DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Runoff, Soil Erosion, and Erodibility of Conservation Reserve Program Land under Crop and Hay Production

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ABSTRACT

There are concerns that restored grasslands currently under the Conservation Reserve Program (CRP) will experience increased soil erosion when they are returned to crop production. Our objective was to compare runoff, erosion, and erodibility on CRP land converted to annual hay production (permanent hayed, PH) and crop production under conventional-till (preplant disk tillage, CT) and no-till (NT) management. Erosion study was conducted in central North Dakota on Typic Argiustoll soil 6 yr after the CRP land had been converted to hay production and crop production with a spring wheat (*Triticum aestivum* L.) –winter wheat–dry pea (*Pisum sativum* L.) rotation. Runoff volumes and soil loss (by alum precipitation of sediment) were measured on 1.5 by 5 m bordered plots on 4% slope under a rainfall simulator delivering 1- to 3-h rains at 50 or 75 mm h^{-1}, followed by three rains of 20 min or less at rates from 25 to 125 mm h^{-1}. Erodibility was calculated from ratios and regressions of soil loss rates versus runoff rates measured at relative steady state. Runoff rates from 50 and 75 mm h^{-1} rains for CT, NT, and PH averaged 9, 12, and 21 mm h^{-1}, respectively, and supported soil loss rates of 20, 7, and 8 g m^{-2} h^{-1}. Erodibility of undisturbed CT, NT, and PH was 1.65, 0.29, and 0.28 g m^{-2} mm^{-1}, respectively, showing NT did not differ from PH and that CT management increased erodibility six-fold above PH. Thorough disk tillage increased erodibility three-fold over CT, 15-fold over NT, and nine-fold over PH. Complete, nondisturbing residue removal increased erodibility less than tillage, from 1.2 times for CT to 2.5 times for NT. Chemically weeded NT exhibited the same low erodibility as the grassland PH treatment under the conditions of study—4% land slope, above average precipitation, and a residue-productive crop rotation. However, erodibility of tilled NT was significantly higher than that of tilled PH, showing the higher inherent stability of grassland surface soil with its perennial plant root structures.

The official governmental purpose for establishment of the CRP in the USA was to remove from production croplands assessed as being highly erodible and reestablish perennial vegetation on them. There is concern that returning CRP lands to crop production may cause accelerated wind and water erosion and soil quality deterioration unless conservation practices are utilized. Studies by Low (1972) have shown that intensive cultivation decreased soil aggregate stability and increased its susceptibility to wind and water erosion in as little as 2 or 3 yr. No-till management reduces disturbance of soil and destruction of plant residue coverage by substituting weed control by xenobiotic chemicals for tillage. Thus, there is interest in determining the extent that NT management compared with forms of CT can maintain the higher erosion-protection potential of re-established CRP grasslands after such land is returned to crop production.

Much effort has been devoted to study effects of such post-CRP land management options as grazing, haying, and crop production on runoff, erosion, and soil properties (Davie and Lant, 1994; Gilley et al., 1996, 1997a, 1997b). Conservation Reserve Program lands themselves had reduced soil losses (Davie and Lant, 1994). Grazing, haying, and burning on CRP-enrolled lands significantly increased runoff and erosion (Gilley et al., 1996). Among tillage practices, use of a moldboard plow on CRP land generated substantial runoff and sediment yields while runoff and sediment production on NT land was similar to that on undisturbed CRP (Gilley et al., 1997a, 1997b).

Gilley and Doran (1998) found that soil losses under rainfall simulation measured soon after several diskings at three CRP sites, were not significantly different from undisturbed losses. When such tilled CRP soils were left fallow with chemical weed control for 1 and 2 yr, and then retilled and erosion-tested, soil losses were significantly higher than on undisturbed land, indicating that much of the soil quality improvement derived from CRP enrollment had been attenuated.

An important soil conservation question for conversion of CRP lands to crop production is the efficacy of no-tillage management compared with various forms of conventional tillage. A number of studies have been conducted over the past 15 or more years comparing effects of CT and NT on runoff and soil water erosion. We have summarized results of soil erosion studies comparing CT and NT in Table 1. Eleven cases from eight references are given with information covering four soil

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Abbreviations: ANOVA, analysis of variance; AsIs, the undisturbed (control) surface condition; CRP, Conservation Reserve Program; CT, conventional till; MWD, mean weight diameter; NT, no-till; PC-TC, permanent cover–tilled conversion treatment; PH, permanent hayed treatment; RsRm, the residue removal surface condition; RUSLE, Revised Universal Soil Loss Equation model.

Table 1. Summary of literature providing information about comparisons of runoff and soil loss under conventional tillage (CT) and no-tillage (NT).

Authors	Soil type and U.S. state	Data source	CT management	NT management	Results: Runoff	Results: Soil loss
Langdale et al. (1979)	Typic Hapludults, Georgia	Small watershed	Disk harrow plus rotary till; soybean [(*Glycine max* (L.) Merr.],	Double cropped barley (*Hordeum vulgare* L.) and sorghum [*Sorghum bicolor* (L.) Moench], grassed waterway	47% annual reduction with no-till	99% annual reduction with no-till
Dickey et al. (1984)	Aquic Argiurdolls, Udic Haplustolls (two sites), Nebraska	Simulated rainfall, runoff plots	Moldboard plow, continuous maize (*Zea Mays* L.)	Continuous maize	8 to 39% rate reduction with no-till	66 to 96% rate reduction with no-till
			Chisel plow; disking; till, plant; continuous maize		0 to 26% rate reduction with no-till	44 to 90% rate reduction with no-till
Blevin et al. (1990)	Typic Paleudalfs, Kentucky	Runoff plots	Moldboard plus disk; maize	Maize	58% annual reduction with no-till	97% annual reduction with no-till
Blough et al. (1990)	Typic Hapludalfs, Pennslylvania	Simulated rainfall, reconstructed soil in bins, laboratory	A bare and smooth soil surface	Smooth soil surface with 30% residue cover and smooth soil surface with a tillage slit and 30% residue cover	25% reduction from 30% residue cover, as compared with the bare and smooth soil surface	50% reduction from 30% residue cover, as compared with the bare and smooth soil surface
West et al. (1991)	Typic Kanhapludults, Georgia	Simulated rainfall, small runoff plots	Disk plus sweep plow; soybean and grain sorghum	No-till grain sorghum	>90% reduction with no-till	>80% reduction with no-till
			CT and residue removal; soybean and grain sorghum	No-till and residue removal; grain sorghum	>42% increase with residue removal	>37% increase with residue removal
			CT fresh tilled without residue (soybean and grain sorghum)		>33% increase with fresh tillage without residue cover	>95% increase with fresh tillage without residue cover
Chichester and Richardson (1992)	Udic Pellusterts, Texas	Small watersheds	Chisel plus disk harrow; wheat (*Triticum aestivium* L.), corn, sorghum rotation	Wheat, corn, sorghum rotation	Little differences between CT and NT	90% reduction with no-till
Seta et al. (1993)	Typic Paleudalfs, Kentucky	Simulated rainfall, runoff plots	Moldboard plus two diskings; simulated row crop seeding	No disturbance	69% reduction in rate with no-till	98% reduction in amount with no-till
Meyer et al. (1999) reduction with	Glossic Fragiudalfs, Mississippi	Runoff plots and small watersheds	Chisel, disk, and ridge-till; soybean	Soybean maize, sorghum and cotton (*Gossypium hirsutum* L.)	10 to 25% no-till	70 to 80% reduction with no-till

orders in six U.S. states. None of the studies involve CRP lands, and all but one used small watersheds or runoff plots. Results for CT vs. NT comparisons of runoff were that CT increased runoff in two cases, runoff was about the same for CT and NT in one case, and the median result was that NT caused approximately 25% decrease in runoff (Table 1). Soil losses under NT were decreased an average of approximately 80% compred with CT.

Gilley et al. (1997b) have shown that the superior erosion-resistance potential of NT for CRP lands converted to crop production compared with CT practices was correlated with retention of soil structural integrity and maintenance of soil organic matter level under NT. Thus, examination of principal soil quality indicators may serve to indicate relative resistance or vulnerability of land to erosion. Effects of CRP enrollment on soil quality appear to include maintenance or increase of organic matter and improved soil-aggregate stability, which are associated with improved infiltration and reduced erodibility. Karlen et al. (1999) reported that CRP sites in Iowa generally had a higher percentage of water-stable soil aggregates than croplands. No-till evaluated after periods of up to 10 yr improved aggregate size and stability compared with CT on croplands (Elliott and Efetha, 1999; Arshad et al., 1999). However, Unger (1999) found few differences in soil wet aggregate stability among NT, reduced tillage, and tillage by disc or moldboard plus disc within the first 3 yr after conversion from CRP grassland. Interpretation of differences in soil quality indicators among post-CRP treatments can be complex, and results for single property effects can appear counter-intuitive. For example, Wienhold and Tanaka (2000) found that tension infiltrometer values measured on CT-managed former CRP land were greater than values on NT plots.

Soil erosion by rainfall events is a complex, chaotic, dynamic, and distributative soil and land surface process best understood by multiscalar analysis. Processes of soil particle detachment, deposition, and transport are separable at sufficiently small time and space scale but are linked at larger scales. Over smaller areas and earlier in rainstorms, rainfall impact and raindrop splash are considered to dominate rainwater erosivity and soil transport; over larger areas, at more downslope positions, and further into rainstorms, runoff flow is considered to dominate erosivity and transport.

It is difficult to separate the soil hydrological part of the erosion process—infiltration, runoff, drainage, and seepage flows—from the purely erosional part. Huang (1998) demonstrated that hydrologic flow at the soil surface—drainage or seepage—could change effective soil erodibility and erosion regime. Soil transport and runoff from one part of the hillslope affects another part, as has been experimentally demonstrated by Zheng et al. (2000). To overcome effects of these complexities in rainfall simulation studies, it is useful to establish a relative steady-state runoff condition and make use of soil loss and runoff measurements made under such a condition.

Soil erodibility is resistance or vulnerability to energy expenditure by erosive agents. We define erodibility as the ratio between soil loss over an area and the water erosivity driving the loss. Comparison of soil and land use treatments on a soil erodibility basis renders results more generalizable and interpretation of results more objective than is the case with comparisons of runoff and soil losses alone. Rainfall intensity is used as the primary erosivity indicator at shorter times and smaller areal scales. Larger areas and greater time scales generally require use of runoff as the measure of erosivity. However, there is evidence that runoff is an effective erosivity indicator at the 1-m^2 scale or less. Huang (1995) and Zhang et al. (1998) combined runoff with slope angle to demonstrate an effective measure of erosivity. Truman and Bradford (1995) showed that combining runoff and rainfall intensity produced a better indication of rainstorm erosivity than use of rainfall intensity alone.

Literature exists on effects of land use and management options on runoff, soil erosion, and soil quality indicators after converting CRP lands to crop production and has been reviewed here. However, we found little research indicating how to partition differences in soil erosion measured on different forms of tillage management into components of soil erodibility attributable to presence or absence of surface residue or attributable to consolidated soil surface versus tillage-disturbed soil.

In this study we assumed that partitioning of soil erodibility into components associated with presence or absence of crop residue or a soil cohesive (non-tilled) condition could be achieved by comparing soil loss and runoff measured under rainfall simulation applied to various surface condition treatments such as: (i) land in its undisturbed state; (ii) land with complete but nondisturbing residue removal, and (iii) land that had been thoroughly tilled, followed by smoothing with a rake.

The objectives of the study were (i) to determine soil conservation potentials of land use managements applied to CRP-enrolled land, including hay production and crop production under CT and NT management, through application of rainfall simulation and determination of generated runoff and soil loss, and (ii) to partition soil erodibility of post-CRP land use treatments into components associated with plant residue-covered and soil cohesive (non-tilled) surface conditions.

MATERIALS AND METHODS

Study Site and Agronomic Treatments

Land at the site of the soil erosion study had been in wheat-based crop production for at least 10 yr before enrollment in the CRP program in 1989, at which time it was seeded to a mixture of alfalfa (*Medicago sativa* L.) and wheatgrass (*Agropyron* spp.). Due to unsatisfactory results, the area was reseeded in 1991. The research site (46° 44′ 51″ N, 100° 59′ 15″ W) was located in Morton County, North Dakota about 10 km southwest of the city of Mandan. Annual precipitation averages 400 mm, with 70% of the rainfall occurring from May through September. Average annual temperature is 5.2°C, and long-term monthly averages range from 21.5°C in July to −12.8°C in January.

Beginning in 1994, an experimental agronomic design consisting of four 73.2 by 30.5 m replicate field blocks was established at the site. Each block was split into eight 9.1 by 30.5 m plots, six of which were used for crop production treatments, one plot was used as an annually hayed reference treatment, and one plot was used as an undisturbed CRP reference.

Crop production was performed with a 3-yr rotation of spring wheat–winter wheat–dry pea, which was repeated twice during the period 1995 through 2000 for a duration of six cropping seasons. Soil-crop management treatments consisted of CT with one preseeding tillage with a tandem disk, NT, and an intermediate tillage treatment not addressed in this soil erosion study. The reference hay production treatment (PH) consisted of plots subjected to annual forage harvest in late June or early July.

A split-split plot design was imposed on the crop production area. Half of the cropped plots were hayed and half were not at the beginning of the experiment, with each of these 27.4 by 30.5 m areas containing all three tillage treatments. Nitrogen-fertilized and non-N-fertilized areas of 64.1 by 15.2 m size were established perpendicular to initially hayed and non-hayed areas. Thus crop production and annually hayed plots, but not undisturbed CRP reference plots, had N-fertilization treatments. Elementary subplots in this design were 9.1 by 15.2 m in size.

Initial haying and herbicidal killing of vegetation on crop production areas was performed in 1994. All seeding was performed with a John-Deere 750 no-till drill (John Deere, Moline, IL) and crop plants were seeded in rows 19 cm apart. Crop rows were in an east-west direction parallel to land slope. Nitrogen-fertilization was applied to crop production plots and PH plots at a rate of 67 kg N ha^{-1} broadcast annually before seeding. Cropped plots also received 11 kg P ha^{-1} annually with the seeding operation. Applications of pre-and post-seeding herbicide were made as necessary for weed control. The principal pre-emergent herbicide used was glyphosate (N-[phosphonomethyl] glycine isopropylamine salt).

Soil Erosion Treatments

Starting in mid-August 2000, following dry pea harvest in early August, areas were prepared for rainfall simulation study on one replication of the agronomic experiment on plots that had received N-fertilization. Soil at the land area actually used for the soil erosion study is classified as Williams loam (fine-

Table 2. Soil properties of the surface soil zone (approximately 0–10 cm) at the research site. Soil at the site is classified as Williams loam (fine-loamy, mixed, superactive, frigid Typic Argiustolls).

Land use treatment	Particle-size distribution			Initial moisture	pH		Organic C	Total N
	Sand	Silt	Clay		Water	0.01*M* $CaCl_2$		
	%			g kg^{-1}			g kg^{-1}	
Conventional-till	**49.4**	**40.6**	**10.0**	**42**	**5.94**	**5.53**	**21.5**	**2.0**
No-till	**47.0**	**39.0**	**14.0**	**115**	**5.89**	**5.41**	**25.6**	**2.3**
Permanent hayed	**48.6**	**39.4**	**12.0**	**107**	**6.17**	**5.79**	**28.0**	**2.5**
Permanent cover-tilled conversion	**48.6**	**39.4**	**12.0**	**59**	**6.37**	**5.95**	**17.7**	**1.4**

loamy, mixed, superactive, frigid Typic Argiustolls). Initially hayed and initially nonhayed plot areas were included in the study. Land use treatments included CT, NT, and PH from the agronomic experiment, and a permanent cover–tilled conversion (PC-TC) treatment. The PC-TC treatment was outside of the agronomic study area but within about 20 m of it and was established on a 20 by 75 m previously undisturbed CRP area. This area was mowed and raked in May 2000, and then tilled six times at approximately biweekly intervals with an offset disk during June and July 2000.

The PH treatment was closely mowed and vegetation raked off before start of the study. Then, on each of the land use treatments with the exception of PC-TC, three surface condition treatments were established: (i) undisturbed areas that were left as is (AsIs); (ii) after establishment of 1.5 by 5 m runoff-erosion plots (see below), residue was removed (RsRm) within each plot by close hand clipping and removal of plant material by vigorous raking using hands (finger raking); and (iii) a tilled treatment was established by first closely cutting vegetation and residue on 5 by 9 m areas with a rotary mower and then closely cutting it with a lawn mower. Material was raked off and the areas were tilled by two or more passages of a tandem disk.

Slopes at areas where soil erosion studies were performed averaged 3.8% and ranged from 3.1 to 4.9%. Soil properties at the site were measured on samples from the 0- to 10-cm soil depth and are presented in Table 2. Particle size was measured with a pipette method. Soil pH was measured at a 1:1 solid/solution ratio in both water and a 0.01-*M* $CaCl_2$ solution. Organic C and total N were analyzed by a dry combustion method (model CHN-2000, Leco Corp., St. Joseph, MI).

Soil coverage by crop residue was determined with a photographic technique in the spring of 2000 after seeding of the dry pea crop. The method used was to take nadir view photographs with a camera held by a metal frame about 2 m above the soil surface. Each photograph was evaluated at 50 points. Measurements in Spring 2000 indicated that treatments used for rainfall simulation had levels of soil coverage by crop residue of 62% for CT, 92% for NT, and 94% for PH treatments.

Rainfall Simulation and Soil Erodibility Measurement

Twin sets of 1.5 by 5 m runoff-erosion plots were established with members of a pair sharing a common, long border. Galvanized steel plates were driven into the ground, leaving 5 to 10 cm aboveground, pits were excavated at the downslope ends, and runoff collectors were set in place. Subsequent plot preparation included collecting topsoil samples (about 10 cm wide by 10 cm deep) for measurement of soil properties, clipping and finger-raking the RsRm treatment, and smoothing out visual irregularities with a rake on tilled treatments. Runoff plot pairs either consisted of one AsIs and one RsRm plot, or of two tilled plots. Only tilled plots were established for the PC-TC treatment.

A set of four programmable oscillating-type rainfall simulation troughs (Foster et al., 1979) spaced 1.4 m apart were set on a frame over the twin runoff plots so that the troughs were perpendicular to the long axis of the plots. (The rainfall simulator set over the twin runoff plots constitutes one setup here.) Each simulation trough had five Veejet nozzles (part No. 80100, Spraying System Co. Wheaton, IL) spaced 1.07 m apart. Vertical distance between nozzles and the soil surface was about 2.5 m. During rainfall simulation, nozzle pressure was kept at approximately 40 kPa (6 psi). This rainfall simulator can be set to the selected rainfall intensity, ranging from 15 to 200 mm h^{-1}, by programming the oscillation frequency of the nozzles. Rainfall simulation equipment was designed and constructed at the National Soil Erosion Research Laboratory, USDA-ARS, West Lafayette, IN.

Water purified by reverse osmosis to low conductance level was used. The planned program of rainfalls started with an initial rain of 50 mm h^{-1} for the majority of setups, but 75 mm h^{-1} for plots with higher infiltration rates. (All three non-tilled NT setups and one of three non-tilled CT setups had 75 mm h^{-1} long initial rains.) Initial rain lasted from 1 to 3 h until a relative steady-state runoff condition had been reached, as indicated by about 10% or less variation in runoff volumes. This was followed by 15- to 25-min rains of 25, 75, and 100 mm h^{-1} or 75, 100, and 125 mm h^{-1} for a 50-mm h^{-1} initial rain, or of 100 and 125 mm h^{-1} for a 75-mm h^{-1} initial rain. Relative steady state in these noninitial rains was considered to have been reached when runoff volumes had stabilized to roughly 20% or less variation. Wind screens were set up on two sides of most of the erosion plot setups.

During initial rainfall, runoff and sediment sample collection was started when it appeared that runoff was originating from all or a considerable fraction of the plot. Runoff rate was measured by collecting runoff water in a 9-L bucket at about 1- to 3-min intervals depending on runoff rate. Samples for soil loss measurement were collected in 1-L polypropylene heat-resistant plastic bottles. Every runoff sample was immediately followed by a sample for sediment determination. Sample collection continued to the end of the initial longer rains. Four runoff and sediment sample pairs were collected for each subsequent rain. A smaller number of runoff samples were collected for analysis of water quality and C and N contents of sediments.

Saturated alum solution was added to sediment sample bottles to flocculate suspended material. After settling overnight, excess water was decanted and the bottles were placed in an oven at 105°C for dry weight determinations.

Soil samples taken for soil property analyses were air dried at 35°C and prepared for chemical analyses by moderate-effort crushing of larger aggregates and subsequent screening using a 2-mm sieve.

Wet Aggregate-Size Distribution and Stability

A wet-sieving machine similar to that described by Yoder (1936), with a displacement of 38 mm and a frequency of 36 cycles min^{-1}, was used to obtain wet aggregate-size distribution on air-dried soil that passed a 4.75-mm sieve and was retained on a 2-mm sieve. A 50-g subsample was placed on filter paper, and was prewetted by capillarity with deionized water under 0.5 J kg^{-1} suction on a 33-kPa suction plate overnight. Subsamples were subsequently sieved in deionized water for 15 min using a 4.75-, 2, 1-, 0.5-, and 0.21-mm series. After sieving, the soil suspension was passed through 0.125- and 0.053-mm sieves to obtain additional size classes. Materials caught on each sieve were oven-dried at 105°C. The procedure was replicated for each sample at least three times. Mean weight diameter was used to express aggregate stability.

RESULTS AND DISCUSSION

Soil Properties

Antecedent soil water content affects runoff and erosion, and infiltration rate is inversely related to initial water content. Water contents at the 0- to 10-cm depth of the NT and PH land use treatments averaged 115 and 107 g kg^{-1}, respectively (Table 2), and water contents of CT and PC-TC treatments were 42 and 59 g kg^{-1}. These results appear to reflect greater soil coverage by residue in the NT and PH treatments and effects of tillage on CT and PC-TC treatments. Dao (1993) also reported that soil moisture contents in NT were higher than in CT in the spring under winter wheat cropping. Soil texture in the 0- to 10-cm depth was loam (Table 1), but soil mixed over the 0- to 30-cm depth was determined to be sandy loam (data not shown). Average soil pH values of the CT and NT crop production treatments were 5.74 and 5.65, respectively, more acidic than pH 5.98 and 6.18 for the PH and PC-TC treatments, respectively (Table 2), reflecting effects of N-fertilization of crop production treatments and soil mixing by tillage. Lower organic C and total N values for the PC-TC treatment were probably the result of the greater extent of soil mixing that occurred because of relatively deeper, multiple tillages that were applied in this treatment.

Runoff and Erosion on Non-Tilled Treatments

There were no significant differences between average runoff rate measurements (Table 3) on non-tilled CT and NT land use treatments at any rainfall intensity. Although there was a difference in initial water content between CT (42 g kg^{-1}, Table 2) and NT treatments (115 g kg^{-1}), this did not result in significant difference in runoff rates.

Average runoff rates on PH plots were significantly greater than NT values for 75 mm h^{-1} rainfall, significantly greater than CT and NT values at 100 mm h^{-1}, and numerically greater than at 50 mm h^{-1}. Runoff rates from the PH treatment were from 72 to 94% greater than CT and NT averages at rainfall intensities of 50 to 100 mm h^{-1}. One explanation could be that the basal biomass of annual plants in the PH treatment occupied enough soil area so as to diminish infiltration.

No significant differences in runoff rates existed between RsRm and AsIs conditions within land use treatments (Table 3). However, RsRm runoff rates were numerically greater than AsIs values within CT and PH land use treatments, but not within NT. A partial explanation of this pattern would be that removal of residue in CT exposes soil to sealing action of raindrop impact, which would be considerably lessened in the NT and PH treatments with their greater amounts of coarse organic material near the soil surface.

Average soil loss rates measured on the CT land use were significantly greater than NT values at 100 mm h^{-1} rainfall and numerically greater than NT and PH soil loss rates at all four rainfall rates from 50 to 125 mm h^{-1} (Table 3). Conventional till soil loss rates were from 1.8 to 4.2 times greater than NT values. Our soil loss results, measured at relative steady state, are in accord with the studies referenced in Table 1, which indicated that soil erosions losses on NT were 40 to 98% less than losses on CT. Seven out of eight of these studies measured cumulative soil losses while one study measured loss rates at relative steady state.

Average soil loss rates for the non-tilled PH treatment were not significantly different than NT values at any rainfall rate, but PH values were numerically greater than NT values at rainfall rates of 50 through 125 mm

Table 3. Runoff rates and soil loss rates measured under relative steady state conditions in non-tilled and tilled treatments.†

Rainfall rate	CT AsIs‡	CT RsRm‡	CT Avg. non-tilled§¶	CT Tilled#	NT AsIs‡	NT RsRm‡	NT Avg. non-tilled¶	NT Tilled#	PH AsIs‡	PH RsRm‡	PH Avg. non-tilled¶	PH Tilled#	PC-TC#
mm h^{-1}							Runoff rate, mm h^{-1}						
25				6.4 (2,x)				4.0 (2,x)	3.5 (2,a)	5.2 (2,a)	*4.4*		6.0 (4,x)
50	8.5 (1††,a)	10.2 (2,a)	*9.6 p*	18.2 (4,xy)	7.7 (2,a)	14.4 (1,a)	*9.9 p*	14.0 (4,y)	14.7 (3,a)	18.9 (3,a)	*16.8 p*	6.6 (4,y)	26.5 (4,x)
75	9.4 (3,a)	22.7 (3,a)	*16.1 pq*	47.3 (4,xy)	15.7 (3,a)	13.6 (3,a)	*14.7 q*	38.4 (4,xy)	27.1 (3,a)	32.5 (3,a)	*29.8 p*	28.1 (4,y)	50.9 (4,x)
100	25.7 (3,a)	41.7 (3,a)	*33.7 q*	70.8 (4,xy)	31.8 (3,a)	29.1 (3,a)	*30.5 q*	59.1 (4,xy)	49.3 (3,a)	63.8 (3,a)	*56.6 p*	54.4 (4,y)	77.0 (4,x)
125	40.2 (3,a)	60.6 (3,a)	*50.4 p*	85.2 (2,x)	56.2 (3,a)	51.0 (3,a)	*53.6 p*	61.8 (2,y)	28.3 (1,a)	78.7 (1,a)	*53.5 p*	75.5 (4,xy)	
							Soil loss rate, g m^{-2} h^{-1}						
25				6.5 (2,x)				5.3 (1,x)	1.2 (2,a)	2.3 (2,a)	*1.8*		9.2 (4,x)
50	16.1 (1,a)	12.6 (2,a)	*13.8 p*	50.9 (4,y)	7.6 (2,a)	8.4 (1,a)	*7.8 p*	33.5 (4,z)	6.3 (3,a)	11.0 (3,a)	*8.6 p*	30.0 (4,z)	69.9 (4,x)
75	23.0 (3,a)	35.2 (3,a)	*29.1 p*	199.2 (4,xy)	5.9 (3,a)	8.0 (3,a)	*6.9 p*	121.9 (4,yz)	8.6 (3,a)	24.1 (3,a)	*16.4 p*	67.7 (4,z)	216.8 (4,x)
100	37.3 (3,ab)	84.5 (3,a)	*60.9 p*	352.1 (4,xy)	12.4 (3,b)	26.5 (3,ab)	*19.5 q*	226.9 (4,yz)	14.6 (3,ab)	37.8 (3,ab)	*26.2 pq*	146.4 (4,z)	393.7 (4,x)
125	55.9 (3,a)	122.3 (3,a)	*89.1 p*	649.8 (2,x)	13.9 (3,a)	43.0 (3,a)	*28.5 p*	407.6 (2,xy)	23.9 (1,a)	87.6 (1,a)	*55.8 p*	215.3 (4,y)	

† CT, conventional-till; NT, no-till; PH, permanent hayed; PC-TC, permanent cover–tilled conversion; AsIs, the undisturbed (control) surface condition; RsRm, the residue removal surface condition. Non-tilled data is italicized and tilled data is underlined.

‡ Values in a row having the same letter starting with an a are not significantly different at the $P = 0.1$ level according to Tukey's studentized range test.

§ Average non-tilled weighted by number of replications.

¶ Values in a row having the same letter starting with p are not significantly different at the $P = 0.1$ level according to Tukey's studentized range test.

Values in a row having the same letter starting with x are not significantly different at the $P = 0.1$ level according to Tukey's studentized range test.

†† Indicates number of replicates.

h^{-1} (Table 3). The greater PH soil loss rates are probably due to PH runoff rates being greater than NT runoff rates. Our results showing no statistically significant differences between average soil loss rates measured on PH and NT treatments are broadly similar to those reported by Gilley et al. (1997b) at two Iowa Mollisol soil and land sites with CRP land converted in part to corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] crops.

Soil loss rates for AsIs and RsRm surface conditions within land use treatments at various rainfall intensities were not significantly different (Table 3). Nevertheless, RsRm soil loss rates were numerically greater than AsIs values within land use treatments in all cases but one. The numerical disparity between RsRm and AsIs values for the three land uses was greater at higher rainfall intensities, approaching or exceeding 3 to 1 at 125 mm h^{-1} rainfall. This shows the increasing importance of surface residue for providing protection against increasing erosivity of flowing runoff combined with increased rainfall intensity.

Effects of Tillage on Runoff and Erosion

The effects of thorough disk tillage on runoff rates varied among land use treatments. Tilled CT runoff rates were from 1.7 to 2.9 times greater than those from non-tilled treatments. Tilled NT values were from 1.2 to 2.6 times greater than non-tilled, and tilled and non-tilled PH values were numerically similar, with tilled runoff rates being on average 0.9 times non-tilled (Table 3). These results show that the considerable amount of root biomass and other soil quality assets of the PH treatment's grass-alfalfa mixture were able to maintain some stability of surface soil after thorough tillage so that infiltration capacity was not significantly diminished. Neither CT nor NT management treatments were able to do this when disrupted by tillage.

Thorough tillage increased soil loss considerably more than it increased runoff (Table 3). Tillage increased erosion the least at 50-mm h^{-1} rainfall, and tilled soil loss rates were 3.7, 4.3, and 3.5 times greater than from non-tilled CT, NT, and PH treatments, respectively. Increases in soil loss rates were greater at higher rainfall intensities, and ratios of tilled to non-tilled rates ranged from 5.8 to 7.3 times for the CT treatment, from 11.6 to 17.7 times for the NT, and from 3.9 to 5.6 times for the PH (Table 3).

Patterns of runoff and erosion results among the four tilled treatments were generally consistent (Table 3). For the 50-, 75-, and 100-mm h^{-1} rainfalls, the numerical order of runoff rates was: PC-TC > CT > NT > PH. Numerical orders for the 25 and 125-mm h^{-1} rainfalls were similar. There were significant differences between the highest and lowest runoff rates at each rainfall rate except 25 mm h^{-1} (Table 3).

The pattern of results for soil loss rates among the tilled treatments was the same as that for runoff rates, but more consistent. There were significant differences among the soil loss rates at all rainfall rates above 25 mm h^{-1} (Table 3). For the tilled CT and NT treatments, increases in soil loss rates at higher rainfall intensities were greater than increases in runoff rates: loss rates at 125-mm h^{-1} rainfall compared with those at 50 mm h^{-1} were 12.8-, 12.2-, and 7.7-fold greater for CT, NT, and PH treatments, respectively, while the same 125- vs. 50-mm h^{-1} comparison for runoff rates shows 4.7-, 4.4-, and 11.4-fold increases. This pattern of results indicates that the PH land use has superior resistance to erosion by higher-erosivity rainstorms compared with the CT and NT crop production managements when land is rendered more vulnerable by tillage.

Soil Erodibility

Erodibility values at different rainfall intensities were determined as the ratio of soil loss rate to runoff rate at a relative steady state for individual erosion plots and reported as averages (Table 4). Erodibility values of non-tilled NT treatments at various rainfall rates did not differ greatly from those of non-tilled PH treatments, while CT treatment erodibility values were about three times or greater than NT and PH values. Erodibility values of tilled treatments were considerably greater than those of non-tilled treatments. For example, at the 75-mm h^{-1} rainfall, tilled CT, NT, and PH treatments had average erodibility values of 4.7, 3.3, and 2.7 g m^{-2} mm^{-1}, which were 2.8, 4.0, and 4.0 times greater than the respective non-tilled erodibility values.

The sequence of erodibility values measured at successively greater rainfall intensities for a given land use and surface condition treatment provides information about the nature and stability of the erosion process. Regressions of erodibility versus rainfall rate for non-tilled treatments were not significant at the 0.05 probability level (Table 4). Erodibility increased with rainfall

Table 4. Soil erodibility values (soil loss rate divided by runoff rate) for land use and surface condition treatments at different rainfall rates.†

	Ratio, (soil loss rate)/(runoff rate)									
	CT			NT			PH			
Rainfall rate	AsIs	RsRm	Tilled	AsIs	RsRm	Tilled	AsIs	RsRm	Tilled	PC-TC
mm h^{-1}	g m^{-2} mm^{-1}									
50	1.89	1.35	3.35	1.41	0.58	2.63	0.61	0.61	6.17	2.73
75	1.75	1.60	4.62	0.37	1.28	3.32	0.55	0.81	2.75	4.29
100	1.20	1.95	5.16	0.38	1.34	4.12	0.45	0.63	2.80	5.11
125	1.24	1.98	7.61	0.25	1.07	6.51	0.85	1.11	2.97	
R^2 ‡	ns	ns	0.31*	0.30+	ns	0.44**	ns	ns	0.21+	0.57**

† CT, conventional-till; NT, no-till; PH, permanent hayed; PC-TC, permanent cover–tilled conversion; AsIs, the undisturbed (control) surface condition; RsRm, the residue removal surface condition.

‡ R^2 values of regression of erodibility values vs. rainfall rates are given. Significance of R^2 values is indicated as: ns, not significant; +, $0.10 > Pr \geq 0.05$; *, $0.05 > Pr \geq 0.01$; **, $Pr < 0.01$.

rate for the tilled CT, NT, and PC-TC treatments, but not for the PH treatment. This result demonstrates that the PH land use possesses superior resistance to erosion by higher-intensity rainstorms compared with the other land uses when all of these treatments are made more vulnerable by tillage.

Tillage largely destroys surface residue and soil consolidation features of treatments and near-surface plant and root structures become more important in resisting erosion. The lack of increase of erodibility of the tilled PH treatment at higher rainfall rates (Table 4) indicates the relative erosion-protective potential of perennial plants' root structures and crown zone material. Soil erodibility values of the PC-TC, tilled CT, and tilled NT treatments increased 1.5-, 1.6-, and 1.9-fold as rainfall intensity was increased from 50 to 100 mm h^{-1} (Table 4). This indicates that the perennial plant root structures and crown materials present in CRP land had been largely destroyed by multiple tillages that had been applied to the PC-TC treatment.

Our soil erodibility measurements may be compared with results of others using similar methodology–rainfall simulation and measurement at relative steady-state runoff. Averaging across 50- and 75-mm h^{-1} rain intensities, our results obtained at 4% slope were: CT and NT AsIs erodibility, 1.79 and 0.79 g m^{-2} mm^{-1}, respectively; tilled CT and NT, 3.98 and 2.93 g m^{-2} mm^{-1} (Table 4). Seta et al. (1993) measured erodibilities of NT and CT (as moldboard plowing plus two diskings) after row crop seeding on cultivated Kentucky Typic Paleudalf soil at 9% slope, finding 34.6 and 1.89 g m^{-2} mm^{-1} for CT and NT, respectively. Erodibility measurements made after corn seeding by Dickey et al. (1984, Table 1) on continuous corn land in Nebraska with CT (disk tillage) and NT yielded the following 2-yr averages: Udic Haplustolls, 10% slope, CT—50.8 g m^{-2} mm^{-1}, NT—14.9 g m^{-2} mm^{-1}; Aquertic Argiudolls, 5% slope, CT—35.3 g m^{-2} mm^{-1}, NT—15.2 g m^{-2} mm^{-1}. Erodibility values measured at 9 to 10% slope can be adjusted to 4% slope by lowering them by about 30% according to Liebenow et al. (1990). These comparisons indicate superior stability of restored grassland converted to crop production by either no-tillage or lower conservation tillage (our CT). The domination of high residue-producing crops—spring wheat and winter wheat—in our 3-yr rotation is an important factor conferring relative stability against erosion.

To obtain general, summary soil erodibility values for land use and surface condition treatments, linear regressions of soil loss rates vs. runoff rates were performed across rainfall intensities. Regressions are graphed in Fig. 1 and results are listed in Table 5. These erodibility

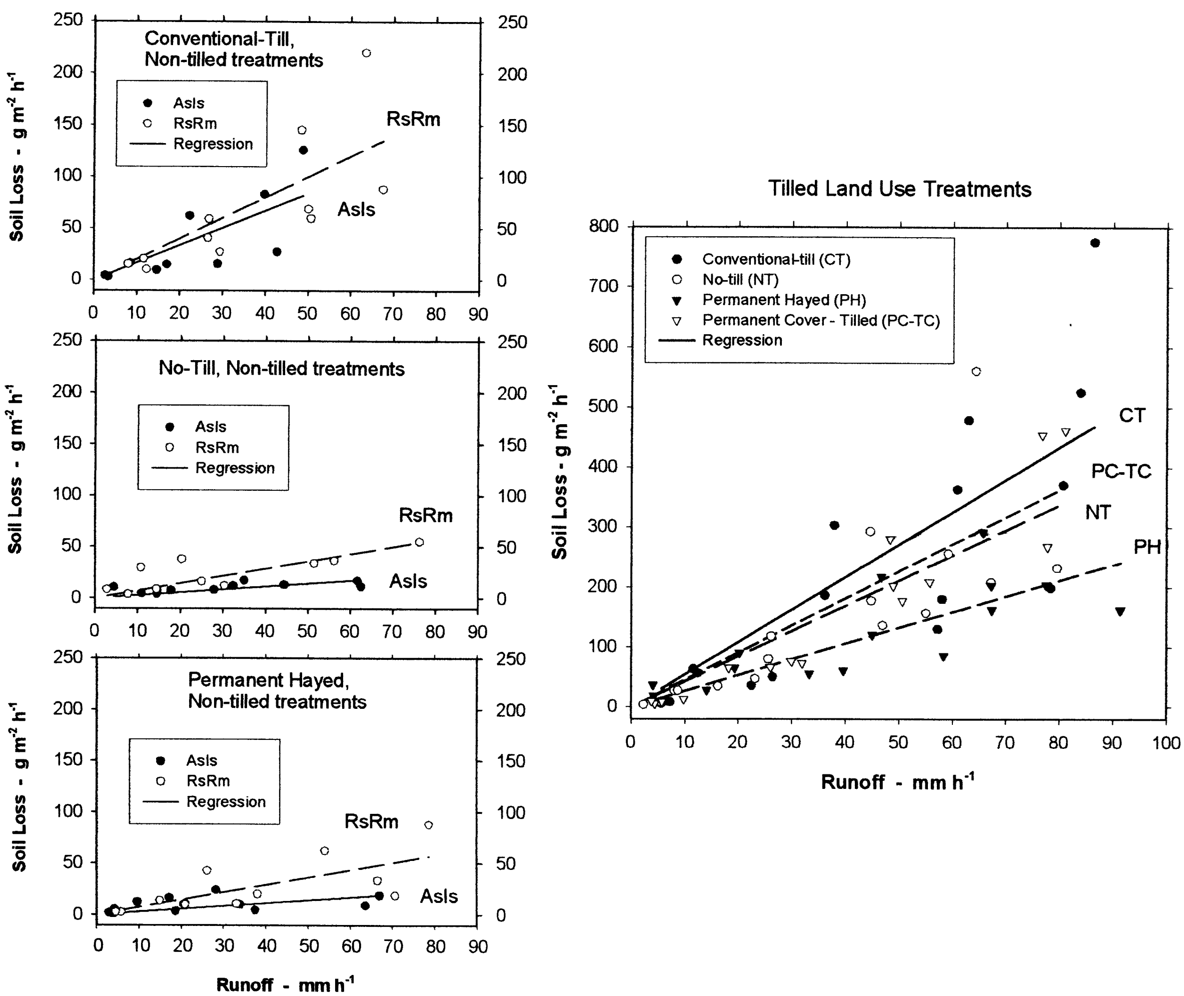

Fig. 1. Linear regression of soil loss rates against runoff rates, both measured at relative steady state for non-tilled and tilled land use treatments.

Table 5. Soil erodibility by linear regression of soil loss rate vs. runoff rate with no intercept and calculation of theoretical percentage of full erodibility under tillage removed by non-tilled soil surface treatments.

Treatment†	Soil erodibility	R^2	SE of regression	$LSD_{0.10}$	Percentage of erodibility	The erodibility is removed by
	g m^{-2} mm^{-1}		g m^{-2} mm^{-1}		%	
CT-AsIs	1.651	0.772	0.299	0.780	69.5	lack of disturbance plus residue
CT-RsRm	1.994	0.811	0.305	0.780	63.2	lack of disturbance alone
CT-Tilled	5.418	0.842	0.607	1.504	100	
NT-AsIs	0.290	0.849	0.039	0.187	93.1	lack of disturbance plus residue
NT-RsRm	0.715	0.858	0.097	0.187	83.0	lack of disturbance alone
NT-Tilled	4.213	0.809	0.529	1.311	100	
PH-AsIs	0.280	0.618	0.066	0.246	89.4	lack of disturbance plus residue
PH-RsRm	0.722	0.767	0.120	0.246	72.6	lack of disturbance alone
PH-Tilled	2.638	0.869	0.264	0.654	100	
PC-TC	4.650	0.938	0.308	0.826		

† CT, conventional-till; NT, no-till; PH, permanent hayed; PC-TC, permanent cover–tilled conversion; AsIs, the undisturbed (control) surface condition; RsRm, the residue removal surface condition.

values have some conceptual similarity to the so-called K-factor values of the well-known empirical Revised Universal Soil Loss Equation (RUSLE) water erosion model (Renard et al., 1997). However, the erodibility concepts differ because the RUSLE K-factor makes use of a measure of rainfall energy for the erosivity denominator of erodibility in contrast to our use of runoff rate.

In general, erodibility regressions for the three PH treatment soil surface conditions (Table 5) had the lowest R^2 values, 0.62 to 0.87, followed by those for CT (0.78–0.84) and NT (0.81–0.86), with PC-TC having the highest regression value, 0.94. A result of great interest to soil conservationists is that the regression-derived erodibility of the NT-AsIs treatment, 0.29 g m^{-2} mm^{-1}, was not significantly different from the PH-AsIs treatment erodibility, 0.28 g m^{-2} mm^{-1}. However, erodibility of the CT-AsIs treatment, 1.65 g m^{-2} mm^{-1}, was about six times greater than erodibility of the NT-AsIs and PH-AsIs treatments, indicating the protective ability of NT crop management. The finding that CT-AsIs had about six times the erodibility of NT-AsIs shows the loss of erosion protecting potential caused by moderate, preplanting tillage (single passage with a tandem disk) used annually in the conventional-till treatment. The destructive potential of even a single, relatively moderate, conservation-type tillage operation is thus demonstrated quantitatively here.

Soil loss rate values revealed no significant differences between AsIs and RsRm surface conditions within land use treatments (Table 3). However, regression-derived erodibility of the PH-AsIs condition, 0.28 g m^{-2} mm^{-1}, was significantly less than that of the PH-RsRm, 0.72 g m^{-2} mm^{-1} (Table 5). Similarly, erodibility of NT-AsIs was significantly less than that of NT-RsRm, 0.287 versus 0.715 g m^{-2} mm^{-1}, respectively. Non-soil-disturbing removal of residue had much less effect on the CT land use treatment, as the erodibility of CT-AsIs was not significantly different than that of CT-RsRm. These results indicate that crop residues, in the case of the NT treatment, and both residues and plant crown structures in the case of the PH treatment, are important for providing stability to NT and PH soils, and that these factors appear to be less important in CT soil.

Tilled treatments yielded regression-derived erodibility values in the order: CT, 5.4 g m^{-2} mm^{-1}; PC-TC, 4.7 g m^{-2} mm^{-1}; NT, 4.2 g m^{-2} mm^{-1}; PH, 2.6 g m^{-2} mm^{-1} (Table 5). This is similar to the ordering of soil loss rate results (Table 3), except that tilled PC-TC loss rates were somewhat greater than those for CT. The only significant difference among erodibility values of tilled treatments was between PH and all the others as a group (Table 5). Just as soil loss rates were greater for tilled than for non-tilled treatments, so too were erodibility values.

Assuming that erodibility measured on a thoroughly tilled land use treatment represents the maximum erodibility value for that treatment, we can calculate the percentage of that erodibility that is removed by either not tilling (consolidated surface soil condition) or by not removing residue through a comparison of the soil surface treatments. This has been performed (Table 5), and calculations show that the combination of not tilling the soil and not removing residue (the AsIs condition treatment) results in 89, 93, and 70% decrease of erodibility values for the PH, NT, and CT treatments, respectively. Comparable values for not tilling alone (from the RsRm surface condition treatment) were 73, 83, and 63% for PH, NT, and CT, respectively (Table 5). This fractionation of total erodibility shows that destruction of soil surface cohesion and structures by tillage is numerically of greater importance to erodibility than is non-disturbing but complete loss of plant residues.

Wet Aggregate Stability

Studies have shown greater wet aggregate stability to be correlated with lower soil-inherent erodibility—which is erodibility dependent on nonstructural, nonplant material-associated soil properties. Aggregate stability data for this study are tabulated in Table 6. Aggregate stability determined by immersion and oscillation can be expressed as: (i) mean weight diameter (MWD); (ii) percentage of macroaggregates (from 4.75- to 2.0-mm diam.); and (iii) percentage of microaggregates (<0.212-mm diam.). Soil with greater aggregate stability will have greater MWD, greater macroaggregate percentage, and less percentage of microaggregates (Tisdall and Oades, 1982; Angers and Carter, 1996; Nemati et al., 2000).

Our analyses show (Table 6) that aggregate stability indicators for non-tilled treatments were in the following sequences (most stable to least): PH > NT > CT. This correlates in reverse sequence of observed soil erodibility values for the tilled treatments.

Table 6. Soil aggregate stability for data for conventional-till (CT), no-till (NT), permanent hayed (PH), and permanent cover–tilled conversion (PC-TC) land use treatments. Data in parentheses are standard errors of mean.

Size classes	CT-non-tilled	CT-tilled	NT-non-tilled	NT-tilled	PH-non-tilled	PC-TC
mm	%					
			Micro- and macroaggregates			
4.75–2	69.4 (0.8)	61.1 (1.4)	71.1 (2.6)	62.3 (1.4)	75.7 (2.8)	76.2 (2.0)
2–1	8.6 (1.5)	8.8 (1.0)	7.9 (1.9)	8.7 (1.9)	7.8 (1.3)	6.8 (1.1)
1–0.5	2.0 (1.1)	2.7 (0.2)	2.4 (0.5)	2.7 (1.3)	1.8 (0.1)	2.1 (0.3)
0.5–0.212	5.0 (0.8)	7.7 (0.2)	5.7 (0.4)	7.5 (2.0)	3.9 (1.1)	4.6 (0.5)
0.212–0.125	3.9 (0.1)	5.6 (1.3)	3.7 (0.3)	5.1 (2.9)	2.5 (0.2)	2.4 (0.2)
0.125- 0.053	3.6 (0.4)	4.5 (0.1)	3.4 (0.1)	3.2 (0.8)	2.7 (0.2)	2.3 (0.2)
<0.053	7.6 (2.0)	9.7 (0.4)	5.8 (0.7)	10.5 (0.6)	5.6 (0.6)	5.6 (0.4)
			Total microaggregates			
<0.212	15.1	19.8	12.9	18.8	10.8	10.3
			Mean weight diameter			
	mm					
	2.52 (0.05)	2.26 (0.05)	2.57 (0.07)	2.29 (0.09)	2.71 (0.09)	2.71 (0.06)

Aggregate stability indicators of the tilled CT and NT treatments showed that they had less stability than the three non-tilled treatments. For example, microaggregate percentages for tilled CT and NT were 19.8 and 18.8%, respectively, and this compares with microaggregate percentages of 10.8, 12.9, and 15.1% for non-tilled PH, NT, and CT treatments, respectively. Results for the PC-TC treatment were outside of this pattern: aggregate stability indicators for PC-TC were similar to those of the non-tilled PH treatment. These results may have been caused by multiple tillages of the PC-TC treatment, resulting in some reformation of aggregation through mechanical action.

Application of Results

Runoff and soil loss from rainfall simulation at successive rain intensities allows us to see how soil-inherent erodibility varies with changing soil and land use and management conditions. Soil erodibility values at successively greater rainfall intensities provide information about the stability of soil and land management alternatives under higher, but less probable soil erosion challenges, while calculation of erodibility values across rainfall intensities provides comparison of overall ability of soil managements to resist erosion.

Our results show that a wheat-dominated crop rotation after 6 yr of no-till management on reseeded grassland (the CRP program) yielded similar soil erodibility values as CRP grassland that had been managed for hay production during the same 6-yr period. The erosion-protective potential of mixed vegetation hayland can be maintained after re-establishment of crop production through careful no-tillage management. The principal components of this system are: (i) weed control by xenobiotic chemicals of which the current dominant agent is the broad-spectrum phytocide, glyphosate; (ii) crop rotations including or dominated by species yielding durable and effective residues, especially small grains such as wheat; (iii) crop seeding with a no-till drill; and (iv) operation of harvesting machinery so that suitable crop residue is left standing upright and so that residue passing through the machinery (the so-called chaff) is uniformly distributed back on the land.

The spring wheat–winter wheat–dry pea crop rotation in this study generates considerable durable wheat residue 2 out of 3 yr. Other regional crop rotations will have lesser soil coverage. Scientists at USDA-ARS, Mandan, ND, have shown that sequences of crops containing pulses (bean, dry pea, soybean, etc.) and the regionally common sunflower crop will generate significantly less soil coverage by residues than small grain-dominated sequences (Krupinsky et al., 2002; Merrill et al., 2002). Furthermore, our study was performed in late summer. However, Northern Great Plains soils and lands tend to be more vulnerable to erosion in spring, when melting of a near-surface layer underlain by frozen soil increases risk of water erosion. Finally, in a semiarid–subhumid area, wind and water erosion synergistically interact, accelerating erosion hazard. Periodically occurring droughts lead to simultaneous lowering of soil coverage by residue, decline of soil aggregation status, and large increase of soil erosion hazard (Merrill et al., 1999). However, the 6 yr of crop production that took place before the performance of this erosion study (1995–2000) occurred during years of higher-than-average rainfall.

The result of this study with the greatest immediate conservation impact is the finding that CRP land converted to crop production with a higher-residue crop rotation and no-till management can possess the same low soil water erodibility as CRP land managed as hayed grassland. However, overall conclusions that may be drawn from this must be limited by the agro-environmental circumstances of the study. Root structures under NT-managed annual crop production would be assumed to have less persistence than those under the PH-grassland treatment. It would be a reasonable supposition that some combination of more erosion-inducing conditions than found in our study could increase soil erodibility of the cropland NT treatment above that of the grassland PH treatment. Such conditions would include: (i) greater land slope, (ii) a crop rotation with more low residue-producing species, (iii) critically limiting precipitation during the years of the agronomic study, which leads to less surface residue and to less soil aggregation (Merrill et al., 1999), and (iv) more fragile, coarser-textured soil.

The finding that undisturbed cropland NT had the same low erodibility as the undisturbed grassland PH treatment must be considered alongside our finding that erodibility of tilled NT was significantly greater than that of tilled PH. In various forms of so-called organic farming systems, tillage is needed to control weeds and periodically establish legume crops. Also, the currently growing phenomenon of herbicide-resistant weeds is another inducement for farmers to practice tillage. In these contexts, research comparisons of soil erodibility that include tilled land use treatments become more environmentally and agronomically relevant.

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