Repeated Freeze-Thaw Cycle Effects on Soil Compaction in a Clay Loam in Northeastern Montana

In recent years, there has been an increased global concern regarding the impact of soil compaction on crop production and soil quality in modern mechanized agricultural farming systems. Farm equipment is heavier than ever before, and many farmers have resorted to energy intensive deep tillage to alleviate compaction. Freeze-thaw processes influence the physical properties of soil, primarily soil compaction and structure. A 3-yr field study was established in fall 2009 to investigate the effects of the dynamics of freeze-thaw cycles (FTCs) on soil compaction in a clay loam. Results showed that frequent FTCs over the winter generally alleviated soil compaction at the 0- to 30-cm depth. During the winter of 2009–2010, soil penetration resistance (PR) in compacted treatments that were subject to freezing and thawing conditions was significantly reduced by 73, 68, and 59% at depths of 0 to 10, 10 to 20, and 20 to 30 cm, respectively. In compacted soils that were not subject to freezing, PR was significantly reduced by approximately 50, 60, and 46% at the same respective depths of the soil profile presumably due to the biology of soil and disruptive effects of shrink-swell cycles caused by frequent wetting-drying processes. These results demonstrate that repeated FTCs can alleviate soil compaction and alter soil physical quality. We conclude that FTCs associated with typical winter weather conditions are the most effective and economical way to alleviate soil compaction and improve soil structure through the dynamics of FTCs.

Abbreviations: CEC, cation exchange capacity; CI, cone index; FTCs, freeze-thaw cycles; NGP, northern Great Plains; PR, penetration resistance.

Soil compaction is defined as the packing effect of applied external forces that include heavy farm equipment (i.e., tractors, trucks, and harvesters), livestock, and raindrops which can cause a reduction in soil bulk volume and large pores. Soil compaction adversely impacts soil physical properties that affect crop production directly through effects on soil structure and aggregation, large pore space, roots growth, aeration, and water and nutrient movement (Hamza and Anderson, 2005; Batey, 2009). Soil compaction is a global problem due to mechanized modern agricultural systems and is considered one of the most widespread types of soil degradation affecting agricultural land, soil quality, and crop production. It affects approximately 68 million hectares of land worldwide due to vehicular traffic alone (Flowers and Lal, 1998).

Soil compaction due to farming operations is an acknowledged problem in the northern Great Plains (NGP) of the United States (Jabro et al., 2009a, 2011; Montana, North Dakota, and Minnesota producers, personal communications, 2007, 2011, 2012) and in millions of hectares around the world. Deep tillage is
often used to alleviate compaction, but farmers in the NGP area question whether or not this is necessary because they have observed large changes in soil structure from its compacted state in the fall to a much more mellow state in the spring. The few studies that have been done on the effects of freezing on compaction were done in much warmer locations and concluded that there was little effect. In the NGP, most areas experience several months with an average air temperature well below freezing. This freezes the soil to depths typically exceeding one meter. We have seen large changes in soil structure over the winter but have not quantified these changes. By lessening soil compaction, growers will not only increase their bottom line but also progress toward increased global food production at a time when that is becoming increasingly important.

One of the processes affecting soil compaction is repeated cycles of FTCs over winter. Freeze-thaw cycles have been defined in different ways and differed considerably among studies (Baker and Ruschy, 1995; Lehrsche, 1998; Ho and Gough, 2006; Henry, 2007; Edwards, 2013). Ho and Gough (2006) calculated FTCs using the daily maximum and minimum temperature above 0°C and below 0°C, respectively.

Repeated seasonal cycles of freeze-thaw can naturally alleviate soil compaction in which water in the pore space expands during freezing and contracts during thawing processes. Unger (1991) and Henry (2007) indicated that reduction in soil penetration resistance and bulk density observed in agricultural soils over winter was attributed to the disruptive effects of frequent FTCs on soil structure and particle configuration.

Other soil processes such as periodic cycles of wetting-drying processes can also reduce the effectiveness of soil compaction due to shrink-swell dynamics. This mechanism is more pronounced particularly in clayey soils with 2:1 lattice expansible clay minerals such as smectite and montmorillonite (Parker et al., 1982; Abou Najim et al., 2010).

Research studies conducted to investigate the effect of freeze-thaw processes on soil physical properties and primarily soil compaction and structure have yielded highly inconsistent results. Numerous studies indicated that repeated FTCs break down soil structure and reduce aggregate stability (Leo, 1963; Bisal and Nielsen, 1967; Asare et al., 1999; Oztas and Fayetorbay, 2003). Other previous studies showed that freeze-thaw processes reduce soil compaction, enhance aggregation, and improve other soil physical and hydraulic properties (Sillanpaa and Webber, 1961; Benoit, 1973; Asare et al., 1997, 1999; Lehrsche, 1998; Sahin et al., 2008; Edwards, 2013; Fouli et al., 2013).

To date the effectiveness of the freeze-thaw mechanism for alleviating soil compaction is not clearly understood. The paucity of information on the effect of repeated FTCs on soil compaction and the ambiguous nature of this type of research suggest the need for additional studies of FTCs’ effect on soil compaction. Thus, a 3-yr study was conducted to evaluate the dynamics of repeated FTCs on soil compaction in a clay loam soil in the NGP region. In this study, soil compaction was also evaluated under unfrozen soil conditions.

**MATERIALS AND METHODS**

**Experimental Design**

A split-split plot arrangement was used for this study. Four replications each consisting of four plots were laid out. Within each replication two of the plots were kept above freezing while the other two were allowed to freeze. One of the plots subject to freezing and one of the plots protected from freezing were compacted and the remaining two were left uncompacted. Thus, each replication had a frozen compacted, frozen uncompacted, unfrozen compacted, and unfrozen uncompacted treatment (Fig. 1). Soil temperatures were monitored to verify that the soils designated as those protected from freezing did indeed remain above freezing, and it allowed us to quantify the number of FTCs at each depth in the soils subject to freezing conditions. The amount of compaction was quantified with a soil penetrometer. The soil moisture measurements were monitored to ensure that there were no significant differences in moisture between treatments that could influence the penetrometer measurements. No significant differences in soil moisture were observed, so these data are not presented.

**Soil and Site Description**

A 3-yr soil freeze-thaw field experiment was initiated in fall 2009 at the Montana State University Eastern Agricultural Research Center (EARC) located approximately 2 km north of Sidney, MT, United States (latitude 47.7255 N, longitude 104.1514 W, and altitude approximately 650 m). The soil at the study site was classified as Savage clay loam (fine, smectitic, frigid Vertic Argiustolls), consists of deep, well drained, nearly level soils formed in alluvial parent material. The soil contains an expansible 2:1 smectite clay mineral. Soil particle size distribution indicated the textural class of the surface layer (0 to 30 cm) to be consistently within the clay loam classification. The amount of sand, silt, and clay in the soil at 0- to 30-cm depth ranged from 200 to 210, 410 to 430, and 370 to 380 g kg⁻¹, respectively. The soil contained 1.6% organic matter, pH ranged from 6.2 to 6.8, and cation exchange capacity (CEC) ranged from 22.7 to 24.7 cmol kg⁻¹ soil at the 0- to 30-cm depth.

The study area was planted to sugarbeet (Beta vulgaris L.) in 2008 and barley (Hordeum vulgare L.) in 2007. The last
tillage was performed in the fall of 2008 following the sugarbeet harvest. On 24 Oct. 2008 the area was disked (JD640, John Deere, Moline, IL), roller harrowed on 31 Oct. 2008 (Brillion, Brillion, WI), and leveled (Eversman 4512, Eversman, Denver, CO) once on 04 Nov. 2008. Weeds were controlled with applications of glyphosate applied with an all-terrain vehicle.

**Compaction Process Description**

A farm truck with a single rear axle was loaded to simulate a truck at harvest loaded to the maximum legal road weight (Fig. 2). The truck was equipped with two tires 22.9 \( \times \) 50.8 cm (9.00 \( \times \) 20 nominal Society of Automotive Engineers size) with a measured 101.6 cm outside diameter on the front axle and four of the same size tires mounted as duals on the rear axle. The tires were inflated to 587 kPa (85 psi). The loaded truck weighed 12,628 kg. The rear axle weight was 9308 kg and the front was 3320 kg. The area was compacted by reversing the truck onto the plot starting at the east edge of the plot (Fig. 1). The truck was then driven forward and to the west the width of the dual wheels on the rear axle and then backed onto the plot again. This process was repeated until the truck was at the west edge of the plot. The truck was then moved half of a tire width to the east so the strip of soil that was not compacted between the duals on the first pass would be compacted by the passes that the truck made as it made the second pass to the east edge of the plot (Fig. 1). There were still some ridges present in the plots where the soil squeezed up between the duals, so 2 d after the truck passes were made a steel roller was used to flatten the ridges. The roller was 1.2 m in diameter and weighed 1887 kg. This caused only additional compaction and facilitated placing the thermocouples at appropriate depths and prevented excessive air movement under the heating blankets (Multi-Duty 7.010 × 3.353 m Thaw and Cure, Powerblanket, Salt Lake City, UT). Volumetric moisture content in soil before compaction process was near field capacity, approximately 34 to 35% (Table 1). The soil was compacted only in the first year of the study (fall 2009).

**Temperature and Moisture Sensor Installation and Monitoring**

Thermocouples were used to monitor soil temperatures in the plots. Type T 0.52 mm\(^2\) (20 AWG) Teflon insulated wire was cut to the length required for each combination of plot, depth, and data logger. The thermocouple junctions were formed with a spot welder (HotSpot 1, DCC Corporation, Pennsauken, NJ). The thermocouples were taped to a 9.5-mm-diameter fiberglass rod so that the depth of insertion and distance between the thermocouples could be accurately controlled. The holes created by the penetrometer measurements were used for the thermocouples which were installed at depths of 5, 10, 15, 30, and 61 cm in the center of each plot.

Hydra Probes (Stevens Water Monitoring Systems, Portland, OR) measured soil moisture and temperature in four of the plots at one probe per treatment (see Fig. 1 for sensor placement details). Soil moisture content and temperature were monitored every 2 h. The sensors were connected to three CR10x data loggers though an AM416 and an AM16/32b multiplexer (Campbell Scientific, Logan, UT). The loggers recorded the data every 30 min and relayed it to a computer located in the research location’s office building via a Bluetooth radio transmitter (SD202, Initium Co., Sungnam-shi, Korea).

The plots were covered on 8 Oct. 2009, 24 Oct. 2010, and 5 Oct. 2011 and were uncovered on 7 June 2010, 17 May 2011, and 17 May 2012. Heating blankets commonly used on concrete (Multi-Duty 7.0 \( \times \) 3.4 m Thaw and Cure, Powerblanket, Salt Lake City, UT) were installed on the plots designated to be kept frost free (Fig. 1). They were controlled by a thermistor buried 1.7 cm deep and placed 20 cm from the corner of the blanket. The controllers (DuroStat 102720, FarmTec, Dyersville, IA) were set to supply power to the blanket when the thermistor registered 2°C and shut the power off when the temperature reached 4°C. Each blanket had its own temperature controller and was wired to a separate electrical circuit breaker. The plots that were not heated were covered with laminated polyethylene tarps to provide conservation of moisture as in the unfrozen (heated) treatments that were covered with blankets. The blankets and tarps are impermeable [<57 perm SI (57 kg s\(^{-1}\) m\(^{-2}\) Pa\(^{-1}\)), <1 perm US (57.2135 ng s\(^{-1}\) m\(^{-2}\) Pa\(^{-1}\))]. Plots were uncovered after the last frost of each year (Fig. 3).

![Fig. 2. Wheel tracks from a farm truck during the compaction process.](image-url)
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The blankets covering the plots over the winter were anchored at each grommet with stakes constructed from 9.5-mm-diameter steel rods that measured 41 cm long. The stakes were sharpened at one end and a flat washer was welded 10 cm from the other end to provide complete contact with the grommet, and a 10-cm piece of the same rod was welded at 90° to the rod to provide a handle to facilitate extraction.

Soil Penetration Resistance Measurements

The trailer-mounted penetrometer sensor (Veris Technologies, 2002) was used to obtain initial PR measurements in fall 2009 due to the high density of the soil created by the compaction process at moisture contents near field capacity in clay loam. It was unfeasible to measure PR at these higher levels of soil compaction using a hand-held digital penetrometer. Conversely, the trailer-mounted penetrometer sensor was not used to measure PR for other sampling dates to avoid soil disturbance and compaction from a trailer-mounted device and the pickup truck under wet soil conditions. Soil PR readings were recorded in 2.5-cm increments to a depth of 30 cm. Soil PR measurements were made by pushing a hand-held digital cone penetrometer (Field Scout, SC 900 Soil Compaction Meter, Spectrum Technologies, Plainfield, IL) into the soil at the center of the plots (one measurement per plot).

Penetrometer measurements are usually reported as the cone index (CI) which is the shear resistance of the soil. Cone index is measured in Pascals and is described as $CI = F/\pi (d/2)^2$, where $F$ is total force needed to push the penetrometer into the soil in Newtons (N), and $d$ is diameter of the cone (Randrup and Lichter, 2001).

At the time of soil PR measurements, soil water content was determined for each of the 16 plots using a digital TDR soil moisture meter (Field Scout, TDR 300 Soil Moisture Meter, Spectrum Technologies). This device was equipped with 20-cm-long rods spaced 3.3 cm apart that are mounted on a 90-cm-long handle. The rods are pushed into the soil by means of the handle, the soil moisture value is displayed on the LCD readout, logged to internal memory, and the process is repeated at the next location. Dates of soil PR and average volumetric moisture content measurements from the surface to 30-cm depth are given in Table 1. All PR measurements and compaction processes were performed at moisture contents near soil field capacity (34–35%), estimated by Jabro et al. (2009b).

Freeze-Thaw Cycles

In our study, freeze-thaw cycles were calculated using a daily maximum soil temperature above +0.5°C and a daily minimum soil temperature less than -0.5°C. Table 2 shows the number of FTCs at the depths of 5, 10, 15, and 30 cm. Soil temperature measurements showed that soil froze to a depth of 61 cm and several FTCs occurred at depths exceeding 30 cm.

Statistics

Statistical analyses were performed using the mixed model of SAS software, with each sampling date (fall or spring) as a repeated measures variable of SAS (SAS Institute, 2011). Treatments were considered as the fixed effect and replication or blocks as the random effect. Means separations were done using the least square means test in SAS (Littell et al., 1996), differences among treatments were reported as significant at $P = 0.05$.

Table 1. Volumetric soil moisture content (0–20 cm) at the time penetration resistance measurements.

<table>
<thead>
<tr>
<th>Date of sampling</th>
<th>Season</th>
<th>Mean</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 Aug. 2009</td>
<td>Fall09</td>
<td>35.3</td>
<td>37.5</td>
<td>34.2</td>
</tr>
<tr>
<td>14 June 2010</td>
<td>Spr10</td>
<td>34.1</td>
<td>36.8</td>
<td>33.9</td>
</tr>
<tr>
<td>27 Sept. 2010</td>
<td>Fall10</td>
<td>34.0</td>
<td>36.7</td>
<td>33.4</td>
</tr>
<tr>
<td>08 June 2011</td>
<td>Spr11</td>
<td>34.7</td>
<td>36.2</td>
<td>33.4</td>
</tr>
<tr>
<td>02 Sept. 2011</td>
<td>Fall11</td>
<td>34.8</td>
<td>36.1</td>
<td>33.9</td>
</tr>
<tr>
<td>06 June 2012</td>
<td>Spr12</td>
<td>34.2</td>
<td>36.7</td>
<td>33.1</td>
</tr>
</tbody>
</table>

Table 2. Freeze-thaw cycles for frozen compacted and frozen uncompacted soils at depths of 0–5, 5–10, 10–15, and 15–30 cm in Savage clay loam.

<table>
<thead>
<tr>
<th>Year</th>
<th>0–5 cm</th>
<th>5–10 cm</th>
<th>10–15 cm</th>
<th>15–30 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frozen compacted treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009–2010</td>
<td>20</td>
<td>13</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>2010–2011</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>19</td>
</tr>
<tr>
<td>2011–2012</td>
<td>33</td>
<td>20</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>Frozen uncompacted treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009–2010</td>
<td>19</td>
<td>10</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>2010–2011</td>
<td>22</td>
<td>23</td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td>2011–2012</td>
<td>37</td>
<td>24</td>
<td>16</td>
<td>14</td>
</tr>
</tbody>
</table>
The least square means is the SAS term that refers to the more common term marginal means, which is sometimes referred to as estimated marginal means (SAS online documentation: http://onbiostatistics.blogspot.com/2009/04/least-squares-means-marginal-means-vs.html and http://support.sas.com/onlinedoc/913/getDoc/en/statughtml/glm_sect34.htm).

RESULTS AND DISCUSSION
Compacted and Uncompacted Soils

Compacted treatments had higher PR values than 1.5 MPa at depths greater than 2.5 cm, reaching a maximum of nearly 2.2 MPa at the 5- and 7.5-cm depths (Fig. 4). Uncompacted treatments did not exceed 1.5 MPa, except in the case when PR approached 1.6 MPa at the 5- and 7.5-cm depths. Soils with PR values exceeding 1.5 MPa were considered compacted (Kulkarni, 2003; Copas et al., 2009). Soil PR values for compacted plots were significantly greater than those under uncompacted plots. Compacted soil exhibited considerable soil strength due to compressive forces applied to the soil from wheel passes of the truck during the compaction process at near field capacity water content.

Frozen Soil Conditions

Soil PR in compacted soils that had been subjected to frozen conditions was significantly reduced by 73, 68, and 59% over one winter (November 2009 to April 2010) at depths of 0 to 10, 10 to 20, and 20 to 30 cm, respectively (Fig. 5a, 5b, and 5c). The average soil PR in compacted frozen treatments decreased by approximately 67% (from 2.10 MPa to 0.69 MPa) at the 0- to 30-cm depth.

Frequent FTCs over winter 2009 to 2010 and early spring 2010 alleviated a majority of soil compaction at depths of 0 to 10, 10 to 20, and 20 to 30 cm. The significant reduction in PR of the top 0 to 30 cm of the soil profile was due to dynamic effects of frequent FTCs on soil structure, pore space, and particle configurations. This natural mechanism is caused when the volume of soil pore water expands and creates forces that cause soil particles to push and contract repeatedly during freezing and thawing processes, respectively (Kohnke, 1968; Taylor and Ashcroft, 1972), where soils in the NGP region typically freeze and thaw often during winter and early spring in most years. This substantial mitigation in soil PR and strength due to natural processes and the dynamic activity of the freeze-thaw phenomenon is considered good news to farmers because little or no compaction means more soil pore space, better soil structure, and a healthier root environment which are essential to air, water, nutrient movement, plant growth, and root distribution in soil ecosystems.

Fig. 4. Initial soil penetration resistance profile of compacted and uncompacted soils measured in fall 2009. Error bars represents two standard errors of the mean.

Fig. 5. Temporal variations of soil penetration resistance (PR) for compacted and uncompacted soils under frozen conditions at depths of 0 to 10 cm (a), 10 to 20 cm (b), and 20 to 30 cm (c). Same lowercase letters indicate that means within a treatment are not significantly different at $P \leq 0.05$. Same uppercase letters indicate that means within a treatment are not significantly different at $P \leq 0.05$. 
Penetration resistance of frozen uncompacted soils in spring 2010 was not significantly different from other subsequent four sampling dates for all three sampling depths (Fig. 5a, 5b, and 5c). In the frozen uncompacted treatments, soil PR was significantly influenced by FTCs and reduced by approximately 73, 66, and 49% over winter and early spring of 2009 to 2010 at depths of 0 to 10, 10 to 20, and 20 to 30 cm, respectively (Fig. 5a, 5b, and 5c). Averaged across three depths, soil PR decreased by approximately 62% (from 1.34 MPa to 0.51 MPa), providing optimum soil conditions for plant growth, despite the initial value of PR 1.34 < 1.5 MPa which was initially classified as uncompacted soil (Kulkarni, 2003; Copas et al., 2009). This considerable decrease in soil PR of the upper 0 to 30 cm of the soil profile was likely caused predominantly by the effects and dynamics of repeated FTCs on the arrangement and orientation of soil particles as well as formation of new patterns and geometry of pore spaces in the soil (soil structure). These results were in agreement with those found by Lehrsch (1998), Oztas and Fayetorbay (2003), and Edwards (2013) in terms of soil aggregate stability and porosity as affected by FTCs.

No significant differences in soil PR were observed between spring 2010 and subsequent sampling dates throughout the course of this study (Fig. 5a, 5b, and 5c).

Unfrozen Soil Conditions

In unfrozen compacted soils, PR was significantly reduced by 50, 60, and 46% over one winter (November 2009 to April 2010) at depths of 0 to 10, 10 to 20, and 20 to 30 cm, respectively (Fig. 6a, 6b, and 6c). Averaged across three soil depths, PR in compacted treatments decreased by approximately 52% (from 2.16 to 1.03 MPa). This reduction in soil PR at the surface of soil profile (0–30 cm) may be due to the biology of soil, increased microbial, mycorrhizal, microfaunal activities, and disruptive effects of shrink-swell cycles caused by frequent drying-wetting processes under warm conditions where soils were prevented from freezing with electrically heated blankets (Henry, 2007). This presumed biological and physical behavior may have caused a reduction in soil compaction and changes in soil structure. Expansive clayey soils such as Savage clay loam (37–38% clay; 1.6% organic matter) used in this study are susceptible to shrink-swell behavior and cracks were visible on the surface under dry conditions. (Abou Najm et al., 2010). These soils absorb water, then water enters into spaces between the soil lattices of 2:1 smectite clay minerals and as more water is absorbed, the lattice plates are forced further apart, leading to an increase in soil pore pressure causing soil structure to change (Basma et al., 1996;
Andrieux et al., 2011; Fouli et al., 2013). Further, the dynamics of shrink-swell due to drying-wetting processes can result in considerable changes in soil structure and porosity. Our results concurred with those found by Abou Najm et al. (2010) on Savage clay loam. When dry soils are wetted after rainfall or irrigation events, they expand or swell; conversely, a wet soil shrinks on a drying period creating cracks, and the cracks disappear when soil expands or swells after irrigation and rainfall (Abou Najm et al., 2010). However, the compacted soil under unfrozen conditions was returned to optimum soil conditions for plant growth due to the effects of periodic drying-wetting processes over winter of 2009 to 2010 and early spring of 2010. No significant differences in soil PR were observed between spring 2010 and subsequent sampling dates.

Similarly, in unfrozen uncompacted soils, PR was significantly reduced by 72, 54, and 33% over winter and early spring (November 2009 to April 2010) at depths of 0 to 10, 10 to 20, and 20 to 30 cm, respectively (Fig. 6a, 6b, and 6c). Averaged across the three soil sampling depths, PR in uncompacted treatments decreased by approximately 53% (from 1.33 MPa to 0.63 MPa). The magnitude in soil PR reduction in both compacted and uncompacted treatments under unfrozen conditions was almost identical. The reduction in soil PR in the uncompacted treatment was caused by reasons mentioned in the preceding section (i.e., soil microbial activity and shrink-swell behavior in expansive clayey soil). The low values in soil PR of the top 0 to 10 cm may be caused by loosened soil particles from the presence of a thick layer of algal growth on the soil surface in the spring of 2010 (Fig. 3).

Figure 7 illustrates PR profiles to a depth of 0 to 30 cm of initially compacted soil in fall 2009 (fall09), following frozen conditions and measured in spring 2010 (spr10) and unfrozen conditions and measured in spring 2010 (spr10). Significant reductions in soil PR were observed between initially compacted soil in fall 2009, and frozen compacted and unfrozen compacted soil in spring 2010 over winter of 2009 to 2010 and early spring of 2010. These reductions in PR were due to soil freeze-thaw and shrink-swell mechanisms in clay loam soil. Our results concurred with those found by Unger (1991), Henry (2007), Parker et al. (1982), and Abou Najm et al. (2010). However, the compacted soil under frozen conditions was returned to optimum soil conditions for plant growth due to the effects of FTCs over winter 2009 to 2010 and early spring of 2010 (Fig. 7). These results demonstrated that repeated FTCs can alleviate soil compaction, alter soil physical quality, and contribute to a healthy soil ecosystem for root growth.

CONCLUSIONS

This study evaluated the effect of FTCs on soil compaction in a clay loam in the semiarid NGP. Soil PR in frozen compacted treatments was decreased by 67% over one winter (November 2009 to April 2010) at the 0- to 30-cm depth due to dynamic effects of frequent FTCs on soil structure. Similarly, in frozen uncompacted treatments, soil PR was decreased by approximately 62% (from 1.34 to 0.51 MPa) thus providing better soil conditions for plant growth. In unfrozen compacted soils, PR was significantly reduced by approximately 52% (from 2.16 to 1.03 MPa) in the top 0 to 30 cm of the soil profile presumably due to the biology of soil and disruptive effects of shrink-swell cycles caused by frequent drying-wetting processes.

The results from this study could save growers considerable time, money, and energy currently required to alleviate soil compaction using other methods such as subsoiling and deep tillage. Our findings demonstrated that repeated freeze-thaw cycles can alleviate soil compaction, improve soil structure, alter soil physical quality, and create optimal soil conditions required for the profitable growth of agricultural crops. Some naturally occurring weather patterns can provide mechanisms to reverse soil compaction and enhance soil structure through the dynamics of freeze-thaw cycles that occur in soils in Montana and other parts of the country.

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REFERENCES

Flowers, M., and R. Lal. 1998. Axle load and tillage effect on soil physical...


