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Sediment losses from cropland furrows

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Abstract Simulation experiments are performed using a physically based mathematical model which treats the dynamic interrelations of runoff erosion, soil characteristics, and movement of eroded soil along bedded furrows. Data from a field study of bedded rows with furrow gradients ranging from 0.5 to 6.5% are simulated, and the role played by sediment and furrow parameters are examined. Results from the simulations agree well with field measurements. These experiments show that soil losses depend greatly on the furrow gradient. Much of coarsest sediment may deposit at the flatter gradients but most will be carried at the intermediate gradients, and furrow rilling may occur at steep gradients.

Les pertes de sol des rigoles agricoles

Résumé Un modèle mathématique permet la simulation des processus physiques d'érosion superficielle, en relation avec les caractéristiques du sol, et le mouvement des particules solides dans les rigoles. Les données d'une étude *in situ* de rangées de rigoles inclinées de 0.5 à 6.5% permettent l'examen de l'intéraction des sédiments avec les caractéristiques des rigoles. Les résultats des simulations sont en accord avec les données du terrain. Ces expériences démontrent que les pertes de sol dépendent largement de la pente des rigoles. Les pentes les plus faibles peuvent provoquer le dépôt des particules tandis que les fortes pentes peuvent causer l'incision des rigoles. Les pentes intermédiaires correspondent au transport des particules.

INTRODUCTION

Cropland fields with bedded rows are common for cotton in the humid South, and ridged rows are used for other crops and cropping conditions throughout the United States. For situations where these rows have a continuous gradient in one direction, they function as micro-watersheds that drain only the runoff from between adjacent row ridges. For such conditions, the row sideslope is a short interrill area that discharges its runoff and sediment into the row furrow. Runoff then flows down the furrow, carrying part of all of the sediment from the row sideslopes and possibly scouring additional sediment by rill erosion from the furrow. Research conducted at the USDA Sedimentation Laboratory has served to evaluate row runoff rates, erosion rates, and sediment size distributions resulting from rainstorms of different intensities for a wide range of soils and cropping conditions.

Results from these and other field studies on small plots provide data for evaluating sediment movement along crop rows and sediment losses from typical intensively cropped agricultural fields. Computer simulations of sediment transport along flow systems of cropland fields offer a technique for greatly expanding the usefulness of the plot data. Using simulations we can study sediment losses from cropped fields and evaluate potential control measures for a much wider range of conditions than can be obtained entirely from experiments. The formulation and evaluation of one such model is described in the present paper. Because of space limitations, presentation of the mathematical formulation is limited to a brief outline of the model. The model verification is based on the field data reported by Meyer & Harmon (1984).

REPRESENTATION OF FURROW PROCESSES

Flow and sediment movement on croplands is envisioned as uniformly distributed over a system of parallel furrows. The furrows are considered to be prismatic, evenly spaced, and having identical cross-sectional shape. Sediment flux and flow are the same in all furrows for a spatially uniform rainfall. Thus, a single furrow is used in this model as the basic flow unit in simulating cropland processes. As rain falls over the furrow area, part of it may infiltrate into the soil. The remaining rainfall excess accumulates in the furrow and flows downfurrow, carrying with it the soil detached by the rain and by the erosive power of runoff itself. Any sediment particles that the flow cannot transport are deposited along the furrow. Depending on the flow characteristics, deposition or erosion may occur along the entire furrow; in other instances, deposition may be occurring along the upper end and erosion near the lower end.

MODELLING PROCEDURE

To postulate a model of the above processes, we have introduced various approximations, most based on experimental observations. These simplifying criteria are suitable for the intended use of the present model which is to study the effect of different row-sideslope erosion rates, sediment size distributions, and sediment densities (resulting from rainstorms of different intensities on different soils and cropping systems) on the rate and size composition of sediment lost from bedded fields of low to moderate slopes and various lengths at different rain intensities. For the experimental data to which the model applies, these approximations are not very restrictive.

These approximations include:

(a) Each storm is characterized by a constant rainfall intensity. Storms of different intensities may be studied, one at a time.

(b) Rainfall excess is spatially and temporally uniform with a non-limiting duration. This parameter is an input to the model obtained from either field measurements of the runoff rate or infiltration predictions.

(c) The sediment movement along the furrow proceeds under such conditions that bed features such as ripples and dunes are not in evidence. Thus, furrow flow resistance is solely characterized by bed surface roughness.

(d) The upstream end of the furrow coincides with the "micro-watershed divide" and, consequently, there is no upstream inflow to the furrow.

(e) The cross-sectional shape and slope of the furrow vary slowly all along its length and are not severely altered by erosion or deposition over the duration of the rainfall event. This is a reasonable assumption as long as scour along the furrow does not become appreciable. Cropped fields of low and moderate gradient seldom have much rill erosion along the furrows, because the flow is of a nonerosive velocity and/or because its transport capability is filled by sediment from the row sideslopes, leaving no potential for scour. However, on steeper fields, rilling may be severe and render the prismatic configuration inadequate;

(f) Lateral sediment delivery is generated at a constant rate by the impact of raindrops on the surface of the row sideslopes not covered by runoff. The properties of the soil eroded from the sideslopes are considered spatially and temporally uniform. The delivery rate and composition of eroded soil are inputs to the model obtained from either field studies of the type described below or from interrill erosion predictions.

In the present case, water and sediment movement in a furrow are modelled using a one-dimensional characterization. Flow and sedimentation processes are described by continuity equations and approximations for water movement and sediment transport. These equations are solved by analytical and numerical methods to yield flow and sediment distributions along the furrow (Alonso *et al.*, 1981, 1987). Inputs to the model are the furrow geometry and experimental data discussed in the following section on rate of runoff, sediment delivery, and sediment size distribution from the row sideslopes. The model in turn predicts the flow rate, sediment discharge, composition of the sediment load, scour erosion, and sediment deposition for the furrow as functions of downfurrow distance.

MODEL VERIFICATION

The authenticity of a computational model involving several simplifying approximations can only be assessed by simulating the prototype response. The present model was designed to evaluate soil losses and sediment size distributions from a range of conditions that are typical of intensively cropped fields. Data obtained from field experiments are presently available for about 20 soils ranging from clays to sandy loams and several cropping systems at rainstorm intensities ranging from 10 to more than 100 mm h^{-1}. The model was used initially to determine the effect of furrow gradient and rain intensity on the rate and physical characteristics of sediment losses from bedded crop rows. The field data collection procedures and results from this preliminary evaluation are presented in the following sections.

FIELD STUDIES

Bedded rows were established on a field of a well-aggregated Loring silt loam soil. Row sideslopes averaged 23% steepness, and row furrow gradients were exactly 0.5, 2.0, 3.5, 5.0, and 6.5%. Rows were 0.96 m wide and 9.3 m long, and plots were initially in a bare, tilled condition. A series of rainstorms was applied at intensities of 26, 70 and 108 mm h^{-1} by a multiple-intensity rill/row rainfall simulator with the same general characteristics as the single-nozzle rainfall simulator used for row-sideslope experiments (Meyer & Harmon, 1979). Runoff samples were collected periodically during all rainstorms to obtain data on runoff and erosion rates. Additional samples were collected to evaluate the size distributions of the sediment eroded during the different conditions studied.

An identical series of rainstorms was applied with a row sideslope rainfall simulator to adjacent 0.91 by 0.96 m plots that duplicated a section of the longer plots. These runoff samples were used to evaluate row-sideslope erosion, runoff, and sediment size distribution, and the results were assumed to represent sediment delivery from the row sideslopes to the furrows of the longer plots.

RESULTS AND DISCUSSION

Soil losses

The measured and simulated soil losses from the ends of the furrows for rainstorm intensities of 26, 70, and 108 mm h^{-1} are shown in Table 1. The measured rates represent averages of replicated tests. The simulated total losses compare well with the measured losses over the entire range of field conditions. Both field observations and computer simulations indicate (a) deposition of sideslope sediment at 0.5% gradient, (b) little to moderate scour at 2.0, 3.5 and 5.0% runs, and (c) serious scour at 6.5%. These data show how much of the sediment lost was eroded from the row sideslopes (interrill erosion) and how much from the row furrow (rill erosion). For the conditions studied, approximately 20% of the row width was covered by runoff. Therefore, erosion per unit area as measured from the row sideslopes was multiplied by 0.8 to obtain the measured rate of sediment lost from the

Table 1 Sediment losses from a row furrow and source of that sediment for different rainstorm intensities on Loring silt loam

	Measured			Predicted		
Furrow grade (%)	Total loss (kg h^{-1})	Loss from sideslope (kg h^{-1})	Depos.(+) scour (-) (kg h^{-1})	Total loss (kg h^{-1})	Loss from sideslope (kg h^{-1})	Depos.(+) scour (-) (kg h^{-1})
Rainstorm of 26 mm h^{-1}						
0.5	1.3	2.1	+ 0.8	0.9	1.8	+ 0.9
2.0	2.3	2.1	- 0.2	2.3	1.8	- 0.5
3.5	2.9	2.1	- 0.8	2.7	1.8	- 0.9
5.0	2.8	2.1	- 0.7	2.8	1.9	- 0.9
6.5	3.2	2.1	- 1.1	3.3	1.9	- 1.4
Rainstorm of 70 mm h^{-1}						
0.5	7.9	12.2	+ 4.3	7.2	11.3	+ 4.1
2.0	15.2	12.2	- 3.0	13.7	11.5	- 2.2
3.5	15.3	12.2	- 3.1	14.9	11.5	- 3.4
5.0	15.5	12.2	- 3.3	16.1	11.7	- 4.5
6.5	21.4	12.2	- 9.2	21.0	11.7	- 9.3
Rainstorm of 108 mm h^{-1}						
0.5	15.6	31.4	+15.8	15.2	25.1	+ 9.9
2.0	34.0	31.4	- 2.6	31.4	25.8	- 5.6
3.5	34.9	31.4	- 3.5	36.2	26.1	-10.0
5.0	36.2	31.4	- 4.8	37.6	26.4	-11.2
6.5	43.3	31.4	-11.9	43.0	26.5	-16.5

sideslopes. To predict the loss from the sideslopes the measured erosion per unit area was multiplied by the simulated exposed interrill area. These different procedures explain the differences between measured and predicted total soil losses from the sideslope areas. The net rate of deposition or scour was calculated as the algebraic difference between the total loss from the row furrow and the total soil loss from the sideslopes. Deposition indicates that some of the sediment eroded from the row sideslopes deposited along the flow part of the furrow. Scour indicates that the flow caused rill erosion in addition to transporting all the sediment eroded from the row sideslopes.

To understand these results, one must recognize that erosion in general, and losses from furrows specifically, are governed by the factor that is limiting, available detached soil or transport capability. The rates of erosion from the row sideslopes are quite close to the total losses from the furrows at gradients of 2.0, 3.5, and 5.0% (Table 1). At these gradients, the runoff was transporting essentially all of the available sediment, but it was not eroding much additional soil by scour or rilling. The sediment losses at 0.5%

were less than the available soil, so transport was limiting and much of the sediment from the row sideslopes was depositing in the furrows. This buildup of deposited sediment was clearly evident in the furrows following the tests, and it was duly predicted by the model. For runs at rainfall intensities equal or greater than 70 mm h^{-1}, and for all runs at 6.5% gradient, major rilling in the furrow was both observed in the field and predicted by the model. In these instances, total sediment loss included soil eroded by scour along the furrow in addition to the soil eroded from the row sideslopes. The levelling of the total loss trend between furrow gradients of 2.0 and 5.0% is obvious. Of course, the gradient at which deposition essentially ceases and the gradient where rilling begins may be different for other row lengths, soils, cropping conditions, and rainstorm characteristics, but the trend of the sediment loss data may be expected to follow that shown in Table 1.

Composition of sediment losses

The measured and predicted sediment size distributions for 0.5, 3.5, and 6.5% gradient at 108 mm h^{-1} are presented in Table 2. This table also gives the measured size distribution of the sediment lost from the sideslopes. The predicted distributions compared reasonably well with the observed values.

The eroded sediment was observed to contain coarse particles as large as 15 and 20 mm in size. This result is confirmed by recent research which has established that many well aggregated soils erode with a large portion of

Table 2 *Size distribution of sediment lost from sideslopes and from a row furrow for a rainstorm of 108 mm h^{-1} on Loring silt loam (distributions are given in mass % for furrow gradients of 0.5, 3.5, and 6.5%)*

Sediment size (mm)	*Loss from sideslopes*	*Total loss at end of furrow*					
		Measured			*Predicted*		
		0.5%	*3.5%*	*6.5%*	*0.5%*	*3.5%*	*6.5%*
≤0.004	*12.8*	*15.7*	*9.4*	*8.0*	*18.2*	*8.8*	*7.9*
≤0.008	*14.5*	*23.3*	*12.3*	*10.8*	*20.7*	*13.3*	*9.7*
≤0.016	*28.1*	*44.1*	*25.4*	*22.8*	*39.6*	*24.7*	*20.8*
≤0.032	*58.0*	*76.1*	*55.3*	*48.5*	*78.3*	*52.4*	*44.6*
≤0.063	*71.5*	*83.3*	*68.9*	*60.1*	*92.0*	*65.1*	*56.4*
≤0.125	*75.1*	*86.5*	*72.9*	*64.9*	*94.6*	*69.5*	*60.9*
≤0.250	*79.4*	*88.7*	*76.6*	*69.2*	*96.2*	*72.5*	*65.5*
≤0.500	*85.6*	*91.0*	*81.2*	*76.5*	*97.8*	*76.7*	*73.2*
≤1.000	*93.8*	*94.7*	*89.4*	*85.7*	*99.2*	*84.3*	*82.9*
≤2.000	*98.7*	*97.7*	*95.8*	*92.2*	*99.9*	*92.6*	*90.2*
All sizes	*100.0*	*100.0*	*100.0*	*100.0*	*100.0*	*100.0*	*100.0*

their sediment in the form of very coarse aggregates (Meyer *et al.*, 1980).

The model tends to overestimate the amount of deposition of the larger fractions at the lowest gradient. Nevertheless, the model correctly predicts a shift of the sediment loss distribution towards a finer composition as a result of the deposition of the coarser material. Allowing for the variability that is common with field experiments such as those described in this paper, the data clearly indicate that all sizes delivered from the sideslopes were lost from the furrow at the 3.5% gradient. This result tends to reinforce the above conclusion that sediment is transported at near equilibrium capacity at the intermediate gradients.

At 6.5% gradient, the additional coarse material detached by the concentrated flow significantly increases the content of aggregate size sediment lost from the furrow. This increase occurs at the expense of a relative decrease in the content of clay and silt size sediment.

The field sediment size data indicate that as the furrow gradient increases from 0.5 to 6.5%, the clay size portion of the total sediment loss decreases by about 50%, the silt size portion decreases by about 25%, and the sand/aggregate size portion experiences a twofold increase.

The simulation runs conducted at intensities of 26 and 70 mm h^{-1} show, in general, trends similar to those at 108 mm h^{-1}. Of course, the rates of sediment loss were greatly different. Nevertheless, it is apparent from the present results that row furrow gradient affects the size distribution of sediment lost from bedded rows and the rate of loss of different sediment size classes. The capability of the present model to predict the rate of sediment loss for different size classes is an important asset. This information is critically needed in the proper design of both vegetative and hydraulic sediment filters, since not all filters are capable of retaining all sizes.

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