Reprinted from the *Soil Science Society of America Journal*
Volume 62, no. 4, July–Aug. 1998
677 South Segoe Rd., Madison, WI 53711 USA

Fall Contour Ripping Increases Water Infiltration into Frozen Soil

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ABSTRACT

Crop residue management to trap snow and soil management to improve water infiltration into frozen soil might reduce spring runoff and increase soil water storage. We hypothesized that soil macropores created by tillage would improve water infiltration when the soil was frozen. This hypothesis was tested by ripping a Dooley sandy loam (fine-loamy, mixed Typic Argiboroll) in the fall of the year and then measuring water infiltration when the soil was frozen. A single subsoiling shank was used to rip soil to a depth of 0.3 m at 6-m contour intervals. Ripping was compared with no ripping using a randomized experimental design having three replications. Studies were conducted during 4 yr near Culbertson, MT, on plots seeded annually to spring wheat (*Triticum aestivum* L.). Soil water was measured with neutron attenuation and gravimetric methods. We used a constant-head (100 mm) method to measure water infiltration into frozen soil and a rainfall simulator for unfrozen soil. Final infiltration rate on frozen, ripped soil averaged 16 vs. 2 mm h^{-1} without ripping. Final unfrozen infiltration rate in spring was 34 mm h^{-1} with ripping vs. 15 mm h^{-1} without ripping. Average spring water content of the top 1.2 m of soil, to a distance 1.5 m downslope from a rip, was 32 mm greater with ripping than without ripping at comparable slope positions. There were no wheat yield differences between treatments. Contour ripping can decrease water runoff, and seems best suited where spring runoff and soil erosion caused by heavy winter snows is a problem.

SOIL FREEZING AND THAWING affect large agricultural areas, as well as range and forest land. It is estimated that during some portion of the year, 50% of the earth's land mass may be frozen (Sharratt et al., 1997). Formanek et al. (1990) estimated that freezing and thawing impact 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 in the USA. Some of the most productive agricultural soils in the USA are affected by periodic freezing and thawing. Therefore, from an agricultural perspective, defining interactions of freezing and thawing on the productivity and sustainability of the soil resource is of high importance.

Considerable research has been conducted to identify problems and possible solutions to runoff and erosion hazards caused by freezing and thawing of soil. However, implementing solutions on a 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. For example, Allmaras et al. (1979) showed that erosion control in eastern Oregon often requires combinations of tillage, residue management, contouring, and terracing. But, even the best management practices may fail to reduce water runoff and erosion when the soil is frozen or partially frozen (Saxton et al., 1981).

Hydraulic conductivity of frozen soils is inherently low and there is a strong association of frozen soils with increased runoff, flood-producing runoff, soil erosion, and sediment production (Tigerman and Rosa, 1951; Storey, 1955; Johnson and McArthur, 1973). Frozen soil layers limit water infiltration and focus runoff into topographic depressions where large ephemeral ponds may form (Baker and Spaans, 1997). These depression-focused recharge areas may represent a pollution source, especially where water tables are close to the surface (Derby and Knighton, 1997). Soil water content at the time of freezing is the primary factor affecting soil hydraulic conductivity and consequently water infiltration rates when the soil is frozen (Kane, 1980). Additionally, the freezing process causes water to flow from unfrozen soil to the freezing front. Pikul et al. (1989) showed typical patterns of water redistribution near the soil surface during diurnal freezing and thawing cycles. Water flow paths become increasingly tortuous as pore space fills with ice.

When soils freeze in a dry condition, air-filled pores provide important preferential water flow paths through frozen soil and increase water infiltration. Macropores created by tillage can be especially important to water infiltration because these pores would normally be drained of water at the time of freezing (Gray et al., 1990; Zuzel and Pikul, 1987). 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 with fields that were

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Published in Soil Sci. Soc. Am. J. 62:1017–1024 (1998).

Abbreviations: CWI, cumulative water infiltration; FDD, freezing degree days; WIR, water infiltration rate.

not chiseled. On the other hand, Lal and Steppuhn (1980) reported in a literature review that tillage did not increase overwinter soil water storage on the Canadian prairies. 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. These results (Pikul et al., 1992) were from experiments conducted on a loess silt loam, in eastern Oregon, where soils frequently freeze but at shallow depths compared with typical soil freezing patterns in the northern Great Plains.

Combinations of stubble management for snow catch and contour ripping for water infiltration can reduce runoff and increase soil water storage. In a study in southern Saskatchewan, Canada spring wheat yielded more on plots managed for snow catch and water infiltration than on undisturbed stubble check plots (Gray et al., 1990). New harvest technologies like stripper headers (Wilkins et al., 1996) leave wheat fields with tall stubble for maximum snow catch.

Various mechanical treatments such as ripping, pitting, and contour furrowing have been used on rangelands to create surface storage and increase water infiltration. Contour furrowing in eastern Montana on sloping land with low infiltration capacity improved precipitation-use efficiency and increased snow water accumulation by 60% and soil water recharge by 161% compared with natural range (Wight and Siddoway, 1972; Neff and Wight, 1977).

To successfully grow a crop every year on the semiarid Great Plains, it is necessary to efficiently use growing-season precipitation and to conserve as much precipitation as possible between harvest and seeding. Poor soil water storage efficiency, enhanced soil erosion, and development of saline seeps are associated with summer fallow (Tanaka and Aase, 1987; Black and Bauer, 1988). Methods to increase snowmelt infiltration into frozen soil need to be considered as part of management plans in regions where soil water limits plant growth and where soil erosion from spring runoff may be a problem.

Previously, we presented the concept of contour ripping as a tillage strategy to improve water infiltration into frozen soil. Three silt loam soils from Oregon and a sandy loam from Montana were tested (Pikul et al., 1996). Oregon sites had a Mediterranean climate while the Montana site had a continental climate. Water infiltration data (1993 Day 1 and 1994 Day 1) from this study were called "Montana, site 4" in Pikul et al. (1996). With the exception of one test reported by Pikul et al. (1996), ripping increased water infiltration into frozen soil compared with unripped checks. In one case, there was little infiltration benefit from ripping a dry pulverized soil because loose soil flowed into the rip and obliterated the rip path. In this study we tested the concept of contour ripping in a manner that would typify farmer practice in an annual small grain production system. Our objectives were to (i) investigate soil ripping as a tillage practice to improve water infiltration into frozen soil and (ii) evaluate soil water storage and spring wheat yields as a consequence of ripping.

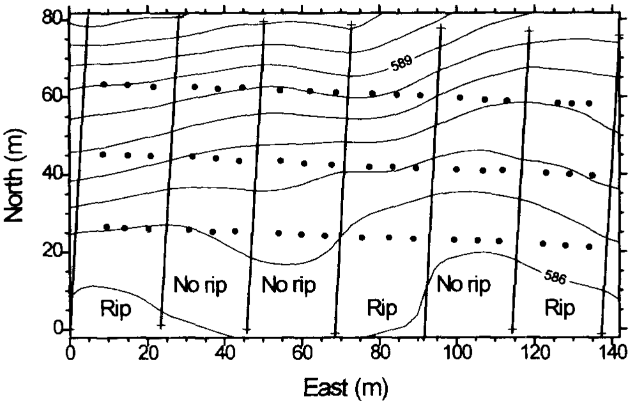

Fig. 1. Topographic map (meters of elevation) of the test area showing plot layout of rip and no-rip treatments. Soil water sampling locations are indicated by a solid circle.

MATERIALS AND METHODS

Experimental Site

Field experiments were conducted during four winters at a research site (Fig. 1) near Culbertson, MT, on a Dooley sandy loam with about a 5% slope. Dooley sandy loam formed in a mantle of eolian or alluvial material overlying glacial till. Glacial till is at a depth of about 0.5 m. Prior to 1975 the experimental area was in grass. Between 1975 and 1991 the land was cropped in a wheat–fallow rotation. Spring wheat has been grown every year since 1991. Medium-crown sweeps, 0.45 m wide and operated about 0.1 m deep, have been the principal tillage tool. Plots that were ripped were called "rip" and plots that were not ripped were called "no rip". Each fall, soil in the rip treatment was ripped with a single shank to about 0.3 m deep on about 6-m intervals parallel to the slope contour. Year to year, these intervals were adjusted so that we did not rip in exactly the same slope position. There was no other tillage in the fall after harvest. The objective of fall ripping was to create large soil fractures that remained open to the surface throughout the winter. We did not attempt to evaluate performance of a given tillage tool to achieve this objective. We used a 50-mm-wide straight-shank chisel in 1991 to create a rip when the soil was frozen 0.1 m deep. In 1992 and 1993 we used a 50-mm-wide rigid parabolic subsoiling shank before the soil froze. In 1994 we used a shank from a Tye Paratill before the soil froze.

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 (Fig. 1). Statistical comparisons of means were made using analysis of variance at a 0.05 probability level ($P = 0.05$).

All plots received 34 kg N ha^{-1} broadcast as NH_4NO_3 prior to seeding spring wheat. Seedbeds were prepared with 0.45-m-wide medium-crown sweeps operated about 0.1 m deep. Treatments were seeded on the contour to 'Lew' 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 wheat 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 by 1.46 m swaths on the contour.

Soil at the infiltration test site was grid sampled (54 points) at the start of the experiment (Fig. 1). Soil samples from this initial sampling were used to both characterize the experimental site and calibrate our neutron attenuation equipment (CPN Model 503 DR hydroprobe, Campbell Pacific Nuclear, Martinez, CA). Soil cores (0.032-m diam.) in 0.3-m segments were taken to a depth of 1.8 m. The midsection (0.15 m) of each segment was saved for measurement of bulk density and gravimetric water content. Immediately following core extraction, the hole was cased with a section of steel electrical conduit, and an initial count ratio was taken at the mid-depth of each sample segment. Volumetric water was calculated as the product of bulk density and gravimetric water. Linear regression was used to obtain a relation of volumetric water and count ratio for the top 0.3 m of soil ($n = 54$, $R^2 = 0.56$) and remaining depths ($n = 265$, $R^2 = 0.91$). The hydrometer method was used to determine soil texture on samples from each segment.

Soil water content was determined using neutron attenuation to measure soil water storage and water use. Water storage efficiency is the ratio of soil water storage to precipitation. Three 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 (Fig. 1). Soil water was measured to a depth of 1.8 m at 0.3-m increments just prior to soil freeze-up and at soil thaw. Water measurements using neutron attenuation were also made on the day of infiltration tests for the 0- to 0.3- and 0.3- to 0.6-m depths. Soil water content of the 0- to 0.05-m depth was determined gravimetrically outside of the infiltrometer frame at the time of infiltration measurements.

At spring thaw in 1994 and 1995, soil water profiles were measured at eight positions along a 3-m transect perpendicular to the rip. Cores were taken at transect positions of 0.3, 0.6, 0.9, and 1.5 m upslope and downslope from the center line of a rip located at about 32 m north (Fig. 1) and at similar slope positions (32 m north) on plots that were not ripped. In 1994, a duplicate set of measurements was also taken at 55 m north (Fig. 1) on rip and no-rip plots. Soil cores were 0.032-m diam. and taken to a depth of 1.2 m at 0.15-m increments. Volumetric water was calculated as the product of gravimetric water and average bulk density for each sampling depth. For example, average bulk densities ($n = 54$) for the 0- to 0.3-, 0.3- to 0.6-, 0.6- to 0.9-, and 0.9- to 1.2-m depths were 1.49, 1.54, 1.62, and 1.66 Mg m^{-3}, respectively. Coefficients of variation for these respective depths were 6.1, 4.3, 5.5, and 7.5%.

During the winter months, soil temperature was measured at 0.05-, 0.1-, 0.2-, 0.3-, 0.6-, and 0.9-m depths on rip and no-rip treatments using three thermocouples wired in parallel to spatially averaged temperature. In 1994–1995, a depth of 0.7 m rather than 0.9 m was used. For temperatures (T) below freezing, soil-freezing degree days were calculated as $(T_{\max} + T_{\min})/2$. Air temperature at 2.0 m was used to calculate air-freezing degree days. Soil temperature was used to estimate the depth of frozen soil.

Infiltration Tests on Frozen Soil

Infiltration tests on frozen soil were made using infiltrometer frames that were 1.16 m long by 0.61 m wide by 0.3 m deep. We installed the frames on each replication of each treatment prior to soil freezing in 1992, 1993, and 1994. Infiltration frames were centered over the rips with the long axis of the infiltration frame oriented parallel to the rips. Frames on the no-rip treatment were oriented with the long axis parallel to the wheat rows. 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. Care was taken to preserve an undisturbed soil monolith within the frames. Bentonite clay was used to seal inside edges of the infiltration frames to prevent water leakage along the metal–soil interface.

Constant-head infiltration tests were made in January 1993 when the soil was frozen to a depth that exceeded 0.9 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 would naturally accumulate in the rip or in the furrow of the seed row. Ponded tests were also desirable because the simple logistics of the method enabled us to take a complete set of measurements during two consecutive days. Average depth of ponded water was 100 mm. Measurement intervals were 0.25 h. Approximate constant head was maintained by manually adding water as necessary to achieve water surface contact with a hook gauge. Water temperature for all infiltration tests was close to 0°C to imitate the temperature of runoff from snowmelt. At the start of the infiltration test, an estimate of surface storage was made by rapidly filling the rip or furrow with water. Infiltration tests lasted 2 h on the first day, followed by a 1-h test on the second day.

Infiltration Tests on Unfrozen Soil

Water infiltration into unfrozen soil was measured in June 1993 to evaluate overwinter soil subsidence on the rip treatments. A Palouse rainfall simulator (Bubenzer et al., 1985) was used as a sprinkler infiltrometer to apply water at a rate of about 40 mm h^{-1} to 1.16 by 1.16 m infiltration frames (1.35 m^2). Electrical conductivity of Missouri River water (Culbertson, MT, municipal water supply) used for the infiltration tests was 0.7 dS m^{-1} and concentration of cations was 0.157 g L^{-1}. The simulator has two rainfall heads that were used to simultaneously test rip and no-rip treatments. Simulated rainfall mimics low-intensity storms of the inland Pacific Northwest. Typical summer rainstorms in the northern Great Plains are high intensity and of short duration. The Palouse simulator produces drop sizes that are about 1.3- to 1.8-mm diameter. By comparison, natural rainfall with intensities of about 50 mm h^{-1} has drop sizes that are about 1- to 5-mm diameter (Wischmeier and Smith, 1958). Therefore, the test soil was not exposed to rainfall energy exceeding that of naturally occurring storms.

Infiltration frames were constructed of heavy-gauge steel. We installed the frames in an area of the plots set aside from customary spring tillage and planting in 1993. Thus, the last soil disturbance in the infiltration test area was during fall ripping in 1992. Installation methods for the frames used in the rainfall simulator tests were similar to those used for the constant-head infiltration tests.

Water application rate was determined by collecting the runoff from a 1.35-m^2 calibration pan placed over the infiltration frame before and after each test. Infiltration was calculated as the difference between application rate and runoff rate. Excess water was removed from within the infiltration frame by vacuum. Water was applied for 5 h on Day 1, followed by 20 h off with no water applied. On Day 2, water was applied for 3 h. This cycle is often described as a dry and wet run and is conducted to reduce the confounding effects of variable soil water content during infiltration tests.

A soil bulk density profile of the top 0.6 m of the no-rip treatment was determined after the infiltration tests. The last soil disturbance on these treatments was at planting in the spring of 1992. Samples were taken using a tube sampler described by Allmaras et al. (1988). Nine cores were taken from within the infiltration frames.

RESULTS AND DISCUSSION

Experimental Site

Soil textural analyses for each of the grid sampling locations (Fig. 1) in the top 0.08 m concur with the sandy loam mapping unit (Smetana, 1985) for the Dooley surface soil (Table 1). However, at the 0.3- to 0.6-m depth, our textural analysis found evidence of a sandy loam, sandy clay loam, and sandy clay. These textural classes

Table 1. Selected soil properties of the test site.

	Sand	Silt	Clay	Organic C	pH
	%	%	%	g kg^{-1}	
	0–0.08-m depth				
Average	69.5	16.7	13.8	11	5.9
Standard deviation	3.8	2.5	1.8	1.3	0.5
Maximum	75.9	25.7	20.8	13.5	7.7
Minimum	53.6	12.1	10.9	8.8	5.3
	0.3–0.6-m depth				
Average	48.8	23.8	27.4	nd†	7.9
Standard deviation	12.3	5.6	8.2	nd	0.5
Maximum	78.2	34	41.3	nd	8.7
Minimum	30	9.2	11.3	nd	6.7

† Not determined.

have been mapped along with the plot locations and infiltration test area (Fig. 2). Location of soil textural differences at the 0.3- to 0.6-m depth (Fig. 2) cannot be predicted by topographic relief (Fig. 1) and consequently the randomized design of this experiment appears appropriate for the random textural characteristics of a glacial till soil.

Water infiltration rate is a function of soil texture as well as other soil factors. In previous reports we have shown the water infiltration management difficulties associated with this sandy loam soil (Pikul and Aase, 1995, 1997) for unfrozen soil conditions. The classification of sandy loam suggests that this soil should not have reduced infiltration capacity. However, we have measured final infiltration rates as low as 5 mm h^{-1}. This soil settles very firmly following rainfall, possibly due to the low organic matter levels and gradation of sand, silt, and clay. We believe the decline in water infiltration, during unfrozen infiltration tests, was due to the rearrangement of soil particles or filtration of finer particles into soil pores (Pikul and Aase, 1995).

We anticipated that rip tillage would create important surface-connected macropores, therefore bypassing layers of low permeability near the surface. Layers of low permeability can be both frozen soil and thin surface crusts. Further, we speculated that if this bypass water was intercepted by highly permeable sand in the lower portion of the profile, then infiltration rate into the soil would be improved. The typical Dooley series (Smetana, 1985) has an Ap sandy loam horizon (0–0.15 m), a Bt2 sandy clay loam horizon (0.15–0.58 m), and a 2Ck loam horizon (0.58–0.94 m). The low values of water permeability reported (Smetana, 1985) for these horizons were 51, 15, and 1.5 mm h^{-1}, respectively. In general, the infiltration test areas for the rip treatments were underlain by a sandy clay loam (a soil texture having a lower permeability than sandy loam) more often than the infiltration test areas of no-rip treatments (Fig. 2).

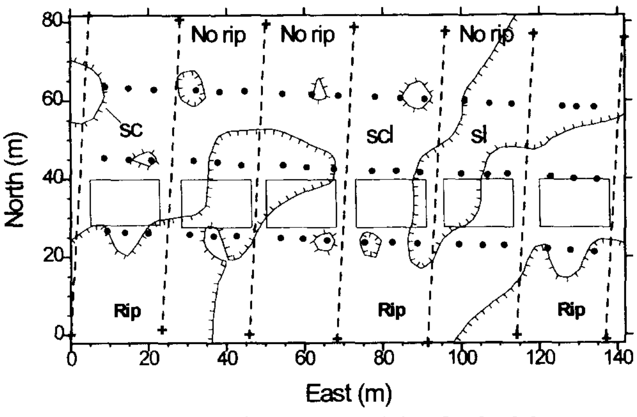

Fig. 2. Soil textural map for the 0.3- to 0.6-m depth of the test area identifying sandy clay (sc), sandy loam (sl), and sandy clay loam (scl). Soil sampling locations are indicated by a solid circle. Rectangles on each plot identify the general area where infiltration measurements were made.

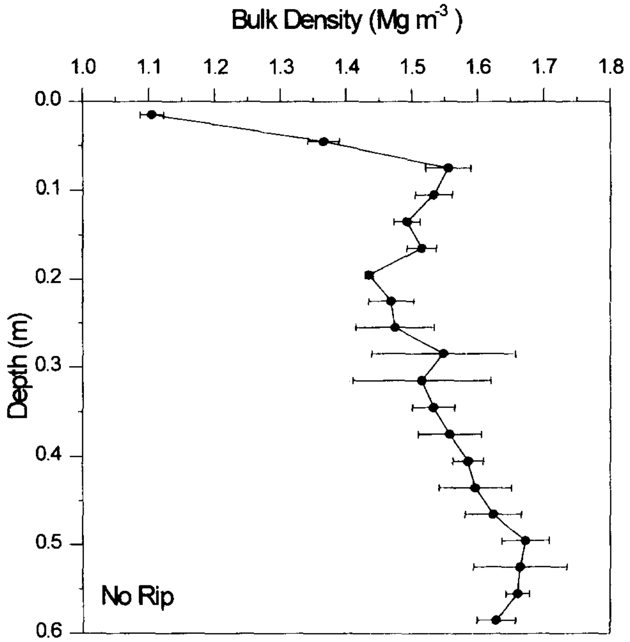

Fig. 3. Average soil bulk density for the test area taken outside of the rip. Error bars show ±1 standard deviation.

Surface crusting and subsurface layers of high bulk density may limit water infiltration. There was a distinct increase in soil bulk density at about 0.08 m (Fig. 3) on the no-rip treatment. Bulk density measurements were not made on the rip treatment. The increase in bulk density at about 0.08 m was not unique to these experi-

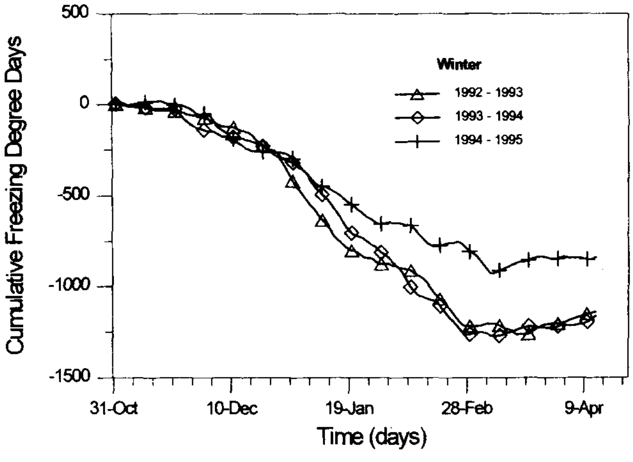

Fig. 4. Cumulative air freezing degree days (°C).

Table 2. Cumulative freezing degree days (FDD) and selected soil parameters on the day of the frozen soil infiltration tests in 1993, 1994, and 1995.

Winter	Day of infiltration test	Snow depth	Snow water equivalent	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		Soil temperature at 0.3 m	
					Rip	No rip	Rip	No rip	Rip	No rip
		mm	mm	°C	°C	°C	m	m	°C	°C
1992–1993	20–21 Jan.	180	28	−799	−158	−150	0.9	0.9	−3.7	−3.2
1993–1994	16–17 Feb.	430	69	−1077	−48	−27	0.3	0.3	−0.9	−0.7
1994–1995	1 Feb.–31 Jan.	340	27	−654	−95	−93	0.7	0.6	−1.1	−1.3

mental plots because a similar soil bulk density feature was identified in a study adjacent to this (Pikul and Aase, 1995). We think that this compact layer was the result of repeated shallow tillage operations using sweeps. Pikul and Aase (1995) reported that infiltration was not significantly different among tillage and crop management treatments even though bulk density differed among tillage treatments.

Culbertson, MT, is in an area of low Chinook frequency (Caprio et al., 1981). The soil can freeze as early as the first part of November and remain frozen through March. We used cumulative air-freezing degree days (FDD) to characterize the weather for the test years (Fig. 4). The winters of 1992–1993 and 1993–1994 had similar air FDD (Fig. 4) but the winter of 1993–1994 had the least frozen soil and cumulative soil FDD at 0.3-m depth (Table 2). During the 1993–1994 winter, 430 mm (69 mm snow water equivalent) of snow provided thermal insulation, thereby reducing the depth of frozen soil compared with the other two winters (Table 2). Good snow retention during the winter of 1993–1994 was probably a consequence of both favorable weather and tall stubble (0.6-m stubble height).

Infiltration Tests

There were significant differences in water infiltration rate (WIR) and cumulative water infiltration (CWI) between treatments on the first of the two consecutive days of water infiltration measurement (Table 3, Fig. 5). Three-year-average CWI for 2-h readings was 110 mm on the rip treatment and 18 mm on the no-rip treatment. Surface storage and macropore storage accounted for 51 mm of the CWI on the rip treatment and 7 mm on the no-rip treatment. Surface storage is seen as the amount of cumulative water infiltration plotted at time zero (Fig. 5). Final WIR, which was the rate of water infiltration at the end of a 2-h test, was 16 mm h^{-1} on the rip treatment and 2 mm h^{-1} on the no-rip treatment. These measurements show that enhanced water intake on the rip treatment was a consequence of both increased storage and infiltration capacity and not simply storage alone.

On the second day of the tests, surface and macropore storage was 12 mm on the rip treatment and 1 mm on the no-rip treatment. Increased storage alone accounted for greater CWI (Fig. 5) on the rip treatment. There were no differences in final infiltration rates between treatments (Table 3). 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 in pores, underlying the rip, froze following the first test and plugged water-conducting channels that were previously air filled. Visual inspection of large cracks and fissures near the surface of the rip treatment revealed that tillage-induced soil macropores were drained and ice free. These measurements reveal inherent limitations to ripping. We speculate that during natural snowmelt conditions, refreezing of water in soil pores subsequent to a midwinter thaw might substantially reduce water infiltration. Cumulative water infiltration rates on the first and second days of the tests are shown in Fig. 5.

Our water infiltration measurements were made within steel frames that were installed when the soil was unfrozen. Steel material has a greater thermal conduc-

Table 3. Soil and water infiltration characteristics for infiltration tests on frozen soil.

Day of infiltration test	Treatment	Soil water on first day of test 0–0.05 m	0–0.3 m	0.3–0.6 m	Surface storage	Temperature of water used for test	Infiltration final rate	Cumulative infiltration†
		$\mathrm{m^3\ m^{-3}}$	$\mathrm{m^3\ m^{-3}}$	$\mathrm{m^3\ m^{-3}}$	mm	°C	$\mathrm{mm\ h^{-1}}$	mm
20 Jan. 1993	Rip		0.18a‡	0.16a	49a	0	12a	98a
	No rip	0.30	0.18a	0.12a	11b	0.3	1b	17b
21 Jan. 1993	Rip				9a	0	3a	14a
	No rip				0b	0	1a	2b
16 Feb. 1994	Rip		0.20§	0.16	56a	2.5	9a	99a
	No rip	0.24	0.18	0.18	5b	3.0	1b	14b
17 Feb. 1994	Rip				11a	2.2	2a	15a
	No rip				0b	1.2	1a	1b
31 Jan. 1995	Rip		0.16a	0.14a	49a	3.5	27a	134a
	No rip	0.53	0.13b	0.10a	6b	3.5	5b	24b
1 Feb. 1995	Rip				17a	4.2	14a	33a
	No rip				2b	3.7	4a	5b

† Cumulative values for 2-h test on Day 1 and 1-h test on Day 2.

‡ Means within columns and sampling dates followed by the same letter are not significantly different ($P = 0.05$).

§ Due to equipment malfunction, water measurements were not made on all replications of rip and no-rip treatments.

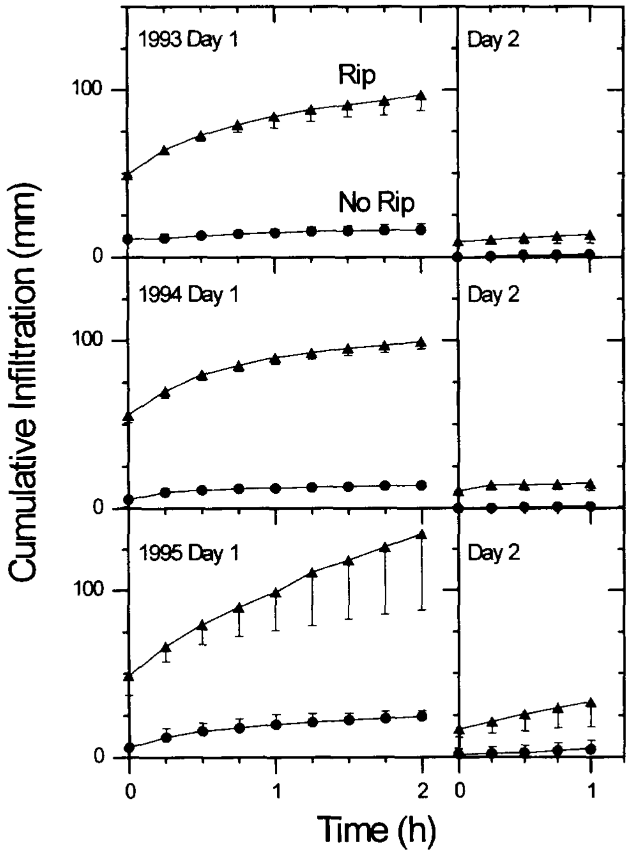

Fig. 5. Water infiltration into frozen soil on the first and second day of infiltration tests in 1993, 1994, and 1995. Error bars are shown as −1 standard deviation on the rip treatment and +1 standard deviation on the no rip treatment.

Table 5. Soil water to a depth of 1.22 m measured in a 3-m transect perpendicular to the rip and at comparable slope positions on no-rip treatments.

Treatment	Soil water
	mm
6 Apr. 1994	
Rip	291a†
No rip	251b
12 Apr. 1995	
Rip	261a
No rip	236b

† Means followed by the same letter within sampling date are not significantly different (P = 0.05).

tivity than soil material and, in this respect, the presence of the frames may have artificially affected the soil thermal regime around the frames. Most likely, soil in immediate contact with the steel would have cooled more rapidly than surrounding field soil, resulting in a deeper depth of frozen soil around the frames. However, we think that accelerated soil heat loss due to the steel frames was minimal because both frames and soil were thermally insulated by ample snow cover (Table 2) in all years.

Water infiltration measurements demonstrated the potential for storing more soil water on ripped plots than on unripped plots. However, we failed to detect differences in soil water storage efficiency, water use by wheat, or wheat yield between treatments (Table 4). Soil water storage was determined using the grid of 54 neutron access tubes shown in Fig. 1. Individual tubes were several meters distant from the rips and water channeled into the rip during spring runoff was not enough to thoroughly wet the soil and be detected at the neutron access tubes.

Gravimetric soil water measurements along 3-m transects centered perpendicularly over the rip showed that spring runoff entered the rip. Soil water content differences between treatments were significant (Table 5). There was >69 mm snow water equivalent (Table 2) at the start of a thaw on 27 Feb. 1994. The snow was melted by 14 March. Visual observations during this rapid thaw confirmed runoff on no-rip plots and water accumulation in rips. Results from soil temperature measurements suggest that water infiltrated to the 0.3-m depth on the rip treatment because soil temperature at 0.3 m was consistently lower on the rip treatment than on the no-rip treatment until shortly after the start of thaw (Fig. 6).

Water infiltration measurements using a rainfall simulator provided evidence that soil macropore structure created by fall ripping in 1992 was still present in June of the following year. During the winter of 1992–1993 the soil froze deeper than 0.9 m and there was 60 mm of precipitation received as snow. Final water infiltration rate on Day 2 of the tests was 34 mm h^{-1} on the rip treatment and 15 mm h^{-1} on the no-rip treatment (Fig. 7). These measurements help to support the results of our winter-infiltration tests where we show enhanced water infiltration on plots that have been ripped.

Infiltration rates into frozen soil are closely linked to

Table 4. 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	0.60a‡		0.46a		0.29a		0.76a	
No rip	0.67a		0.49a		0.37a		0.66a	
Water use, mm								
Rip		331a		301a		338a		
No rip		341a		290a		348a		
Wheat yield, kg ha^{-1}								
Rip		2577a		2157a		2958a		292a
No rip		2463a		2182a		2880a		249a
Precipitation, mm	50	344	60	318	64	243	97	

† Crop hail damaged in 1995.

‡ Means of water storage efficiency, water use, and wheat yield within the same column and followed by the same letter are not significantly different (P = 0.05).

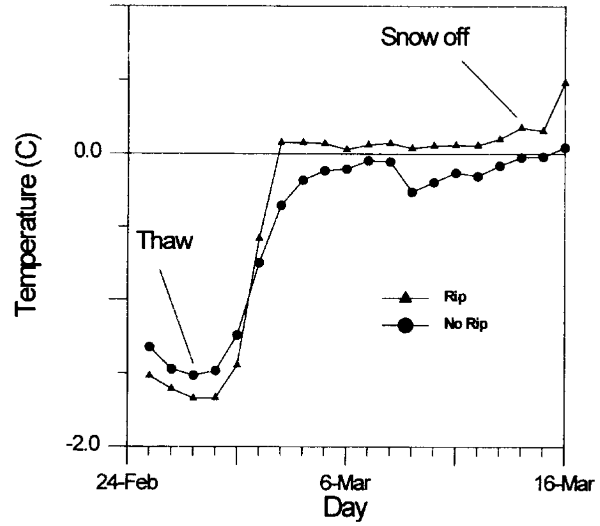

Fig. 6. Soil temperature at 0.3 m during spring thaw in 1994. Temperature sensors at 0.3 m are at the depth of tillage on the rip treatment.

soil water content when the soil freezes. Continuous cropping affords opportunities to efficiently use precipitation and to reduce soil erosion. Aase and Pikul (1995) showed, from the standpoint of yield and water-use efficiency, that annual spring wheat production, using no tillage, was the most efficient crop and soil management practice. In the field experiment reported by Aase and Pikul (1995), soil water content in the top 0.6 m at the onset of soil freezing on plots following spring wheat harvest was 70% of that following fallow (data not published). This soil condition is desirable for enhanced infiltration because annually cropped soils freeze at lower water contents than fallowed soils. We made no direct comparisons of infiltration into frozen soils on fallowed fields and annually cropped fields. Nevertheless we speculate, because of soil water content differences, that infiltration will be greater on annually cropped soils than on fallowed soils.

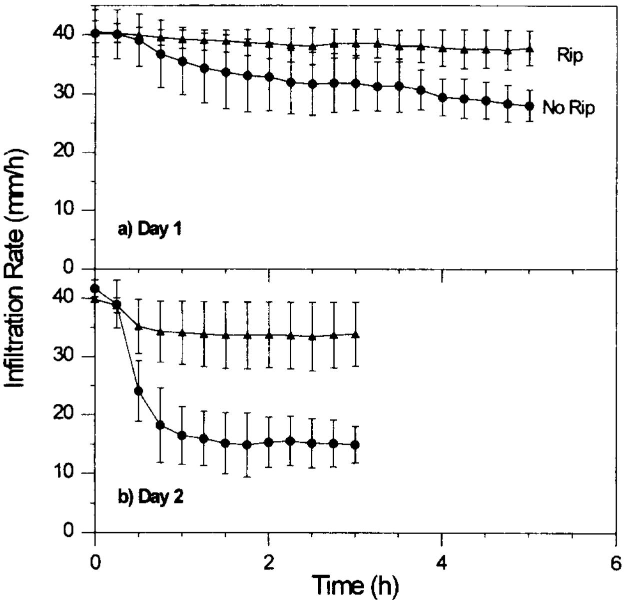

Fig. 7. Water infiltration into thawed soil on the (a) first and (b) second day of infiltration tests in June 1993. Error bars show ±1 standard deviation.

CONCLUSION

Soil ripping combined with annual cropping has potential to improve water infiltration into frozen soil and possibly reduce water runoff during spring thaw. Ripping created a system of surface-connected macropores (large fractures) that served to bypass nearly impermeable ice-rich frozen soil near the surface and increase water infiltration even when the soil was frozen to depths that exceeded the depth of ripping. These same voids also provided detention storage. We think that annual cropping provides a soil environment conducive to water infiltration into frozen soil because soil water is utilized by the crop during the summer and consequently the soil enters the winter months in a relatively dry state. Because we found no wheat yield differences between treatments, contour ripping is perhaps best suited to specific sites within fields plagued by continual runoff and soil erosion problems. Control of runoff is desirable to minimize the potential for off-site flooding. Control of soil erosion associated with rapid runoff will stabilize crop yield and maintain soil productivity.

ACKNOWLEDGMENTS

We thank David Harris, agricultural research technician, for careful maintenance of the plots; Dennis Lokken, biological research technician, for assistance with the water infiltration measurements; and the Washington state office of the Natural Resources Conservation Service for loan of the rainfall simulator.

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