UPLAND DRAINAGE RESPONSE TO NO-TILLAGE WINTER WHEAT PRODUCTION

John D. Williams, Research Hydrologist, johnd.williams@ars.usda.gov; David S. Robertson, Hydrologic Technician/Professional Geologist; Stewart B. Wuest, Soil Scientist; USDA-ARS Columbia Plateau Conservation Research Center, PO Box 370, Pendleton OR 97801

Abstract: Conventional tillage practices, combined with a two year winter wheat-fallow rotation, have long been identified as substantial sources of sediment in the interior Pacific Northwest (PNW). No-tillage crop production has been shown to be an effective means of reducing run-off and erosion in a wide variety of environments and cropping systems, but not at commercial scales in the PNW. Our objective was to compare runoff and soil erosion from a conventional tillage, wheat-fallow two-year rotation and a no-tillage four-year rotation within a small watershed to provide results that would be representative of conservation effectiveness at the field scale. Two neighboring drainages, 5.8 ha and 10.7 ha, in the 340 mm y^{-1} precipitation zone of northeastern Oregon, were instrumented to record rainfall, runoff, and erosion over a four-year period (2001 through 2004). In addition to drainage scale monitoring, small 1 m^{-1} runoff collectors were installed within the drainages to capture hillslope soil and water movement during 2003 and 2004. One drainage was cropped to a winter wheat–fallow rotation using conventional inversion tillage (tillage fallow). The second drainage was cropped in a four-year no-tillage rotation: winter wheat–chemical fallow–winter wheat–chickpea. We recorded 13 runoff events from the inversion tillage system and 3 from the no-till system. Annual runoff and erosion from the inversion tillage drainage were 1.3 mm and 0.07 Mg ha^{-1} versus 0.1 mm and <0.01 Mg ha^{-1} from no-tillage drainage. There was substantially more runoff and soil movement at the small plot scale, 79 mm y^{-1} and 11.01 Mg $ha^{-1}y^{-1}$ from the conventional tillage treatment and 23 mm y^{-1} and 0.21 Mg $ha^{-1}y^{-1}$ from the no-tillage treatment. Soil erosion observed in this research is a fraction of that reported for similar tillage practices outside of the PNW. The no-tillage cropping system was more effective in reducing runoff and soil erosion and provides producers with an ability to protect soil and water resources in the dryland PNW.

INTRODUCTION

More than 900,000 ha are planted to winter wheat following fallow each year in the interior Pacific Northwest (PNW), USA (Smiley 1992). Soil erosion in this system has been recognized since 1909 (McGregor 1982). Susceptibility to soil loss is so great that unprotected soil moves downslope in the absence of rainfall when the top 3 to 4 cm of soil thaws and becomes a viscous, flowing slurry (Zuzel and Pikul 1987). Under these conditions, average soil loss rates range from 3 to 50 Mg of soil $ha^{-1}y^{-1}$ (Zuzel et al. 1982; Nagle and Ritchie 2004) and exceed the established USDA soil loss tolerance limits of 2.2 to 11.2 Mg $ha^{-1}y^{-1}$ for sustained economic productivity in most areas of the region (Renard et al. 1997).

Efforts to reduce soil erosion on steep slopes and otherwise susceptible soils rely mainly on conservation practices that leave crop residues on the surface and promote infiltration of rain falling predominantly during winter months when crop cover is minimal (McCool et al. 1995). No-till is a conservation tillage practice that leaves the soil undisturbed from harvest to

planting, promotes soil macroaggregates formation (Cambardella and Elliott 1993), leaves considerable residue on the soil surface. These soil surface conditions promote infiltration of rainfall and snowmelt. Water runoff and concomitant soil erosion can be reduced by 40% to 80% in the presence of 1 to 2 Mg ha^{-1} of crop residue compared to bare soil (McCool et al. 1995). In northeastern Oregon, Zuzel and Pikul (1993) similarly reported that percent straw cover and soil loss were inversely correlated (r = 0.99). No-till research in the dryland region of the PNW has been limited to small plot experiments, and the runoff occurred only in conjunction with frozen soil (Khalid and Chen 2003).

The objectives of this study were to compare runoff and soil erosion from conventional winter wheat-fallow with intensive tillage versus a 4-year cropping system with no tillage. The results presented here emphasize water movement and soil erosion in two drainages typical of the steep rolling terrain found within the inland PNW.

METHODOLOGY

Site description: In October 2000, two small neighboring ephemeral drainages were instrumented within the Wildhorse Creek watershed (45°49'0.43"N, 118°38'35.46"W) near Pendleton, Oregon (figure 1). The drainages consisted of one first-order and one zero-order (table 1) (Fritz et al. 2006). The soils were well drained Walla Walla silt loams (coarse-silty, mixed, superactive, mesic Typic Haploxerolls—US; Kastanozems—FAO). Soil development occurred within a mantle of loess derived from Pleistocene aeolian deposits onto basalt flows of the Miocene Epoch (Johnson and Makinson 1988). Meteorological records dating from 1931 at the USDA Columbia Plateau Conservation Research Center and Oregon State University Columbia Basin Agricultural Research Center (CPCRC/CBARC) 11 km south of the research site show minimum and maximum air temperatures of −34°C and 46°C, with a 71 year average mean annual temperature of 11°C. Approximately 70% of precipitation occurs between November and April from maritime fronts that produce low intensity storms averaging 0.5 mm h^{-1}, equivalent to accumulations of 1.5 mm over 3 h (Brown et al. 1983). Long-term annual precipitation averages 422 mm. Snow cover is transient, with accumulated snow subject to rapid melting by frequent warm fronts. Soil erosion in the PNW occurs predominately from January through March (Zuzel et al. 1982, 1986).

Table 1 Description of drainages used.

Drainage	Area (ha)	R_r*	Elevation at flume (m)	Maximum slope (%)	Aspect
No-till	10.7	0.05	535	30	Southeast
Inversion tillage	5.8	0.08	540	20	East

* R_r = Relief ratio defined as R/L, where R is the elevation difference between outlet at the flume and headwater divide, and L is the maximum length of the basin measured in the same units as R along a line parallel to the main channel.

Cultural Practices and Field Plots: The first-order drainage was evenly divided into four plots to accommodate all phases of a four-year rotation (figure 1). Each phase of the rotation,

winter wheat (*Triticum aestivum* L.)–chemical fallow–winter wheat–chickpea (*Cicer arietinum* L.), was represented each year in the drainage, with each of the plots cycling through the rotation in the four years of study (table 2). Crops were simultaneously seeded and fertilized using a hoe-type, no-till drill. The zero-order drainage was farmed using conventional inversion tillage to produce winter wheat in a two-year, crop–fallow rotation. Primary tillage was with a moldboard plow, secondary tillage consisted of cultivation, injection fertilization, and two to three passes through the field with a rodweeder. The conventionally tilled crop was seeded with a double-disc-opener drill. Fertilizer was applied in May preceding the fall planting of wheat in the inversion tillage drainage. A meteorological station located on the divide between the two drainages recorded precipitation, air temperature, soil temperature at 25 mm and 50 mm depths, wind speed and direction, solar radiation, and relative humidity (Oviatt and Wilkins 2002).

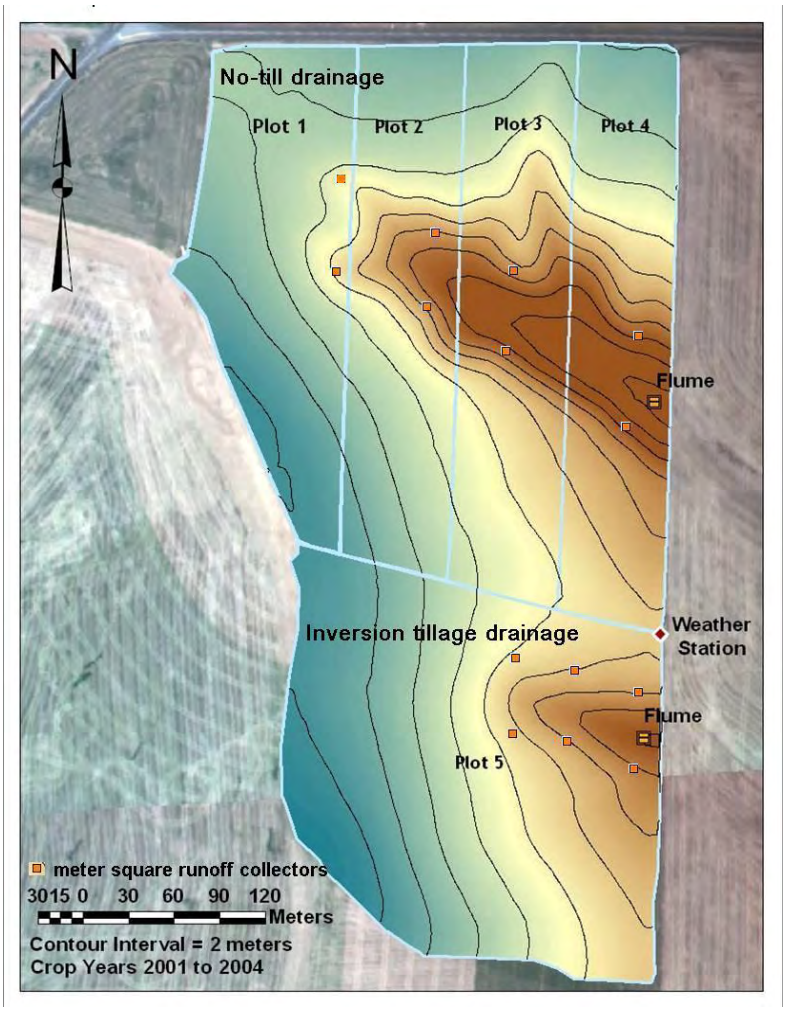

Figure 1: Plot layout and topography of matched drainages in the Wildhorse Creek watershed, northeastern Oregon. Color gradient is demonstrates elevation change at the research site.

Table 2 Rotation assigned to no-till and inversion tillage drainages for crop years 2001 – 2004.

	No-tillage				Inversion-tillage
	1	2	3	4	5
2001	CP†	CF	SW	WW	F
2002	WW	WW	CF	CP	WW
2003	CF	CP	WW	WW	F
2004	WW	WW	CP	CF	WW

†CP–chickpea; CF–chemical fallow; F–fallow (inversion tillage); SW–spring wheat; WW–winter wheat.

Monitoring and sampling procedures. In crop years 2003 and 2004, six metal runoff collectors were placed on backslope positions in each watershed from November through March, the typical erosion season (figure 2). Each runoff collector consisted on a 1 m^2 metal frame. The containers were checked periodically and runoff was collected after multiple events to avoid overflow. Total annual runoff and eroded material were determined by weighing, drying, and reweighing material collected in the containers.

At the mouth of each drainage, runoff was measured with 23 cm Parshall flumes (figure 1). Flow stage was recorded using ultrasonic distance sensors, and flow rate was calculated using a standard rating curve (USDI 2001). Runoff samples were collected using flow activated, commercial storm water samplers using a liquid level switch at a stage of 1 cm or greater. Samples (0.5 L) were collected every 40 minutes, for up to eight hours of continuous runoff. Samples were analyzed for suspended sediment concentrations (SSC) (Glysson and Grays 2002). Bedwash traps (188 L plastic livestock water-trough covered with a slatted top) were installed immediately upstream from the flumes. Event values for eroded material are the total of suspended sediment concentrations plus the weight of the bed wash.

Experimental design and statistical procedures: This study was designed as a field-scale, eight-year, side-by-side, spatially unreplicated comparison of two crop production systems in adjoining headwater drainages. The results reported here are from the first complete four-year rotation. The experimental units are the drainages. All statistical tests were conducted at $P < 0.05$. With acknowledgement of pseudoreplication (Hurlbert 1984), data were analyzed using paired "t" tests (Microsoft Office Excel 2003, Microsoft Corp., Redmond, WA) and PROC GLM in SAS (SAS Inst., Cary, NC). Annual values from 1 m^2 plots for 2003 and 2004 ($n = 2$) and individual event runoff ($n = 11$) and soil erosion ($n = 10$) data were obtained using paired "t" tests to demonstrate treatment differences. Drainage and 1 m^2 plot runoff data were standardized as a ratio of runoff to precipitation (R:P ratios) during November through March, when the 1 m^2 plots were in place, for comparative discussion with no-till responses in dissimilar climates.

RESULTS AND DISCUSSION

Monthly precipitation for January through February in 2001 and December through May in 2002 was drier than normal. Large soil losses in this region typically result from hydrologic processes involving either rain on frozen soil, with or without snow cover, or rain on snow-covered unfrozen soil. These events occur from one to five times each year (Zuzel et al. 1986).

Conditions of continuous deep frozen soil or frequent freeze-thaw cycles did not occur at any time during 2001 through 2004.

Residue cover was significantly ($P \leq 0.05$) greater in the no-till (67% cover) than in the inversion-tillage (5% cover) plots. In 2003, the inversion-tillage drainage was fall burned and moldboard plowed, leaving a bare but rough surface that provided abundant detention storage. Inversion tillage with residue burning is a common practice in the PNW region to control weeds, especially downy brome (*Bromus tectorum*). In 2004, the inversion-tillage drainage was cultivated once, fertilized, and rod-weeded twice before fall seeding.

Runoff and soil erosion: The inversion-tillage system produced significantly ($P \leq 0.05$) more runoff, 3.4 times (79 mm vs. 23 mm), and eroded material, 52 times greater (11.01 Mg ha^{-1} vs. 0.21 Mg ha^{-1}) on the hillslopes (1-m^2 plots) than the no-tillage system. At the drainage scale, thirteen runoff and soil erosion events occurred during 2001 to 2004 (table 3). Runoff and soil erosion values at this scale were significantly less in the no-till system compared to the inversion tillage system, where 13 times more runoff (1.3 mm vs. 0.1 mm) and 35 times more eroded material (0.07 Mg ha-1 vs. <0.01 Mg ha-1) were produced than in the no-till system.

Table 3 Runoff and erosion events in no-till and inversion tillage drainages, 2001 through 2004.

Date	Precipitation*				Event Type†	Drainage			
			Intensity			Inversion tillage		No-tillage	
	Total (mm)	Duration (hr:min)	Maximum (mm h^{-1})	Mean (mm h^{-1})		RO‡ (mm)	EM (Mg ha^{-1})	RO (mm)	EM (Mg ha^{-1})
26 Jan 03	15.6	21:43	6.2	2.1	NFS	0.3	0.01	0.0	0.00
29 Jan 03	14.4	13:46	4.3	1.7	NFS	0.4	0.02	0.1	<0.01
30 Jan 03	14.6	21:10	7.8	2.2	NFS	0.5	0.07	0.2	<0.01
31 Jan 03	16.9	16:04	11.8	2.5	NFS	ND§	0.03¶	0.2	<0.01
23 Jan 04	26.6	31:15	3.5	1.3	RS	ND	ND	0.0	0.00
26 Jan 04	2.4	49:54	1.0	0.3	RS	0.3	<0.01	0.0	0.00
28 Jan 04	19.5	39:24	11.4	2.1	RS	0.6	0.04	0.0	0.00
06 Feb 04	10.3	21:15	5.0	1.7	NFS	0.3	0.01	<0.1	0.00
16 Feb 04	11.6	10:13	4.3	1.7	NFS	0.6	0.14	0.0	0.00
17 Feb 04	7.6	15:08	5.5	1.8	NFS	0.3	0.05	0.0	0.00
24 Feb 04	9.2	09:54	17.4	4.1	NFS	0.3	0.05	0.0	0.00
15 Apr 04	24.9	08:29	14.1	4.7	NFS	0.3	ND	0.0	0.00
08 Jun 04	23.7	15:32	15.2	4.9	NFS	1.3	ND	0.0	0.00
Mean	15.27	23:19	8.3	2.3					

* Precipitation intensities are based on tipping bucket, instantaneous values standardized to mm h^{-1}.
† Storm types: NFS = rain on non-frozen soil, RS = rain on snow (discontinuous patches of frozen soil)
‡ RO = runoff, EM = eroded material.
§ ND = not determined, event observed but data were not collected.
¶ Estimated from bedwash sample.

Soil erosion data collected at the drainage scale from four events and runoff data from two events were not collected because of equipment failure. We were able to obtain a partial measure of eroded material for one of these events (31 January 2003) by relying on the

material collected in the partially filled bedwash trap. Although we were able to collect stage data for events on 15 April 2004 and 8 June 2004, we felt it inappropriate to use these values in our analysis because the bedwash trap in the inversion tillage treatment overfilled with eroded material. Photographic records of one of the missed snow melt events (23 January 2004), where sediment-sampling equipment failure occurred in conjunction with frozen soil, show relatively clear water running from under the snow through the flume, suggesting the amount of soil lost during that event was negligible. The events from which we lost data were not unusual; based on records at CBARC/CPCRC, daily rainfall return periods (the expected frequency of a storm of a given size occurring), were one year for the two events occurring in January 2003 and 2004 when runoff and erosion data were lost, and 1.8 years and 1.6 years for events in April and June 2004 when erosion data were lost. Because of these missed events, the annual soil loss values reported for the inversion tillage watershed are lower than actually occurred.

None of the four runoff and soil erosion events recorded in the no-till drainage occurred as the result of rainfall on frozen soil or exceptionally long storms (table 3). The maximum rainfall intensity on January 31, 2003, was higher than the mean intensity for all runoff events, but there were three higher intensity storms that did not generate runoff in the no-till drainage (table 3). Otherwise, there was nothing unusual about the weather associated with these events. There was sufficient ground cover in the plot nearest the flume (no. 4) in the no-till drainage in 2003 and 2004 to limit runoff and soil erosion; residue cover was 64% in the wheat following chickpeas crop (2003), and over 95% in the chemical fallow in 2004 (table 2). While we cannot eliminate the crop rotations in 2003 and 2004 as the causal factors for runoff that occurred in plot number 4, it is just as likely the runoff was the result of activities associated with the installation of the flume and sediment-sampling equipment. In the inversion-till drainage, however, we have photographic evidence of runoff and rill formation well into the upper part of the drainage.

January through February in 2001 and December through May in 2002 were drier than normal, which apparently accounted for the lack of runoff during these years. Soil loss values were well below the expected range of 3 to 50 Mg ha^{-1} yr^{-1} reported by Zuzel et al. (1982). Three events occurred with rainfall on snow covered, patchily frozen soil, but the total accumulated soil loss during these three days amounted to less than the fourth largest event recorded during 2001 through 2004. The four largest erosion events occurred with rain on unfrozen soils at moderate rainfall intensity and accumulation. The largest of these events, on February 16, 2004, resulted from a storm with a mean rainfall intensity of 1.7 mm h^{-1} and accumulation of 11.7 mm, and the smallest event, on February 24, 2004, with an mean intensity of 4.1 mm h^{-1} and accumulation of 9.2 mm

.

<u>Hydrologic response of 1-m^2 collectors vs. entire drainage</u>: Measured in flumes at the mouth of either drainage, the average runoff from the inversion tillage drainage in 2003 through 2004 was 3 mm, or 1% of the erosion-season precipitation (264 mm) for this year. In contrast, hillslope runoff, measured in 1 m^2 collectors, was 79 mm, or 30% of the precipitation. The difference between hillslope and drainage runoff leaves 76 mm that apparently infiltrated into the lower slope and drainage bottom before reaching the flume. Assuming a homogeneous distribution of precipitation across these drainages, this represents a substantial redistribution

of precipitation once it fell to the earth's surface. With less localized runoff, the no-till system apparently maintained a more homogenous distribution of precipitation across the landscape, resulting in more stored water on hillslopes.

At the field scale, the dominant erosion process in this region is the concentration of runoff on bare soil surfaces and formation of rills (Zuzel et al. 1982). We observed an example of this process in the inversion tillage drainage, where we recorded more erosion in the 1 m^2 plots in 2003 than 2004, but suspended sediments at the drainage bottom were greater in 2004 than 2003. This inverse relationship resulted from the abundant detention storage at the drainage scale following moldboard plowing in the fall of 2002, which limited soil erosion to very local redistribution on the back slopes during winter 2003. In 2004, after rod-weeding, planting, and weathering reduced the detention roughness, water concentrated further upslope into on the sides of the drainage, coalescing into a concentrated channel at the drainage bottom. In other words, the rough-plowed condition resulted in large amounts of soil moving downhill, without much rill development, whereas the smooth seeded condition probably resulted in less total soil movement, but much greater flow energy and more efficient long-distance delivery. This applies only to the tilled soil, as we never observed rills in the no-till drainage.

With few studies conducted under similar weather and soil conditions, comparisons to findings from studies conducted in different environments are useful to gain a sense of relative responses of management practices. Our results are corroborated by results from two sites within 10 km of this research site that effectively bracket the size and slope conditions of the research site reported here. Runoff and soil erosion were monitored through the same set of weather events at a 1.5 ha hillslope (23% slope) and a second paired drainage (18 ha and 25 ha). Both sites were managed as no-till systems, and neither runoff nor erosion was observed during crop years 2001 to 2004. Prior to beginning these studies, both sites had a long history (100 years) of winter wheat–summer fallow managed with inversion tillage, which resulted in severe soil erosion that is physically visible in the form of a small gully adjacent to the hillslope site and was photographed at the paired drainage site.

In general, soil erosion recorded at the study site was less than that under different cropping systems and meteorological conditions reported elsewhere in the literature (table 4). Given that the plots and drainages in this study are on substantially steeper slopes, one would expect greater rates of erosion if the region did not have such low rainfall intensities and small raindrop size (Bubenzer et al. 1985). At the small plot scale, we recorded 0.21 Mg $ha^{-1}y^{-1}$ in the no-till and 11.01 Mg $ha^{-1}y^{-1}$ in the inversion tillage systems, which are within the range reported in the other studies. Interestingly, the other study from the PNW (Khalid and Chen 2003) reported a no-till value similar to our results at the 1 m^2 scale. A relatively larger value for the inversion tillage in this study than reported by Khalid and Chen (2003) was likely the result of slope; whereas we installed our 1 m^2 plots on steep drainage backslope positions, Khalid and Chen's plots were at shallower shoulder-slope positions. All of the other studies were conducted under substantially different climatic conditions. Values reported from 1 m^2 plots by Castro et al. (1999) are also within a factor of two of our values, but their larger scale values for no-till are more similar to those reported for larger scale studies from other high rainfall regions. Two exceptions of greater runoff to precipitation ratios in no-till occurred where no-till practices had created smooth surfaces without the detention storage necessary to

capture spring and summer rainfall (McGregor and Greer 1982; Edwards et al. 1993). Despite the differences in climate, soils, topography, and crop, the relative difference in hydrologic response between no-till and inversion tillage that we report is not unusual.

Table 4 Comparison of runoff ratios and soil erosion from this study to other reported hydrologic and erosion research.

Authors	Location (State or Province)	Study duration (years)	Cropping systems	Plot or drainage area	Slope (%)	Runoff ratio*		Soil erosion (Mg $ha^{-1}yr^{-1}$)	
						NT†	IT	NT	IT
Williams et al. (this report)	Oregon	2	Wheat-fallow, wheat and chickpeas	1 m^2	15 - 20	0.09	0.31	0.21	11.01
		4		5.8 - 10.7 ha	15 - 20	<0.01	0.01	<0.01	0.11
Khalid and Chen, 2003	Washington	3	wheat	1 m^2	3 - 5	0.07	0.01	–	–
McGregor and Greer, 1982	Mississippi	3	Corn	0.01 ha	6 - 7	0.26	0.31	0.77	17.54
				0.5 - 1.0 ha		0.32	0.25	0.48	0.86
Angle et al., 1984	Maryland	5	Corn	0.2 - 0.4 ha	6 - 7	0.01	0.03	3.33	26.22
Dickey et al., 1984	Nebraska	2	Wheat	0.03 ha	4	0.11	0.52	0.18	5.74
Edwards et al., 1993	Ohio	6	Corn and soybean	0.5 - 1.0 ha	7 - 10	0.07	0.05	0.47	0.51
Shipitalo and Edwards 1998	Ohio	28	Corn and soybean	0.5 - 1.0 ha	7 - 10	<0.01	0.16	0.01	5.34
Castro et al., 1999	Planalto Médio in Rio Grande do Sul, Brazil	3	Oats and soybean	1 m^2	5 - 9	0.06	0.16	0.2	4
		5		0.01 ha	–	0.5	3.1	0.4	8.5

* Runoff ratio = runoff/precipitation.
† NT = no-till, IT = inversion tillage.

Such comparisons, however, are hampered by differences in study duration, and the degree of replication of experimental treatments. The values reported Shipitalo and Edwards (1998) are based on replicated data collected from treatments that have been in place for over three decades and encompassed a range of meteorological events, whereas other studies took place over fairly short time frames (table 4). Our study was conducted during years with relatively

few of the storms that cause the greatest amount of erosion in this region (Zuzel et al. 1986). Consequently, quantitative inferences that can be drawn from the results are limited. Nagle and Ritchie (2004) conducted a landscape-scale evaluation of soil erosion in the Wildhorse watershed, using 137Cs and other nucleotides resulting from radioactive fallout. They reported rates of 2.48 Mg $ha^{-1}y^{-1}$ from a 5% slope in pasture since 1971, and 5.12 Mg $ha^{-1}y^{-1}$ from a winter wheat/summer fallow field on a 5% slope. These values represent an integration of large and small soil erosion events that have occurred since atmospheric testing of nuclear weapons ended in 1963. The soil erosion rates we report exceed these values even though they result from a relatively mild meteorological period.

CONCLUSION

A field scale, side-by-side comparison of runoff and erosion was undertaken for a conventional inversion tillage system and a no-till system using two small drainages in northeastern Oregon. Significantly less runoff and soil erosion occurred within the no-till drainage. This was not only true at the drainage scale, but also at a localized 1-m^2 scale on mid slopes. This study demonstrates that adoption of no-till production systems in the semiarid wheat producing region of the interior PNW will provide substantial soil and water conservation benefits. In addition, this study brings to light the substantial amount of water and soil that moves down slope in inversion tillage systems even without the development of rills or loss of soil from the drainage. Although the total amount of soil lost from these drainages during the 4-year period of study may seem small compared to published tolerance values, the continual shift of soil toward drainage bottoms represents a persistent and permanent loss of productive capacity at a rate far exceeding soil replacement rates.

REFERENCES

Angle, J.S., G. McClung, M.S. McIntosh, P.M. Thomas, and D.C. Wolf. 1984. Nutrient losses in runoff from conventional and no-till corn watersheds. Journal of Environmental Quality 13(3):431-435.

Brown, B., J.D. Istok, R.W. Katz, and A.H. Murphy. 1983. Statistical analysis of climatological data to characterize erosion potential. 2. Precipitation events in eastern Oregon/Washington. Special Report 687. Agriculture Extension Service-Oregon State University, Corvallis, OR.

Bubenzer, G.D., G.D., M. Molnau, and D.K. McCool. 1985. Low intensity rainfall with a rotating disk simulator. Transactions of American Society of Agricultural Engineers 28(4):1230-1232.

Cambardella, C.A., and E.T. Elliott. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Science Society of America Journal 57(4):1071-1076.

Castro, N.M. dos.R., A.V. Auzet, P. Chevallier, and J.C. Leprun. 1999. Land use change effects on runoff and erosion from plot to catchment scale on the basaltic plateau of Southern Brazil. Hydrological Processes 13(11):1621-1628.

Dickey, E.C., C.R. Fenster, R.H. Mickelson, and J.M. Laflen. 1984. Tillage and erosion in a wheat-fallow rotation. Publication of the Great Plains Agricultural Council Bozeman, MT. Montana State University, Cooperative Extension Service.

Edwards, W.M., G.B. Triplett, D.M. Van Doren, L.B. Owens, C.E. Redmond, and W.A. Dick. 1993. Tillage studies with a corn-soybean rotation: Hydrology and sediment loss. Soil Science Society America Journal 57(4):1051-1055.

Fritz, K.M., B.R. Johnson, and D.M. Walters. 2006. Field Operations Manual for Assessing the Hydrologic Permanence and Ecological Condition of Headwater Streams. EPA/600/R-06/126. U.S. Environmental Protection Agency, Office of Research and Development, Washington DC.

Glysson, G.D., and J.R. Grays. 2002. Total suspended solids data for use in sediment studies. In Proceedings of Turbidity and Other Sediment Surrogates Workshop, April 30 – May 2, 2002, Reno, NV.

Hurlbert, S.H. 1984. Pseudoreplication and the design of ecological field experiments. Ecological Monographs 54(2):187–211.

Johnson, D.R., and A.J. Makinson. 1988. Soil Survey of Umatilla County Area, Oregon. USDA-Soil Conservation Service, U.S. Government Printing Office, Washington, DC.

Khalid, A.M., and S. Chen. 2003. The effect of frozen soil depth on winter infiltration hydrology in the Pataha Creek watershed. American Society of Agricultural Engineers Paper No. 032160. St. Joseph, MI.

McCool, D.K., R.I. Papendick, and J. E. Hammel. 1995. Surface residue management. In Crop Residue Management to Reduce Erosion and Improve Soil Quality, ed. Papendick, R.I., and W.C. Moldenhauer, 10-16. USDA-Agricultural Research Service, Conservation Report Number 40.

McGregor, A.C. 1982. Counting Sheep: From Open Range to Agribusiness on the Columbia Plateau. University of Washington Press, Seattle, WA.

McGregor, K.C., and J.D. Greer. 1982. Erosion control with no-till corn for silage and grain. Journal of Environmental Quality 25(1):154-159.

Nagle, G.N., and J.C. Ritchie. 2004. Wheat field erosion rates and channel bottom sediment sources in an intensively cropped Northeastern Oregon drainage basin. Land Degradation and Development 15(1):15-26.

Oviatt, H.S., and D.E .Wilkins. 2002. USDA-ARS meteorological monitoring in northeastern Oregon. Pp. 15-25, In Columbian Basin Agricultural Research Special Report 1040, ed. Bechtel, A., and H.S. Oviatt, 16-25. Oregon State University, Agricultural Experiment Station, Pendleton, OR.

Renard, K.G., G.R. Foster, G.A. Weesies, D.K. McCool, and D.C. Yoder (coordinators). 1997. Predicting Soil Erosion by Water: A Guide of Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agriculture Handbook No. 703, Washington, DC

Shipitalo, M.J., and W.M. Edwards. 1998. Runoff and erosion control with conservation tillage and reduced-input practices on cropped watersheds. Soil and Tillage Research 46(1-2):1-12.

Smiley, R.W. 1992. Estimate of cultivated acres for agronomic zones in the Pacific Northwest. In Columbia Basin Agricultural Research Special Report 894, ed. Chastain, T., 86-87. Oregon State University, Agricultural Experiment Station, Pendleton, OR.

USDI, Bureau of Reclamation. 2001. Water Measurement Manual. US Government Printing Office stock number 024-003-00180-5, Washington D.C. http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/chap08_10.html (confirmed 29 September 2009)

Zuzel, J.F., R.R. Allmaras, and R. Greenwalt. 1982. Runoff and soil erosion on frozen soils in northeastern Oregon. Journal Soil and Water Conservation 37(6):351-354.

Zuzel, J.F., and J.L. Pikul, Jr. 1987. Infiltration into a seasonably frozen agricultural soil. Journal Soil and Water Conservation. 42(6):447-450.

Zuzel, J.F. and J.L. Pikul, Jr. 1993. Effects of straw mulch on runoff and erosion from small agricultural plots in northeastern Oregon. Soil Science 156(2):111-117.

Zuzel, J.F., J.L. Pikul, Jr., and R.N. Greenwalt. 1986. Point probability distributions of frozen soil. Journal of Climate and Applied Meteorology 25(11):1681-1686.