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Soil Technology 7 (1995) 327-341

SOIL
TECHNOLOGY

Furrow erosion and aggregate stability variation in a Portneuf silt loam

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Abstract

Numerous soil factors, including aggregate stability, affect erosion rates from irrigated furrows. Since aggregate stability varies within growing seasons, furrow erosion may vary as well. The study objectives were to (1) measure furrow erosion and aggregate stability periodically over two growing seasons, (2) statistically characterize the temporal variation in furrow erosion and aggregate stability, and (3) relate variation in erosion rates to changes in aggregate stability and other soil properties. Erosion rates from replicated, previously unirrigated furrows in fallow plots on a Portneuf silt loam (coarse-silty, mixed, mesic *Durixerollic Calciorthid*) at Kimberly, Idaho, USA, were measured every 2–3 weeks from mid-May through mid-August 1988, and from late-April to late-August 1989. During each 6.5-h irrigation, three furrows in 1988 and four furrows in 1989 were irrigated at an inflow rate of 11.3 $l \cdot min^{-1}$. At each irrigation, soil samples were taken to a depth of 5 cm from the bottom of furrows adjacent to or near those irrigated. From these samples, soil gravimetric water content was measured and aggregate stability was determined by wet sieving. Erosion from furrows not previously irrigated varied greatly when measured throughout two growing seasons. For both years, erosion rates were significantly lower later in the growing season than earlier. For a 4.0% slope area in 1988, furrow erosion rates varied over the entire season by a factor of six or more while aggregate stability varied (increased) by only 17%. Thus, aggregate stability was not significantly correlated with furrow erosion rates.

Keywords: Rill erosion; Runoff; Soil physical properties; Surface irrigation; Temporal variation; Water content; Water erosion

1. Introduction

Furrow erosion from irrigated cropland is a serious problem that decreases yield potential and degrades surface water quality. Furrow or rill erosion from either irrigation or rainfall

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Elsevier Science B.V.
SSDI 0933-3630(95)00002-X

is affected by flow rate (Meyer et al., 1975), the furrow's slope gradient (Berg and Carter, 1980; Meyer and Harmon, 1985), slope length (Mosley, 1974), slope shape (Foster and Wischmeier, 1974), crop residue (Gilley et al., 1986), and the soil's rill erodibility (often predicted using hydraulic shear, Elliot et al., 1989).

Variation over time in furrow erosion rates (Rauws and Govers, 1988) may be caused by many factors, including tillage (Kemper et al., 1985), climate (Coote et al., 1988), and natural reconsolidation (Brown et al., 1990). Temporal changes in rill development and rill erosion have been studied for plot surfaces tilled once then subjected to rainfall over extended periods of time (Mosley, 1974). An improved understanding of the factors causing these changes over time will permit us to develop management practices to better control furrow erosion.

Soil physical properties affect a soil's susceptibility to rill erosion. Rill erodibility has been related to surface cohesion (Rauws and Govers, 1988), compaction, soil water content, sand content, and aggregate stability (Kemper et al., 1985; Govers, 1991).

Aggregate stability is a measure of an aggregate's resistance to breakdown. Temporal variation in aggregate stability and erodibility affects a soil's susceptibility to water erosion (Alberts et al., 1987; Coote et al., 1988). Aggregate stability varies for some soils from year to year (e.g., Bullock et al., 1988) and within a growing season (Perfect et al., 1990; Ellsworth et al., 1991; Lehrsch and Jolley, 1992). In the intermountain region of USA's Pacific Northwest, aggregate stability is often lowest after spring thaw, increases rapidly early in the spring, then more slowly over the summer, finally reaching its maximum near the end of the fall (Bullock et al., 1988). Over winter, as a consequence of moist soil freezing and thawing numerous times, aggregate stability commonly decreases (Lehrsch et al., 1991). These temporal changes, when characterized, can be used to improve erosion prediction models, modify irrigation management systems, and develop production practices to control erosion more effectively (Kemper et al., 1989).

Alberts et al. (1987) and Imeson and Kwaad (1990) recommended studying temporal changes in soil properties, including aggregate stability. These changes in aggregate stability during the growing season may account for part of the variation in furrow erosion and sediment loss rates often observed from one irrigation to the next during an irrigation season. Temporal variation in aggregate stability (Lehrsch and Jolley, 1992) may affect furrow erosion rates over a growing season. Thus, the objectives of this study were to (1) measure furrow erosion and aggregate stability periodically over two growing seasons, (2) statistically characterize the within-season variation of each, and (3) relate variation in erosion rates to changes in aggregate stability and other soil properties.

2. Methods and materials

2.1. Experimental overview

The study was conducted on a fallowed Portneuf silt loam (coarse-silty, mixed, mesic *Durixerollic Calciorthid*) near Kimberly, ID, USA. The Portneuf soil formed in loess and had a pH (1:1 in water) of 8.0, 1.7% organic matter and, per the USDA classification system, 20% clay and 65% silt. On slopes of 3% or more, irrigation-induced erosion and

Table 1
Irrigation schedules and precipitation in 1988 and 1989

Date of irrigation	Days after first irrigation	Precipitation since previous irrigation (mm)
1988		
18 May	0	-
21 June	34	34
6 July	49	3
26 July	69	0
8 August	82	0
17 August	91	0
1989		
26 April	0	-
17 May	21	19
7 June	42	6
5 July	70	7
2 August	98	11
29 August	125	5

subsequent tillage have often exposed a lighter-colored, calcium carbonate- and silica-enriched B horizon, having a pH (1:1 in water) of 8.4, 0.9% organic matter, and about 21% clay and 70% silt. The Portneuf soil is unstable (Lehrsch et al., 1991) and quite susceptible to furrow erosion (Kemper et al., 1988). Annual precipitation for the area averages 230 mm, of which a total of approximately 50 mm occurs during the months of May through August.

The 1988 site had a cascading-plot arrangement, with the upper plots or furrow sections having an average slope of 1.6% and the lower plots an average slope of 4.0%. The 1989 site was less steep with no slope break; slopes averaged 1.2%.

2.2. Experimental design and statistical analyses

The experimental design was completely random with three furrows per irrigation in 1988 and four furrows per irrigation in 1989. Each furrow was a replicate. The treatments were 6.5-h irrigations of previously unirrigated furrows. Irrigations were conducted at various times during 1988 and 1989 (Table 1).

A preliminary examination revealed that the erosion rates required a common log transformation to equalize their variances. After being so transformed, they were analyzed using an analysis of variance (SAS Institute, Inc.[1], 1985). For final presentation, all means and confidence limits that were determined on the logarithm scale were back-transformed. All other data, without transformation, were analyzed using an analysis of variance and presented in their original units. In the figures, the mean and its 95% confidence interval were

[1] Trade names are included for the benefit of the reader and do not imply endorsement of the product by the USDA.

plotted on each sampling date. Within a growing season, means from adjacent dates were, in general, statistically different from one another if their confidence intervals did not overlap.

2.3. 1988 study

During the 1986 growing season, the site was cropped to field bean (*Phaseolus vulgaris* L.). During the summer of 1987, the site was in fallow. On 19 October 1987, the site was disked to a depth of 12 cm. Two days later, it was roller-harrowed to 8 cm. After two more days had passed, furrows were formed every 76 cm across the study area. Thereafter, no more tillage or cultivation was performed. Throughout the experiment, the site was maintained vegetation-free with contact herbicides or by hoeing without disturbing the bottoms of the furrows.

In the summer of 1988, sets of three adjacent, previously unirrigated furrows were randomly selected in the study area and irrigated at an inflow rate of 11.3 $l \cdot min^{-1}$ for 6.5 h at various times from mid-May through mid-August (Table 1). Flow rates from each 30.5-m furrow section were measured using small, long-throated trapezoidal furrow flumes (Brown and Kemper, 1987). The outflows from the upper 1.6% furrow sections ranged from 5.0 to 7.4 $l \cdot min^{-1}$. These measured outflows were the inflows to the lower 4.0% slope sections.

One-liter runoff samples were collected at the downstream end of each furrow flume at selected time intervals throughout each irrigation. These runoff samples were vacuum-filtered through preweighed, 24-cm Whatman[1] #50 hardened filter paper. The filter paper containing eroded sediment was oven-dried and reweighed to determine sediment concentrations. Net soil loss per unit area for each irrigation was calculated using the difference between the inflow rate × inflow sediment concentration and the outflow rate × outflow sediment concentration. These soil loss rates were taken as measures of erosion rates.

2.4. 1989 study

During the 1988 growing season, this site was cropped to maize (*Zea mays* L.), which was harvested as silage on 26 September. Four days later, the site was disked to 12 cm. On 7 November, it was roller-harrowed to 8 cm. Two days later, furrows were formed every 76 cm across the site. For the duration of the study, we performed no other tillage or cultivation.

In the summer of 1989, sets of four adjacent, previously unirrigated furrows were irrigated at an inflow rate of 11.3 $l \cdot min^{-1}$ at either 3- or 4-week intervals from late-April through late-August (Table 1). Flow rates and sediment concentrations from these 1.2%-slope, 61-m furrows were measured as in 1988.

2.5. Soil sampling

At each irrigation, we used a flat-bottomed shovel or hand trowel to collect soil samples in the shape of a rectangle from the bottom of furrows adjacent to or near those irrigated. These samples on which we later measured aggregate stability were 8 cm wide (perpendicular to the furrow), 18 cm long (parallel to the furrow), and 5 cm deep. From each furrow section next to each replicate, two soil samples were taken. In 1988, the first sample was taken approximately 10 m from the head of the furrow and the second 20 m from the head. In 1989, the first sample was taken approximately 20 m from the head of the furrow and the second 40 m from the head. To collect a soil sample, the soil around each rectangular lock was carefully excavated, then the sample was undercut with the shovel or trowel. The soil samples were then transported, without being crushed, to the laboratory where they were air-dried within 24 h by being spread in a 3-mm thick layer on plastic trays placed in an indoor drying cabinet with forced-air circulation. The air-dry soil was then sieved to obtain 1–2 mm aggregates. Prior to wet sieving, these aggregates were pre-wet for 30 min to 0.30 $kg \cdot kg^{-1}$ using a non-heating vaporizer (Humidifier Model No. 240, Hankscraft[1], Reedsburg, WI, USA). Subsequently, they were sieved in distilled water for 3 min (Kemper and Rosenau, 1986). Concretions were considered sand particles with diameters greater than 0.26 mm. Aggregate stability was reported as the percent by weight of aggregates that remained stable after wet sieving.

Separate samples were collected to determine the water content of the soil before each irrigation. Whenever furrows were irrigated in 1988, one additional disturbed sample was taken in an unirrigated border irrigation furrow to a depth of 5 cm from each corner of the irrigated area. From these four samples, the gravimetric water content of the soil in the bottom of the furrows was determined. In 1989, a disturbed soil sample for water content was taken with each sample taken for aggregate stability. These two samples, one for aggregate stability and one for water content, were taken within 0.45 m of each other in the same furrow. Thus, in 1989, soil water content was measured eight times at each irrigation, twice from each of four furrows.

3. Results and discussion

3.1. Furrow erosion

3.1.1. 1988 study

Erosion rates from furrows not previously irrigated varied greatly over the season (Fig. 1). In some cases, relatively large differences in erosion occurred between consecutive irrigations.

For four of the six irrigations, the erosion rates on the 4.0% slopes differed little from the erosion rates on the 1.6% slope sections (Fig. 1). Erosion or sediment loss rate is often a 1 to 3 power function of furrow slope (Foster and Meyer, 1972b; Kemper et al., 1985).

Lower-than-expected erosion rates from the 4.0% slopes were likely caused by both flow- and soil-related factors. First, inflows to the 4.0% sections were only 58% of those to the 1.6% sections, about 6.6 $l \cdot min^{-1}$ vs 11.3 $l \cdot min^{-1}$. Second, outflows from the 4.0% sections were about 80% of those from the 1.6% sections, 4.1 to 5.9 $l \cdot min^{-1}$ vs 5.0 to 7.4 $l \cdot min^{-1}$. Erosion is directly proportional to flow rate (Foster and Meyer, 1972b; Kemper et al., 1985). Third, because of the sediment already present in the inflow to the 4.0% sections, less carrying capacity was available for sediment transport on the steeper slope sections (Foster and Meyer, 1972a). Fourth, on the 4.0% sections, the fast-flowing water rapidly

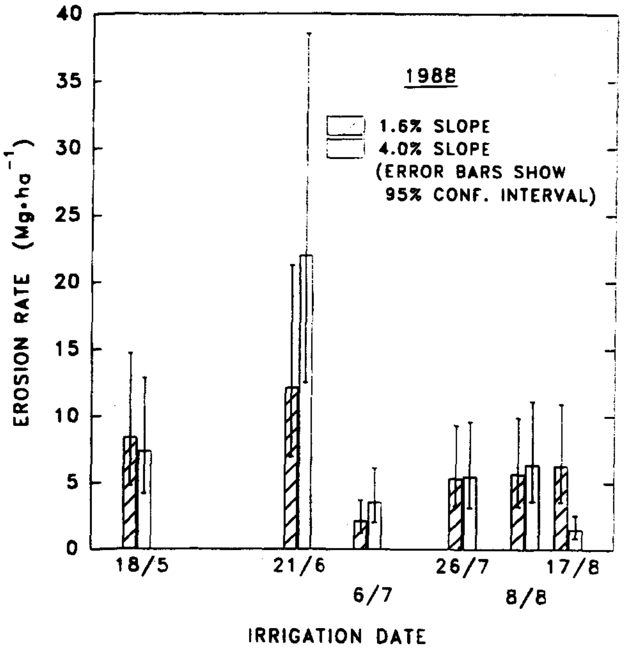

Fig. 1. Furrow erosion rates in 1988 from slopes of 1.6 and 4.0%. Inflow rates were 11.3 $l \cdot min^{-1}$ for the 1.6% slopes and approx. 6.6 $l \cdot min^{-1}$ for the 4.0% slopes.

eroded the furrows to form relatively deep, narrow channels. Field observations indicated that erosion decreased markedly when the channels eroded to reach a more resistant soil layer that better withstood the shear stress of the flowing water (Kemper et al., 1985). Brown et al. (1990) also reported a reduction in rill erosion rate once the channel had eroded to encounter a soil layer more resistant to detachment.

The erosion rates in 1988 (Fig. 1) varied from date to date but displayed no consistent trend over the entire irrigation season. The greatest erosion occurred by far on 21 June. This mid-June occurrence of a season-long maximum in furrow erosion is a commonly observed phenomenon on medium-textured soils in southern Idaho. On 21 June from the 1.6% slope section, much of the eroded soil being transported in the flowing water consisted primarily of relatively large, intact aggregates with diameters of approx. 3–4 mm. Alberts et al. (1980) also identified large aggregates in rill flow.

On 21 June, the erosion rate from the 4.0% slope greatly exceeded that from the 1.6% slope but, on 17 August, the opposite was true. This inconsistency was confirmed by our analysis of variance that revealed a significant ($P < 0.013$) interaction between irrigation date and furrow section slope. On 17 August, the erosion rate from the 1.6% slope was over 4 times that from the 4.0% slope. For that irrigation, we observed more headcuts on the 1.6% slope than on the 4.0% slope. Headcuts occur most in furrows with slopes exceeding 1% (Brown et al., 1988). The erosion process of headcutting adds much sediment to the furrow stream (Brown et al., 1988). Meyer et al. (1975) noted that erosion near headcuts was substantial.

Erosion rates varied from one irrigation to the next, even when the furrow slope gradient was the same (Fig. 1). The statistical analysis revealed that the erosion rates from the 1.6% slope sections differed significantly ($P \leq 0.02$) between the second and third and between the third and fourth irrigations. For the 4.0% slopes, the erosion rates differed ($P \leq 0.01$)

between the first and second, between the second and third, and between the fifth and sixth irrigations. Moreover, erosion rates in the fall were either the lowest or among the lowest measured at any time during the irrigation season.

3.1.2. 1989 study

In contrast to the apparently random variation in furrow erosion rates over the 1988 growing season, the 1989 erosion rates exhibited a clear trend over time (Fig. 2). As the growing season progressed, erosion from the 1.2%-slope furrows decreased steadily at a decreasing rate, approaching a late season average of approximately 0.10 $Mg \cdot ha^{-1}$. From 17 May to 7 June, the measured erosion rate dropped by over 50%. An appropriate nonlinear function to characterize such a steady response, when fit to the data using least squares, was

$$\mathrm{Log}_{10}(\text{Erosion Rate}) = -0.973 + 0.754 \times \exp(-0.0297 \times \text{Day}) \quad (1)$$

where Erosion Rate was the furrow erosion rate in $Mg \cdot ha^{-1}$, and Day was the number of days after the first irrigation of the season (Table 1). Values predicted using Eq. 1, after being back-transformed, are plotted on Fig. 2 along with the measured erosion rates.

Furrow erosion rates in 1989 from 1.2% slopes were, on average, only 4% of those in 1988 from 1.6% slopes (Fig. 1). Many researchers (e.g., Elliot et al., 1989) have suggested that a critical hydraulic shear exists below which little or no detachment or erosion occurs. If so, then the hydraulic shear exerted on the furrow's wetted perimeter by the runoff from the 1.2% slopes in 1989 may have been less than the critical shear for the Portneuf silt loam under the imposed experimental conditions. The relative magnitudes of the erosion rates shown in Figs. 1 and 2 are consistent with that interpretation.

These erosion rate differences from 1988 to 1989 (Figs. 1 and 2) were not related to furrow stream advance rates (data not shown), which are directly proportional to aggregate breakdown by slaking in the furrows (Kemper et al., 1988). On the 1.6% slopes in 1988,

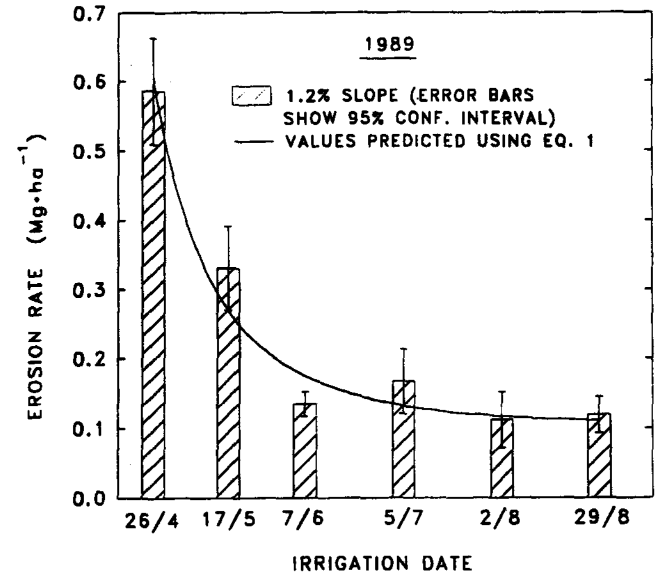

Fig. 2. Furrow erosion rates from 1.2% slopes at different irrigation dates in 1989.

the furrow stream advanced at 0.034 $m \cdot s^{-1}$ but at 0.055 $m \cdot s^{-1}$ on the 1.2% slopes in 1989. The faster advance on the 1989 site is difficult to explain. There was little or no residue in the furrows of either the 1988 or 1989 site. Of the two sites, one would expect the flatter 1989 site, cropped to maize for silage the year before, to exhibit slower rather than faster advance rates.

Since furrow erosion is directly proportional to outflow or runoff rates (Foster and Meyer, 1972b; Kemper et al., 1985), we examined infiltration that could have explained the erosion rate differences from 1988 to 1989. Infiltration, when expressed as percent of inflow volume, did not vary ($P > 0.23$) from one irrigation to another during the 1988 season (data not shown). It was, however, affected by slope gradient. The infiltration into the 1.6% slopes, 42%, was significantly greater ($P \leq 0.0001$) than that into the 4.0% slopes, 22%. In contrast, during the 1989 season, infiltration varied significantly ($P \leq 0.0001$) from one irrigation to another (Fig. 3). The season-long average infiltration into the 1.2% slopes in 1989, about 32%, was 76% of that into the 1.6% slopes in 1988. More infiltration in 1988 reduced runoff (data not shown) and the furrow stream's sediment carrying capacity, and should have reduced erosion, compared to 1989. Thus, the greater erosion in 1988 is not explained by infiltration differences.

The infiltration data of Fig. 3 do explain, however, the trend in erosion rates over the 1989 season (Fig. 2). With significantly less infiltration or intake in April and May, runoff was greater which, in turn, exerted more shear force on the furrow's wetted perimeter. This was at least one cause of the relatively high erosion rates early in the 1989 irrigation season (Fig. 2).

3.1.3. Variation in 1988 compared to 1989

In both 1988 and 1989, erosion rates from previously unirrigated furrows were significantly lower late in the season than they were early in the season (Figs. 1 and 2). This difference in erosion between spring and fall has been observed numerous times in both

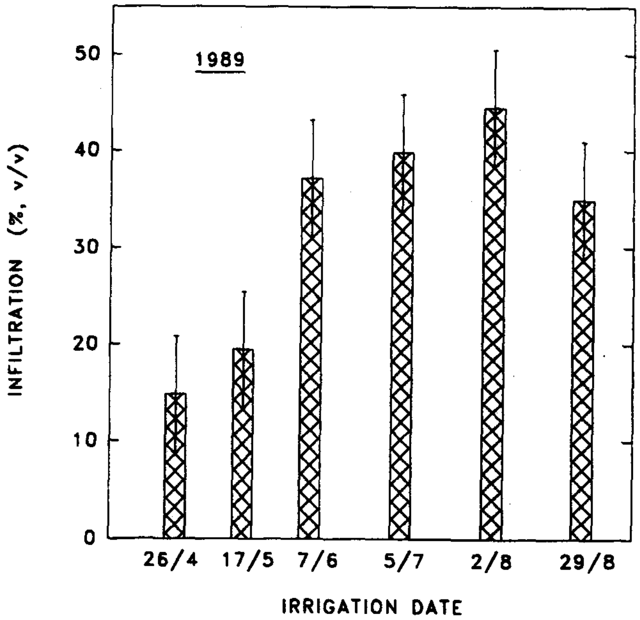

Fig. 3. Infiltration into 1.2% slopes at different irrigation dates in 1989.

cropped and fallow plots in southcentral Idaho (Berg and Carter, 1980; Kemper et al., 1985). The manner in which erosion rates in this study decreased over time, however, was clearly not the same from one year to the next. In 1989, but not in 1988, a monotonic decrease with time was observed (Fig. 2). Different trends from year to year may be caused by infiltration differences (as discussed above) or slight differences in surface soil water contents from light precipitation or heavy dew at the start of the irrigation, known to affect furrow erosion rates (Kemper et al., 1985). In cropped areas, composition of added organic material or residue decomposition rate could cause aggregate stability variation (Lehrsch and Jolley, 1992) that may, in turn, affect soil erodibility (Coote et al., 1988).

Residue decomposition may well have been responsible, at least in part, for the erosion trends differing from 1988 to 1989. The site tested in 1988 had been cropped to field bean for three consecutive years, then fallowed in 1987. During the summer fallow period, microorganisms likely decomposed much of what little crop residue was present before the experiment was conducted. In contrast, the site tested in 1989 had been cropped to maize the previous growing season. So at this site, continual microbiological breakdown of the previous year's crop residue likely released polysaccharides and other organic extracellular compounds (Harris et al., 1966) that may have altered surface soil physical properties that, in turn, steadily reduced erosion rates over the 1989 irrigation season (Fig. 2).

3.2. *Aggregate stability*

3.2.1. *Trends over the 1988 season*

Aggregate stability, in general, tended to increase from mid-May through mid-August (Fig. 4). The trend of change in aggregate stability from one irrigation to the next, however, differed between the 1.6 and 4.0% slopes. For the 1.6%-slope data, though the trend was upward, there were no statistically significant differences found in aggregate stability from

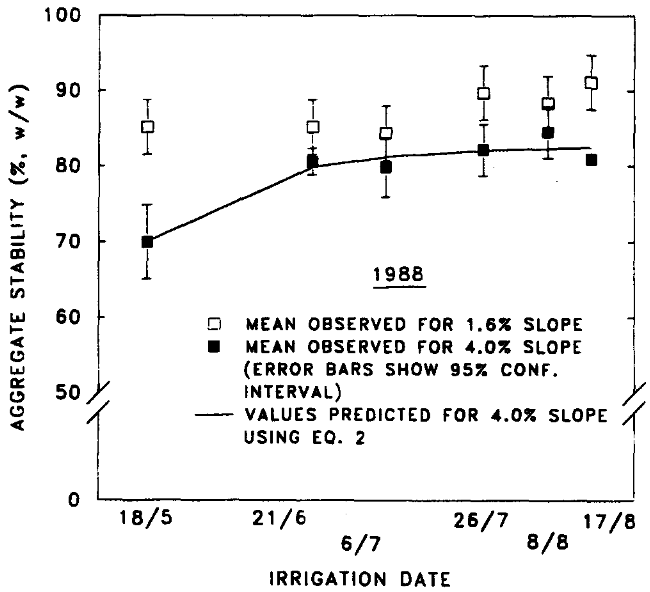

Fig. 4. Aggregate stability from slopes of 1.6 and 4.0% at different irrigation dates in 1988. The confidence interval for the aggregate stability of the 4.0% slope measured on 17 August was too narrow to be shown.

one irrigation to the next. In addition, no model we examined performed very well in characterizing the temporal variation in the aggregate stability of the 1.6%-slope furrow sections.

In contrast, for the 4.0% slope in 1988, aggregate stability increased steadily and significantly at a decreasing rate from the first through the fifth irrigation (Fig. 4). Microbiological activity may have played a role in this steady stability increase more apparent on the steeper slopes. In the spring and early summer, as the soil dried it would have warmed, encouraging microbial breakdown of any remaining plant residues and microbiological production of polysaccharides and other organic exudates that stabilize aggregates (Harris et al., 1966). Young et al. (1990) noted that differences in microbial activity and breakdown of organic compounds were factors responsible for temporal changes in aggregate stability. A nonlinear function describing this response, fitted using least squares, was

$$\text{Aggregate Stability} = 82.6 - 12.6 \times \exp(-0.0448 \times \text{Day}) \quad (2)$$

where Aggregate Stability was the percent by weight of stable aggregates and Day was as defined above. Values predicted using Eq. 2 along with the observed means are plotted on Fig. 4.

3.2.2. Slope gradient and water content effects on aggregate stability in 1988

Aggregate stability measured in 1988 on soil samples taken in furrows was consistently greater on flatter furrows (1.6%) than on steeper furrows (4.0%) at each irrigation (Fig. 4). The lower aggregate stability on the 4.0% slopes was likely a consequence of the lower organic matter content (0.9%) of the pale brown or whitish-colored subsoil prevalent on the surface of the steeper slopes. Gollany et al. (1991) found aggregate stability to be less for erosion-exposed subsoil horizons that were lower in organic carbon than Ap horizons.

Water content differences from one slope to the other, in general, were small (Table 2). For five of the six irrigations, the difference was no greater than 0.013 $kg \cdot kg^{-1}$. Such slight water content differences between slopes had no consistent effect on the aggregate stability measured at each irrigation (Fig. 4).

The difference in aggregate stability between the 1.6% and 4.0% slope sections on 18 May is notable (Fig. 4). Differences in water contents or drying history in the spring prior to the onset of the study on 18 May could have been responsible. Unfortunately, since no monitoring of the site occurred prior to 18 May, one can only speculate as to the cause.

Table 2
Water contents of soil samples taken to a depth of 5 cm in row furrows in 1988

Slope (%)	Water content ($kg \cdot kg^{-1}$)					
	Irrigation date					
	18/5	21/6	6/7	26/7	8/8	17/8
1.6	0.116	0.044	0.054	0.037	0.018	0.028
4.0	0.104	0.079	0.041	0.030	0.017	0.026

Water content changes from the beginning to the end of the season appeared to influence aggregate stability through the season. From May through early August in 1988, Portneuf aggregate stability increased steadily on the steeper slopes (Fig. 4) as water contents decreased (Table 2). This steady increase in stability with time has been seen in other intermountain-region soils of the Pacific Northwest (Bullock et al., 1988). This trend, a recovery phenomenon if you will, could have been caused by the chemical precipitation of slightly soluble bonding agents at contact points between soil particles (Kemper and Rosenau, 1984). These bonding agents could have been gypsum, silica, or carbonates of calcium and magnesium (Harris et al., 1966). The precipitation of bonding agents at particle contact points would have been a consequence of the drying that occurred in these soils over these months (Table 2).

The aggregate stabilities measured on samples from the 1.6% slopes (Fig. 4) provide additional evidence for this chemical precipitation with drying. By 26 July, the soil water content had dropped (Table 2) to 0.037 $kg \cdot kg^{-1}$, approaching air-dryness, about 0.02 $kg \cdot kg^{-1}$. By this time, apparently all bonding agents had precipitated because, from 26 July on, aggregate stability increased little for the remainder of the season (Fig. 4). The lack of rainfall (Table 1) and the very low soil water contents (Table 2) also minimized aggregate stability variation from 26 July through 17 August.

3.2.3. *Trends over the 1989 season*

Aggregate stability varied little and in a seemingly random manner from one irrigation to another (Fig. 5). Thus, for the second consecutive year on two different sites, aggregate stability of Portneuf silt loam on slopes of 1.6% or less did not exhibit statistically significant temporal variation from May through August.

In 1989, there was little relation between aggregate stability measured over the growing season and the water contents of soil samples taken in the furrows at each irrigation (Table 3). The soil dried steadily from April through July but the aggregate stability response over

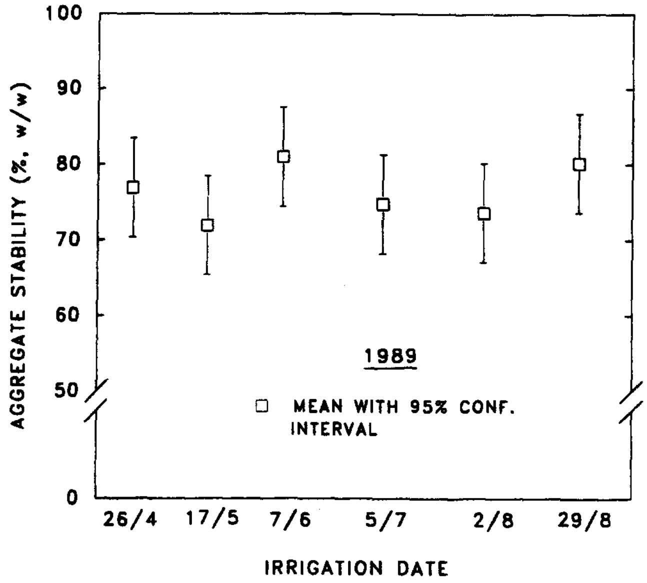

Fig. 5. Aggregate stability at different irrigation dates in 1989.

Table 3
Water contents of soil samples taken to a depth of 5 cm in row furrows in 1989

Slope (%)	Water content ($kg \cdot kg^{-1}$)					
	Irrigation date					
	26/4	17/5	7/6	5/7	2/8	29/8
1.2	0.158	0.135	0.128	0.046	0.055	0.059

the same period was erratic (Fig. 5). The upper 5 cm of the soil profile did not dry as much in 1989 as it did in 1988 (Table 2) due, in part, to the better distributed rainfall in 1989 (Table 1). If bonding agent precipitation increases aggregate stability, as seen in 1988 (Fig. 4) but not in 1989, it apparently must do so when soil water contents drop below 0.04 $kg \cdot kg^{-1}$. It is possible, however, that other soil factors could have countered any stability increase in 1989 owing to chemical precipitation with soil drying.

3.2.4. Variation in aggregate stability within a growing season and from year to year

The within-season variation in the Portneuf's aggregate stability observed in this study was comparable to that observed in other studies. For Portneuf silt loam in this study, aggregate stability varied in 1988 (Fig. 4) from 84.3 to 91.1% for 1.6% slopes, from 70.0 to 84.5% for 4.0% slopes, and in 1989 from 71.9 to 81.0% for 1.2% slopes (Fig. 5). Portneuf aggregate stability commonly varies over a 10-percentage point range from May through August (Bullock et al., 1988; Lehrsch, unpublished data). Over a 12-month period, however, Portneuf aggregate stability has been found (Bullock et al., 1988) to vary from 72 to 92%, a range twice as large, primarily because of freezing-induced changes (Lehrsch et al., 1991). Other soils that are subject to freezing, particularly when wet, vary greatly in aggregate stability over time (Lehrsch and Jolley, 1992). For Minnesota soils in crop production, aggregate stability varied by a factor of two (Ellsworth et al., 1991).

The Portneuf's temporal variation in aggregate stability differed from 1988 to 1989. For example, for 1.6% slope sections in 1988, aggregate stability was approximately 84% through 6 July and then increased abruptly to approximately 90% for the remainder of the season (Fig. 4), due in part to the lack of rainfall (Table 1) and low soil water contents (Table 2). In contrast, for the comparable 1.2% slope studied in 1989, stability fluctuated erratically from 72 to 81% for the entire irrigation season (Fig. 5). Lehrsch and Jolley (1992), who also observed different trends in aggregate stability variation from year to year, attributed the differences to annual variation in precipitation patterns. As discussed above, differences in soil water contents (Tables 2 and 3) and precipitation (Table 1) from year to year appear responsible, at least in part, for the differing trends found in this study.

3.3. Variation in furrow erosion related to changes in aggregate stability and other factors

Fig. 1 reveals that the furrow erosion rate measured on 4.0% slope sections in 1988 decreased significantly ($P \leq 0.0001$) from 22.0 to 3.5 $Mg \cdot ha^{-1}$ from 21 June to 6 July.

Such erosion response differences from one irrigation to another are likely caused in part by climatic processes, such as rainfall that change antecedent water contents at the soil surface. Two days prior to the irrigation on 6 July, just over 2 mm of rain fell. While the amount was slight, it may have helped reduce erosion rates (Kemper et al., 1985). Many investigators (e.g., Alberts et al., 1987; Imeson and Kwaad, 1990) have found temporal changes in erosion or soil erodibility to be strongly related to water content differences.

In 1989, as furrow erosion decreased steadily (Fig. 2), soil water contents prior to each irrigation also decreased steadily over the first two-thirds of the irrigation season (Table 3). With lower water contents in the soil mass just beyond the wetting front, the resultant potential gradient (not measured) may have limited the decrease in soil shear strength and, consequently, decreased erosion. Thus, there is evidence that lower matric potentials (i.e., drier soil profiles) may be serving to help stabilize the sediment or the thin soil seals that line the furrow wetted perimeters (Brown et al., 1988), thereby reducing erosion. Additional research should be conducted studying within-season furrow erosion variation in relation to soil strength or soil water contents in the uppermost 15 mm of soil along the furrow's wetted perimeter.

For the data from both study years, the correlation between furrow erosion rates and aggregate stability was not statistically significant. Three reasons for this finding are likely. First, the depth of sampling was probably too great. Furrow erosion occurs at the furrow's wetted perimeter. Thus, soil matrix properties within, say, 3 to 15 mm of the soil surface in the furrow should relate better to erosion rates than properties measured at greater depths below the soil surface. Second, as noted above, the magnitude of the change in aggregate stability from May to August was slight, making significant correlations more difficult to detect. Vapor wetting soil aggregates to a water content of 0.15 $kg \cdot kg^{-1}$ instead of 0.30 $kg \cdot kg^{-1}$ (Bullock et al., 1988) or analyzing field-moist aggregates (Lehrsch and Jolley, 1992) may have increased the magnitude of the detected aggregate stability change. Lehrsch et al. (1991) suspected that air-drying of aggregates prior to vapor wetting masked some temporal variation in aggregate stability. Third, the pronounced variation in measured erosion rates among replications, often observed in field studies (Meyer and Harmon, 1985), increased the proportion of unexplained variation in the statistical relation.

4. Conclusions

Furrow erosion rates in the same irrigation season varied by factors of up to two in 1989 or even six in 1988 for consecutive irrigations. In each of two study years, erosion rates were lower late in the growing season than they were early in the season. Additional field observations confirmed that furrow erosion rates in the fall were often less than they were earlier in the spring. The likelihood of such pronounced variation in erosion from one irrigation to another should be considered if one seeks to predict furrow erosion for a single irrigation, or for an entire growing season. A non-linear function that decreased steadily at a decreasing rate characterized the temporal variation in erosion in 1989.

For two consecutive years on two different sites with slopes of 1.6% or less, the wet stability of aggregates air-dried, then pre-wet, did not vary significantly within a growing season. In 1988, however, aggregate stability did increase significantly on 4.0%-slope furrows from mid-May through mid-August.

A portion of the season-long trends in erosion rates seemed to be explained by soil water content trends over the season. In contrast, slight though significant increases, up to 17%, in aggregate stability were not statistically correlated with changes in furrow erosion, due in part to much variation in measured erosion rates among replications.

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