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Landscape benching from tillage erosion between grass hedges☆

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Abstract

Grass hedges are narrow (1–2 m wide) parallel strips of stiff, erect, grass planted near to or on the contour of fields but crossing swale areas at angles convenient for farming. They serve as guides for contour cultivation, retard and disperse surface runoff, cause deposition of eroded sediment, and reduce ephemeral gully development. After three years of tilled fallow between mixed-species hedges, the average grade of 18 m wide tilled strips between 1.5 m wide hedges was reduced from 0.068 to 0.052 as a result of surface lowering below hedges and on the shoulders of swale areas combined with increases in elevation above hedges. Annual surveys show progressive lowering of high spots and filling of low spots as contours lines more closely aligned with hedges. Survey data indicated annual erosion rates of nearly 250 t ha^{-1} $year^{-1}$. Both RUSLE and WEPP over-predicted erosion rates, partly because backwater and slope modification affects were not considered. A tillage translocation model predicted enough soil movement to account for 30–60% of the observed changes. A combination of tillage translocation and water erosion/deposition provides the best explanation for the observed aggradation/degradation patterns. © 1999 Elsevier Science B.V.

Keywords: Erosion control; Bench terraces; Vegetated barriers; Tillage translocation

1. Introduction

Grass hedges are narrow strips of dense perennial vegetation that are planted close to land slope contours and spaced at 1–2 m vertical intervals across cropped fields. Hedges are a water and soil erosion control technology that has been widely used in the tropics (Kemper et al., 1992) and that is now a recognized type of conservation buffer in the United States, termed ‘vegetative barriers’ by the USDA-NRCS (Dabney et al., 1993).

The runoff and erosion control effectiveness of grass hedges depends on land slope, which may change over time. As soil is removed downslope of grass hedges and sediment is trapped upslope of grass hedges, the steepness of the cropped interval is reduced, which slows runoff and reduces future erosion. Therefore, while hedges reduce runoff and erosion as soon as they are well established, their conservation benefits will increase over time if

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benches develop. Another consequence of benching, however, is that large gradients of soil fertility and other properties can develop as subsoils become exposed (Turkelboom et al., 1997); amendments or deep tillage may or may not maintain productivity in these areas. An understanding of the effects of hedge species composition and of alternative tillage practices on the rate and nature of land slope changes resulting from farming between grass hedges is therefore needed if meaningful long-term conservation planning is to be done.

The significance of tillage translocation of soil on hillslopes has received increasing recognition (Lindstrom et al., 1992; Govers et al., 1994; Lobb et al., 1995). Govers et al. (1994) described tillage translocation as a linear function of slope gradient

$$\text{Soil flux} = -kS, \quad (1)$$

where S is slope gradient and k a constant representing the amount of soil translocated downslope (mass/length of travel) per tillage operation. With two known exceptions, values of k that have been published refer to tillage up and down slope. Lindstrom et al. (1992) indicated that k for moldboard plowing across-slope (360 kg/m) was similar to that for plowing up and down a slope (330 kg/m). Poesen et al. (1997), on the other hand, reported that for a duckfoot chisel, k was 282 kg/m when used up and down slope, but only 139 for contour tillage. For comparison, Govers et al. (1994) found chisel plowing up and down slope had a k of 111 kg/m. Lighter and slower moving implements tend to produce lower k values (Govers et al., 1994; Lobb et al., 1995). Since average the tillage erosion rate per unit area is calculated by dividing soil flux by slope length, the impact of tillage translocation is greatly increased on fields divided into a number of narrow independent tilled strips by a series of hedges.

The objective of this study was to compare the influence of 10 vegetative species combinations planted as 1.5 m wide hedges on sediment trapping and landscape benching when the area between the hedges was maintained as tilled fallow for three years. Analysis of available data is used to try to assess the relative contributions of water erosion and tillage erosion to observed soil translocation and landscape benching.

2. Methods

The study area was located on a Loring silt loam soil (fine-silty, mixed thermic Typic Fragiudalfs) derived from loess located near Coffeeville, MS. The test field had a fairly uniform 0.068 slope. Three parallel 1.5 m wide hedges were established close to the contour and spaced 19.2 m apart on centers (Fig. 1). Each hedge was composed of 10 vegetative 9.1 m long segments. The species combinations evaluated were selected to compare a variety of vegetation types that provided a combination of stiff stems to resist concentrated flow and dense ground cover to resist sheet erosion (Table 1). The hedges were established during the summer and autumn of 1992 after the hedge strips were tilled (Table 2); the remainder of the slope remained covered with resident mixed grass sod until July 1993 when tilled fallow management began.

A baseline topographic survey was taken prior to tillage in July 1993 at the center of each hedge segment and at four locations (1.5 m apart) upslope from the center of each hedge and two locations downslope of each hedge (Fig. 1). After this initial survey, a tilled fallow management was initiated on the study site (Table 2). Tillage was accomplished using an offset tandem disk, a chisel plow, and a do-all (combination of a reel pulverizer and a finishing harrow) except for the 1.2 m immediately upslope of the hedges where a tractor-powered rototiller was used. To minimize runoff water flow parallel to the hedges, each 9.1 m hedge segment was separated by four hay bales, placed end to end, perpendicular to each hedge, and extending 5 m upslope. The upper three of these hay bales were removed prior to each tillage operation and then replaced; the lower hay bale was then removed, the rototiller run, and that bale replaced. Beginning in 1994, a winter wheat (*Triticum aestivum* L.) cover crop was broadcast planted each fall (Table 2).

Additional topographic surveys were taken in August of 1994, 1995, and 1996 with elevation readings taken at the same locations measured in 1993. In August 1997, a global positioning system (GPS) was used to determine the spatial coordinates of the survey points.

During August 1997, bulk density was determined in surrounding untilled sod areas and along transects

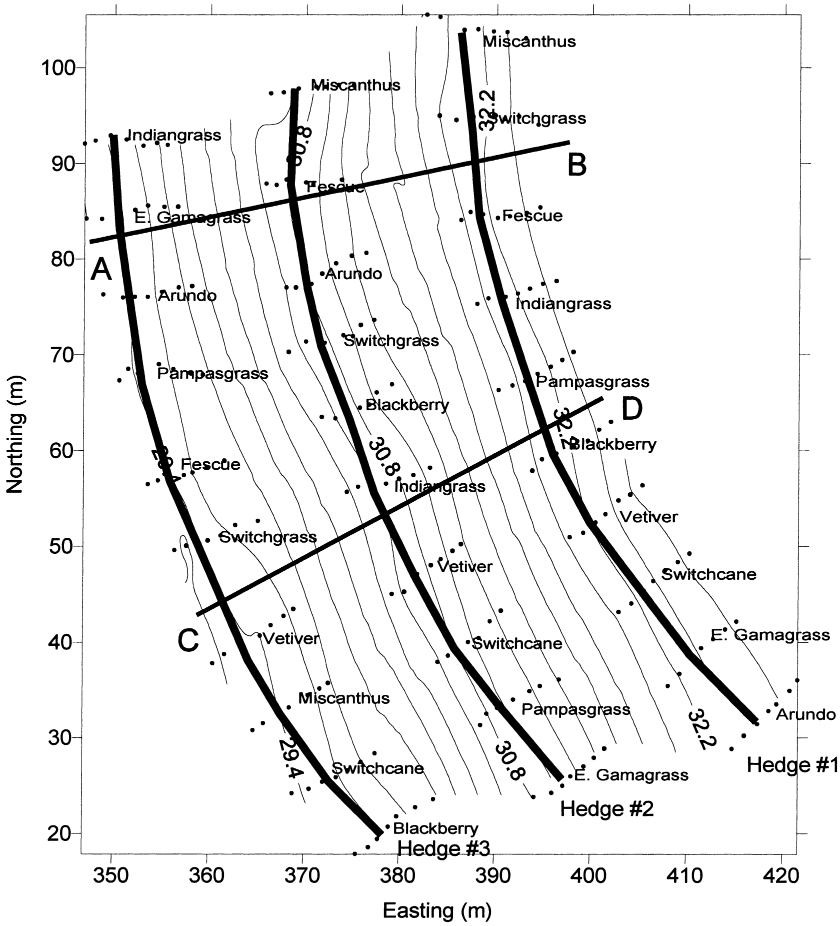

Fig. 1. Initial contour map, based on July 1993 survey elevations, indicating hedges aligned close to contour lines and spaced with about a 1.4 m vertical interval. Species of 9.1 m hedge segments are named. Location of survey points are indicated with dots. Contour interval shown is 0.2 m. Locations of two transects (Fig. 4) evaluated from interpolated topographic grids are indicated.

AB and CD (Fig. 1) as follows: within each hedge, 2 m above each hedge, 2 m below each hedge, midway between the hedges. Wet soil density was measured in 5 cm depth increments using a MS-24 CPN Strata-gage[1] (dual probe with a Cs source) that used gamma transmission between a source and a detector separated by 30 cm. These data were combined with gravimetric soil water content determined on samples taken in 5 cm depth increments, after discarding the top 2.5 cm of soil, from the two access holes at each bulk density measurement location.

All survey data were analyzed by creating grid files with kriging techniques using the Surfer program (Keckler, 1995). Prior to kriging, small adjustments (<1 cm) in elevations were made to all positions, except those directly in the hedge, to reflect the small variations in average bulk density observed in the 25 cm sampling depth; elevation changes reported are therefore based on a constant bulk density value of 1.38 t m^{-3}. Adjustments were not made to elevations within the hedge because sod in these areas had already been disturbed prior to the initial survey. Cut and fill volumes calculated from the difference

[1]Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

Table 1
Planting method and survival of plant species evaluated for potential use as vegetative hedges at Coffeeville, MS in 1992–1996

Plant species combinations	Planning method[a]	1996 % survival
Arundo (*Arundo donax* L.)	SS	88
'Pennlawn' Red fescue (*Festuca rubra* L.)	S(54)	0
Eastern gamagrass [*Tripsacum dactyloides* (L.) L.]	MS	65
'Penlawn' Red fescue (*Festuca rubra* L.)	S(54)	0
Dwarf switchcane [*Arundinaria gigantea* (Walt.) Muhl]	SS	98
'KY 31' Tall fescue (*Festuca arundinacea* Scherb)	S(45)	43
Vetiver grass (Sunshine) [*Vetiveria zizanioides* (L.) Nash]	MS	1
Redtop (*Agrontis alba* L.)	S(27)	0
Blackberry (*Rubus argutus* Link)	MS	98
'Pennlawn' Red fescue (*Festuca rubra* L.)	S(54)	0
Pampasgrass (*Cortaderia selloana* J.A. and J.H. Schultes, Ascher. and Graebn.)	MS	53
'Pennlawn' Red fescue (*Festuca rubra* L.)	S(54)	0
'Lometa' Indiangrass [*Sorghastrum nutans* (L.) Nash]	S(45)	7
'KY 31' Tall fescue (*Festuca arundinacea* Scherb)	S(54)	87
'Alamo' Switchgrass (*Panicum virgatum* L.)	S(22)	88
Miscanthus (Miscanthus sinensis Andrss.)	MS	95
'Penlawn' Red fescue (*Festuca rubra* L.)	S(54)	0

[a] S = established from seed (seeding rate, kg/ha), SS = single shoot vegetative transplanting, MS = multiple shoots (2–3 shoots) vegetative transplanting.

between two kriged surfaces were multiplied by appropriate bulk density values to allow comparison with erosion predictions.

The contribution of water erosion to soil redistribution was estimated by employing two erosion prediction technologies: RUSLE (Renard et al., 1997) and WEPP (Flanagan and Nearing, 1995). RUSLE version 1.06 and WEPP version 98.4 were used. Slopes were described as a series of alternating strips or overland flow elements at a uniform 6.8% slope as illustrated in Fig. 2.

As model inputs, RUSLE required EI_{30} for two-week intervals while WEPP required maximum 5 min rainfall intensity, rainfall duration, and total rainfall on a daily basis. Rainfall intensity data were obtained from a recording raingage located 40 km to the north of the study site, the nearest location that intensity data was available. On an annual basis, studies have shown that the rainfall erosivity index (EI_{30}) does not vary greatly over such distances (McGregor et al., 1995).

In WEPP, the baseline Green and Ampt conductivity parameter (K_e) was set at 3.4 mm/h for the tilled fallow areas based on measurements made on the similar Grenada silt loam soil (Flanagan and Livingston, 1995). Because the grass hedges were never tilled, and this parameter were therefore not periodi-

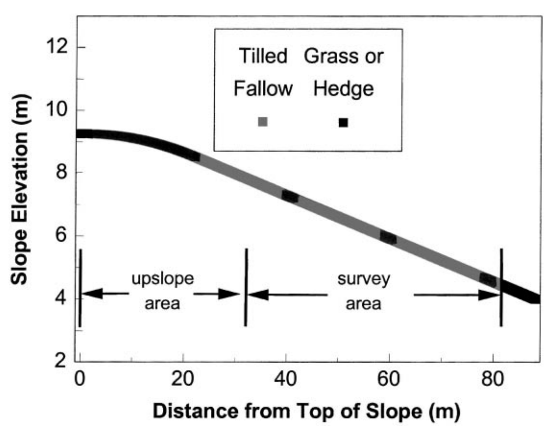

Fig. 2. Schematic of hillslope showing alternating strips of tilled fallow and vegetative hedges and an upslope grassed area to the top of the hill as modeled using RUSLE and WEPP.

Table 2
Tillage and survey activity on hedge plots

Date	Operation
4/92	Roto-tilled and cultipacked hedge row areas
5/92	seeded or vegetatively propagated single-row hedges (vegetative transplants spaced 20 cm on centers)
10/5/92	seeded cool season species
7/14/93	initial survey field prior to summer fallowing with tillage
7/15/93	double disking with breaking disk sod areas between hedges
7/21/93	chisel plow
8/15/93	tandem disk
8/16/93	do-all (smoothing harrow)
9/23/93	chisel plow and do-all
4/15/94	tandem disk
5/13/94	do-all
6/20/94	do-all
6/28/94	tandem disk and do-all
7/5/94	roto-tilled above and below hedges (10′ above and below).
8/2/94	surveyed field
8/22/94	tandem disk
8/24/94	do-all
9/22/94	do-all
10/06/94	tandem disk
10/07/94	broadcast wheat and ran do-all to cover seed
3/24/95	tandem disk
5/24/95	do-all
7/20/95	do-all and Roto-tilled 10′ above and 5′ below hedge
8/2/95	surveyed field
8/14/95	tandem disk and do-all
10/2/95	broadcast wheat and ran do-all to cover seed
5/1/96	tandem disk
5/3/96	roto-tilled 10 feet above and 5 feet below hedges
7/14/96	tandem disk and do all
8/1/96	final survey
8/14/96	tandem disk and do-all
10/21/96	no-tilled drill seeded cereal rye
5/21/97	tandem disk and do-all
8/12/97	bulk density measurements and GPS survey point locations

cally increased in the time-variable case, K_e was increased nine-fold to 30 mm/h for the hedges as recommended for meadow areas by Flanagan and Livingston (1995). To simulate the partial-year erosion prior to the final 1996 survey, WEPP rainfall was set to zero for later dates.

In order to set up appropriate initial conditions for RUSLE, a management file including several years of sod prior to initiation of four years of tillage operations was created. This management file, with separate screens for each tillage year or partial year, was then combined with measured R-factors for each year, and the appropriate operational C-factor for that year was determined. Other inputs used in RUSLE included an initial estimate of $K = 0.53$ t h (ha N)$^{-1}$ (RUSLE estimated an effective annual $K = 0.42$–0.46), roughness ridge height code = 2 (low, 5–7.5 cm height), and soil hydrologic group 2 (B, moderately low runoff potential). Tillage furrow grade was set at 0.5%, an average value for the field (Fig. 1). While actual furrow grade was sometimes as high as 1% at the south end of the field, it was close to zero at the north end, and the hay bales placed perpendicular to the hedges reduced flow along their upper margin.

Since RUSLE 1.06 does not output distributed estimates of erosion and deposition, erosion within the surveyed area (Fig. 2) was estimated indirectly. Separate RUSLE runs were made with the same management file for two hillslope descriptions. One was an 82 m slope with eight slope segments, similar to that depicted in Fig. 2, ending at the bottom of the survey area. The seconds consisted of only two slope segments: a 21.3 m sodded strip upslope of a 12.2 m tilled strip. In both RUSLE hillslopes, the slope of the topmost grassed hillslope element was set at 3%. RUSLE determined the LS-factor to be 0.66 for the 33.5 m slope and 1.25 for the 82 m slope. The difference between the sum of sediment yield plus sediment trapped for the total slope minus the sediment yield of the upslope area (Fig. 2) was used to estimate the erosion from within the surveyed area:

$$E_s = [((SY_t + ST_t)A_t) - (SY_u A_u)] \quad (2)$$

where SY is sediment yield, ST the sediment trapped, A the area, the subscript "t" refers to the total slope, the subscript "u" refers to the area upslope of the survey, and E_s is eroded soil (t) within the surveyed area.

The contribution of tillage to soil translocation was estimated using the model of Govers et al. (1994) presented as Eq. (1) using an assumed value of $k = 200$ kg/m for each tillage operation.

3. Results

Annual rainfall was 1153 mm in 1993, 1341 mm in 1994, 1074 mm in 1995, and 1238 mm in 1996. The 1994 rainfall was close to the long-term average for the area (NOAA, 1995). The RUSLE rainfall (R) factors were 417 N/h in 1993, 563 N/h in 1994, 563 N/h in 1995, and 631 N/h in 1996 (see Renard et al., 1997, p. 327), for a discussion of the units of R). These years had R values similar to the 579 N/h interpolated from the iso-erodent map in the RUSLE handbook (Renard et al., 1997), and somewhat lower than the 10-year (1982–1992) mean value of 752 measured in the area by McGregor et al. (1995).

The three parallel hedges were established with a vertical interval of ≈1.4 m between them (Fig. 1). The initial slope profile of the area was quite uniform with an average steepness of 6.8%. However, there was a concave swale area that passed through the pampas-grass section of Hedge #1, the indiangrass section of Hedge #2 and the vetiver grass section of Hedge #3. Transect CD crossed this area. Also of note was a concave shoulder located near the west edge of the field and below the middle hedge, crossed by transect AB.

Hedge survival varied tremendously among species (Table 1). Vetiver grass, indiangrass and the low-growing companion species red fescue and redtop all had <10% survival after three years. These hedge segments, however, were not devoid of vegetation. Rather, there was considerable volunteer vegetation dominated by blackberry and golden rod (*Solidago* sp.).

Bulk density varied significantly with depth and position (Table 3). Lowest values were observed in the hedges. This may reflect the effect of loosening done during vegetative establishment in 1992 combined with a lack of wheel traffic subsequently. Bulk density was also significantly lower immediately upslope of the hedges. This was a zone of sedimentation and aggradation. Bulk density was similar in the un-tilled

Table 3
Soil bulk density was lower within and immediately above hedges than below or mid-way between hedges where densities were similar to surrounding sod areas in 1997

Soil depth (cm)	Surrounding grass	Within hedge	2 m upslope (t/m^3)	2 m downslope (t/m^3)	Midway between (t/m^3)
5	1.35	1.10	1.29	1.30	1.37
10	1.41	1.18	1.30	1.40	1.41
15	1.40	1.24	1.33	1.45	1.42
20	1.34	1.30	1.31	1.44	1.41
25	1.34	1.34	1.30	1.44	1.42
Mean [a]	1.37c	1.23a	1.31b	1.41c	1.41c

[a] Means in row followed by different letters are significantly different ($p < 0.05$).

surrounding grass and in the other sampling locations within the tilled areas between the hedges. There was a trend toward increased bulk density under tilled areas at depths of 20 and 25 cm, compaction possibly caused by repeated tillage, a lack of root growth, and deeper exposure of subsoil horizons.

Changes in surface elevation between 1993 and 1996 are indicated in Fig. 3. Soil elevation changes in the center of the hedges were generally small, <0.05 m. Maximum elevation increases of 0.2 m were located ca. 1 m upslope of the edge of the hedges and were most pronounced in the swale positions. The maximum elevation decrease of 0.25 m was located 1.5 m below the bottom hedge in the swale position. Below the upper hedges, however, maximum decreases were found on shoulder positions rather than in the swale. During the three year period, slope steepness calculated as the difference in elevation from 1.5 m upslope of the center of one hedge to 1.5 m downslope of the center of the next hedge was reduced from 6.8% to 5.2%. Whether the slope between these points actually remained uniform as implied in this calculation, is discussed subsequently. Integration of the data represented in Fig. 3 indicates that the net volumes of aggradation and degradation approximately balanced (Table 4). Similarly, the areas of aggradation and degradation each accounted for ca. 50% of the surveyed area. At an average bulk density of 1.38 t/m^3, average changes in depth of $\pm$0.06 m reflected overall erosion and deposition of 760 t ha^{-1} over three years. The approximate balance of erosion and deposition suggests that inputs into the surveyed area from upslope (see Fig. 2) were approximately balanced by export of sediment below the area.

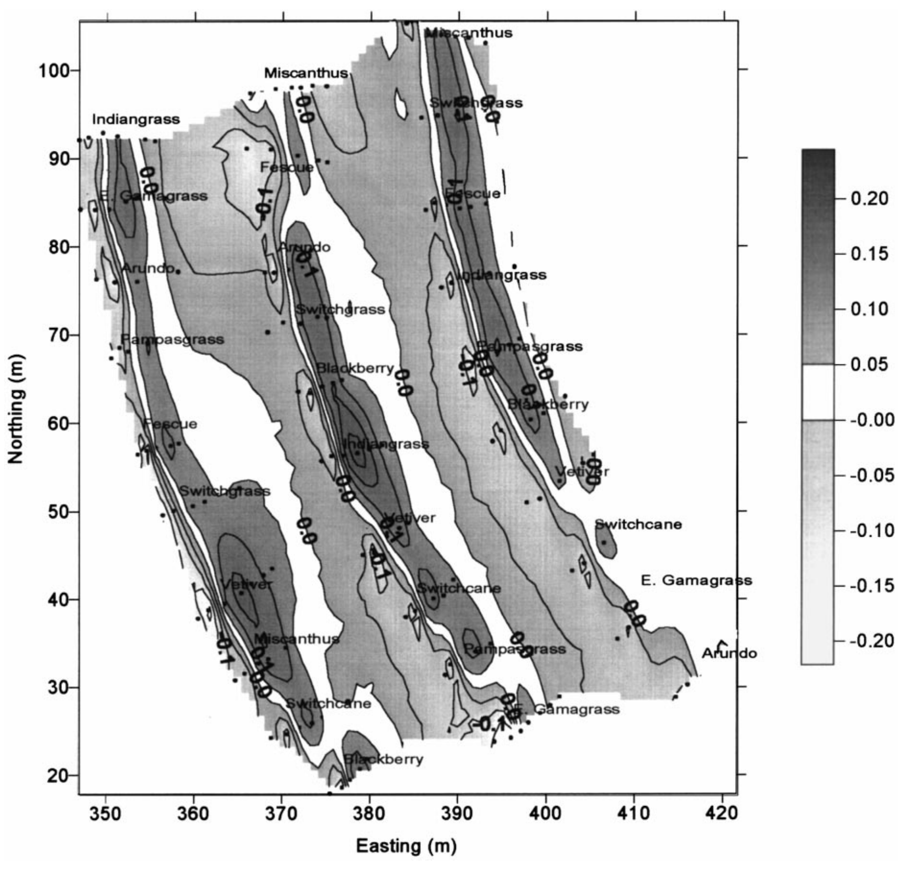

Fig. 3. Elevation differences between 1996 and 1993 surveys. Positive values, including the all white areas, indicate aggradation (deposition) and negative values degradation (erosion).

Table 4
Erosion and deposition rates calculated using the WEPP and RUSLE models, measured by topographic surveying and calculated for tillage erosion and deposition

	RUSLE			WEPP			Survey			Tillage		
	t	ha	t/(ha year)	t	ha	t/(ha year)	t	ha	t/(ha year)	t	ha	t/(ha year)
Input from upslope of survey area	91	0.27	112	32	0.27	40				29	0.27	36
Eroded within survey area	404	0.36	374	449	0.36	416	149	0.20	248	87	0.36	81
Deposited within survey area	230	0.04	1920	131	0.04	1092	147	0.20	245	87	0.04	725

Note: See text for calculation procedures.

The effect of these elevation changes on slope profiles along the two transects indicated in Fig. 1 are presented in Fig. 4. As indicated generally above, increases in elevation occurred throughout the area where survey points were collected above the hedge and decreases occurred below the hedges, and relatively little change occurred within the hedges themselves. More degradation occurred over the AB transect, located on a convex slope position and more aggradation over the CD transect, crossing a swale. Aggradation was greatest ca. 2 m upslope of the hedges. The lack of survey points for 9 m distances between the hedges is a weakness of the data set. However, except for the area below hedge #2 in the AB transect, the amount of elevation change in this interpolated region is relatively small. It may be observed in Fig. 4 that the slope is not completely uniform between the first surveyed point below one hedge and the last survey point above the next hedge downslope. Rather, slopes were reduced more than average over a distance of ca. 5 m above each hedge.

3.1. WEPP predictions

WEPP outputs predictions of erosion/deposition at 100 points for each hillslope element. WEPP predictions of accumulative erosion and/or deposition (Fig. 5) showed a clear pattern of erosion on the tilled areas and deposition on the hedge areas. Average elevation decreased more downslope of each successive hedge as runoff accumulated. Predicted erosion was greatest immediately below each hedge where the difference in transport capacity and sediment load was greatest. The 'spikeness' of deposition in the hedges is caused by the different influences of discrete storm events during the period of record.

WEPP predicted lower annual erosion rates for degrading areas and predicted higher deposition rates for aggradation areas than the rates than observed with surveys during the three-year tillage period from July 1993 to August 1996 (Table 4). Approximately 35% of the soil eroded between the hedges was predicted to be trapped in the succeeding hedge.

The WEPP-predicted patterns of erosion and deposition differed from those observed in the survey data. Predicted heights of deposition (Fig. 5) were greater than any observed in the survey (Fig. 4), while depths of degradation were smaller. WEPP predicted that all sediment would be trapped within the hedges, not above them. This is because the current version of WEPP does not account for backwater effects and because deposited sediment does not feed back to alter the slope description and so does not affect future erosion and deposition. During the four year simulation, predicted sediment deposition would result in slope reversals that violate model assumptions if the slope file were updated without some kind of smoothing. Predicted erosion would be decreased and predicted sediment trapping would be increased if backwater and slope feedback effects were considered.

3.2. RUSLE predictions

Reflecting prior land use, rainfall distribution, tillage timing, and the presence or absence of a cover crop, the RUSLE estimated *C*-factors for the tilled portions of each year were 0.74 in 1993, 0.91 in 1994, 0.74 in 1995, and 0.71 in 1996. The *P*-factor RUSLE calculated for the 82 m slope with 1.5 m hedges was 0.79 and the corresponding sediment delivery ratio (SDR) = 0.47; for the 33.5 m slope, both the *P*-factor

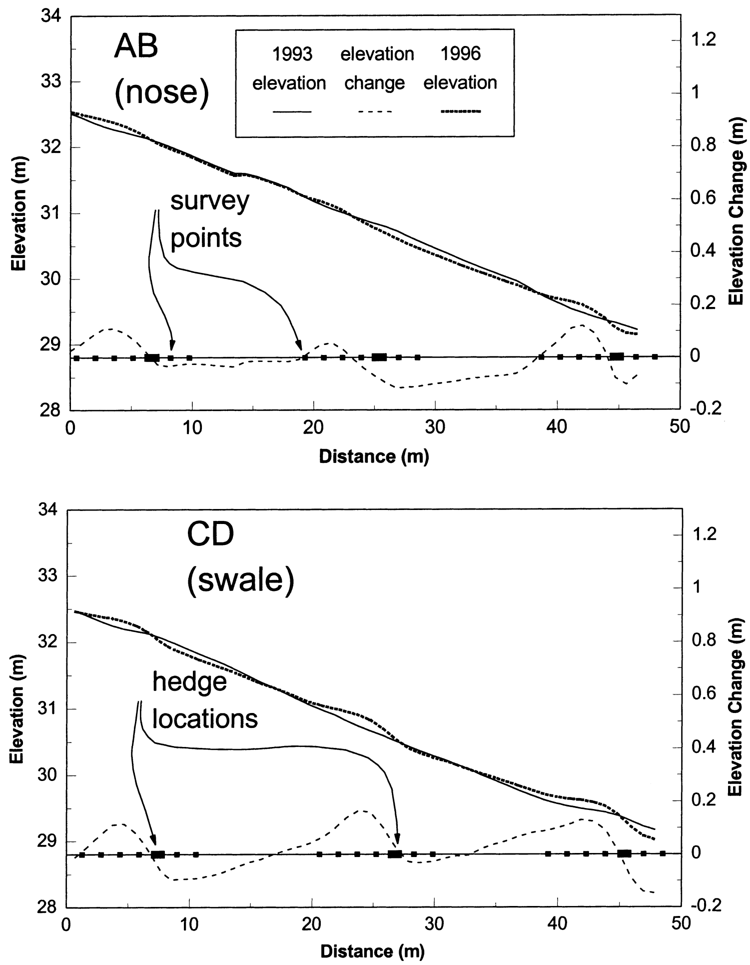

Fig. 4. Two transects based on surveys conducted in 1993. Transect AB crosses a convex slope position while CD comprises a swale (see Fig. 1).

and the SDR were 0.81. The *P*-factor predictions did not differ between years.

Erosion and deposition rates within the surveyed area were calculated from the difference between the sum of sediment yield plus trapped sediment for the total slope (82 m long, eight slope elements) and the sediment yield from the area upslope of the survey area (33.7 m, two slope elements) using Eq. (2). The stripcropping *P*-subfactor was set equal to 1, while the contour *P*-subfactor was retained ($P_c = 0.87$).

Over the tillage period, RUSLE predicted erosion rates of 1122 t ha^{-1} from the surveyed area with an additional 336 t ha^{-1} from the upslope area. With a sediment delivery ratio of 0.47, RUSLE estimated that 54% (0.47/0.87) of the sediment eroded from the entire hillslope would be deposited somewhere on the slope as a result of the grass strips (Table 4). While, RUSLE did not explicitly output the location of predicted erosion and deposition, it is like WEPP in that it does not currently account for backwater or slope change effects. Thus, its predicted location of sediment deposition is the same as WEPP, in the hedges.

To overcome the lack of backwater consideration when narrow grass hedges are modeled with RUSLE 1.06, Toy and Foster (1998) recommended modeling such systems with an 'effective width' rather than the actual width of the grass. They recommended the

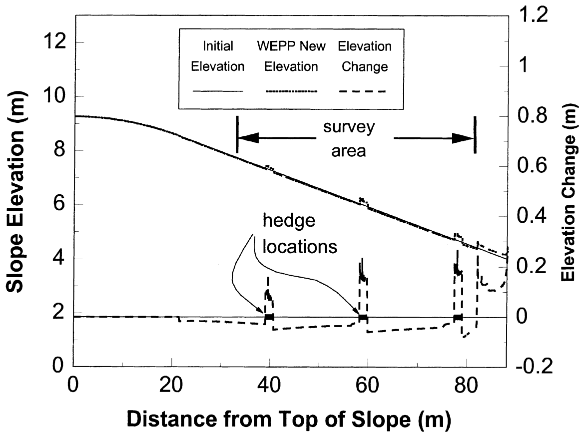

Fig. 5. Initial surface elevation and that resulting from accumulative water erosion and deposition over a four-year WEPP 98.4 simulation; WEPP predicts sediment is trapped only within the grass and predicted deposition would cause slope reversals.

following minimum strip widths, as a percent of hillslope length: 12% for hillslope of <5%, 8% for slopes of 5–10%, and 4% for slopes of 10–15 slopes. Actual strip widths were recommended for slopes steeper than 15% because backwaters distances would be negligible. Increasing effective hedge widths to 3, 4.5, and 6 m, as suggested by Toy and Foster (1998) to account for backwater effects, decreased SDR to 0.17, increased the aggrading area to 0.11 ha, increased predicted sediment deposition by 169 t, and increased calculated hedge sediment trapping efficiency to 80% (1 − 0.17/0.87).

3.3. Tillage translocation prediction

During the four-year study period, 26 tillage operations occurred: eleven disk harrowings, two chisel plowings, and 13 do-all passes (Table 2). Employing Eq. (1) with an assumed average $k = 200$ kg/m and a slope gradient of 0.068, soil flux due to tillage within each tilled strip is estimated to be 354 kg/m. This would represent flux into as well as out of the survey area. For each of the 17.7 m wide tilled strips above hedges, this flux represents an annual soil loss rate of 67 t/(ha year) due to tillage spanning three years of tilled fallow.

Since there are three tilled strips and three hedges, the total tillage erosion and sediment retained above the hedges within the survey area is estimated to be 1060 kg/m, or 87 t along the 82 m hedges (Table 4). Within the survey area, 100% of soil eroded by tillage is assumed retained in the non-tilled hedge strips.

4. Discussion

There were no differences in sediment aggradation observed due to hedge species. Indeed, the largest amounts of aggradation in hedges #2 and #3 occurred upslope of hedges whose primary species had died and been replaced with volunteer vegetation (blackberries and golden rod). These results demonstrate the controlling influence of local topography in determining the location of maximum soil aggradation. In situations such as that studied, where concentrated runoff is limited, any no-till vegetated strip can result in significant benching and the density of vegetation is less important. In larger fields, however, where concentrated runoff occurs, species composition and stem density are critical to hedge performance (Dabney et al., 1995).

The soil loss estimates of RUSLE and WEPP generally agreed with each other but are two to three times higher than the estimate of eroded mass from the survey data. Trapped sediment predictions generally agreed with the mass calculated from survey elevation changes and measured bulk density, but predicted sediment was located in the wrong place. Observed deposition rates were four-to-eight-fold lower than predicted because the aggrading areas was five times larger than the hedges themselves. WEPPs predicted efficiency of sediment trapping of 35% was low. Erosion plot research of hedges on a silt loam soil with 4% slope indicated close to 70% sediment trapping (McGregor et al., 1997). This twice as high as the sediment trapping predicted by WEPP and similar to that predicted by RUSLE if an 'effective' hedge widths were employed.

The survey data indicated that half of the survey area was degrading and the other half was aggrading. The exact size of these areas is uncertain because of the lack of data points in the areas midway between the hedges. Nevertheless, the soil elevation changes in these middle areas had to be small, and the larger changes above and below the hedges are well documented. Some uncertainty always exists with survey data since elevation depends greatly on rod placement. Three observations argue that the magnitude of such errors was small in this case. First, the four surveys (only the first and last of which were discussed herein) show a consistent, progressive modification of the landscape. Second, the pattern of change is interpretable rather than random. Third, the magnitude of change is large (mean $\pm$ 0.06 m) relative to probable errors of rod placement on the fine seedbed condition that existed at the time of each survey. An error of 1 cm in mean elevation of readings would correspond to only a 17% error, or 25 t, in estimated soil erosion. This uncertainty is small compared to that associated with the erosion and tillage translocation models.

The current models cannot account for the variation of erosion and deposition observed between transects AB and CD (Fig. 4). They cannot predict that aggradation would extend several meters upslope of the hedges. The addition of backwater effects and slope evolution considerations would improve performance since both would reduce energy slope in the vicinity of the hedges and therefore would reduce erosion and cause sediment deposition upslope of each hedge. On the other hand, landscape evolution that causes the steepness of the hedge strip to increase will lead to increased erosion predictions unless roughness or residue cover can be modeled separately in the tilled and hedge strips. This can be done in WEPP, but not within the RUSLE 1.06 *C*-factor.

Dabney et al. (1995) showed that where significant backwaters develop, sediment deposition can be greatest 1–3 m above grass hedges, as was observed in this study. However, backwaters alone can not account for the observed patterns. The small contributing area (0.67 ha) would limit the amount of runoff and the steep slopes would limit backwater extent. Also, although deposition was greatest in swale areas, aggradation was observed above most of the hedges. Therefore, a combination of tillage translocation followed by erosion and redistribution of translocated material best explains the observed patterns.

Tillage erosion at a point depends on the balance of soil translocated into the control volume compared to the amount translocated out of that volume. If slopes are uniform, there are equal additions and removals in the control volume are equal so tillage erosion goes unseen and soil depth is only affected where slope gradients change. Thus, tillage caused degradation is most evident on convex slopes and aggradation is most evident on concave slopes. Such translocation can explain the difference between transects AB and CD. Soil may have been translocated in the direction of tillage from the area of the AB transect convexity (Fig. 1) toward the CD transect concavity. Tillage translocation is also evident at field boundaries, which are lines of zero flux. This is why grass hedges, by creating a large number of discontinuities and field boundaries amplify the impact of tillage translocation on landscapes.

Recent studies in which the effects of water erosion and tillage translocation have been quantitatively compared (Quine et al., 1994; Govers et al., 1996) have reported that, tillage accounted for 50–70% of soil movement in steep (0.15–0.20 gradient) European agricultural landscapes receiving conventional tillage. Water erosion tended to be more visible than tillage translocation and may be the dominant means of transport in ephemeral flow areas, but the ability of tillage to make the gullies that form in these areas 'ephemeral' by filling them back in annually, and spreading the decrease in elevation more uniformly, proves that tillage can move just as much soil.

In the present case, the tillage translocation model accounted for $\approx$60% of the observed soil movement. However, both water erosion models predict more soil movement than was observed. Several reasons for the excess water erosion predictions can be suggested. First, the lack of backwater and landscape evolution effects previously discussed. Second, the hedges may reduce the runoff amounts or velocities more than predicted; this is especially true with RUSLE predictions since hedge effects appear only in the *P*-factor and so influence only sediment trapping not predicted erosion as calculated herein. Third, the depths of predicted soil erosion may have exceeded the depth of tillage; if a less erodible layer were reached, actual erosion would be less than predicted.

The patterns observed via survey suggest that tillage was the dominant factor modifying the landscape. Water erosion will not explain that the largest amount of degradation was observed on the convex knob downslope of the miscanthus and fescue segments of hedge #2 (Figs. 1 and 3). The fact that maximum aggradation occurred 1–2 m upslope of the hedges is consistent with the way tillage was preformed. Most heavy tillage operations were stopped one hay bale width (1.2 m) upslope of the hedges and only light rototilling was done closer to the hedges. The mass balance observed in the survey data is what would be expected if tillage translocation were the dominant mechanism. If water erosion had occurred as predicted, the grass below the survey area should have been inundated with sediment, and this was not observed. Therefore, the most appealing interpretation of the data is that grass hedges reduced water erosion rates more than predicted by both models, for reasons suggested above, and that tillage translocation was responsible for 60% of observed soil movement. Clearly, a more complete and quantitative understanding of tillage translocation during cross-slope tillage is needed to substantiate this interpretation.

Water erosion and tillage translocation work together to modify landscapes. The increased deposition observed above hedges #2 and #3 relative to hedge #1 and the maximum erosion occurred observed below the low point in hedge #3, where flows were most concentrated, are consistent with water erosion mechanisms because runoff, erosion rate, and sediment available for deposition increase with distance downslope. Thus, a combination of water erosion/deposition and tillage translocation provides the best explanation for the observed aggradation/degradation patterns. We believe that contour tillage removed soil from the convex portions of the field and from immediately below hedges and deposited it in concave areas and immediately above hedges. Concentrated runoff redistributed material deposited in the swales by tillage and deposited in the backwater and reduced slope areas developed by the hedges. The net result of these processes was the gradual alignment of contour lines with the hedges and the beginning of the development of bench terraces as the tilled surfaces were leveled. A significant start on this process, resulting in the development of a 0.2–0.25 m step across the hedges, was made in just three years of tilled fallow management.

5. Conclusions

No differences were observed between hedge species in landscape benching. In this field, local topography controlled results with concave areas aggrading and convex areas degrading.

A need exists for a comprehensive database of tillage translocation transfer functions for a variety of tillage tools operated on the contour of a range of slopes at different speeds and depths.

The narrow width of tilled strips in fields managed with grass hedges make them useful for quantifying the magnitude of tillage translocation. The magnitude of change created from multiple passes of a given implement would be large compared to survey errors if a firm seedbed were created. Confounding rainfall erosion effects could be eliminated by conducting the tillage operations during a brief interval of time.

Tillage erosion may have accounted for 30–60% of soil movement and landscape benching observed between grass hedges from three years of tilled fallow of silt loam soil on 6.8% slope in Mississippi, USA.

6. Abbreviations

k	constant with dimensions kg/m indicating the amount of soil translocated downslope, per unit length of contour line, by each tillage operation
S	soil slope gradient expressed as a fraction (dimensionless)
WEPP	Water Erosion Prediction Project, a computer model
RUSLE	revised universal soil loss equation, a computer model
K_e	Green and Ampt soil hydraulic conductivity parameter used in WEPP (mm/h)
EI_{30}	rainfall parameter of a storm used in RUSLE, the product of total kinetic energy and maximum 30 min intensity (N/h)
R	annual erosivity factor used in RUSLE (N/h)
K	soil erodibility factor in RUSLE with dimensions t h/(ha N)
LS	slope length and steepness factor used in RUSLE (dimensionless)
C	crop management factor used in RUSLE (dimensionless)
P	conservation practice factor used in RUSLE (dimensionless)
P_c	contouring subfactor of RUSLE P factor (dimensionless)
SDR	sediment delivery ratio used in RUSLE (dimensionless)

E_s	soil eroded in the topographically surveyed hillslope area as estimated with RUSLE (t)
SY_t	sediment yield from the total hillslope estimated from RUSLE (t/ha)
St_t	sediment trapped on the total hillslope estimated from RUSLE (t/ha)
A_t	total area of the hillslope (ha)
SY_u	sediment yield from the hillslope upslope from the surveyed area (t/ha)
A_u	area of the hillslope upslope from the surveyed area (t/ha)

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