	1.19	0.109	1.37	0.182	0.028
10-15	1.30	0.119	1.37	0.118	0.200
15-20	1.31	0.065	1.38	0.123	0.186
Iowa Site					
0-5	0.98	0.017	1.04	0.065	0.195
5-10	1.25	0.058	1.44	0.117	<0.001
10-15	1.20	0.105	1.34	0.111	0.013
15-20	1.22	0.109	1.37	0.043	0.003

Table IV. Mean organic carbon values and standard deviations for the depth intervals sampled in this study and the P values for the statistical comparison of compacted to non-compacted values by depth.

Depth Interval (cm)	Mean carbon values Non-compacted (%)	Standard Deviation Non-compacted	Mean carbon values Compacted (%)	Standard Deviation Compacted	P value
North Dakota					
0-5	4.56	0.266	2.41	0.675	0.003
5-10	2.49	0.094	1.35	0.301	0.001
10-15	1.54	0.127	1.20	0.305	0.007
15-20	1.79	0.337	1.47	0.367	0.007
Iowa					
0-5	5.19	1.42	5.71	1.65	0.25
5-10	3.52	0.59	2.75	0.25	0.051
10-15	2.77	0.061	1.60	0.15	<0.0001
15-20	1.97	0.062	1.24	0.068	0.0004

Table V. Mean g organic C/cm^3 of soil values and statistics for the depth intervals sampled in this study and the P values for the statistical comparison of compacted to non-compacted values by depth.

Depth Interval (cm)	Mean C Values Non-compacted (g C/cm^3)	Standard Deviation Non-compacted	Mean C Values Compacted (g C/cm^3)	Standard Deviation Compacted	P value
North Dakota					
0-5	0.038	0.0079	0.025	0.0032	0.021
5-10	0.030	0.0023	0.018	0.0037	0.002
10-15	0.020	0.0032	0.016	0.0039	0.005
15-20	0.024	0.0047	0.020	0.0037	0.059
Iowa					
0-5	0.051	0.018	0.058	0.013	0.267
5-10	0.044	0.010	0.040	0.003	0.190
10-15	0.034	0.004	0.022	0.006	0.001
15-20	0.024	0.003	0.017	0.003	0.001

The C/N ratios tend to be higher in the non-compacted soils than in the corresponding compacted soils, although the differences observed were only statistically significant for about half of the depth comparisons (Table VI). Lower C/N ratios indicate a higher state of decomposition of organic matter (45). This makes it appear that compaction of the soil is affecting the relative amounts of highly decomposed versus slightly decomposed organic matter in the soil. This may be due to restricted root growth in the compacted soils leading to reduced vegetative growth, as observed by (5) and (14), and thus reduced additions of organic matter to the soil system. Reduced organic matter additions would in turn lead to soils with lower nutrient status, making them less able to support plant growth. Visual evidence from the study sites indicates less vigorous plant growth in the compacted soils when compared to the non-compacted soils (Figure 1).

Table VI. Results of the t-test analysis comparing C/N ratios for the four depth intervals sampled in this study.

Depth Interval (cm)	Mean C/N Ratio, Non-Compacted	Standard Deviation Non-Compacted	Mean C/N Ratio, Compacted	Standard Deviation, Compacted	P Value
North Dakota					
0-5	11.06	1.90	8.85	0.81	0.024
5-10	9.43	2.53	8.12	0.24	0.090
10-15	8.19	0.38	7.90	0.98	0.307
15-20	6.24	2.03	5.41	2.06	0.302
Iowa					
0-5	10.17	0.87	10.17	0.48	0.500
5-10	9.46	1.01	9.43	0.82	0.480
10-15	10.00	0.97	8.58	1.26	0.028
15-20	9.50	1.30	7.86	0.81	0.023

Figure 1. The Mormon Trail at the Iowa study site in August. The trail runs from the lower right to the upper center portion of the photo. Note the reduced vegetative growth in the trail in this late summer view.

Some researchers would argue that the reference point for this study should be a subsurface horizon that can be identified in both the compacted and non-compacted soils. It is felt that this approach is not the appropriate one for this study. The times involved in this study range from approximately 60-150 years since initial compaction at the study sites. While 60-150 years is not an overly long period of time compared to the formation time for many soils, it is a much longer period of time than the 1 to 10 years covered in most of the compaction studies that have been done. At the research sites utilized in this study, we have new surfaces and new surface conditions created by the compacting events. For the last roughly 150 years, the compacted surface of the Iowa site has served as the soil's surface and has been subjected to all the soil forming factors that have also been working in the non-compacted soils. The same is also true of the compacted surface of the North Dakota site over the last 60-70 years. Over those time periods, the compacted surface layers have exerted influence on properties such as infiltration, aeration, thermal conductivity, penetration resistance, or any other process that influences these soils as relates to plant growth, microbial activity, chemical reactions, etc.; in short, the compacted layers have influenced pedogenesis in these soils. Numerous researchers have shown significant pedogenic processes occurring over time periods similar to or less than those addressed in this study (46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59). For these reasons, it is felt that using the surface as a reference point in this study is justified.

CONCLUSIONS

A number of changes due to compaction were evident in the soils at both the sites studied. Bulk density, organic carbon, and EC_a values were consistently different in the compacted versus non-compacted soils. Darker soil colors were also consistently found at greater depths and roots were more abundant in the non-compacted soils. Some changes in C/N ratios that may be related to compaction were observed, and a zone of platy structure, a structure that is not common in prairie soils but can be caused by compaction, was found in the compacted soils at the North Dakota site. Each of these differences is attributed to the compaction that took place at the two study sites several decades before this research.

ACKNOWLEDGEMENTS

The research reported in this paper was partially supported through grants from the Iowa Science Foundation administered by the Iowa Academy of Science and the Iowa State University Graduate Student Senate Professional Advancement Program. The author thanks Mr. Ronald Jackson (Murray, IA) and Ms. Yvonne Vander Vorst (Linton, ND) for allowing access to the study sites, Lisa Brevik, Thomas Fenton, Jeffrey Homburg, M.A. Lauterbach, and Louis Moran for assistance with field and/or laboratory work, and Pauline Wagner and Art Amundson for assistance in establishing the history of the North Dakota study site.

REFERENCES

1. Plaster E J: "Soil Science and Management, 3rd Edition." New York: Delmar Publishers, 1997.
2. DeNeve S and Hofman G: Influence of Soil Compaction on Carbon and Nitrogen Mineralization of Soil Organic Matter and Crop Residues. Biol Fertil Soils 30: 544-549, 2000.
3. Kayombo B and Lal R: Effects of Soil Compaction by Rolling on Soil Structure and Development of Maize in No-till and Disc Ploughing Systems on a Tropical Alfisol. Soil Tillage Res 7½: 117-134, 1986.
4. Assaeed AM, McGowan M, Hebblethwaite PD and Brereton JC: Effect of Soil Compaction on Growth, Yield, and Light Interception of Selected Crops. Ann Appl Biol 117(3): 653-666, 1990.
5. Tu JC and Tan CS: Effect of Soil Compaction on Growth, Yield, and Root Rots of White Beans in Clay Loam and Sandy Loam Soil. Soil Biol Biochem 23(3): 233-238, 1991.
6. Douglas JT: Soil Compaction Effects on Second-Harvest Yields of Perennial Ryegrass for Silage. Grass Forage Sci 52(2): 129-133, 1997.
7. Naeth MA, Pluth DJ, Chanasyk DS, Bailey AW and Fedkenheuer AW: Soil Compacting Impacts of Grazing in Mixed Prairie and Fescue Grassland Ecosystems of Alberta. Can J Soil Sci 70: 157-167, 1990.
8. Proffitt APB, Bendotti S, Howell MR, and Eastham J: The Effect of Sheep Trampling and Grazing on Soil Physical Properties and Pasture Growth for a Red-Brown Earth. Aust J Agric Res 44: 317-331, 1993.
9. Brevik EC, Fenton TE and Moran LP: Effect of Soil Compaction on Organic Carbon Amounts and Distribution, South-Central Iowa. Environ Pollut 116: S137-S141, 2002.
10. Wert S and Thomas BR: Effects of Skid Roads on Diameter, Height, and Volume Growth in Douglas-fir. Soil Sci Soc Am J 45:629-632, 1981.
11. Boag B: Effect of Soil Compaction on Migratory Plant-Parasitic Nematodes. Crop Res 25(1): 63-67, 1985.
12. Bostrom U: The Effect of Soil Compaction on Earthworms (Lumbricidae) in a Heavy Clay Soil. Swed J of Agric Res 16(3): 137-141, 1986.
13. Binet F, Hallaire V and Curmf P: Agricultural Practices and the Spatial Distribution of Earthworms in Maize Fields. Relationships Between Earthworm Abundance, Maize Plants, and Soil Compaction. Soil Biol Biochem 29(3/4): 577-583, 1997.
14. Sveistrup TE and Haraldsen TK: Effects of Soil Compaction on Root Development of Perennial Grass Leys in Northern Norway. Grass Forage Sci 52(4): 381-387, 1997.

15. Brady NC and Weil RR: "The Nature and Properties of Soils, 13th Edition." Upper Saddle River, NJ: Prentice Hall, 2002.
16. Troeh FR, Hobbs JA and Donahue RL: "Soil and Water Conservation for Productivity and Environmental Protection, 4th Edition." Upper Saddle River, NJ: Prentice Hall, 2004.
17. Voorhees WB: Relative Effectiveness of Tillage and Natural Forces in Alleviating Wheel-Induced Soil Compaction. Soil Sci Soc Am J 47: 129-133, 1983.
18. Froehlich HA, Miles DWR and Robbins RW: Soil Bulk Density Recovery on Compacted Skid Trails in Central Idaho. Soil Sci Soc Am J 49: 1015-1017, 1985.
19. Stohlgren TJ and Parsons DJ: Vegetation and Soil Recovery in Wilderness Campsites Closed to Visitor Use. Environ Manage 10(3): 375-380, 1986.
20. Vora RS: Potential Soil Compaction Forty Years After Logging in Northeastern California. Great Basin Nat 48(1): 117-120, 1988.
21. Reisinger TW, Pope PE and Hammond SC: Natural Recovery of Compacted Soils in an Upland Hardwood Forest in Indiana. Northern J Appl Forestry 9(4):138-141, 1992.
22. Etana A and Haakansson I: Swedish Experiments on the Persistence of Subsoil Compaction Caused by Vehicles with High Axel Load. Soil Tillage Res 29: 167-172, 1994.
23. Sharratt BS, Voorhees WB, McKintosh G and Lemme G: Persistence of Soil Structural Modifications Along a Historic Wagon Trail. Soil Sci Soc Am J 62: 744-777, 1998.
24. Voorhees WB, Nelson WW and Randall GW: Extension and Persistance of Subsoil Compaction Caused by Heavy Axle Loads. Soil Sci Soc Am J 50: 428-433, 1986.
25. Monti PW and MacKintosh EE: Effect of Camping on Surface Soil Properties in the Boreal Forest Region of Northwestern Ontario, Canada. Soil Sci Soc Am J 43: 1024-1029, 1979.
26. Kimball SB: "The Mormon Pioneer Trail." Salt Lake City, UT: Mormon Trail Association, 1997.
27. Wroblewski DV and Lunde NJ: "Soil Survey of Emmons County North Dakota." Washington, D.C.: U.S. Government Print Office, 185p, 1980.
28. Hershfield DM: The Frequency of Freeze-Thaw Cycles. J Appl Meteorology 13:348-354, 1974.
29. Bluemle JP: "Geology of Emmons County, North Dakota." Bismarck, ND: North Dakota Geological Survey Bulletin 66 - Part I. 69 pp, 1984.
30. Chowdhery AA: "Soil Survey of Clarke County, Iowa." Washington, DC.: U.S. Government Print Office, 1989.
31. Soil Survey Staff: "Soil Survey Laboratory Methods Manual." Lincoln, NE: Soil Survey Investigations Report No. 42, Version 3.0, 1996.

32. Blake GR and Hartge KH: "Bulk Density." In Methods of Soil Analysis. Madison, WI: ASA-CSSA-SSSA, p 363-375, 1986.
33. Boellstorff JD: Proceedures for the Analysis of Pebble Lithology, Heavy Minerals, Light Minerals, and Matrix Calcite-Dolomite of Tills. In Standard Procedures For Evaluation of Quaternary Materials in Iowa (Hallberg, Ed) Iowa City, IA: Iowa Geological Survey Technical Information Series No. 8, p 31-60, 1978.
34. McNeill JD: "Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers, Tech. Note TN-6." Mississauga, Ontario: Geonics Ltd., 1980.
35. McNeill JD: "Electrical Conductivity of Soil and Rocks, Tech. Note TN-5." Mississauga, Ontario: Geonics Ltd., 1980.
36. Brevik EC and Fenton TE: The Relative Influence of Soil Water Content, Clay, Temperature, and Carbonate Minerals on Soil Electrical Conductivity Readings Taken With an EM-38 Along a Mollisol Catena in Central Iowa. Soil Surv Horizons 43(1): 9-13, 2002.
37. Malicki MA, Campbell EC and Hanks RJ: Investigations on Power Factor of the Soil Electrical Impedance as Related to Moisture, Salinity, and Bulk Density. Irrigation Sci 10: 55-62, 1989.
38. Rhoades JD and Corwin DL: Soil Electrical Conductivity: Effects of Soil Properties and Application to Soil Salinity Appraisal. Commun Soil Sci Plant Anal 21(11&12): 837-860, 1990.
39. Bradford JM and Peterson GA: Conservation Tillage. In Handbook of Soil Science (Sumner, Ed) Boca Raton, FL: CRC Press, p G-247-G-270, 2000.
40. Rinaldi VA and Cuestas GA: Ohmic Conductivity of a Compacted Silty Clay. J Geotech Geoenviron Engineering. 128(10): 824-835, 2002.
41. Robinson CA, Cruse RM and Kohler KA: Soil Management. In Sustainable Agriculture Systems (Hatfield and Karlen, Eds) Ann Arbor, MI: Lewis Publishers, p 110-134, 1994.
42. McCarthy DF: "Essentials of Soil Mechanics and Foundations, Basic Geotechnics, 6th Edition." Upper Saddle River, NJ: Prentice Hall, 2002.
43. Fernandez RN, Schulze DG, Coffin DL and Van Scoyoc GE: Color, Organic Matter, and Pesticide Adsorption Relationships in a Soil Landscape. Soil Sci Soc Am J 52: 1023-1026, 1988.
44. Schulze DG, Nagel JL, Van Scoyoc GE, Henderson TL, Baumgardner MF and Stott DE: Significance of Organic Matter in Determining Soil Colors. In Soil Color. Madison, WI: SSSA Special Publication no. 31, p 71-93, 1993.
45. Troeh FR and Thompson LM: Soils and Soil Fertility. New York: Oxford University Press, 462 p, 1993.

46. Borovskiy VM and Dzhamalbekov YU: Rate of Soil Formation During Irrigation in Southern Kazakhstan. Soviet Soil Sci 10(5): 487-493, 1978.
47. Griffin TM and Rabenhorst MC: Processes and Rates of Pedogenesis in Some Maryland Tidal Marsh Soils. Soil Sci Soc Am J 53: 862-870, 1989.
48. Dahlgren RA, Ugolini FC, Shoji S and Sletten RS: Soil-forming processes in Alic Melanudands under Japanese pampas grass and oak. Soil Sci Soc Am J 55: 1049-1056, 1991.
49. Graham RC and Wood HB: Morphologic development and clay redistribution in lysimeter soils under chaparral and pine. Soil Sci Soc Am J 55: 1638-1646, 1991.
50. Skvortsova YB and Yakimenko YY: Impact of forest and meadow vegetation on the microstructures of long-ploughed soils. Pochvovedenie 11:39-50, 1991.
51. Moffet CA, Richardson JL, Lura CL and Arndt JL: Soil development differences under larch, cottonwood, and prairie in north-central North Dakota. Soil Surv Horizons 35: 48-55, 1994.
52. Graham RC, Ervin JO and Wood HB. Aggregate stability under oak and pine after four decades of soil development. Soil Sci Soc Am J 59: 1740-1744, 1995.
53. Ulery AL, Graham RC, Chadwick OA and Wood HB: Decade-scale changes of soil carbon, nitrogen and exchangeable cations under chaparral and pine. Geoderma 65:121-134, 1995.
54. Quideau SA, Chadwick OA, Graham RC and Wood HB: Base cation biogeochemistry and weathering under oak and pine: a controlled long-term experiment. Biogeochemistry 35: 377-398, 1996.
55. Tice KR, Graham RC and Wood HB: Transformation of 2:1 phyllosilicates in 41-year-old soils under oak and pine. Geoderma 70: 49-62, 1996.
56. Dahlgren RA, Singer MJ and Huang X: Oak tree and grazing impacts on soil properties and nutrients in a California oak woodland. Biogeochemistry 39:45-64, 1997.
57. Quideau SA, Graham RC, Chadwick OA and Wood HB: Organic carbon sequestration under chaparral and pine after four decades of soil development. Geoderma 83:227-242, 1998.
58. Dixon-Coppage TL, Davis GL, Couch T, Brevik EC, Barineau CI and Vincent PC: A Forty-Year Record of Carbon Sequestration in an Abandoned Borrow-Pit, Lowndes County, GA. Soil Crop Sci Soc Florida Proc 64: in press.
59. Kovda I, Brevik EC, Fenton TE and Gerasimova M: The impact of white pine (Pinus strobus) on a Mollisol after seven decades of soil development. J Iowa Acad Sci. in press.