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Crop and Soil Management to Increase Water Infiltration into Frozen Soil

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ABSTRACT

Crop and soil management to trap snow and reduce spring-runoff have potential to increase soil water storage. A randomized field-design using ripped and non-ripped soil was used to test whether tillage improved water infiltration into frozen soil. Studies were conducted on annually grown spring wheat (*Triticum aestivum* L.) near Culbertson, Montana. Soil was a Dooley sandy loam (fine-loamy, mixed Typic Argiboroll). Ripping was with a single shank at regular intervals on the contour. Soil water was measured using neutron attenuation and volumetric determinations. Final infiltration rate on frozen soil averaged 17 mm h^{-1} and 2 mm h^{-1} on ripped and non-ripped treatments, respectively. In spring, average water content of the top 1.2 m of soil, to a distance 1.5 m downslope from the rip, was 32 mm greater on ripped treatments compared to non-ripped treatments at comparable slope positions. There were no differences in wheat yield between treatments. Infiltration measurements show that soil ripping has potential to decrease water runoff.

Key Words: soil ripping, ponded infiltration, preferential flow, spring wheat, soil water storage

INTRODUCTION

Soil freezing and thawing affect large agricultural areas, as well as range and forest land. Within the United States, Formanek et al. (1990) estimated that nearly 1.2 million km^2 of crop land, 1.3 million km^2 of forest land and 1.8 million km^2 of grazing land are impacted by freezing and thawing. From an agricultural perspective, defining interactions of freeze-thaw on movement of water and chemicals is of high importance.

Water infiltration into frozen soil is primarily determined by soil water content at the time of freezing (Kane, 1980). The freezing process also induces water flux from unfrozen soil to the freezing front. Typical patterns of water redistribution near the surface during diurnal freezing and thawing cycles have been shown by Pikul et al. (1989). An increasingly tortuous water flow path develops as pore space fills with ice. In the inland Pacific Northwest, which has a winter precipitation pattern, soils often freeze at a high water content resulting in a nearly impermeable condition. Air-filled macropores provide important preferential water flow paths through frozen soil and increase water infiltration (Gray et al., 1990; Zuzel and Pikul, 1987).

The importance of freeze-thaw on agricultural lands as related to runoff and erosion hazards is recognized and considerable research has been conducted to identify problems and possible solutions. However, implementing solutions at the field scale can be difficult. Typically, soil erosion control efforts have been through tillage and residue management systems that maintain adequate surface roughness and suitable amounts of crop residue on the surface. Allmaras et al. (1979) have shown that erosion control in eastern Oregon often requires combinations of tillage, residue management, contouring, or terracing. Growers must plan on having sufficient residue cover following fall planting. The Natural Resources Conservation Service (NRCS) determines percentage surface cover to meet acceptable soil loss tolerances, but even the best management practices may fail to reduce water

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runoff and erosion when the soil is frozen or partially frozen (Saxton et al., 1981).

On rangelands, various mechanical treatments such as ripping, pitting and contour furrowing have been used to create surface storage and increase water infiltration opportunity. For example, in eastern Montana contour furrowing of sloping land with low infiltration capacity improved precipitation-use efficiency (Wight and Siddoway, 1972). Where snowfall is significant, contour furrowing of range land increased snow water accumulation by 60% and soil water recharge by 161% compared to natural range (Neff and Wight, 1977).

On cropland, the objectives of tillage are to incorporate residues or amendments, control weeds and prepare the soil for seeding. Tillage to specifically prepare fields for spring runoff is generally not a consideration. Experiments designed to test the effect of tillage on overwinter soil water storage are often executed using whole-field tillage implements such as disk or chisel plows. Interpretation of the effectiveness of tillage on water infiltration is difficult because whole-field tillage destroys vertical crop residue essential for snow trapping and increases evaporative soil water loss. On the Canadian prairies, where snowfall accounts for approximately 30% of the annual precipitation, Maulé and Chanasyk (1990) reported that snowmelt recharge, measured from fall to post-melt in the spring, was 36% greater in fields that were chiseled in the fall compared to fields that were not chiseled. Contrary to the findings of Maulé and Chanasyk (1990), earlier literature reviews (Lal and Steppuhn, 1980) reported that on the Canadian prairies, tillage did not increase overwinter soil water storage.

Management practices that combine the use of stubble management for snow catch and contour-ripping for water infiltration have potential to reduce runoff and increase soil water storage. In southern Saskatchewan, Canada, Gray et al. (1990) reported greater spring wheat yields on plots that had been managed for snow catch and water infiltration than on undisturbed stubble check plots. In the inland Pacific Northwest where freezing and thawing account for a significant portion of soil erosion problems, Saxton et al. (1981) used slot-mulching, also termed vertical mulching (Spain and McCune, 1956), to reduce water runoff from frozen soil. Saxton et al. (1981) found that water runoff was 10 times greater on no-till check plots as compared to slot mulch plots. Pikul et al. (1992) have shown that soil ripping can intercept and infiltrate meltwater through frozen soil and that spacing of soil rips can be estimated from historic precipitation patterns and permeability of unfrozen subsoil.

Methods that increase snowmelt infiltration when the soil is frozen need to be considered as part of the management plan in regions where soil water limits plant growth and where soil erosion may be a problem. Our hypothesis is that tillage-induced macroporosity provides important preferential water flow paths through slowly permeable frozen soil. Our objective was to investigate soil ripping as a tillage practice to improve water infiltration into frozen soil.

MATERIALS AND METHODS

Field experiments were conducted during 4 winters near Culbertson, Montana on a Dooley sandy loam with about a 5% slope. Spring wheat was grown annually since 1991. Each fall, except 1991, a single 50-mm-wide parabolic sub-soiling shank was used to rip the soil 0.30 m deep on 6-m contour intervals. In 1991, a 50-mm-wide straight shank chisel was used to create a rip when the soil was frozen 0.1 m deep. This subsoiling tillage was used on rip plots. There was no subsoiling on plots called no rip.

Statistical design was completely randomized with three replications of rip and no rip treatments. Plots were 79 m long and 23 m wide with the long axis parallel to the slope. Statistical comparisons were made using least significant differences (LSD) at P = 0.05 with the no rip treatment as a control.

Prior to seeding spring wheat, both rip and no rip treatments received 34 kg N ha^{-1} broadcast as ammonium nitrate. Seedbeds for spring wheat were prepared with 0.45-m wide medium-crown sweeps. Treatments were seeded on the contour to spring wheat at about 2.1 million viable seeds ha^{-1} using a double disk drill with 0.2-m row spacing. In all years, except 1993, wheat was harvested using a conventional combine header. Stubble height was about 0.20 m. Stubble remained intact over winter. In 1993, wheat was harvested with a stripper header (Wilkins, et al., 1996) which left stubble almost 0.6 m tall. Wheat yield was measured on each plot at six slope positions by taking 18-m by 1.46-m swaths on the contour.

Infiltration frames were 1.16 m long by 0.61 m wide by 0.3 m deep and were installed on each replication of each treatment prior to soil freezing in 1992, 1993, and 1994. Inside edges of the infiltration frames were sealed with bentonite clay to prevent water leakage along the metal-soil interface. For the rip treatment, infiltration frames were centered over the rip with the long axis of the infiltration frame oriented parallel to the rip. Soil outside the frame and adjacent to the rip was removed, backfilled and packed to eliminate lateral flow of water from inside the frame to the rip. On no rip treatments, frames were oriented with the long axis parallel to the wheat rows. Constant-head infiltration tests were made in January 1993 when the soil was frozen to a depth that exceeded 1 m; in February 1994 when the soil was frozen 0.3 m deep; and in January 1995 when the soil was frozen about 0.6 m deep. Ponded infiltration imitates runoff events where water accumulates in the rip or in the furrow. Average depth of ponded water was 100 mm on no rip treatments. Water temperature for infiltration tests was close to 0° C. An estimate of surface storage was made by rapidly filling the rip or furrow with water.

Soil water content was measured using neutron attenuation. Three neutron access tubes were located at the upper, middle, and lower slope positions for a total of nine tubes per replication and 27 tubes per treatment. Soil water was measured to a depth of 1.83 m at 0.3-m increments just prior to soil freeze-up and at soil thaw. At the time of infiltration tests soil water of the surface 50 mm was determined gravimetrically outside the frame.

At spring thaw, soil water was measured at 0.3 m increments to a depth of 1.2 m along a 3-m transect perpendicular to the rip and at similar slope positions on no rip plots. Cores were taken at 0.3 m intervals along the transect. Gravimetric water measurements were converted to volumetric measurements using an average soil bulk density of 1.58 Mg m^{-3}.

Soil temperature was measured at 0.3 m on rip and no rip treatments using three thermocouples wired in parallel to spatially average temperature. For temperatures (T) below freezing, freezing degree days were calculated as $(T_{max} + T_{min})/2$.

RESULTS AND DISCUSSION

Culbertson, Montana is located in an area of low Chinook frequency (Caprio et al., 1981). Typically, there is one freeze cycle where the soil can freeze as early as the first part of November and remain frozen through March.

Cumulative freezing degree days (FDD) were used to characterize the weather for the test years (Fig. 1). The winter of 1993 had the lowest air temperatures but had the least frozen soil and cumulative soil FDD at 0.3 m (Table 1). During the 1993-1994 winter, tall stubble trapped 69 mm of snow water equivalent (Table 1). Compared to the other two winters (Table 1), additional snow depth during 1993-1994 provided thermal insulation and reduced the depth of frozen soil. Cumulative air FDD for the winter seasons indicate that winters of 1992 and 1993 were similar in that each of these years accumulated about -1270 °C FDD days by the end of February (Fig. 1).

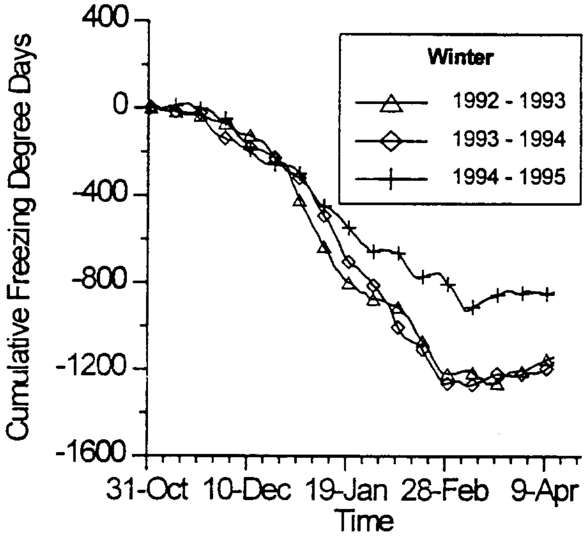

Figure 1. Cumulative air freezing degree days at the infiltration test site.

Table 1. Cumulative freezing degree days (FDD) and selected soil characteristics on the day of the infiltration tests.

Winter	Day of infiltration test	Snow water equivalent (mm)	Cumulative air FDD (from 1 Nov)	Cumulative soil FDD at 0.3 m (from onset of freezing at 0.3 m)		Depth of frozen soil (m)		Soil temperature at 0.3 m (C)	
				Rip	No Rip	Rip	No Rip	Rip	No Rip
1992-1993	Jan 20-21	28	-799	-158	-150	1.0	1.0	-3.7	-3.2
1993-1994	Feb 16-17	69	-1077	-48	-27	0.3	0.3	-0.9	-0.7
1994-1995	Jan 31- Feb 1	27	-654	-95	-93	0.7	0.6	-1.1	-1.3

Table 2. Selected soil and water infiltration characteristics for infiltration tests on frozen soil.

Infiltration Test	Soil water content (m^3m^{-3}) on first day of infiltration tests soil depth			Surface storage	Temperature of water used for test	Infiltration final rate	Cumulative infiltration‡
	0-5mm	0-0.3 m	0.3-0.6 m	mm	°C	mm hr^{-1}	mm
20 Jan 1993							
Rip		0.18	0.16	49*	0	12*	98*
No rip	0.30	0.18	0.12	11	0.3	1	17
LSD(0.05)		ns†	ns	4		6	17
21 Jan 1993							
Rip				9*	0	3	14*
No rip				0	0	1	2
LSD(0.05)				3		ns	8
16 Feb 1994							
Rip		0.20	0.16	56*	2.5	9*	99*
No rip	0.24	0.18	0.18	5	3.0	1	14
LSD(0.05)				8		3	8
17 Feb 1994							
Rip				11*	2.2	2	15*
No rip				0	1.2	1	1
LSD(0.05)				1		ns	7
31 Jan 1995							
Rip		0.16*	0.14	49*	3.5	30	134*
No rip	0.53	0.13	0.10	6	3.5	5	24
LSD(0.05)		0.027	ns	19		ns	74
1 Feb 1995							
Rip				17*	4.2	14	33*
No rip				2	3.7	4	5
LSD(0.05)				9		ns	25

† Significant at the 0.05 probability level (*) or not significant (ns)

‡ Cumulative values for 2 h test on day 1 and 1 h test on day 2

Water infiltration was measured on two consecutive days in each of the three winters. On the first day of the tests there were significant differences in water infiltration rate (WIR) and cumulative water infiltration (CWI) between treatments (Table 2). Three-year average CWI following 2 h was 110 mm on rip treatments and 18 mm on no rip treatments. Surface storage accounted for 51 mm of the CWI on the rip treatments and 7 mm on the no rip treatments. On the second day of the tests, surface storage was 12 mm on the rip treatments and 1 mm on the no rip treatment. Final infiltration rates on the second day of the tests were not significantly different between treatments. On the rip treatment, final WIR on the second day was significantly less than final WIR on the first day of tests. We suspect that water froze in the soil pores following the first test and plugged pores that were previously air-filled. Infiltration rates on the first day of the tests in 1993 and 1994 are shown in Figure 2.

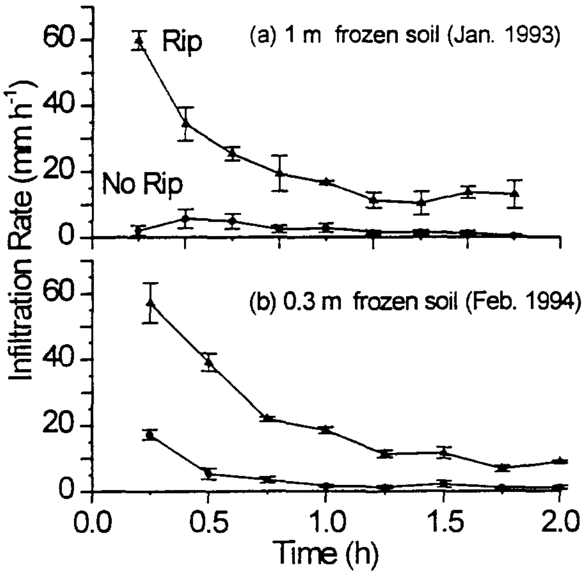

Figure 2. Water infiltration into frozen soil on the first day of infiltration tests in 1993 and 1994. Error bars show one standard deviation.

Table 3. Water storage efficiency, water use by wheat, and wheat yield on rip and no rip treatments

	Winter 1991	Summer 1992	Winter 1992	Summer 1993	Winter 1993	Summer 1994	Winter 1994	Summer 1995‡
Water storage efficiency				%				
Rip	0.60		0.46		0.29		0.76	
No rip	0.67		0.49		0.37		0.66	
LSD(0.05)	ns†		ns		ns		ns	
Precipitation (mm)	50		60		64		97	
Water use				mm				
Rip		331		301		338		
No rip		341		290		348		
LSD(0.05)		ns		ns		ns		
Precipitation (mm)		344		318		243		
Wheat yield				kg ha^{-1}				
Rip		2577		2157		2958		292
No rip		2463		2182		2880		249
LSD(0.05)		ns		ns		ns		ns

† Significant at the 0.05 probability level (*) or not significant (ns)

‡ Crop hail damaged in 1995

At the field scale, our tests failed to show any significant differences in water storage efficiency, water use by wheat, or wheat yield between treatments (Table 3). Water storage efficiency is the ratio of soil water storage to precipitation. Soil water storage was determined using a grid of 54 neutron access tubes. Individual tubes were several meters distant from the rips and consequently soil water measurements at the tube locations did not indicate water changes in close proximity of the rip.

Gravimetric soil water measurements in positions close to the rips provided evidence that spring runoff was channeled into the rip. Within a 3-m transect centered over the rip there were significant differences in soil water content between treatments (Table 4). In 1994, there was over 69 mm of snow water equivalent (Table 1) at the start of a thaw on 27 February. By 14 March all the snow was melted. During this rapid thaw, visual observations confirmed runoff on the no rip plots and water accumulation in the ripping troughs. Soil temperature measurements at the time of melt indirectly suggest that warm water from the surface had infiltrated to the 0.3 m depth on the rip treatment (Fig. 3). Soil temperature at 0.3 m had registered consistently lower on the rip treatment than on the no rip treatment until the thawing began.

Table 4. Soil water to a depth of 1.22 m measured in a 3-m transect over the rip and at a comparable slope position on no rip treatments.

Treatment	Soil water (mm)
6 April 1994	
Rip	291*
No rip	251
LSD(0.05)	30
12 April 1995	
Rip	261*
No rip	236
LSD (0.05)	15

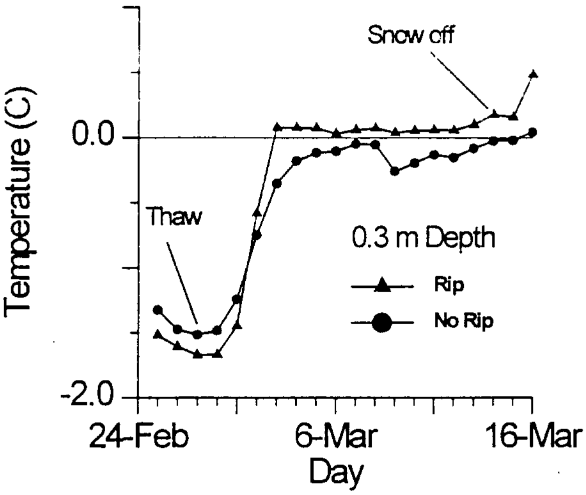

Figure 3. Soil temperature at 0.3 m during spring thaw in 1994. Temperature sensors at 0.3 m are at the depth of tillage on the rip treatment.

Infiltration rates into frozen soil have been shown to be closely linked to soil water content at the time of freezing. Annual wheat cropping provides ideal opportunities to efficiently use precipitation and reduce soil erosion. Previously, we have shown that no-tillage annual spring wheat production was the most efficient crop and soil management from the standpoint of crop yield and water use efficiency (Aase and Pikul, 1995). In an experiment adjacent to this study (data not shown), soil water content in the top 0.6 m of the soil profile at freeze-up on plots following spring wheat harvest was 70% of that following fallow.

From an infiltration stand point it is desirable to annual crop because soil on annual cropped fields freezes at a lower water content than fallow fields. Although we did not directly compare infiltration into frozen soil on fields that were fallowed versus fields that were cropped, we speculate that because of soil water content differences, infiltration will be greater on annually cropped soils than on fallowed soils.

Soil ripping and annual cropping provide soil and crop management to minimize water runoff. Surface crusts and tillage pans are disrupted by ripping and preferential flow paths in the ripping trough serve to bypass the tortuous pathways near the surface and contribute to increased water infiltration. Because there were no differences in wheat yield between treatments, the application of contour ripping seems best suited to situations where runoff and soil erosion are problems. Practices that protect soil from erosion also stabilize yield and maintain soil productivity.

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