# Runoff Through and Upslope of Contour Switchgrass Hedges

**Seth M. Dabney***
**Glenn V. Wilson**
**Keith C. McGregor (retired)**
USDA-ARS
National Sedimentation Lab.
P.O. Box 1157
Oxford, MS 38655

**Dalmo A. N. Vieira**
USDA-ARS
National Sedimentation Lab.
P.O. Box 639
State University, AR 72467

**Grass hedges are specialized vegetative buffers effective in trapping sediment, but less is known about their ability to reduce or redirect runoff. Runoff and sediment yield from natural rainfall were measured during 8 yr from 0.1-ha contour-planted plots with and without 1-m-wide switchgrass (*Panicum virgatum* L.) hedges at their lower ends. Plots had slope lengths of 22 m with a steepness of 5%, were located on silt loam soils near Holly Springs, MS, and were cropped to conventional-tillage corn (*Zea mays* L.). During the first 4 yr of the study, care was taken to conduct tillage is such a way that no soil was thrown into the grass hedge, while during the last 4 yr of the study, primary disk tillage immediately adjacent to the grass hedges created soil berms that acted as low terraces. Hedges reduced the fraction of rainfall that ran off the plots, and hedges with soil berms reduced runoff even more. The runoff curve number (CN) for a 2-yr return period rainfall event was about 78 for plots with no hedges, 70 for plots with hedges, and 61 for plots with hedges with berms. Without berms, 95% of runoff passed through the hedges. In contrast, with berms most runoff (>85% from runoff events <3 mm $d^{-1}$; >55% for events <80 mm $d^{-1}$) flowed upslope of and parallel to the hedges. With or without berms, grass hedges decrease sediment yield by a factor of 0.25 to 0.28.**

Abbreviations: CN, curve number; EI30, rainfall erosivity; RUSLE2, Revised Universal Soil Loss Equation, version 2.

Grass hedges (also called *vegetative barriers*) are narrow strips of dense perennial grass planted close to the contour to reduce and slow runoff, decrease soil erosion, and trap sediment (Dabney et al., 2009). This technology has been used for many years in some parts of the world (Vélez, 1952), but USDA grass hedge research was only reinitiated in the late 1980s (Kemper et al., 1992). Grass hedges represent a special case of the conservation practice called Vegetative Barriers (Code 601) that the NRCS added to its National Handbook of Conservation Practices in 2001. The national practice standard (NRCS, 2003) states that "For this purpose, barriers are designed to slow runoff by increasing path length and by retarding and spreading run-on water ... To redirect flow, a berm must exist at the upslope edge of the barrier and/or a channel must exist immediately upslope of the barrier." Dabney (2006) described berm or channel occurrences averaging 0.15 m in depth at the upslope margin of 7-yr-old grass hedges, but no quantitative measurements of the effects of such oriented roughness features on runoff and sediment transport partitioning have been reported.

The hydraulic roughness of vegetative barriers and other vegetative buffers depends greatly on the flow regime. Dabney (2003) reported that the apparent Manning's $n$ of buffers could vary across two orders of magnitude (0.02–2.0). Vegetative residues trapped against buffer vegetation result in greater hydraulic

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*Corresponding author (seth.dabney@ars.usda.gov).
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resistance, deeper flow depths, and greater opportunity for sediment deposition (Temple and Dabney, 2001; Jin et al., 2002). Because of their relatively large stem diameter (Dunn and Dabney, 1996) and upright growth habit, stiff-grass hedges have a much greater ability to resist inundation than finer stemmed buffers. Hedges achieve their greatest levels of hydraulic resistance in situations where concentrated flows at their upper edge reach depths of 0.2 to 0.3 m (Temple and Dabney, 2001; Dabney, 2003). At low flows that would not submerge finer stemmed vegetation, stiff-grass hedges behave like other grass buffers in the way that they slow runoff and trap sediments. At very low flows that do not submerge surface residues or soil roughness elements, the effects of grass hedges on hydraulic roughness may not even be noticeable.

Where detailed data on soil physical properties are limited, the effect of land management on the partitioning of rainfall between infiltration and runoff is often parameterized in terms of a curve number (Hawkins et al., 2009) or with a bucket model (Kirkby et al., 2008). In the CN conceptual model, no runoff occurs until after an "initial abstraction" is reached, and after that runoff becomes an increasing fraction of rainfall as the difference between total rainfall and total runoff approaches a "maximum detention storage" and the runoff rate asymptotically approaches the rainfall rate. In contrast, in the bucket model, no runoff occurs until after a "runoff threshold" is reached, and after that runoff is a constant fraction of the additional rainfall. The "initial abstraction" and the "runoff threshold" are equivalent and account for processes such as infiltration, interception, and surface storage that take place before runoff begins. The difference between the two conceptual models is in how additional rainfall is partitioned between infiltration and runoff.

Vetiver grass (*Vetiveria zizanioides* L.) has been promoted for use as a grass hedge in tropical regions (www.vetiver.org/, accessed 14 Apr. 2011, verified 21 Sept. 2011), but a lack of cold hardiness limits its use in much of the continental United States. Switchgrass is a native grass with a wide region of adaptation in the United States (Dewald et al., 1996; Dunn and Dabney, 1996; Dabney et al., 1999) and the characteristics needed for use as a stiff-grass hedge. Switchgrass has received much attention as a bioenergy crop (McLaughlin and Kszos, 2005). Dabney et al. (2009) demonstrated how stiff-grass hedges planted for soil conservation purposes could provide a biomass harvest while maintaining significant conservation benefits.

Several researchers have reported rainfall simulator studies to quantify the runoff and erosion reduction benefits of narrow grass buffers and stiff-grass hedges (Raffaelle et al., 1997; Gilley et al., 2000; Blanco-Canqui et al., 2006). Using natural rainfall plots, Dabney et al. (2009) found that the conservation benefits of stiff-grass hedges on erosion plots that were farmed up and down the slope (perpendicular to the hedges) increased with hedge age and management that left residues (hedge trimmings) in the field. The objectives of this study were to: (i) evaluate the benefits of grass hedges in reducing natural rainfall runoff and soil erosion when farming is done on the contour; (ii) determine the influence of berms created by tillage adjacent to the hedges on conservation benefits; and (iii) parameterize the runoff results in terms of the bucket model and explore the implications of the results in terms of a corresponding CN representation.

## MATERIALS AND METHODS

The study was conducted at the North Mississippi Branch of the Mississippi Agricultural and Forestry Experiment Station, Holly Springs, MS, on four 45-m-wide and 22.1-m-long plots with 5% slopes on Providence (a fine-silty, mixed, active, thermic Oxyaquic Fragiudalf) and Memphis (a fine-silty, mixed, active, thermic Typic Hapludalf) silt loam soils. These plots were established in 1959 and have been used for a variety of studies, several focused on determining the contouring **P** factor for the Universal Soil Loss Equation (Carter et al., 1968; McGregor et al., 1969, 1996; Mutchler et al., 1994). A concrete channel located on the lower boundary of each plot was set at a 0.3% grade to direct runoff to a 0.3-m H flume with an N-2 size Coshocton-wheel runoff sampler that had been modified as described by Carter and Parsons (1967). Coshocton-wheel composite samples were collected in tanks located in sumps downslope from each plot.

During 1995, in preparation for this study, the plots were uniformly cropped to soybean [*Glycine max* (L.) Merr.] and two of the plots, N5 and E5, were selected to receive switchgrass hedges. This selection was not random. Rather, as discussed below, the plots assigned to grass hedges had been generally assigned "poorer" management (less fertilizer, more intense tillage, wider rows; see supplementary Table 1) and had experienced greater runoff and erosion during the 1960 to 1994 period. Switchgrass was seeded in a 1-m-wide strip just upslope of the concrete collector during the spring of 1995, and hedges were clipped to a height of 0.4 m in October. Throughout 1996, gaps in the hedges were filled by transplanting grass clumps from a nursery area. The hedge plots were further modified by the addition of 0.15-m H flumes with N-1 sized Coshocton-wheel samplers to allow sampling of runoff and sediment that was redirected by the hedge and transported laterally off the plot immediately upslope of the grass hedges (Fig. 1). These additional flumes and samplers were designated N5X and E5X.

Beginning in 1996, the plots were cropped to conventional tillage corn that was planted flat and exactly on the contour rather than parallel to the hedges or the collection troughs (Fig. 1). The corn rows were placed on the contour, which resulted in point rows running into the hedges. The crop was planted with a four-row planter and the point row ends were planted by hand. Conventional tillage consisted of disking twice to a depth of 0.13 m, chisel plowing to a depth of 0.2 m, and harrowing with a "do-all" (a combination implement comprising a rolling stalk chopper followed by a spike-tooth harrow) to smooth the field and create a seedbed before planting. Corn was planted in 0.97-m rows, generally in early April of each year, and harvested in September. Corn stalks were shredded after harvest, and the residue was left on the plots. The average corn grain yield during the 8 yr of this study was 8.0 Mg $ha^{-1}$ $yr^{-1}$.

During the years 1996 through 2000, care was taken so that the disk and chisel plow did not run close enough to the hedges

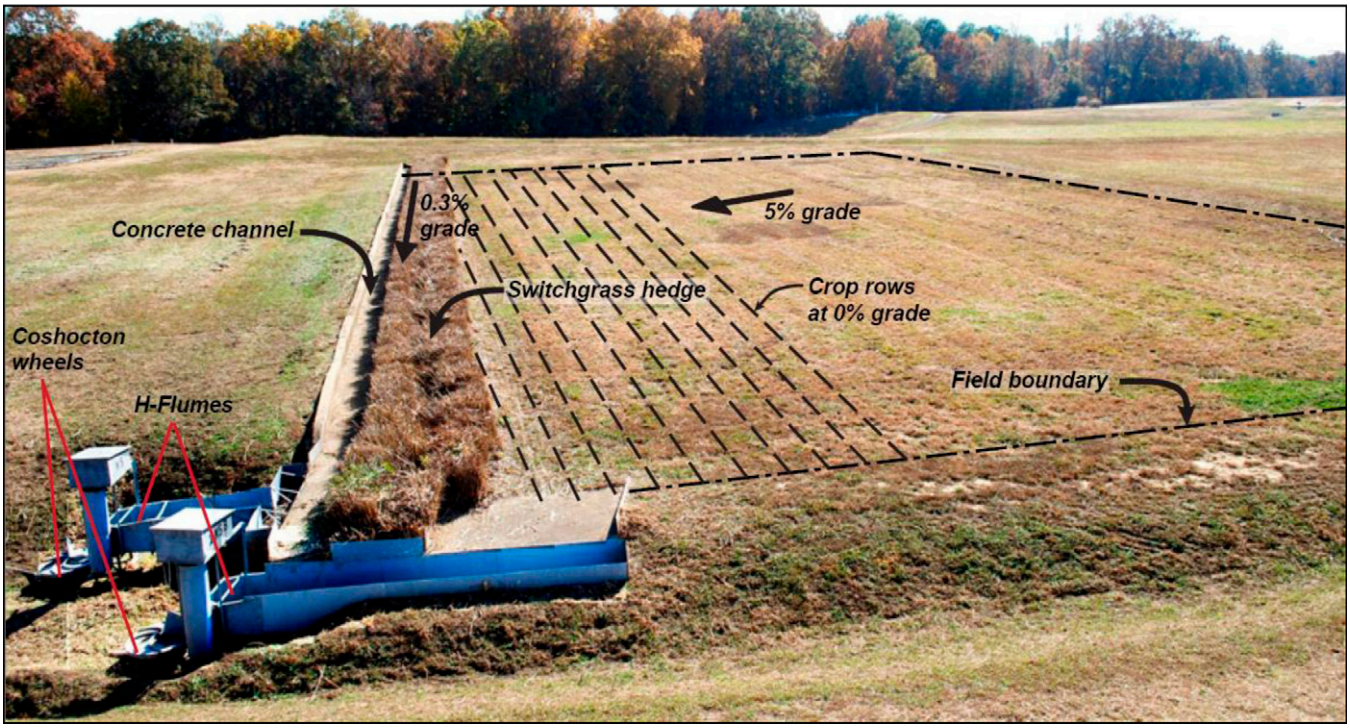


**Fig. 1. Runoff plots were 22 m long and 46 m wide; tillage was performed parallel to the grass hedge and the downslope plot boundary at a 0.3% gradient; corn planting was on a true contour. Runoff passing through the hedges or flowing laterally upslope of the hedges was measured and sampled separately.**

to throw clods into the grass, and the do-all was used to smooth any dead furrow at the lower edge of the tilled area. Starting in April 2001 and continuing annually through 2004, the primary tillage was moved closer to the hedges and any soil thrown against the hedges was left in place. This change to a more conventionally applied tillage system resulted in the development of a 12- to 16-cm-high earthen berm centered at the upslope edge of the hedges as described by Vieira and Dabney (2011). Because redirected runoff flowing upslope of the hedges was greatly increased by the development of the soil berms, during August 2001, the 0.15-m N5X and E5X H flumes and N-1 size Coshocton-wheel samplers were replaced with larger 0.3-m H flumes and N-2 size samplers.

Switchgrass hedges were managed by clipping to a height of 0.6 m twice each year, during May or June and again in October. When cutting the hedges, clippings that fell in or above the hedge were left, while clippings that fell in the concrete channel were collected and discarded. At each clipping, a sample of the clippings was collected, dried, weighed, and returned to the plot area.

Runoff was quantified by digitizing charts from FW-1 water level recorders (Brakensiek et al., 1979). If the water level recorder record was lost, the volume of the Coshocton-wheel sample was used to estimate the runoff using plot-specific calibration equations. Breakpoint rainfall with about 5-min resolution was determined from charts of a 20.3-cm-diameter weighing rain gauge located on site and was used to determine the rainfall erosivity (EI30) of each event with >12.7 mm of rainfall and for smaller storms with 15-min intensities exceeding 25 mm $h^{-1}$ (Renard et al., 1997). Storms were separated when 6 h passed with <1.3 mm of rainfall. In some cases, Coshocton-wheel samples accumulated runoff from several storms occurring within a few days (over a weekend or holiday). In this analysis, single and multiple rainstorm precipitation totals associated with individual composite runoff samples were treated as individual observations; the effects of this aggregation of rainfall events on storm statistical distributions are discussed below.

Runoff and erosion data from the grass hedge establishment year (1996) were not considered in the analysis. The period from 1 Jan. 1997 to 30 Sept. 2004 was divided into no-berm (before 4 Apr. 2001) and berm periods, based on the date of the first tillage operation that threw soil into the grass hedges (Vieira and Dabney, 2011). Berms existed only as a subcategory of the hedge treatment, and the experiment was analyzed as if there were three treatments: (i) no hedge (1997–2004); (ii) hedge, no berm (1997–2001); and (iii) hedge, berm (2001–2004).

## Data Analysis

### Rainfall–Runoff Relationships

The CN method is widely used to transform rainfall event depth ($P$) into storm runoff depth ($Q$). The NRCS (2004) maintains official tabulated CN values reflecting the soil hydrologic group and land management. These values are routinely used in several operational erosion and water quality models that are driven by daily rainfall. It is therefore of some interest to know the effect of grass hedges on CN values.

The storage index $S$, sometimes called the *maximum retention* or *loss parameter*, is a mathematical transform of the CN and has the same units as precipitation. This storage index represents the maximum amount of rainfall that will not appear as runoff even for very large rainfall events. Using SI units, $S$ (mm) is related to CN by

$$S=\frac{25,400-254\text{CN}}{\text{CN}} \quad [1]$$

This storage index varies from ∞ to 0 as the CN varies within its mathematical limits of 0 to 100. When the initial abstraction ($I_a$), the amount of rainfall that occurs before runoff begins, is taken as 0.2$S$, as is currently assumed in NRCS (2004), the CN method postulates that $P$ and $Q$ are related by

$$Q=\frac{(P-0.2S)^2}{P+0.8S} \quad [2]$$

The quadratic equation represented by Eq. [2] can be solved to give an estimate of $S$ for any $P$–$Q$ pair (Hawkins et al., 2009):

$$S=5\left[P+2Q-\left(4Q^2+5PQ\right)^{0.5}\right] \quad [3]$$

An alternative to the CN method is the bucket model, in which runoff is described as a fixed fraction of the abstracted rainfall. Montgomery and Clopper (1983) found that this formulation described their data equally as well as the CN method and this formulation was adopted in the Pan-European Soil Erosion Risk Assessment model (Kirkby et al., 2008). In this formulation,

$$Q=p(P-P_0) \quad [4]$$

where $P_0$ is the rainfall where runoff just begins and $p$ is the proportion of additional rainfall that appears as runoff.

Observed runoff and precipitation pairs were analyzed by ANOVA using Proc Mixed (SAS Institute, 1996) in SAS 9.1.3 to estimate runoff as a linear function of event rainfall depth:

$$Q=a+bP \quad [5]$$

Equation [5] was fitted to all $P$–$Q$ pairs with minimum $P$ thresholds of 0, 12.7, 25.4, and 38.1 mm. This approach used all of the data above the selected threshold and allowed evaluation of the impact of varying $P$ thresholds on estimates of the runoff threshold and runoff fraction. Based on this formulation, $I_a$ and $P_0$ are equal and can be estimated as $a/b$ (the value of $P$ where $Q = 0$), and $b$ in Eq. [5] is an estimate of $p$ in Eq. [4]. The behavior of the corresponding CN was investigated by using the regression equation (Eq. [5]) to generate corresponding predicted values of $Q$ for a specified $P$ and then solving for an effective $S$ using Eq. [3]. An effective CN was then determined from $S$ using Eq. [1]. The assumption that $I_a = 0.2S$ was tested as a check on the applicability of Eq. [3].

Several methods, including least squares, frequency matching, and asymptotic curve fitting, are in use for directly estimating CN values from measured data (Hawkins et al., 2009; Cao et al., 2011). The original CN method was developed using the largest annual events, the "annual floods" with a 2-yr return period, from small-watershed records. This approach requires a long-term data record in order that the median be representative of the population. To have an adequate number of events available, smaller storms may be included in the analysis, but including runoff from small rainfall events results in higher CN estimates because runoff from small rain events only occurs for antecedent conditions that are favorable for runoff production or from high-intensity rainfall events. Data censoring methods have been used to alleviate this problem (Hawkins et al., 1985; Feyereisen et al., 2008; King and Balogh, 2008; Cao et al., 2011), but iterative searching through ordered rain event data often stops as soon as a large rain that produces little runoff is encountered. Asymptotic methods require selection from among several models and that cannot be done a priori (Hawkins et al., 2009). Direct calculation of CN from Eq. [3] based on natural or ordered (highest $P$ paired with highest $Q$) rainfall–runoff pairs can result in wide variations in CN observations between the limits of 0 and 100. Preliminary analysis found that this variability rendered the treatment effects insignificant in ANOVA of the current data set, whereas the bucket model showed that there were statistically significant treatment differences in the runoff fraction, as discussed below.

### Runoff Flow through or above Grass Hedges

To test the effect of berms on the partitioning of runoff flow through vs. redirected by the hedges, only data from the plots with hedges were considered and the natural logarithm of runoff upslope of the hedges was regressed on the logarithm of total plot runoff. This allowed estimation of a power function of runoff flowing upslope of the hedges during the berm and no-berm periods as a function of runoff event size.

### Hedge Effects on Sediment Yield

Sediment yield estimates were analyzed using the Revised Universal Soil Loss Equation, version 2 (RUSLE2) formulation, which assumes that erosion is linearly related to EI30, the product of an event's total kinetic energy and the event's maximum 30-min intensity (Renard et al., 1997). To strengthen statistical tests of hedge and berm effects, variation in the data caused by predictable changes in soil cover conditions was removed by dividing sediment yield observations by the corresponding monthly RUSLE2 $C$ factors calculated for the management system used on the plots. The adjusted sediment yield values were then used in an ANOVA to test hedge and berm effects using EI30 as a covariate. Because the berm and no-berm periods experienced different weather, a second ANOVA that used unadjusted sediment yield values was also conducted in which month was included as a class variable to account for seasonal effects. Using this analysis, the average monthly sediment yield for each treatment was calculated as the product of 8-yr average monthly rainfall erosivity times the estimated monthly slope of the sediment yield vs. the EI30 relationship of each of the three treatments.

## Statistical Analysis

In the total runoff and sediment yield analyses, the experimental design was a split plot, with main unit having three treatments with two plots for each treatment, where two of the plots were the same for two of the treatments (hedge, berm and hedge, no berm). Month was used as a class variable to remove systematic seasonal variation in runoff responses to rainfall. Each storm was a repeated-measure subunit, with rainfall depth or EI30 used

as a covariate to explain the effect of a storm on the runoff depth or sediment yield. Each plot provided an estimate of this relationship and plot-to-plot variations between the trend estimates were considered random coefficients and were used as a component of the subunit error for statistical analysis. The residual was lack-of-fit pooled across all plots for each treatment and was used as the subsampling error. The error used for an $F$ test involving the covariate (rainfall depth or EI30) were based on this subunit error.

In the case of partitioning runoff between flow parallel to or passing through grass hedges, the design was a split plot where the main unit was berm, with two plots per main unit, and the subunit was event. The logarithm of total runoff was a covariate used to explain the effect of a storm on the logarithm of runoff upslope of the hedge, with lack-of-fit included in the subunit error using an autoregressive covariance structure for repeated measures.

# RESULTS

## Rainfall Depths

The complete record of rainfall events (separated by 6 h with <1.3 mm of rain) recorded at Holly Springs from 1959 through 2004 is reported in supplementary Table 2, and multiple storm contributions to individual composite runoff samples are recorded in supplementary Table 3. Our analysis focused only on the period 1996 to 2004. The populations of individual storms and composite rainfall depths associated with individual runoff measurements were both fitted by a $\gamma$ distribution (Table 1). Goodness-of-fit statistics indicated that the observed and expected frequency distributions were not statistically different for the $\gamma$ distribution, in contrast to other distributions that were fitted: normal, lognormal, and Weibul. An extreme event occurred between 26 and 29 Nov. 2001 when three individual rainstorms with depths of 79, 10, and 187 mm were sampled as a composite 276-mm event. Inspection of Table 1 reveals that the November 2001 event exceeded the 100-yr return period for both individual and combined event trends. Excluding this combined event marginally improved the $\gamma$ fit but had little effect on the resulting $\gamma$ distribution parameter estimates (Table 1).

**Table 1. Parameters of individual and combined rainfall events for the period 1996 to 2004 fitted to a gamma distribution, and the resulting rainfall depths for several return periods.**

| Effect | Individual events | Combined events | Combined events without 26–29 Nov. 2001† |
|---|---|---|---|
| Events, no. $yr^{-1}$ | 77.2 | 58.4 | 58.2 |
| Threshold, mm | 0.25 | 0.51 | 0.51 |
| Shape ($\alpha$) | 0.906 | 0.863 | 0.882 |
| Scale ($\sigma$), mm | 17.59 | 23.27 | 22.76 |
| Return period, yr | Size of predicted event (rainfall depth, mm) | | |
| 0.5 | 61 | 72 | 71 |
| 1 | 73 | 88 | 87 |
| 2 | 85 | 103 | 102 |
| 5 | 101 | 124 | 122 |
| 10 | 113 | 140 | 138 |
| 100 | 153 | 193 | 189 |

† Events on these days exceeded a 100-yr return period but their exclusion had little effect on parameter estimates.

## Effects of Grass Hedges on Runoff Depths

The entire data set of rainfall and runoff pairs is plotted in Fig. 2A and a truncated data set limited to rainfall depths >25.4 mm, and excluding the large November 2001 event, is plotted in Fig. 2B. Also shown in Fig. 2B are the linear regression lines fitted to predict the runoff depth from the rainfall depth for the truncated data set ignoring any effect of month on the regression relationships. The scatter of data points around the regression lines is not all a reflection of unexplained variation, however. Some of the variation is predictable seasonal variation that was represented in the ANOVA by allowing the regression slopes and intercepts to vary between months (Table 2). For all treatments, averaged across months, $I_a$ calculated as $-a/b$ was in the range of 22 to 25 mm, although the values for individual treatments and months varied from 9 to 37 mm. The slope estimates ($b$) reflect the increase in runoff depth per unit increase in rainfall depth after the initial abstraction is exceeded. The average of the 12 monthly slopes for the no-hedge treatment was 0.60. The contrast estimates show that this slope was significantly higher than the 0.46 value of the hedge–no berm treatment, which itself was higher than the 0.30 of the hedge–berm treatment (Table 2). The marginal runoff fractions (slopes) tended to be higher and the initial abstraction (reflecting both slope and intercept) tended to be lower during the winter than during the summer. These seasonal results were similar to those reported by Bosch et al. (2005), who found a linear ("rational") runoff–rainfall relationship, without an intercept, for 0.2-ha plots in Tifton, GA. Feyereisen et al. (2008) explored CN relationships from those same Tifton plots.

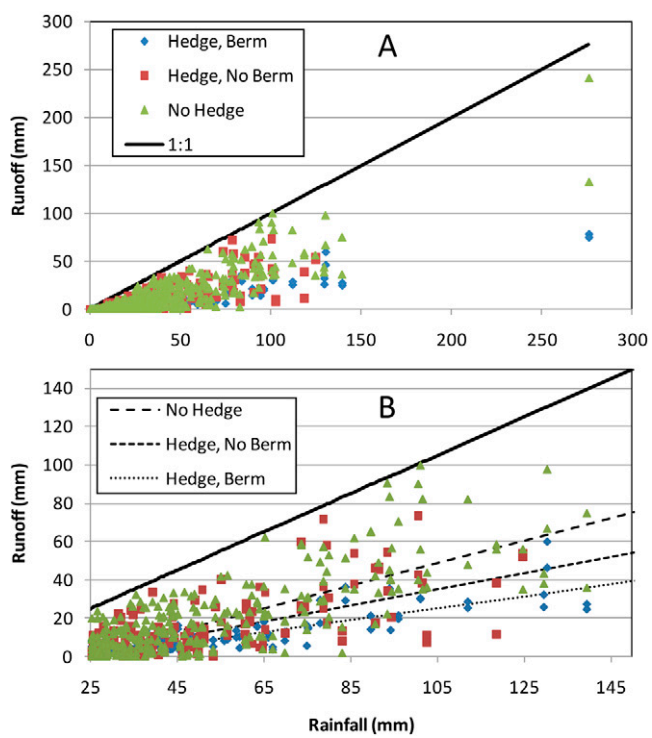


**Fig. 2. Observed rainfall and runoff pairs from contour-planted, conventional-tillage corn as influenced by three grass hedge treatments showing (A) all observations and (B) observations with rainfall > 25.4 and <200 mm that were the basis for the regression lines shown.**

**Table 2. Analysis of variance of total event runoff (mm) from total event rainfall for plots with or without grass hedges and grass hedge plots with or without earthen berms at their upslope edge showing monthly regression slopes and intercepts and contrast estimates of differences in regression slope due to hedge and berm. Analysis based on rainfall events exceeding 25.4 mm.**

| Effect† | Numerator df | Denominator df | *F* | Prob. *F* |
|---|---|---|---|---|
| Treatment (Trt) | 1 | 487 | 5.0 | 0.025 |
| Berm within Trt | 1 | 479 | 3.0 | 0.085 |
| Month | 11 | 488 | 1.2 | 0.28 |
| Trt × month | 11 | 152 | 0.4 | 0.97 |
| Berm × month within Trt | 11 | 127 | 0.6 | 0.81 |
| Rain | 1 | 327 | 246 | <0.001 |
| Rain × Trt | 1 | 95 | 26.2 | <0.001 |
| Rain × berm within Trt | 1 | 150 | 6.2 | 0.014 |
| Rain × month | 11 | 125 | 1.6 | 0.10 |
| Error estimate (variance components) | Error estimate (variance components) | | | |
| Plot within Trt × berm | 0 | | | |
| Plot × month within Trt × berm | 0 | | | |
| Rain × plot within Trt × berm × month | 0.013 | | | |
| Residual | 63.027 | | | |

| Solutions | Intercept (*a*) | | | Slope (*b*) | | |
|---|---|---|---|---|---|---|
| Month | no hedge | hedge–no berm | hedge–berm | no hedge | hedge–no berm | hedge–berm |
| Jan. | −6.18 | −3.92 | −5.01 | 0.56 | 0.42 | 0.26 |
| Feb. | −17.34 | −10.24 | −7.55 | 0.76 | 0.62 | 0.46 |
| Mar. | −12.37 | −5.26 | −9.34 | 0.68 | 0.53 | 0.37 |
| Apr. | −8.41 | −3.90 | −1.86 | 0.44 | 0.30 | 0.14 |
| May | −12.54 | −12.49 | −6.12 | 0.59 | 0.44 | 0.29 |
| June | −10.94 | −15.49 | −5.35 | 0.58 | 0.44 | 0.28 |
| July | −14.35 | −9.18 | −5.12 | 0.52 | 0.38 | 0.22 |
| Aug. | −14.48 | −9.79 | −7.68 | 0.57 | 0.42 | 0.27 |
| Sept. | −13.96 | −11.22 | −4.68 | 0.55 | 0.40 | 0.25 |
| Oct. | −18.87 | −22.89 | −10.85 | 0.60 | 0.46 | 0.30 |
| Nov. | −13.74 | −12.98 | −6.96 | 0.60 | 0.46 | 0.30 |
| Dec. | −16.88 | −23.38 | −10.93 | 0.78 | 0.63 | 0.48 |

| Contrasts | Numerator df | Denominator df | Estimate | Prob *T* |
|---|---|---|---|---|
| Rain × (no hedge vs. hedge–no berm) | 1 | 150 | 0.16 | 0.014 |
| Rain × (hedge–no berm vs. hedge–berm) | 1 | 113 | −0.15 | 0.007 |

† Trt = hedge or no hedge, berm = berm or no berm, month = month of event, rain = total rainfall associated with runoff event.

Using the monthly fitted regression equations, and assuming $I_a = 0.2S$ to allow comparison with values tabulated in NRCS (2004), CN values were calculated for rain depths from 0 to 200 mm using Eq. [2] and [1]. The resulting trends in the predicted CN with various rainfall depths were then averaged across 12 mo to estimate the predicted variation of the CN for the entire year (Fig. 3A) or parts of the year to examine seasonal variation (Fig. 3B). In each case, the apparent CN first declined with increasing rainfall following the $CN_0$ line, corresponding to the CN where the rainfall is equal to $I_a$ (Hawkins et al., 2009). Interestingly, after runoff began, there was often a brief increase in CN, followed by a gradual decline. The brief, abrupt increase in CN after $I_a$ was exceeded is reminiscent of the CN behavior of some watersheds that have been termed "violent" (Hawkins et al., 2009). The subsequent gradual decline of the CN with increasing rainfall is not uncommon, but this dependency means that there is no unique CN value if the linear trend fitted with Eq. [5] actually represents the trend in these data.

The effect of varying the threshold of rainfall depths included in fitting Eq. [5] on the resulting CN estimates is illustrated in Fig. 4A. The $I_a$ estimated as $-a/b$ increased with increasing threshold but always remained smaller than the threshold selected. The higher the threshold selected, the more gradual was the CN decline at large rainfall event depths. Interestingly, selecting a rainfall threshold between 12.7 and 38.1 mm had relatively little effect on the estimated CN values for rainfall between 70 and 100 mm, which corresponds to rainfall events with return periods of 1 to 2 yr (Table 1). If handbook CN values correspond to the median value of "annual floods," the corresponding return period would be 2 yr. At a rainfall depth of 100 mm, the estimated CN for the no-hedge data set was about 78, the hedge–no berm CN was about 70, and the hedge–berm CN was about 61. For comparison, the handbook CN was 82 for contour row crops in good condition on a *C* soil, 80 for contouring plus terracing, and 70 for meadow (NRCS, 2004).

The assumption that $I_a = 0.2S$, which is implicit in Eq. [2] and [3], was examined. For a 100-mm rainfall depth and a 25.4-mm rainfall threshold, $I_a$ was found to be $0.32S$ for the no-hedge treatment (Fig. 4B); the fraction was 0.23 for the hedge–no berm treatment and 0.16 for the hedge–berm treatment (data not shown). These results suggest that the assumption that $I_a = 0.2S$ is not inconsistent with the data.

## Effects of Grass Hedges on Runoff Flow Patterns

The partitioning of runoff between two flow paths, either directly downslope through the hedges or laterally along the upslope edge of the near contour hedges, was found to be influenced by the presence or absence of tillage berms (Vieira and Dabney, 2011) as well as by the storm size (Table 3). The resulting power functions are

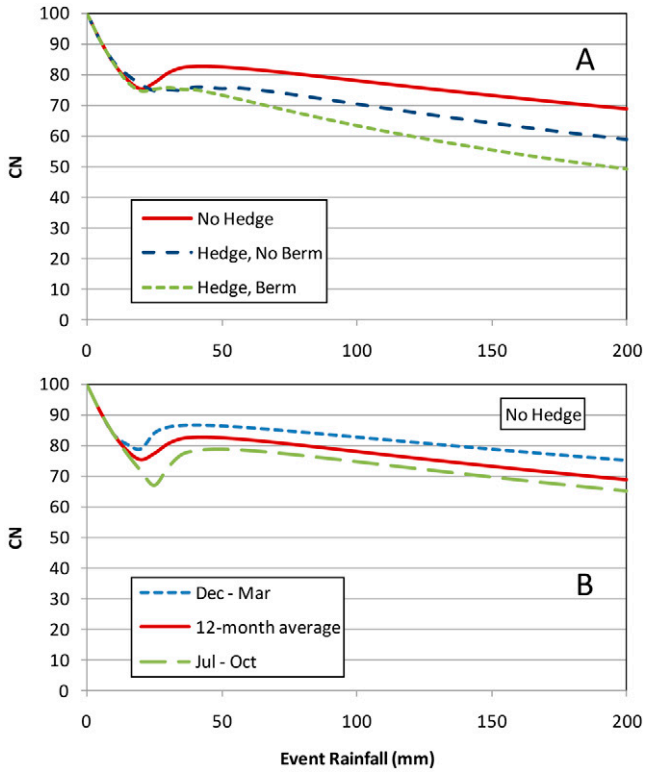


**Fig. 3. Average curve number (CN) calculated with Eq. [2] and [1] from storage index *S* values determined using Eq. [3] and monthly rainfall–runoff regression lines: (A) 12-mo average values for all three treatments and (B) seasonal variation reflecting antecedent runoff conditions for the no-hedge treatment.**

$$R_u = 0.23R^{0.43} \quad \text{hedge, no berm}$$
$$R_u = 0.90R^{0.89} \quad \text{hedge, berm} \qquad [6]$$

where $R_u$ is the runoff flowing upslope of the hedge (mm) and $R$ is the total event runoff (mm). Runoff passing through the hedges may be calculated as $R - R_u$. Based on these relationships, as shown in Fig. 5, most runoff (≥95%) passed through the hedges for moderate to large (>20-mm runoff) storms when no berm was present. In contrast, most of the runoff (55–65%) was redirected upslope of the hedge when a tillage berm was present for these moderate to large (>20-mm runoff) storms. For small events, runoff predominately flowed upslope rather than through the hedges when a berm was developed, with the fraction of total runoff redirected upslope of the hedges increasing from 0.65 to 0.90 as event runoff depth decreased from 20 to 1 mm.

## Effects of Grass Hedges on Sediment Yield

As expected, grass hedges reduced the sediment yield (Fig. 6). The average annual sediment delivery for the annual average rainfall erosivity observed during this study was 6.4 Mg ha$^{-1}$ for the no-hedge treatment, 1.4 Mg ha$^{-1}$ for the hedge–no berm treatment, and 1.5 Mg ha$^{-1}$ for the hedge–berm treatment. In the ANOVA, sediment delivery was significantly related to rainfall erosivity (EI30, Table 4). Hedges, with or without berms, significantly (prob. < 0.01) reduced the sediment yield per unit EI30, as shown by the contrasts in Table 4. Explicitly including the runoff depth (or the variables that affect runoff depth, Table 2) in the regression analysis might reduce the error estimates for predicting the sedi-

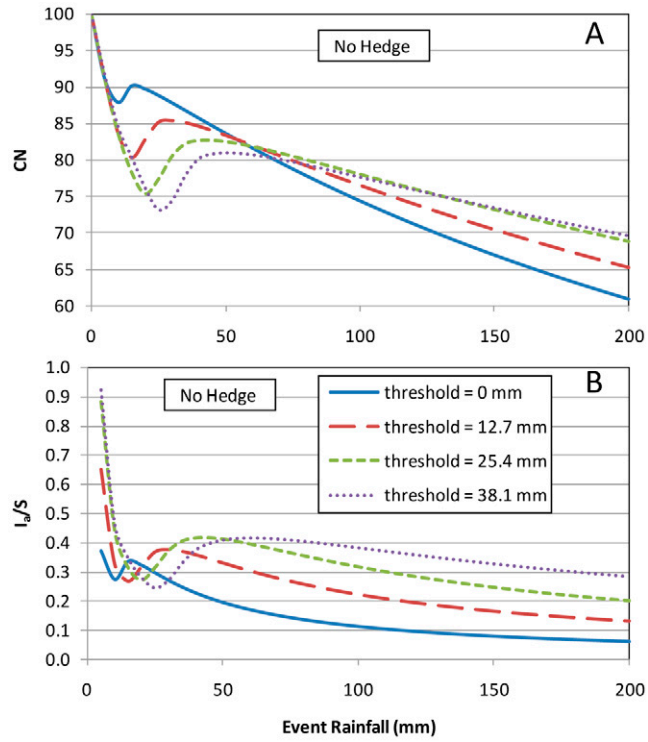


**Fig. 4. (A) No-hedge treatment curve number (CN) responses to event rainfall depth resulting from fitting Eq. [3] using data where rainfall depth exceeded specified minimum thresholds, and (B) the ratio of the initial abstraction $I_a$ to storage index *S*.**

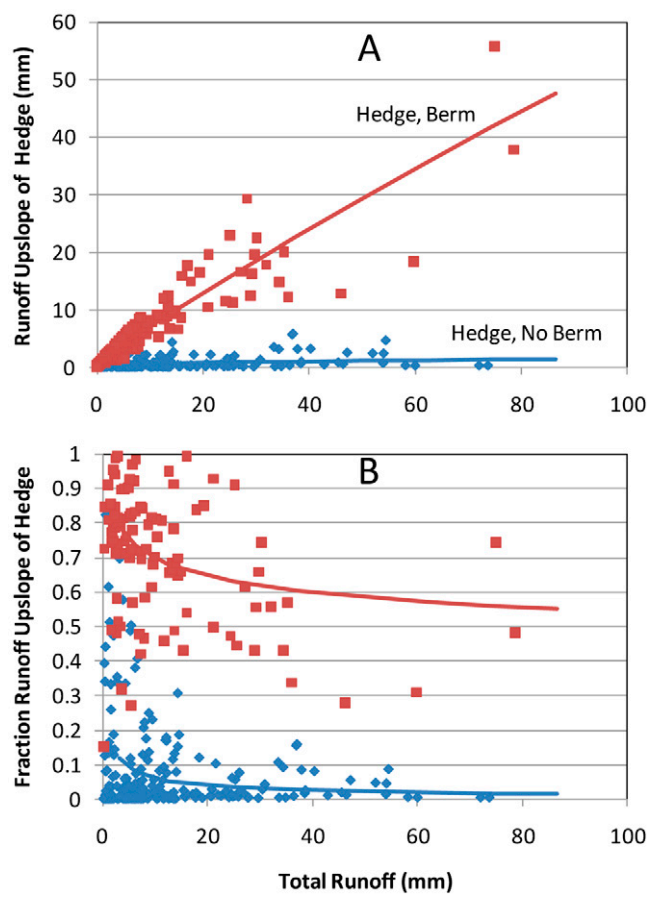


**Fig. 5. The amount of runoff redirected upslope of grass hedges as a function of total runoff depth during periods when a soil berm was allowed to form or not allowed to form, expressed (A) as runoff depth (regression Eq. [6]) or (B) as a fraction of total runoff.**

**Table 3. Analysis of variance of ln(runoff above hedge, mm) from ln(total runoff, mm) for hedge plots with or without earthen berms at their upslope edge.**

| Effect | Numerator df | Denominator df | F | Prob. F |
|---|---|---|---|---|
| Berm | 2 | 2 | 69.4 | 0.014 |
| Ln(runoff) | 2 | 334 | 563 | <0.001 |
| Error estimate | Error estimate | | | |
| Autoregressive [plot(berm)] | 0.287 | | | |
| Residual | 0.56 | | | |
| Solution | | | | |
| Effect | Berm | Estimate | SE | Prob. T |
| Berm | 0 | −1.476 | 0.127 | 0.007 |
| Berm | 1 | −0.111 | 0.064 | 0.229 |
| Ln(runoff) × berm | 0 | 0.428 | 0.048 | <0.001 |
| Ln(runoff) × berm | 1 | 0.891 | 0.028 | <0.001 |

ment yield (Kinnell, 2010). The simple model presented in Table 4, however, provides an opportunity to estimate a RUSLE2 **P** factor attributable to grass hedges. The ratio of the slopes of the sediment delivery–EI30 relationship of the grass hedge treatments to the no–hedge treatments is an estimate of the $P_{hedge}$ subfactor attributable to grass hedges. The $P_{hedge}$ values of 0.25 and 0.28 (Table 4) were not significantly different, and thus hedge effects on sediment yield were not affected by the presence or absence of a tillage berm. This hedge subfactor is not the entire **P** factor of the contour hedge system because even the no–hedge treatment had less erosion due to contour crop rows rather than rows up and down the slope. The $P_{hedge}$ subfactor, the contouring subfactor, and other possible subfactors would be multiplied together to obtain the total **P** factor for a system of grass hedges. The $P_{hedge}$ subfactor found in this study was similar to that reported by Dabney et al. (2009) for similarly aged grass hedges at the bottom of up-and-downhill conventional tillage cotton (*Gossypium hirsutum* L.) plots.

## DISCUSSION

During the historical period from 1960 to 1994, a variety of treatments and plot pairings were used on the same plots studied (supplementary Table 1). Although many of the results remain unpublished, the plots assigned to grass hedges were generally assigned "poorer" management and, during the 1960 to 1994 period, annual soil losses averaged 26 Mg ha$^{-1}$ on the plots that received hedges in 1995 compared with 6.6 Mg ha$^{-1}$ for the plots that never had hedges (supplementary Table 3). With regard to runoff, there was no consistent difference between the pairs of plots during the period 1960 to 1994. These observations emphasize that the runoff and sediment yield reductions due to grass hedges observed in the current study are despite potentially negative residual effects of prior plot management. Previous studies on other plots have found significant residual effects of historical management on future erosion (Mutchler et al., 1985; Mutchler and McDowell, 1990; Dabney et al., 2009).

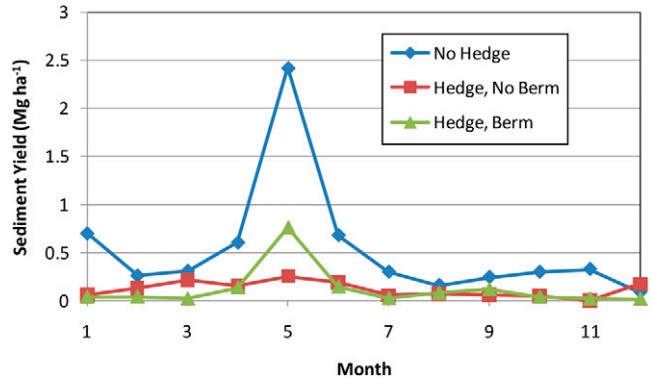


**Fig. 6. Average monthly sediment delivery from contour-planted disk–chisel tillage corn as affected by three grass hedge treatments.**

Tillage-induced berms at the upslope edge of grass hedges greatly altered runoff flow patterns. When berms were not present, runoff generated on the 22.1-m-long plots passed through the hedges almost as if they weren't present, and very little flow was diverted along the hedges. In contrast, when berms were present, the runoff from small events was almost completely diverted by the hedges, and even for large events >50% of the runoff was diverted to flow upslope of the hedges rather than through them (Fig. 5B). Dabney (2006) reviewed the literature that showed how, at small flow rates, the hydraulic roughness of grass hedges was not greater than that of a rough soil surface or a surface covered with crop residues, while at much higher flow

**Table 4. Analysis of variance of event sediment yield (Mg ha$^{-1}$) from total event rainfall erosivity (MJ mm ha$^{-1}$ h$^{-1}$) for plots with or without grass hedges and grass hedge plots with or without earthen berms at their upslope edge. Also shown are estimates of regression slopes, Revised Universal Soil Loss Equation *P* subfactors for grass hedges, and contrast estimates of differences in regression slopes due to hedge treatments.**

| Effect† | Numerator df | Denominator df | F | Prob. F |
|---|---|---|---|---|
| EI30 × berm within Trt | 3 | 2.77 | 72.7 | 0.004 |
| | Error estimate | | | |
| Plot within Trt | 0 | | | |
| Plot within Trt × berm | 0.046 | | | |
| EI30 × plot within Trt × berm | $2.9 \times 10^{-7}$ | | | |
| Residual | 4.49 | | | |
| Solution | | | | |
| Effect | Hedge | Berm | Estimate, Mg h MJ$^{-1}$ mm$^{-1}$ | SE | $P_{hedge}$ |
| EI30 × berm(Trt) | 1 | 0 | 0.0020 | 0.0007 | 0.25 |
| EI30 × berm(Trt) | 1 | 1 | 0.0022 | 0.0007 | 0.28 |
| EI30 × berm(Trt) | 0 | 0 | 0.0079 | 0.0006 | |
| Contrasts | Numerator df | Denominator df | Estimate | SE | Prob. T |
| Hedge–no berm vs. hedge–berm | 1 | 5.58 | 0.0002 | 0.0010 | 0.836 |
| Hedge–no berm vs. no hedge | 1 | 3.71 | 0.0059 | 0.0009 | 0.003 |
| Hedge–berm vs. no hedge | 1 | 3.79 | 0.0057 | 0.0009 | 0.004 |

† Trt = hedge or no hedge, berm = berm or no berm, EI30 = monthly accumulative rainfall erosivity (MJ mm ha$^{-1}$ h$^{-1}$).

rates, the hydraulic roughness of grass hedges could be much larger. Vieira and Dabney (2011) reported that the average height of tillage-induced berms was generally 12 to 16 cm and calculated that water flow depths would not exceed this depth. The fact that runoff was able to pass through the hedges with berms suggests that the berms were not uniform in height or not continuous in extent. There must have been gaps, low places, or holes that allowed some runoff to pass through the hedges. The berms thus acted like small leaky terraces that did not erode when they were overtopped because of the presence of dense residue, canopy cover, and extensive root biomass in the soil.

The presence or absence of tillage-induced berms did not alter the effectiveness of grass hedges in reducing the sediment yield from these 22.1-m-long plots. With or without the berms, grass hedges reduced the sediment yield by a factor of 0.25 to 0.28. For large fields with multiple grass hedges, however, the effect on soil erosion of diverting runoff along the upslope edge of hedges could be complex. By having less runoff accumulation on the hillslope below each hedge, downslope sheet and rill erosion would be reduced because the effective slope length would be reduced. On the other hand, if the diverted runoff was not delivered to a stable outlet, the risk of concentrated flow causing ephemeral gully erosion would be increased where the grass hedges crossed swales.

While the presence of berms did not reduce sediment yield beyond the benefit of the hedges alone, they did reduce the total amount of runoff (Fig. 2B). It follows that the average sediment concentration of runoff passing upslope of the hedges was higher than that of the runoff passing through the hedges. It is likely that the reduced runoff when berms were present was due to the presence of local depressions upslope of the berms and a longer runoff flow path along the hedges that provided additional opportunity time for infiltration.

The observation of significant runoff redirection by near-contour buffers suggests that proper prediction of flow direction and accumulation in a geographic information system context cannot be determined only by the direction of the steepest topographic slope but must also consider the importance of oriented roughness at field margins, as has been noted by others (Takken et al., 2001; Moussa et al., 2002; Nunes et al., 2005; Duke et al., 2006), and that furthermore, the effects of this oriented roughness are a function of storm size.

The conceptual bucket model that rainfall and runoff are linearly related after an initial abstraction assumes that even for very large events there will be a fractional loss of rainfall to infiltration. This conceptual model differs from that underlying the CN model, which assumes that for very large events all additional rainfall becomes runoff. Determining an effective CN by fitting Eq. [3] to rainfall–runoff pairs derived from the linear model resulted in a CN vs. rainfall relationship that mimicked the behavior of "violent" watersheds (Hawkins et al., 2009). The CN increased once the rainfall depth exceeded the initial abstraction and then declined, concave up, at large rain depths. This fitting procedure did not produce a single constant CN, but the result can be used to determine a CN for events of any expected size or return period. For the design of structures, a large design storm may be appropriate. As applied in continuous simulation models where many smaller events are simulated, however, an extreme event or an asymptotic CN value may not be as appropriate as some other value. This analysis demonstrates that some parts of the rainfall–runoff relationship can be explained due to seasonal effects that are related to antecedent soil water content or rainfall intensity characteristics; however, the complex shape of the CN relationship at event depths between 25 and 75 mm (Fig. 3 and 4) may also contribute to the variability commonly observed when CN values are directly fitted to data.

One desirable feature of the method used in this study is that all data above a threshold rainfall (which may be zero) are used in the estimation. In contrast, alternative data censoring methods (Hawkins et al., 1985, 2009) start by ordering natural rainfall–runoff pairs based on rainfall depth and then iteratively calculate average $S$ values for groups of 1, 2, 3, .... $N$ storms until the $P$ for the last storm added exceeds $0.46S$. This process may stop after just a few storms if a large rainfall depth produces very little runoff (Cao et al., 2011). In the method used in this study, all events larger than a threshold may be retained, leading to greater support for estimated CN values. Another advantage is that the method does not require the user to choose among functional forms of the CN–rainfall relation. Also, it does not require that the data set display an asymptotic CN value. Even when an asymptotic trend is fitted, many data sets display a residual rainfall dependency (Hawkins et al., 2009). This method avoids the problem of anomalously high CN values associated with the least squares method because an average is not really fit. Rather, a CN for an appropriate rainfall return period or depth is selected.

With the calculation methods used, the CN values for events with a 1- to 2-yr return period were similar to or slightly lower than handbook values (NRCS, 2004). Observed CN values were larger and $I_a$ values were smaller in the winter than in the summer. The CN estimates were not sensitive to the rainfall depth threshold used to censor the data. In contrast, the estimate of $I_a$ increased with increasing rainfall threshold, but the estimated value was always lower than the rainfall threshold. Using relationships derived with a rainfall threshold of 25.4 mm, which matches common practice (Hawkins et al., 2009), and a 100-mm runoff event, $I_a$ was found to be equal to $0.32S$ for the no-hedge contour corn treatment, $0.23S$ for the hedge–no berm treatment, and $0.16S$ for the hedge–berm treatment. While these results are not all equal to $0.2S$ as assumed in the derivation of Eq. [3], neither are they completely inconsistent with that underlying assumption. If a rainfall threshold of 12 mm or more is used, there was little evidence of a value of $I_a$ close to $0.05S$ (Fig. 4A), which has been suggested as an alternative formulation to the current handbook tables (Hawkins et al., 2009).

## SUMMARY AND CONCLUSIONS

Tillage operations that would be used to limit the expansion of grass hedges caused soil to be thrown into the hedges, forming earthen berms. These berms altered runoff flow patterns and decreased runoff amounts but did not alter the effectiveness of the grass hedges in reducing sediment yield. Grass hedges were found to significantly decrease sediment yield by factors of 0.25

to 0.28 without and with a berm, respectively, which were not significantly different. This annual average "initial abstraction" or "runoff threshold," which is the amount of rain that falls before runoff begins, was found to not be affected by grass hedges and was equal to 22 to 25 mm when the threshold of rainfall depths retained in the regression analysis was 25.4 mm. After the initial abstraction was reached, the marginal increase in runoff per unit increase in rainfall was 0.6 for plots without grass hedges. Adding a grass hedge decreased this marginal fraction to 0.46 and adding a hedge with a berm decreased it to 0.30. For a 100-mm rainfall event, which had a 1- to 2-yr return period, the CN for perfect-contour disk–chisel tillage corn was about 78, with grass hedges about 70, and with hedges containing earthen berms about 61.

When no berm was present, nearly all (95%) of the runoff passed through the grass hedges. In contrast, when a berm was present, 85% of small events and 55% of large runoff events flowed laterally upslope of the grass hedges rather than directly downslope through them. Runoff redirection may reduce sheet and rill erosion downslope but may increase the risk of concentrated flow erosion when hedges cross swales unless a stable outlet is provided.

This study demonstrates the runoff and erosion control functionality that can be achieved by grass hedges. The results support the design criteria embodied in NRCS (2003).

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