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Rotary subsoiling newly planted winter wheat fields to improve infiltration in frozen soil

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Abstract

Water erosion and runoff can be severe due to poor infiltration through frozen soil in the dryland wheat (*Triticum aestivum* L.) production region of the inland Pacific Northwest (PNW), USA. For more than 70 years, farmers and researchers have used various methods of subsoiling to reduce runoff and erosion and to improve infiltration and soil moisture storage. The practice and equipment have evolved from chiseling continuous open channels across hillslopes to the rotary subsoiler that pits the soil. Farmers often subsoil wheat stubble after harvest, but do not employ this practice on newly planted winter wheat fields. These fields are especially vulnerable to erosion because of meager residue cover after a year of fallow. A 6-year field study was conducted in eastern Washington to determine the effect of rotary subsoiling in newly planted winter wheat on over-winter water storage, erosion, infiltration, and grain yield. There were two treatments, rotary subsoiling and control. The rotary subsoiler created one 40 cm-deep pit with 4 L capacity every 0.7 m^2. Natural precipitation did not cause rill erosion in either treatment because of mild winters during the study period. Net change in water stored over winter was significantly ($P < 0.05$) improved with rotary subsoiling compared to the control in 2 of 6 years. Grain yield was not affected by treatments in any year or when averaged over years. In 2003, we simulated rainfall for approximately 3 h at a rate of 18 mm/h on both subsoiled and control plots to determine runoff and erosion responses on frozen soils. Rotary subsoiling reduced runoff ($P < 0.01$) by 38%. Rotary subsoiling also significantly reduced erosion ($P < 0.01$) during the 20–45 min period after runoff had begun. The total quantities of eroded soils were 1.3 and 3.4 Mg/ha for the subsoiled and control treatments, respectively, with inter-rill the dominant erosion process. The average infiltration rate for the control treatment (3.3 mm/h) was half of the rate for the subsoiled treatment (6.6 mm/h), at the end of the 3 h simulation. Rotary subsoiling of newly-planted winter wheat can increase soil moisture stored

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over-winter and reduce runoff and soil loss on frozen soils, but the benefit of this practice for increasing grain yield has not been proven.

Keywords: Water infiltration; Runoff; Pacific Northwest; Summer fallow

1. Introduction

The winter wheat–summer fallow system of farming, where only one crop is produced every two years, has historically proven to be the most reliable and generally most profitable method for growing wheat in the 150–350 mm precipitation zone in the inland PNW (Juergens et al., 2004). Tillage during fallow to control weeds, inject fertilizer, and prepare the seedbed is intensive (i.e., eight or more tillage operations), often leaving soil pulverized and prone to wind and water erosion (Papendick, 1996; Zuzel et al., 1982). When winter wheat is planted into fallow in late summer, residue cover is often lacking and, depending on weather conditions and date of planting, winter wheat seedlings contribute as little as 3% cover by the first of November and the onset of water erosion events.

Infiltration rates for unfrozen silt loam soils in the region are relatively high. Zuzel and Pikul (1987) reported a 15 mm/h infiltration rate in Walla Walla silt loam (coarse-silty, mixed, mesic Typic Haploxeroll), a representative soil for much of this region where 95% of storms have precipitation rates less than 4.5 mm/h (Williams et al., 1998). Soil freezes regularly to a depth of 10 cm, and occasionally to 40 cm (Papendick and McCool, 1994). The most severe erosion generally occurs when snowmelt or rain occur on thawed soil overlying a subsurface frozen layer (Zuzel et al., 1982, 1986). Erosion occurs predominately as rills (McCool et al., 1982) with smaller contributions by sheet erosion, and soil suspension movement below frozen soil surfaces and above plow pans. Zuzel and Pikul (1987) and Pikul et al. (1992) demonstrated that infiltration into frozen silt loam soil could approach zero, depending on the depth of freezing and soil moisture status (Willis et al., 1961). Combined, these events and conditions lead regularly to losses of 5–20 Mg/ha year, and occasionally up to 200 Mg/ha year, in the approximately 900,000 ha planted to winter wheat following summer fallow in this region (USDA, 1978; Smiley, 1992; McCool et al., 1993).

Many, if not most, U.S. farmers pursue the goal of limiting runoff and associated erosion from frozen soils, in an effort to maintain the sustainability of their operations or to meet the eligibility requirements for federal farm programs (Papendick, 1996). Unfortunately, even management practices that combine residue retention, contour tillage and planting, and terraces often do not prevent erosion (Saxton et al., 1981). To reduce erosion, farmers have used various methods of chiseling or subsoiling since the 1930s (Spain and McCune, 1956). Subsoiling, also known as ripping in France and chiseling in the USA and Canada, is the creation of deep channels, without inversion, using knife-like shanks that are pulled through the soil to create continuous grooves 30–60 cm deep and spaced 60–150 cm apart. The desired result is the capture of snowmelt or rain and improved infiltration through frozen soil and/or tillage pan to enhance soil conservation, soil moisture storage, and wheat grain yield. For these reasons, many farmers chisel recently harvested wheat stubble (i.e., start of the fallow cycle) to increase over-winter capture of water for winter wheat planted the following year.

A number of subsoiling techniques have been evaluated in recent years that aim to capture rain and snowmelt in newly planted winter wheat fields, when plants are still in the seedling stage of development. Pikul et al. (1992) chiseled continuous grooves in the soil to a depth of 20 cm, adjusting the spacing between shanks to capture runoff from a range of storms and soil conditions. When depth of freezing is greater than depth of chisel or shank, the effectiveness of subsoiling is reduced or lost (Pikul et al., 1992, 1996).

Schillinger and Wilkins (1997) used shanks in a 2-year experiment to create continuous 25–64 cm deep channels spaced 3.7 or 6.0 m apart. One winter was relatively dry, the second relatively wet. Erosion was less from the subsoiled treatment during both years. They also recorded an increase in soil moisture content to a depth of 1.8 m at 0.9-m down slope from the tillage channels. In both years, wheat grain yield was lower in rows most disturbed by the chisel shank, but was greater in adjacent rows. On a whole-plot basis, there were no differences in grain yield between subsoiled and control treatments in either year. Similarly, Pikul and Aase (1999, 2003) used a paratill to break up a tillage pan in a sandy loam soil, and chiseled narrow channels to a depth of 30 cm. Infiltration and soil strength improved for up to 2.5 years after deep chiseling, but root-zone soil moisture and grain yield showed no response to the treatment. Pikul and Aase (2003) found that subsoiling a sandy loam soil with paratill to a depth of 30 cm improved infiltration, but water drained to below the root zone of wheat. Movement of water below the root zone, loss of nutrients, and possible groundwater contamination are concerns in shallow soils (Pikul and Aase, 1999).

Farmers have shown little interest in chiseling continuous channels on the contour in newly planted wheat fields because: (i) too many wheat plants are destroyed, negating any increase in grain yield potential even though more water might be stored in the soil, and (ii) the likelihood of continuous channels concentrating flow. Continuous channels, if not positioned precisely on the elevation contour, will concentrate flows and erosive force at low points (Saxton et al., 1981). Additionally, channels chiseled into dry soil often refill with dry soil (Saxton et al., 1981; Pikul et al., 1996). To avoid this problem, Wilkins et al. (1991) and Wilkins and Zuzel (1994) chiseled winter wheat fields after the soil had frozen, using a shank with attached rotary pitter, to create infiltration channels with pits. The purpose of the pits was to disrupt the continuity of the groove. This implement did not consistently penetrate the frozen soil. Ponded infiltration rates in plots treated with the implement were greater than rates in control plots. Despite the appearance of some wheat disease, grain yield was not depressed (Wilkins and Zuzel, 1994).

The purpose of rotary subsoiling is to create a large number of individual pits that cause minimum damage to wheat seedlings, eliminate concentrated flow, and reduce power requirements associated with pulling shanks through the soil. Our objectives were to determine if rotary subsoiling (i) reduced runoff and erosion, (ii) increased net soil moisture stored over-winter, and (iii) affected winter wheat grain yield.

2. Materials and methods

2.1. Field layout

Six on-farm experiments were conducted near Harrington, Ritzville, Wilbur, and Lind in Lincoln and Adams counties in east-central Washington, from crop years 1997 through 2003 (Fig. 1). The study was not conducted in 2000–2001 because of early snow. Soils at all sites were deep and well-drained silt loams, formed in loess, with slopes ranging from 10 to 40% (Table 1) (Stockman, 1981; Lenfesty, 1967). Winter precipitation generally does not fill the soil profile. Experiment sites were identified by the farmer cooperators as historically prone to water erosion. Individual plot size ranged from 12 to 26 m wide and 46–58 m long, depending on the available slope area. Experimental design during all years was a randomized complete block with six replications of two treatments: rotary subsoiling and control.

A 2-year rotation of winter wheat summer fallow was practiced at all sites during all years of the study. Tillage during fallow generally consisted of chiseling stubble in the fall, primary spring tillage with either a tandem disk or two passes with a field cultivator plus attached harrow, a separate operation to inject aqua NH_3-N with shanks, and two to four rodweedings (a rotating 3 cm square rod) to control weeds and break capillary continuity in the soil to impede the upward movement of liquid water in summer fallow during dry summer months. Winter wheat was planted from early-to-mid September with a John Deere HZ™ deep-furrow drill on 40 cm row spacing until crop year 2000, after which a John Deere™ hoe drill with 25.5 cm row spacing was used. Uniform stands of winter wheat were achieved each year of the study. Plots were rotary subsoiled each fall following wheat emergence and sufficient rainfall, so that the pits would not collapse and fill with dry soil. The Savage™ model 6565 rotary subsoiler (Fig. 2) created one 40 cm-deep by 5 cm-wide pit every 0.7 m^2 (14,285 pits per ha), each pit with 4 L capacity. The rotary subsoiler was pulled along the contour of the slope by a crawler tractor

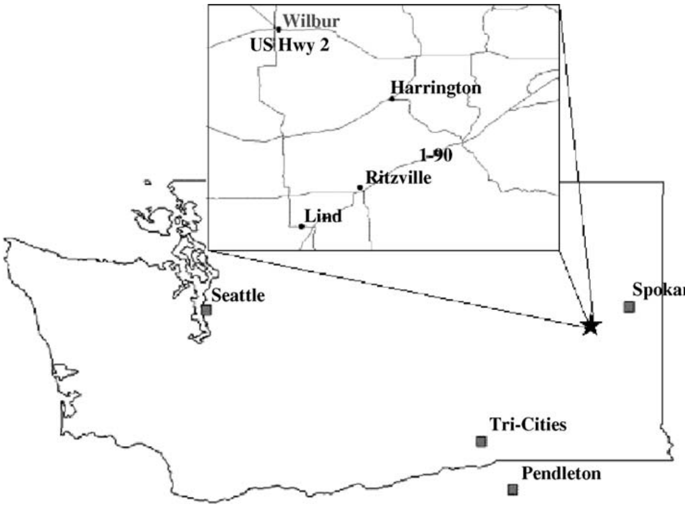

Fig. 1. Rotary subsoil research plots were established near the towns of Wilbur, Harrington, Ritzville, and Lind, Washington during 6 years.

and was lifted out of the soil when crossing control plots.

2.2. Soil moisture, erosion, and grain yield measurement

Soil volumetric water content in the 30–180 cm depth was measured in 15 cm increments by neutron thermalization (Hignett and Evett, 2002). Volumetric soil moisture content in the 0–30 cm depth was determined from two 15 cm core samples using gravimetric procedures (Top and Ferre, 2002). Three access tubes were installed in each plot, i.e., for a total of 36 access tubes, 30 cm down slope from a pit created by the rotary subsoiler. Access tubes were placed in the same general lateral locations in the control treatment. Each spring, multiple-cross-sections of rills found in plots were measured using a drop-pin rill-meter, and the volume of soil lost determined using the relationship developed by McCool et al. (1976). Winter wheat grain yield was measured by harvesting the grain from plants in a

Table 1
Location, soil type, precipitation, frost-free days, and mean annual air temperature during 6 years of rotary subsoiler, field experiment sites in eastern Washington

Crop year	Location	Soil type[a]	Annual precipitation (mm)	Frost-free season (days)	Mean annual temperature (°C)
1997	Wilbur	Bagdad silt loam (coarse-silty, mixed, superactive, mesic Calcic Argixerolls)	318	110–150	9.4
1998	Ritzville	Ritzville silt loam (coarse-silty, mixed, mesic Calcidic Haploxeroll)	284	120–160	9.4
1999	Lind	Shano silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids)	244	140–170	10.0
2000	Harrington	Bagdad silt loam and Endicott silt loam (coarse-silty, mixed, mesic Haplic Durixerolls)	330	110–150	9.4
2001	No study, early snow				
2002	Harrington	Bagdad silt loam and Endicott silt loam	330	110–150	9.4
2003	Harrington	Bagdad silt loam and Endicott silt loam	330	110–150	9.4

[a] Lenfesty (1967) and Stockman (1981).

Fig. 2. Rotary subsoiler in transport position.

swath through each plot with a commercial combine with 9 m-wide cutting platform and auguring grain into a weigh wagon.

2.3. Simulated rainfall and ponded infiltration

The research site was located 11 km southeast of Harrington (47°23′45″N, 118°11′00″W) at an elevation of 671 m and had received approximately half of the expected annual precipitation. We simulated rainfall over two consecutive days in February 2003, at a rate of 18 mm/h, onto plots with 18% slope and an east, southeast aspect. Treatments were control or rotary-subsoiled. The water source for rainfall simulation was precipitation collected from a metal roofed building. Rainfall was simulated using the Pacific Northwest Rainfall Simulator (Williams et al., 1998), onto areas 2 m wide × 10 m long (20 m^2). The temperature of the water used for rainfall and the air temperature inside the simulator covers were recorded to assure consistent ambient conditions across treatments. Simulation continued for 120 min after runoff began. There were four replications in the simulated rainfall measurements of plot runoff and erosion. Four simulator modules rained on four plots simultaneously, two on control plots and two on subsoiled plots. Simulators used on the control treatment during the first set of four plots were used to rain onto subsoiled treatment during the second set. Time to ponding, time to runoff, and runoff in 5 min intervals for 120 min were recorded. Time to fill 1 L bottles with runoff was recorded and the bottles were weighed, dried at 105 °C for 24 h, then reweighed to determine runoff rate and eroded soil mass. Infiltration was calculated as precipitation minus runoff. Residue cover was measured using a modified point frame method (Floyd and Anderson, 1982).

Average pit capacity and infiltration rate were determined on day two of rainfall simulations. Thirteen rotary subsoiler pits were randomly chosen and ponded infiltration was measured as follows: a pit was quickly filled with water to near overflow, and the volume of water used and initial time recorded; when the water level dropped 2–3 cm, the pit was refilled, and the water volume and time recorded again; the refill procedure was conducted twice, for a total of three measurements. Ponded infiltration rate was calculated from all three. The time between the refills averaged 3 min. The results from the thirteen pits were averaged to obtain an estimate of pit volume and infiltration rates at 3, 6, and 9 min after onset of ponding.

2.4. Data analysis

Analysis of variance was conducted for (i) gain in soil moisture in the 180 cm soil profile from the time

Table 2
Over-winter net gain in soil water storage and grain yields during six crop years of a winter wheat–summer fallow rotation as affected by rotary subsoiling newly planted winter wheat

Crop year	Location	Soil water storage			Grain yield		
		Rotary subsoiled (mm)	Control (mm)	Significant[a]	Rotary subsoiled (kg/ha)	Control (kg/ha)	Significant[a]
1997	Wilbur	195	192	ns	4992	4963	ns
1998[b]	Ritzville	18	15	ns	3725	3931	ns
1999	Lind	40	26	**	1469	1652	ns
2000	Harrington	120	96	*	6623	6524	ns
2002	Harrington	88	75	ns	3842	3798	ns
2003	Harrington	126	141	ns	2952	3119	ns
6-year average	All locations	98	91	ns	3934	3998	ns

[a] ns: no significant differences at $P < 0.05$.
[b] Plots were established in December after considerable precipitation had already occurred; thus the low values for net gain in soil water in 1998.
* Significant differences at the 0.05 level.
** Significant differences at the 0.01 level.

experiments were established in November or December until mid March, and (ii) winter wheat grain yield. Treatments were considered significantly different if $P < 0.05$. Data analysis for runoff and infiltration from simulated rainfall was performed using the Mixed Models statement in SAS (1998). Least squares means separation tests were conducted on the response variable if the type three mixed effects were significant ($P < 0.05$).

3. Results and discussion

3.1. Natural erosion, soil moisture storage, and wheat grain yield

Winters were generally mild throughout the study period and no measurable rill erosion occurred in any year in either rotary subsoiled or control plots. However, sediment was observed to have partially filled some of the pits at Wilbur in 1997 and at Ritzville in 1998.

Net gain in water stored over-winter was significantly greater in rotary subsoiled plots compared to the control at Lind in 1999, and at Harrington in 2000 (Table 2). More soil moisture in the subsoiled plots suggests that more water was lost to runoff from the control treatment, probably when the soil surface was frozen although no rill erosion was observed. Averaged over the 6-year study period, net over-winter soil-water gain with rotary subsoiling was not different than for the control (Table 2). Winter wheat grain yield varied widely among sites and years, but there were no differences in grain yield between treatments in any year or when analyzed over years (Table 2).

3.2. Simulated rainfall

Ground cover in rainfall simulation plots was approximately 80% in both treatments and consisted of old wheat stubble and young wheat seedlings (Table 3). Frozen soil was present at the beginning of both days of simulation, to a depth of 5 cm, and had gravimetric soil moisture content of ≈30%. Each plot received simulated rainfall for 3 h, for a total rainfall of 54 mm. Total simulated rainfall was approximately twice the long-term average accumulated precipitation for the month of February for the site (WRCC, 2004), and represents a 24 h storm expected once every 75

Table 3
Percent ground cover provided by wheat stubble and winter wheat seedlings in control and rotary-subsoiled treatments at the time of rainfall simulation at Harrington in 2003

	Control	Subsoiled	$LSD_{0.05}$
Wheat stubble	48.5 (5.2)[a]	53.1 (4.9)	17.4
Wheat seedlings	36.4 (7.9)	26.9 (5.8)	24.0
Total cover	84.9 (3.1)	80.0 (3.6)	11.6
Bare soil	15.1 (3.1)	20.0 (3.6)	11.6

[a] Values in parentheses are standard error.

years. Average temperature of simulated rainfall was 0.6 °C. Air temperature inside the rainfall simulator covers ranged from −5 °C in the morning to 15 °C at the end of simulation in the afternoon, when small pockets of frozen soil could still be found.

3.3. Runoff and infiltration

Time to ponding in both treatments occurred within 10 min and average time to runoff was 50 min after onset of rainfall simulation. There were no significant differences between treatments for either time to ponding or time to runoff. The rotary-subsoiled treatment produced runoff at significantly ($P < 0.05$) lower rates than control treatment, after 75 min of simulation (Fig. 3A, Table 4). The total runoff was 38% lower in the rotary-subsoiled treatment than the control treatment (Fig. 3B, Table 5). At the end of simulation, infiltration rate approached steady state of 3.3 mm/h in the control treatment, just half of the 6.6 mm/h in the subsoiled treatment.

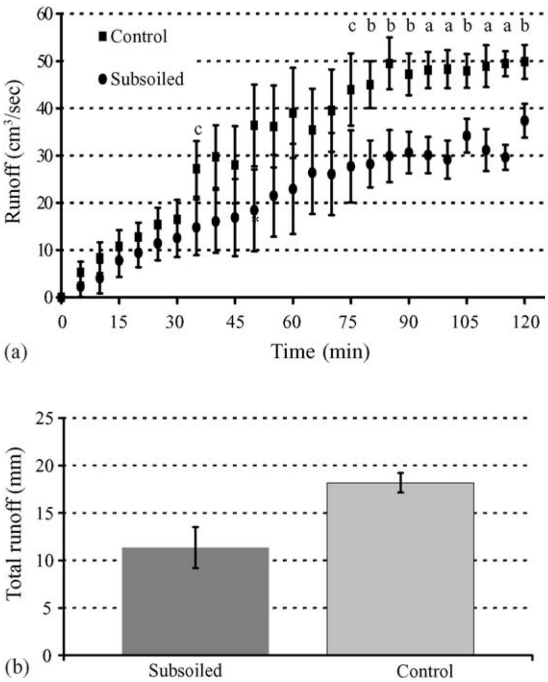

Fig. 3. Runoff averages and standard errors ($n = 4$) from the first 2 h of simulated rainfall on rotary-subsoiled and control treatments at Harrington. (A) Runoff rates in cubic centimeters per second from plots at 5 min intervals following initiation of flow. Letters above incremental data points indicate significance of difference between treatments: a, $\alpha \leq 0.01$; b, $\alpha \leq 0.05$; c, $\alpha \leq 0.10$. (B) Total runoff from 51 ± 1 mm of simulated rainfall.

Table 4
Least significant difference between treatment means needed to obtain 0.01, 0.05, and 0.10 levels of significance for runoff recorded at 5-min intervals after runoff began

Time (min)	Runoff (cm^3/s)			
	$LSD_{0.10}$	$LSD_{0.05}$	$LSD_{0.01}$	Mean difference[a]
5	4.3	5.5	8.3	3.2
10	6.3	8.0	12.1	5.2
15	7.1	8.9	13.5	4.8
20	7.6	9.5	14.4	4.0
25	8.6	10.8	16.3	4.9
30	10.0	12.6	19.1	4.0
35	12.9*	16.3	24.6	13.4
40	15.0	18.9	28.6	14.3
45	17.7	22.2	33.7	11.4
50	18.8	23.6	35.8	18.2
55	18.0	22.6	34.3	14.8
60	19.6	24.6	37.3	16.5
65	18.2	22.9	34.7	9.9
70	17.8	22.4	33.9	12.7
75	15.3*	19.3	29.3	15.7
80	10.3	13.0*	19.7	17.4
85	11.5	14.4*	21.9	19.0
90	9.4	11.9*	18.0	16.7
95	8.8	11.1	16.8*	30.5
100	8.2	10.3	15.6*	19.4
105	10.9	13.7*	20.8	14.6
110	8.8	11.1	16.8*	17.5
115	6.2	7.8	11.8*	20.0
120	9.0	11.4*	17.2	14.0

[a] Mean $runoff_{(control)}$ − mean $runoff_{(subsoiled)}$, $n = 4$.
* Level of significance.

The average capacity of the pits was 3.8 ± 0.4 L, equivalent to a rainfall of 5.4 mm ± 0.6 (mean ± S.E.) falling onto the contributing area of the pit and running into it. In addition to detaining runoff, the pits create infiltration galleries. The average ponded infiltration rate for subsoiled pits was 18.4 ± 2.8 mm/h (mean ± S.E.) after 3 min, 14.9 ± 2.6 mm/h

Table 5
Least significant difference between treatment means needed to obtain 0.01, 0.05, and 0.10 levels of significance for total runoff at 120 min after runoff began

Time (min)	Total runoff (mm)			
	$LSD_{0.10}$	$LSD_{0.05}$	$LSD_{0.01}$	Mean difference[a]
120	4.4	5.6*	8.4	7.0

[a] Mean $runoff_{(control)}$ − mean $runoff_{(subsoiled)}$, $n = 4$.
* Level of significance.

between 3 and 6 min, and 7.0 ± 1.5 mm/h between 6 and 9 min. The decline in infiltration rate over time represents an approach to steady state saturated infiltration. From the time the pits were established in November until we simulated rainfall and measured pit infiltration rates, the plots had received 170 mm of precipitation (NOAA, 2003). Thus, the pits were exposed to substantial slaking and sedimentation; processes that reduce infiltration effectiveness of channels created by chiseling (Wilkins et al., 1996; Schillinger and Wilkins, 1997).

Water infiltration into frozen soil depends on soil texture and structure, tillage practices, quantity of residue on or mixed into soil, soil moisture content at the time of freezing, and the depth of freezing. Infiltration rate increases with increased rainfall intensity or under ponded conditions (Lusby and Lichty, 1983). In soils chiseled after freezing, Pikul et al. (1996) recorded a ponded infiltration rate of about 21 mm/h in soil frozen to a depth of 11 cm. This rate is nearly three times greater than measured (7.0 mm/h) in soil frozen to a depth of 5 cm in our simulated rainfall study, after the soil had thawed in a random sample of pits. This finding suggests that continuous channels are more effective for reducing runoff than independent pits. However, when the depth of frozen soil extended down to 35 cm, infiltration rate for a continuous-channel treatment decreased to 1 mm/h on 1 m^2 plots (Pikul et al., 1996).

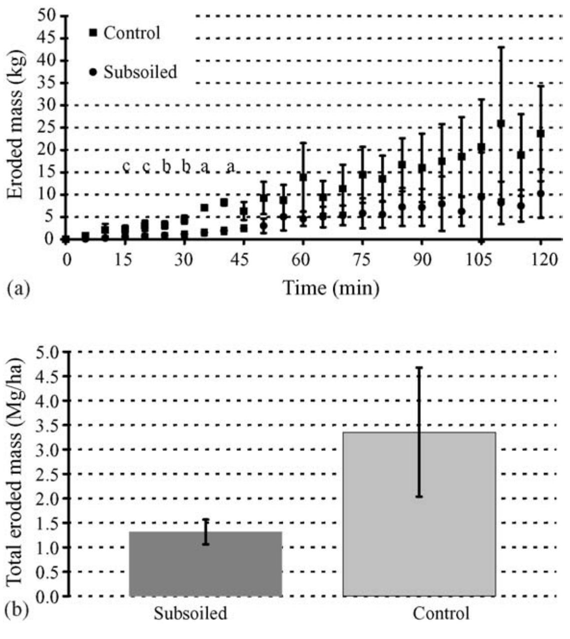

Fig. 4. Eroded material averages and standard errors ($n = 4$) from simulated rainfall plots. (A) Mass of eroded soil (kg) mass from plots at 5 min intervals following initiation of flow. Letters above incremental data points indicate significance of difference between treatments: a, $\alpha \le 0.01$; b, $\alpha \le 0.05$; c, $\alpha \le 0.10$. (B) Total eroded material (Mg/ha) from 51 ± 1 mm of simulated rainfall.

3.4. Subsoiling and erosion

Throughout the simulation event eroded soil mass was greater for the control plots than subsoiled plots. The eroded mass was significantly ($P < 0.05$) greater for the control treatment than for the subsoiled treatment from 15 to 40 min after runoff had begun (Fig. 4A, Table 6). The greater variability in the control versus subsoiled treatments resulted from an exceptionally high erosion rate from one control plot.

Table 6
Least significant difference between treatment means needed to obtain 0.01, 0.05, and 0.10 levels of significance for eroded mass recorded at 5-min intervals after runoff began

Time (min)	Eroded mass (kg)			
	$LSD_{0.10}$	$LSD_{0.05}$	$LSD_{0.01}$	Mean difference[a]
5	0.0120	0.0151	0.0228	0.0077
10	0.0328	0.0413	0.0626	0.0220
15	0.0190*	0.0239	0.0363	0.0201
20	0.0273*	0.0344	0.0522	0.0284
25	0.0193	0.0243*	0.0368	0.0193
30	0.0220	0.0277*	0.0420	0.0399
35	0.0083	0.0104	0.0157*	0.0673
40	0.0180	0.0226	0.0343*	0.0776
45	0.0480	0.0604	0.0915	0.0469
50	0.0873	0.1100	0.1666	0.0757
55	0.0872	0.1099	0.1664	0.0454
60	0.1813	0.2283	0.3459	0.1432
65	0.0904	0.1138	0.1724	0.0532
70	0.1290	0.1624	0.2461	0.0728
75	0.1522	0.1917	0.2905	0.1047
80	0.1259	0.1585	0.2402	0.0973
85	0.1474	0.1856	0.2812	0.1150
90	0.1865	0.2349	0.3559	0.1075
95	0.2056	0.2589	0.3923	0.1162
100	0.2125	0.2676	0.4054	0.1488
105	0.2727	0.3434	0.5203	0.1366
110	0.4055	0.5106	0.7736	0.2162
115	0.2195	0.2764	0.4188	0.1383
120	0.2581	0.3250	0.4925	0.1631

[a] Mean $erosion_{(control)}$ − mean $erosion_{(subsoiled)}$, $n = 4$.
* Level of significance.

Table 7
Least significant difference between treatment means needed to obtain 0.01, 0.05, and 0.10 levels of significance for total eroded mass at 120 min after runoff began

Time (min)	Total eroded mass (Mg/ha)			
	$LSD_{0.10}$	$LSD_{0.05}$	$LSD_{0.01}$	Mean difference[a]
120	3.5831	4.512	6.8363	2.8010

[a] Mean eroded mass$_{(control)}$ − mean eroded mass$_{(subsoiled)}$, $n = 4$.

Despite the shallow depth of freezing, patches of frozen soil remained at the end of the simulations in both treatments. There were no obvious observed or measured differences in the plots used for both treatments other than the pits created by rotary subsoiling. We speculate that the pits detained enough sediment and created sufficiently more soil surface area so that the capacity to carry soil in the runoff was uniformly reduced.

Total eroded soil mass was 3.4 Mg/ha from the control treatment compared to 1.3 Mg/ha from the rotary-subsoiled (Fig. 4B, Table 7). Working with continuous channels created by chiseling, Schillinger and Wilkins (1997) reported annual erosion of 2.8 Mg/ha from the control treatment compared to no soil loss from the chiseled treatment, during a relatively dry winter. However, during a wet winter with four major precipitation events, soil loss was 15.7 and 2.6 Mg/ha in the control and subsoiled treatments, respectively.

Soil erosion resulted from inter-rill processes, predominately sheet wash, although micro-rills were beginning to form by the end of the simulations. Micro-rills formed where water had ponded in furrows or pits, and the water began escaping through cracks in the soil surface that had formed because of drying and freezing. Raindrop splash alone caused little erosion because of the small drop size ($D_{90} \leq 2.5$ mm) produced by the rainfall simulator (Bubenzer et al., 1985).

In our study, where rainfall was simulated at a rate equivalent to the total precipitation expected to fall in a 24 h period once every 75 years (54 mm), the rotary-subsoiled treatment had 40% less soil loss than the control treatment. This reduction in soil loss from rotary subsoiling is greater than the 13% reduction reported by Schillinger and Wilkins (1997) in the third rainstorm of 47 mm precipitation, which was preceded by two storms with an accumulated total precipitation of 159 mm. A direct comparison of results in the two studies is difficult, because of plot size, rainfall intensity, and erosion processes (i.e., inter-rill versus rill).

4. Conclusion

The Columbia Plateau generally experiences several frozen soil events each year. When combined with rapid snowmelt or rainfall, severe erosion on frozen or partially frozen soils may occur. During our 6-year study, the winters were relatively mild and no measurable erosion occurred at the experiment sites because of rainfall or combinations of frozen soil, snowmelt, and rainfall. Rotary subsoiling increased net over-winter soil moisture storage in 2 of 6 years. No measurable rill erosion occurred in either treatment in any year. Winter wheat grain yield did not differ between the rotary subsoiling and control treatments in any year or when analyzed over the 6 years. Rotary subsoiling reduced runoff and soil loss during rainfall simulation onto frozen soil. Reduction in the eroded soil mass for the subsoiled treatment was statistically significant during the 20–45 min period after runoff had begun. Rotary subsoiling reduced runoff by 38% and improved infiltration compared to the control. The infiltration rate for the subsoiled treatment (6.6 mm/h) was twice that for the control (3.3 mm/h). Total quantity of eroded soils were 1.3 and 3.4 Mg/ha for the rotary-subsoiled and control treatments, respectively. Rotary subsoiling will benefit over-winter soil-water storage in some years and has potential to reduce runoff and soil loss during intense and short-duration rainstorms on residue-deficient farmland when soil is frozen or partially frozen. Although the practice has no immediate, apparent affect on crop yield, rotary subsoiling is a low cost practice that ultimately benefits field productivity through soil and water conservation.

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