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Seasonal controls on sediment delivery in a small coastal plain watershed, North Carolina, USA

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Abstract

Field measurements of drainage ditch sedimentation and suspended sediment transport were used to construct a simple sediment budget and relate seasonal variations in vegetation and the hydrological characteristics of storms to sediment dynamics in a small agricultural watershed in North Carolina. Results indicate that seasonal variations in crop coverage and vegetation in drainage ditches influence sediment delivery. Following the harvesting of crops and mowing of drainage ditches in late autumn, conditions are favorable to soil erosion and sediment transport through early spring. Storms need not be very intense or produce large rainfall totals to transport significant sediment loads. The maturation of field crops and ditch vegetation in spring produces conditions less conducive to both soil erosion and sediment transport. Intense summer thunderstorms, however, are capable of mobilizing and transporting significant amounts of sediment. The computed sediment yield of 0.1 Mg/ha/yr probably represents a low estimate that, nevertheless, is an order of magnitude less than measured ditch storage and more than two orders of magnitude less than regional estimates of soil loss on Coastal Plain croplands. The results show that headwater ditches may be decoupled from slopes so that much of the eroded soil is stored within small watersheds rather than being transported out of the basin.

Keywords: Suspended sediment; Soil erosion; Sediment storage; Ditch storage; North Carolina

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1. Introduction

The Atlantic Coastal Plain was long perceived to lack significant soil erosion because of its gentle topography and sandy, permeable soils (Markewich et al., 1990). Considered independently, the low sediment loads characteristic of large rivers draining to estuaries would have appeared to confirm this notion. However, lacking evidence of the remobilization of previously stored sediment, reports of low sediment delivery ratios in Coastal Plain streams (Simmons, 1988; Phillips, 1991) at least suggest the possibility of significant upland erosion coupled with substantial sediment storage (Phillips et al., 1993). Indeed, a mounting body of evidence has accumulated in recent years showing that soil erosion is much more rapid and extensive in the Coastal Plain than previously believed (Beasley, 1979; Dendy, 1981; Lowrance et al., 1986, 1988; Cooper et al., 1987; Sheridan and Hubbard, 1987; Hubbard et al., 1990; Phillips, 1993, 1995; Phillips et al., 1993, 1999a,b; Slattery et al., 1997, 1998, 2002).

The disparity between large soil loss rates and low sediment yields implies extensive colluvial and alluvial storage, redistribution by tillage, and losses to aeolian processes (Cooper et al., 1987; Phillips et al., 1999a,b;

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Pease et al., 2002a). Details of the linkage between upland soil loss and downstream sediment yields, however, remain poorly understood and are only just beginning to be elucidated (Phillips et al., 1999a,b; Slattery et al., 2002). One element of this conundrum concerns sediment transport and storage in small headwater basins. Because the total drainage area of headwater streams comprises the majority of the drainage network, sediment transport and storage in headwater systems are critical to understanding the sediment dynamics of channel networks (Gomi et al., 2004). Although there has been some assessment of suspended sediment in larger drainage basins on the Coastal Plain (Simmons, 1976, 1988), few data are available for small streams, particularly those with drainage areas less than about 10 km^2. Similarly, the role of drainage ditches as sediment sinks remains poorly studied (Phillips, 1997; Moore et al., 2001; Cooper et al., 2002; Landwehr and Rhoads, 2003). These artificial channels may be important because of recent studies suggesting that little of the soil eroded from uplands is transported very far downstream or, perhaps, even beyond individual agricultural fields (Phillips et al., 1999a,b; Slattery et al., 2002). Using pedological evidence on croplands in eastern North Carolina, Phillips et al. (1999a,b) documented extensive on-site colluvial storage, redistribution of eroded soil within individual fields, and storage in adjacent drainage ditches. Slattery et al. (2002) measured on-site soil loss, drainage ditch sedimentation, and the suspended sediment yield in 1996 for a 19.4 ha watershed in eastern North Carolina and computed a sediment delivery ratio of just 2.9%. The results of these studies imply that low-order streams and drainage ditches may not only transport insignificant amounts of sediment (at least in comparison to upland rates of soil erosion), but that they may in fact be significant sediment sinks.

Relationships between discharge and sediment concentration have long been recognized to show substantial variation at both the event and seasonal time scales (e.g., Hjulström, 1935; Leopold and Maddock, 1953; Heidel, 1956; Guy, 1964; Arnborg et al., 1967; Hall, 1967; Gregory and Walling, 1973). Hysteresis effects have been attributed to a variety of different mechanisms and have been used to make inferences about processes of soil erosion, sediment delivery, and sediment sources (Arnborg et al., 1967; Piest et al., 1975; Wood, 1977; Burt et al., 1983; Klein, 1984; Williams, 1989; diCenzo and Luk, 1997; Asselman and Middlekoop, 1998; Hudson, 2003). Most researchers attribute clockwise hysteresis loops to the flushing and subsequent exhaustion of sediment from channel or nearby sources prior to the discharge peak (e.g., Burt et al., 1983), while counterclockwise loops suggest that sediment is delivered by hillslope processes and distant sediment sources (e.g., Klein, 1984). These interpretations, which are often made lacking direct information on sediment sources and erosion processes in the watershed, may suffer from the problem of equifinality (Steegen et al., 2000). Numerous factors such as vegetation, storm characteristics, temperature, antecedent moisture conditions, sediment availability, and gullying may make the identification of causal relationships difficult (e.g., Guy, 1964; diCenzo and Luk, 1997). Sediment fingerprinting techniques have attracted increasing attention as an alternative method (Collins and Walling, 2004), but can only be used where clear differences exist between sediment sources.

The purpose of this study was to examine sediment delivery in a small agricultural watershed on the Coastal Plain of North Carolina. Measurements of suspended sediment yield at the basin outlet and sediment storage in drainage ditches were compared to estimates of upland soil erosion. These data allowed us to construct a simple sediment budget and relate seasonal variations in vegetation and the hydrological characteristics of storms to sediment dynamics in the watershed.

2. Study area and methods

The Littlefield watershed (7.7 km^2) is typical of agricultural landscapes in the Coastal Plain of North Carolina. It is located in the headwaters of Swift Creek (a major tributary to the Neuse River) on the Pleistocene Wicomico marine terrace in southern Pitt County (Fig. 1). Land cover consists of a mixture of woodlands and agricultural fields (tobacco, soybeans, cotton, corn, and pasture) planted on gentle hillslopes with maximum relief of 7 m and typical slope gradients of 0.001 to 0.004. The climate is humid subtropical with an annual rainfall total of about 127 cm. The soils are Ultisols belonging to two general groups (for details, see Phillips et al., 1999a). Most of the soils on uplands and gentle hillslopes are Udults with sandy surficial horizons overlying argillic horizons. Valley-bottom soils along the main drainage ditch are darker, finer-grained Aquults. The watershed is artificially drained by subsurface tile drains and surface ditches. The Main Ditch experiences year-round baseflow, while tributary ditches experience extended periods without flow in summer and autumn. The ditches are re-excavated periodically (every 2–10 yr) to remove accumulated sediments, with the excavated material placed in mounds above channel banks along field edges where some is

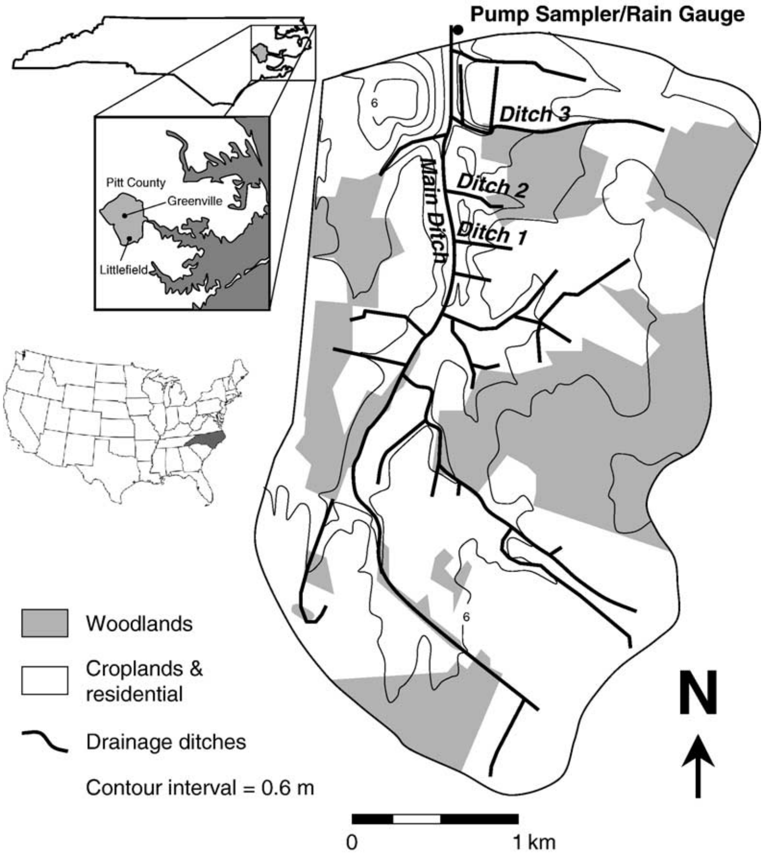

Fig. 1. Study watershed near the town of Littlefield in southern Pitt County, North Carolina.

redistributed within the fields by tillage (Swicegood and Kriz, 1973; Belk and Phillips, 1993; Lange et al., 2000). Grassed maintenance roads along field edges are also elevated by the accumulation of the excavated sediment, providing a vegetated topographic barrier separating fields from the ditches.

2.1. Measurements of drainage ditch storage

Sediment storage in drainage ditches was calculated using cross-section surveys that began in March 1999. These first surveys on the lower 50 m of Ditch 1 were conducted shortly after all the ditches in the watershed had been re-excavated in January 1999 (Lange et al., 2000). The re-excavation of the lower section of Ditch 1 lowered the level of the bed below the outflow culvert (which drains into the Main Ditch) by about 25 cm. Rapid sedimentation established a more graded profile to this culvert prior to the first survey in March 1999. This situation is not unusual in association with re-excavation operations because farmers do not survey to establish stable longitudinal profiles. Rapid adjustments are likely to have taken place immediately following re-excavation. Suspended sediment transport rates were possibly elevated through the ditches immediately following re-excavation, but we were unable to make measurements until February 2001. Beginning in February 2000, the surveys were conducted biannually and expanded to include a total of 56 cross-sections along the entire 420-m length of Ditch 1, a 180-m section of Ditch 2, and a 170-m section of Ditch 3 (Fig. 1). In February 2001, we began surveying an additional 11 cross-sections along a 1.6-km section of the Main Ditch. Because our interest was to estimate sediment fluxes in the ditches for the entire watershed, we did not use the March 1999 survey of the lower 50 m of Ditch 1. Instead, we used the expanded set of measurements (beginning with the February 2000 survey) in our sediment flux calculations. The cross-sectional area of deposition/erosion was computed at each cross-section and multiplied by the distance to the next cross-section. The mass flux determined assuming a bulk density of 1.3 g/cm^3 (Slattery et al., 2002).

Clearly, these data do not tell the entire story of sediment storage/erosion in the drainage ditches at Littlefield. They are, necessarily, a snapshot in the >300 yr of post-settlement landscape modification. Nevertheless, the 4.25-yr record of storage in agricultural drainage ditches at Littlefield is longer than any other reported in the region. While the need to re-excavate makes it obvious that agricultural drainage ditches are aggrading in the region and there has been some documentation of sedimentation rates in artificial channels in wetlands of eastern North Carolina (Belk and Phillips, 1993; Phillips, 1997), with the exception of Slattery et al. (2002), we have no knowledge of any other measurements of ditch sedimentation in an agricultural setting.

2.2. Measurements of sediment output

We used a Sigma 900 MAX automatic water sampler fitted with a pressure transducer to monitor flood stages and a tipping-bucket rain gauge to measure rainfall at the basin outlet. The sampler was programmed to collect 600 ml water samples every 20 min during storms. The sampler intake was located in a fixed position 35 cm above the bed. Suspended sediment concentrations were determined gravimetrically after passing the water samples through microfiber filters using a vacuum-operated filtration system (Pease et al., 2002b). These data were collected from February 2001 through December 2003.

Although the water sampler pumped samples during Hurricane Isabel (18 September 2003), all of the rainfall and some hydrologic data were lost. We used rainfall data collected from a different tipping bucket rain gauge about 15 km north of Littlefield. This was justified by the uniform, widespread nature of the rainfall during the storm. Although the time distribution and amounts were probably similar, these data may have been lagged somewhat behind the rainfall at Littlefield because of the northerly track of the storm. Similarly, we only have information on the time that the flow began to rise, the time and magnitude of the peak discharge, and part of the recession. We applied an SCS dimensionless unit hydrograph (McCuen, 1998) to approximate the shape of the hydrograph, and thus the sediment discharge.

3. Results

Eastern North Carolina was relatively dry during much of the first half of the study period. At nearby Kinston, the annual rainfall total in 2001 was about 20 cm below normal. Wetter conditions returned during 2003 with the total rainfall exceeding the normal by 25 cm through September. On average, the three wettest months of the year (as measured at Kinston) are July, August, and September, but are closely followed by June, March, and January. Even the largest storms were relatively modest in terms of their magnitude–frequency characteristics. None of the storms produced 1-h rainfall totals that exceeded the 2-yr recurrence interval, although Hurricane Isabel generated a 12-h rainfall total equivalent to the 10-yr event. The highest rainfall intensities occurred during summer thunderstorms. The highest 10-min intensity recorded at Littlefield was 10.1 cm/h. Runoff coefficients (i.e., the ratio of surface runoff to rainfall) ranged from 3.3% to 51.6% with a mean of 24.4%. Lag times were generally 2–3 h.

3.1. Ditch storage

The ditch surveys show that bank erosion is not a significant sediment source. Although several cross-sections experienced incision, channel-bed aggradation was dominant throughout most of the ditches (Fig. 2). Average rates of sediment storage along each of the tributary drainage ditches varied considerably from a low of 8.6 kg/m/yr in Ditch 2 to a high of 107.2 kg/m/yr in Ditch 3 (Table 1). Some of the sediment supplied to Ditch 3 was derived from the development of a gully network upstream from the surveyed reach. The field to the north of Ditch 3 also slopes down toward the channel bank and has only a narrow vegetated buffer. In contrast, Ditch 2 has a small drainage area, wider vegetated buffers, and an elevated, grassed maintenance road along the south bank. Vegetated buffers are somewhat elevated along Ditch 1, apparently enough to discourage sediment transport from the fields to the ditch. The highest average storage rate was measured along the Main Ditch (130 kg/m/yr), whose cross-sectional area is about 2–3 times larger than the tributary ditches.

By assuming that storage values at the surveyed cross-sections are representative of unmeasured ditches in the watershed, we extrapolated these values to the entire drainage network. A distinction was made between small tributary ditches that experience extended periods without baseflow (with channel beds that become densely vegetated) and the middle and lower portion of the Main Ditch that experiences year-round baseflow. Average storage values for tributary Ditches 1–3 were assumed to reasonably approximate storage in the remaining 16.3 km of small ditches in the basin. Average storage measured in the lower 1.6 km of the

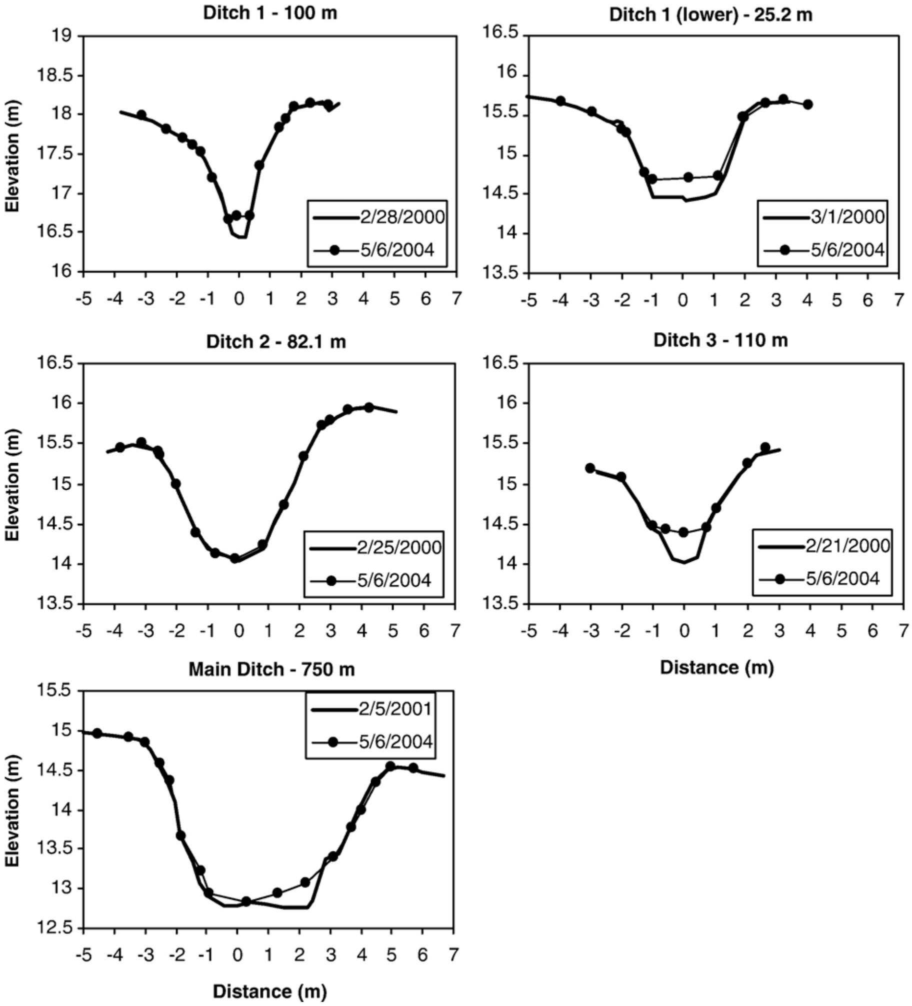

Fig. 2. Examples of drainage ditch sedimentation between February 2000 and May 2004.

Main Ditch was extrapolated to the 2.6 km reach upstream that also experiences perennial flow. This suggests that 1366 Mg/yr of sediment, or 1.76 Mg/ha/yr, was stored in drainage ditches in the watershed. An upper constraint on ditch storage in the watershed was estimated by using the maximum storage rate along the most rapidly aggrading of the tributary ditches (Ditch 3) and the maximum cross-sectional storage rate along the Main Ditch. This would increase the total basin storage to 2978 Mg/yr, or 3.83 Mg/ha/yr.

Table 1
Sediment storage in drainage ditches[a]

	Total ditch storage (Mg)	Annual ditch storage (Mg/yr)	Total storage rate (kg/m/yr)[b]	Number of cross-sections	Ditch length (m)
Ditch 1	71.3	17.0	40.5	21	420
Ditch 2	6.5	1.5	8.6	18	180
Ditch 3	76.7	18.2	107.2	17	170
Main Ditch	676.1	208.1	130.1	11	1600

[a] Ditches 1–3 surveyed from Feb. 2000 to May 2004; Main Ditch surveyed from Jan. 2001 to May 2004.

[b] Annual rate of mass storage per unit channel length.

3.2. Sediment output

Rainfall, discharge, and suspended sediment concentrations were measured for a total of 33 storms during the study period. Equipment malfunctions prevented complete monitoring of storms on several occasions. Table 2 and Fig. 3 show 10 of the most significant sediment-transporting events during the study period for which we have reasonably complete records of sediment concentrations. These storms transported about 80% of the total sediment load measured during the study period.

Table 2
Hydrological and sedimentological characteristics of the storms

Date	Total rainfall (cm)	Stormflow duration (h)	Maximum 10-min rainfall intensity (cm/h)	3-day antecedent rainfall (cm)	Peak discharge (l/s)	Runoff coefficient (%)	Stormflow (cm)	Sediment discharge (Mg)	Peak suspended sediment concentration (mg/l)
21 Mar. 2001	4.5	15.5	3.5	0.0	1,575	5.8	0.3	10.4	1282
14 Jun. 2001	17.2	80.2	7.5	0.0	5,717	24.2	4.1	31.4[a]	442
20 Aug. 2001	7.9	47.5	10.1	1.4	8,940	51.6	4.1	34.8	420
1 Jun. 2002	3.4	8.5	8.2	0.2	804	3.3	0.1	8.6	1345
21 Mar. 2003	4.6	44.7	1.8	0.1	1,447	17.6	0.8	17.4	462
9 Apr. 2003	4.8	26.2	1.5	2.0	1,683	10.6	0.5	7.0	409
23 May 2003	7.5	46.3	1.7	0.0	5,595	43.3	3.2	20.9	215
23 Jul. 2003	5.9	36.7	7.8	0.0	2,987	17.8	1.1	6.7	436
18 Sep. 2003	13.5	50.3	2.9	0.0	7,146	28.2	3.8	14.1	107
14 Dec. 2003	5.0	28.5	2.6	0.0	4,991	41.1	2.1	40.0	578

[a] The sediment discharge is a minimum estimate because we were unable to sample the last discharge peak, which produced the highest 10-min rainfall intensity of this event.

Storms that occurred while vegetation was dormant during the winter and spring (December 1–May 1) generally produced higher suspended sediment concentrations per unit discharge than those in summer and fall (Fig. 4). The one exception was the 1 June 2002 storm (discussed in Section 4.2) that produced the highest sediment concentration measured during the study period (1345 mg/l). Peak discharges during the summer/fall storms, however, were usually much higher than in winter and spring.

All but one of the storms demonstrated moderate to strong clockwise hysteresis in the suspended sediment–discharge relationship (Fig. 3). The hysteresis loop for the second flood peak during Tropical Storm Allison was much more closed than that for the first flood peak, suggesting that significant intrastorm exhaustion of sediment sources occurred. The weakest clockwise hysteresis was evident during Hurricane Isabel, which produced only a very modest increase in sediment concentrations on the rising limb of the storm. Only the 21 March 2003 storm demonstrated counterclockwise hysteresis, with the sediment peak occurring on the falling limb of the first discharge peak.

The sediment discharge at Littlefield was highly variable from storm to storm and on an annual average basis. The sediment yield calculated from all measured storms (including smaller storms not discussed here) was 81.7 Mg from February through December of 2001, 17.5 Mg in 2002, and 149.1 Mg in 2003 for an average of about 85 Mg/yr (0.11 Mg/ha/yr). This value represents a gross approximation for several reasons. A number of large storms were not sampled at all because of equipment failures. Sediment samples could not always be collected through the entire event because of our inability to exchange bottle sets during the night or, in the case of hurricanes and tropical storms, hazardous weather conditions. Additionally, many small storms were not sampled at all. The later deficiency probably had little impact on our estimates of the annual sediment yield because most of the annual sediment load is typically transported by a few large flows (Meade et al., 1990). For example, data from the USGS on nearby Chicod Creek (117 km^2) suggest that 40–50% of the annual sediment load is transported by flows that occur 1% of the year, while 85–95% of the load is transported by flows that occur 10% of the year. The study period also may not be representative of longer-term sediment transport conditions because of the drought conditions that existed through most of the first two thirds of the study period. Estimates from Simmons (1988) and Calvo-Alvarado and Gregory (1997) suggest that it is probably reasonable to expect that typical sediment yields could be two or even three times larger than our calculated values. The data that Simmons (1988) collected for Coastal Plain streams draining rural watersheds affected largely by agricultural activities showed that sediment yields ranged from 0.03 to 0.24 Mg/ha/yr. Calvo-Alvarado and Gregory (1997) reported typical sediment yields of 0.02 to 0.3 Mg/ha/yr for Coastal Plain streams draining agricultural watersheds, and the equation they provided produces a sediment yield of 0.33 Mg/ha/yr for Littlefield. Although the sediment yields measured at Littlefield are within the range of values reported in similar Coastal Plain settings, maximum annual yields could be even higher. For example, during the fourth wettest year on record in North Carolina (1996), Slattery et al. (2002) computed a sediment yield of 0.8 Mg/ha/yr from the Clayroot site, just 20 km from Littlefield.

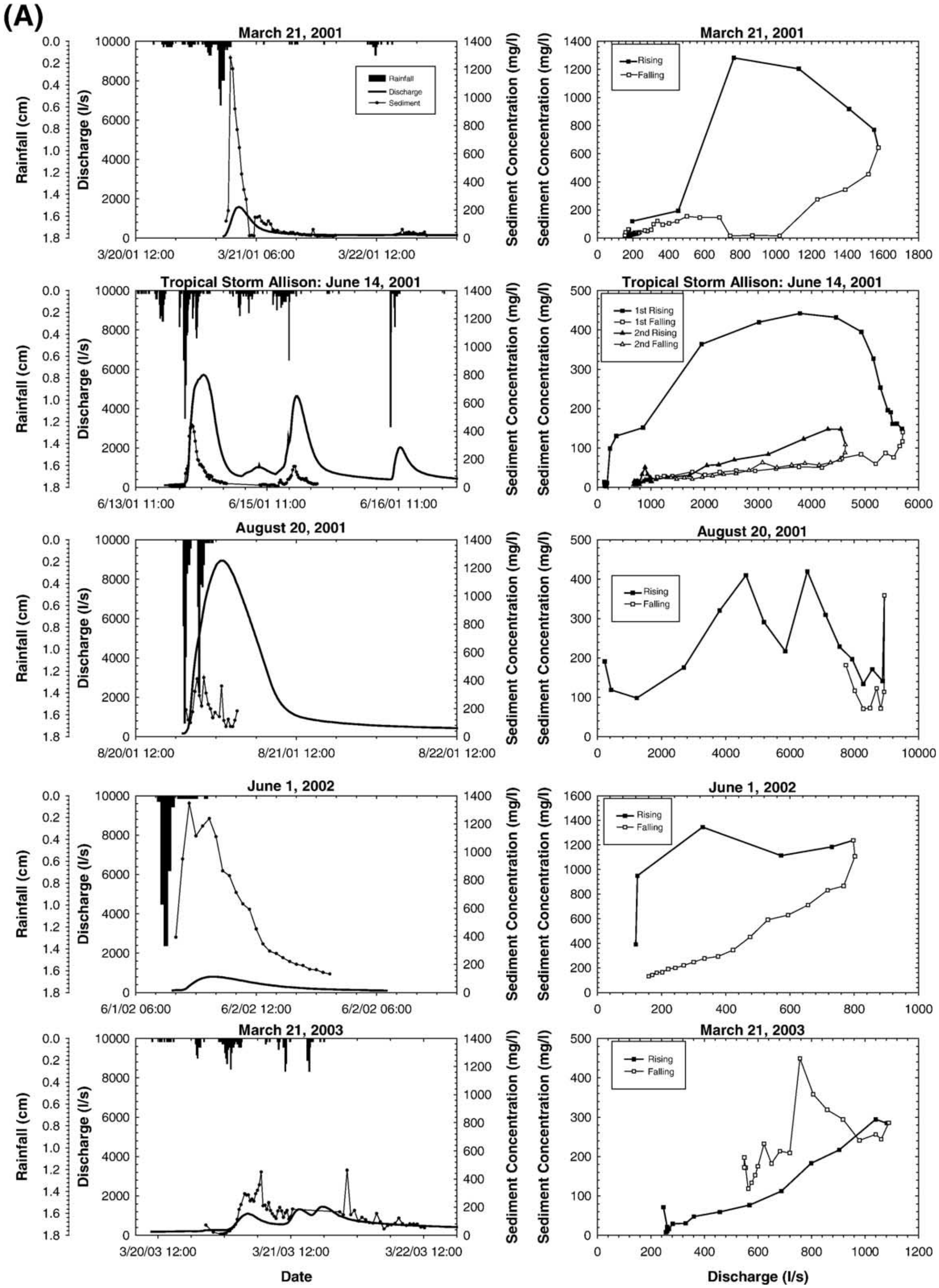

Fig. 3. Storm hydrographs and corresponding discharge–sediment hysteresis relationships for the 10 storms. Note that the scales are different on the hysteresis plots.

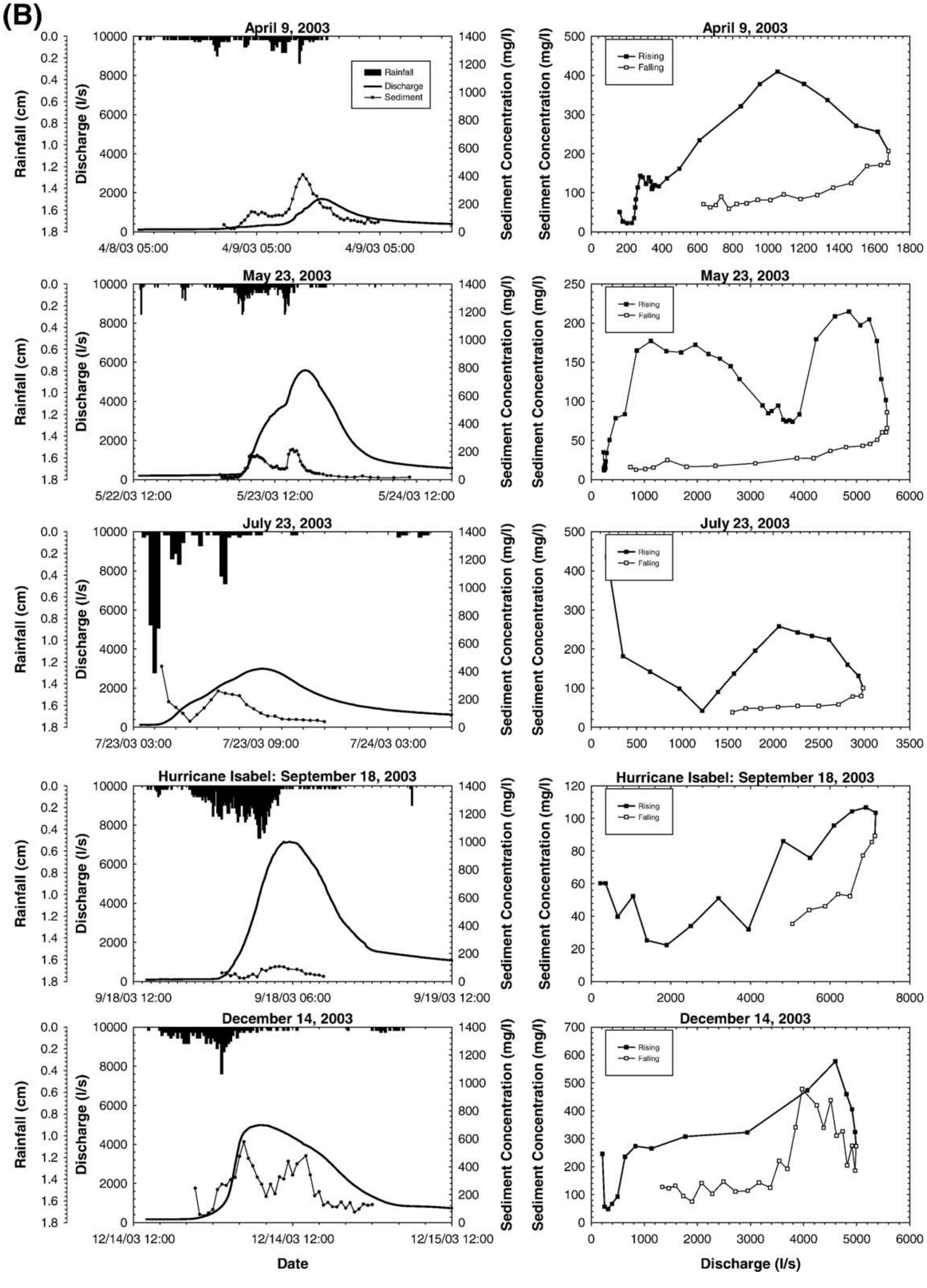

Fig. 3 (*continued*).

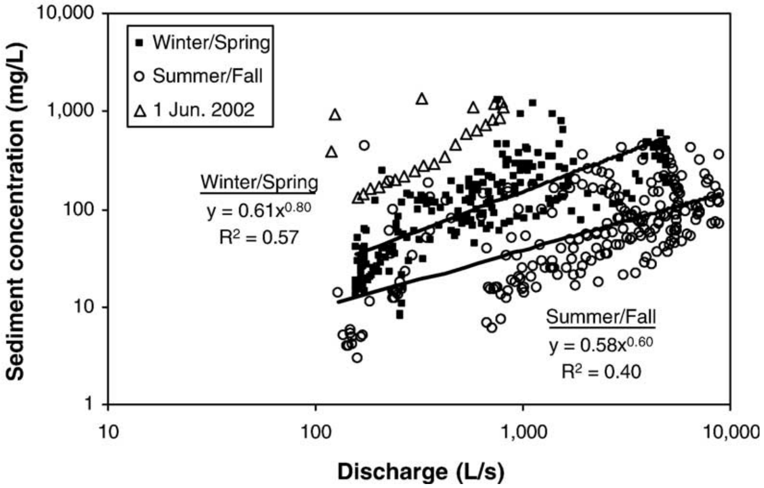

Fig. 4. Seasonal differences in sediment concentration.

3.3. Soil loss

Lacking direct measurements of soil loss at Littlefield, we used soil loss estimates from several other sources. Regional estimates of soil erosion generally fall in the range of 9 to more than 30 Mg/ha/yr (Beasley, 1979; Dendy, 1981; Lowrance et al., 1986, 1988). Using soil-profile truncation on Coastal Plain uplands in North Carolina, Phillips et al. (1993) provided a minimum regional estimate of post-settlement erosion of 9.3 Mg/ha/yr. Slattery et al. (2002) reported an on-site estimate of soil erosion of 27.5 Mg/ha/yr at the Clayroot site. An earlier study at Littlefield used measurements of the truncation of soil profiles near a small family cemetery to obtain a maximum historic erosion rate of 45 Mg/ha/yr (Phillips et al., 1999a). Although Phillips et al. (1999a) recognized that this was undoubtedly an overestimate of all but the most severely eroded soils in the watershed, it provides an upper constraint on rates of soil loss at Littlefield.

3.4. Sediment budget

The sediment budget shown in Table 3 represents a relatively simple accounting of inputs, storages, and outputs. To some extent, this is justified by the particular characteristics of this watershed and others in the region. For example, little evidence exists in the region to suggest that bank erosion is significant (Slattery et al., 2002), and we observed little evidence to suggest its importance at Littlefield. Similarly, colluvial storage at field edges is likely, but these deposits cannot easily be distinguished from accumulations resulting from tillage (Phillips, 1997). Even if our measured sediment yield is unreliably low, or our extrapolation of measured ditch storage to the entire drainage network inflates (or deflates) that component, the sediment delivery ratio still remains low. Depending on the assumptions used, sediment delivery ratio ranges from 0.2% to 3.7%. The suspended sediment yield, while not insignificant, is an order of magnitude smaller than sediment storage in the drainage ditches. Ditch storage, also not insignificant, is an order of magnitude smaller than estimates of soil loss. The inescapable conclusion is that much of the eroded soil is stored on fields before reaching the channel system.

Table 3
Sediment budget

	Annual sediment flux (Mg/ha)
Soil loss	9–45
Ditch storage	1.75–3.83
Sediment yield	0.11–0.33
Sediment delivery ratio	0.2–3.7%

4. Discussion

4.1. Vegetation and seasonality

A variety of arguments have been made to explain seasonal differences in sediment concentrations. Higher concentrations in summer have been related to intense convective rainfall (Walling and Teed, 1971; Kwaad, 1991), the flushing of sediment accumulated during summer dry periods with low baseflow (Gregory and Walling, 1973), high temperatures and low soil moisture (Guy, 1964), and long periods without high flows (Wood, 1977). Seasonal changes in vegetation also clearly have an important influence on suspended sediment transport (Arnborg et al., 1967; Hall, 1967; Klein, 1984; Van Dijk and Kwaad, 1996; Steegen et al., 2000; Swiechowicz, 2002).

Data from Littlefield show that seasonal variations in vegetation cover on agricultural fields, as well as within and along drainage ditches, influence sediment delivery. First-order drainage ditches lacking perennial flow become choked with dense vegetation growth during the summer and act as effective sediment traps (Fig. 5). Although we lack bedload transport data, we observed lobes of sandy bedload moving through the ditches during the winter when vegetation was dormant. The growth of vegetation in ditch bottoms in the spring greatly reduces sandy bedload transport. This is evident particularly in the tributary ditches, but also occurs in the Main Ditch (which experiences perennial flow). The geomorphological effects of in-channel vegetation growth have largely been ignored in the literature (Watson, 1987; Clarke, 2002). Nevertheless, recent research has indicated that drainage ditches can improve water quality by trapping sediment and other agricultural pollutants (Cooper et al., 2000, 2002; Moore et al., 2001). Although studies of the hydraulic effects of in-channel plant growth have largely been limited to grass-lined drainage channels in the U.S., Watson (1987) showed that hydraulic roughness could increase by an order of magnitude during seasonal increases in the growth of aquatic macrophytes. Changes of this magnitude can have a dramatic effect on sediment trap efficiencies and are clearly evident at Littlefield.

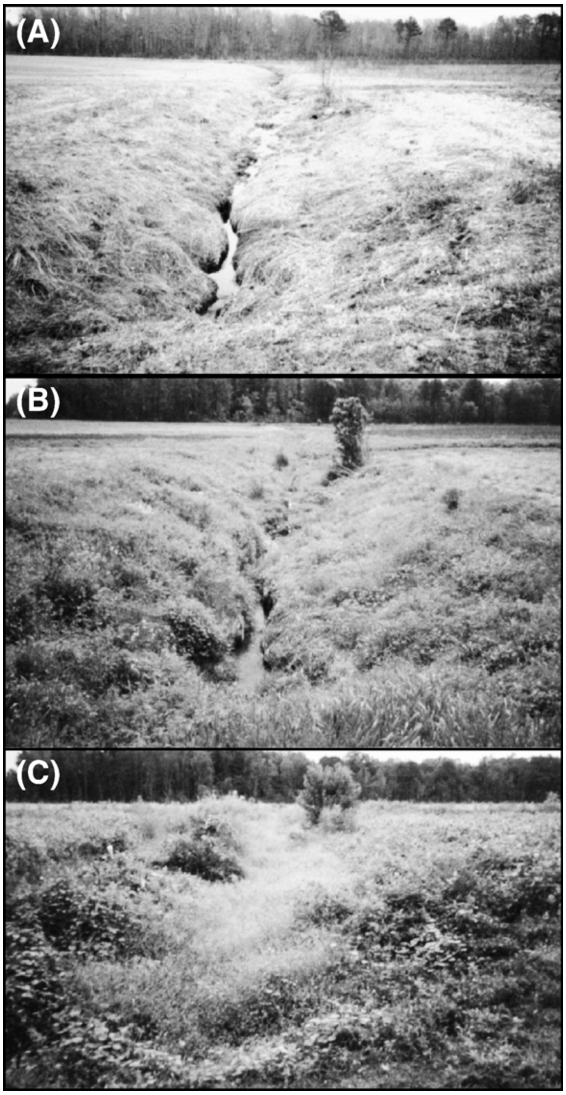

Fig. 5. Changes in vegetation in Ditch 3: (A) January 2001; (B) April 2001; (C) September 2001.

Annual maintenance of the ditches consists of the mowing of vegetation from ditch banks and bottoms in late autumn or early winter after crops are harvested. With hydraulic roughness reduced substantially and with aquatic species in the Main Ditch dying as winter approaches, the ditches become much more efficient conduits for sediment transport, especially the tributary ditches that convey sediment to the Main Ditch. Lobes of sandy bedload derived from tributaries are frequently observed moving through the Main Ditch (Fig. 6). Although some of the fields may be plowed after the autumn harvest, some crop residue is generally retained on the fields before spring plowing and planting. Nevertheless, with crops harvested and sporadic protection from raindrop impacts afforded by crop residue, a substantial portion of the fields are susceptible to erosion by both water and wind (Pease et al., 2002a). This is the setting in late winter and early spring, which may explain how moderately intense rainfall and discharges from storms like the 21 March 2001 event transport relatively large amounts of sediment.

As temperatures rise in May, vegetation in and along the ditches begins to grow rapidly and observations of mobile lobes of sandy bedload cease. Depending on soil moisture conditions and crop rotations, some fields may be plowed and planted. Although increases in vegetation density in late spring and summer tend to reduce erosion and sediment transport, some intense thunderstorms are clearly capable of overcoming the stabilizing effect of vegetation and transporting significant sediment loads. The summer storms of 20 August 2001 and 23 July 2003 illustrate that intense rainfall events are capable of producing moderately high sediment concentrations (>z400 mg/l) despite dense vegetation in the ditches and mature crops on the fields (Fig. 3). In contrast,

Fig. 6. Lobes of sandy bedload in the Main Ditch just upstream from the basin outlet.

Hurricane Isabel did not produce the intense bursts of rainfall characteristic of the other large summer storms. Consequently, it produced a rather low peak sediment concentration (107 mg/l) and a modest sediment discharge for such a large amount of surface runoff.

4.2. Dilution of sediment concentrations

Sediment concentrations appear to be diluted during high discharge events. The two highest sediment concentrations occurred for the 21 March 2001 and the 1 June 2002 storms (Fig. 3). The storm on 21 March 2001 occurred while agricultural fields and drainage ditches had little vegetation to stabilize sediment. This storm produced a modest rainfall total and 10-min intensity and a low runoff coefficient (Table 2). The total sediment discharge (10.4 Mg) was moderate despite the second highest suspended sediment concentration recorded (1282 mg/l). The thunderstorm on 1 June 2002, however, was very short and intense. Low antecedent moisture conditions following a dry spring (just 9 cm of rain during the previous two months) produced the lowest runoff coefficient of the study period. This storm also occurred during the transition to maximum vegetation density in the ditches and while crop coverage was moderate. Although this storm generated the smallest volume of surface runoff and the smallest discharge of the 10 storms examined, it produced the highest sediment concentration (1345 mg/l). With less than half the volume of surface runoff as the March 2001 storm, the total sediment discharge (8.6 Mg) was nearly as large because high concentrations were sustained above 400 mg/l for twice as long. Little dilution of sediment concentrations occurred because these storms had the lowest runoff coefficients and the lowest volume of surface runoff during the study period. In contrast, even though the largest stormflow and discharge events transported the largest total sediment loads (e.g., Tropical Storm Allison and the 20 August 2001 storm), dilution kept sediment concentrations at moderate levels. This implies that the rate at which sediment is supplied during storm events is limited. Similarly, Steegen et al. (2000) also found that increased vegetation cover during the summer reduced sediment production from fields, which led to the dilution of sediment concentrations. At Littlefield, vegetated ditches are also effective at trapping sediment and reducing delivery to the outlet.

4.3. Hysteresis

The dominance of clockwise hysteresis loops in previous studies has been interpreted to suggest that a storm produced a sufficiently high discharge to mobilize nearby sources of sediment (along the channel and on nearby fields) and that these sources were exhausted on the rising limb of each storm hydrograph (Arnborg et al., 1967; Walling, 1974; Wood, 1977; VanSickle and Beschta, 1983; Klein, 1984; Jeje et al., 1991; Asselman and Middlekoop, 1998). However, several alternative explanations have been proposed including the length of time between events (Walling and Teed, 1971; Wood, 1977; Burt et al., 1983), the duration of the event (Wood, 1977; Jeje et al., 1991), variable contributions from gullies (diCenzo and Luk, 1997), higher rainfall intensities at the beginning of storms (Jeje et al., 1991), and a reduction in the erosive effects of rainfall and increased inputs from baseflow after the peak discharge (Gregory and Walling, 1973; Wood, 1977). In particular, Steegen et al. (2000) suggested that clockwise hysteresis was produced not by sediment flushing and exhaustion, but by the supply of sediment from distant hillslope sources. In this scenario, sediment from sources close to the basin outlet reach the outlet quickly and are less likely to be deposited, producing a sediment peak that precedes the discharge peak. The probability of deposition, however, increases with travel time to the outlet. Thus, even substantial contributions of sediment from distant sources may not reach the outlet in abundance because this sediment is more likely to be deposited upstream during its longer travel path to the outlet, leading to lower concentrations on the falling limb of the storm hydrograph. This explanation is appealing at Littlefield, particularly during the growing season, because of gentle hillslope and channel gradients and the hydraulic effects of the dense vegetation present in the ditches (Watson, 1987).

4.4. Slope-channel decoupling

The efficiency of slope-channel coupling has been shown elsewhere to play a major role in determining the magnitude of downstream sediment transfer (Harvey, 1994; Phillips, 1995; Fryirs and Brierley, 1999; Slattery et al., 2002; Swiechowicz, 2002; Gomi et al., 2004). Several studies have shown that significant colluvial storage occurs along field edges (Cooper et al., 1987; Phillips, 1997; Phillips et al., 1999a), which may or may not imply delivery to channels. Gullies can also be important sediment sources (Piest et al., 1975; diCenzo and Luk, 1997; Steegen et al., 2000), but the development of rill and gully networks on fields at Littlefield are not necessarily linked to the channel system (Fig. 7). The ditches may be effectively decoupled from areas of accelerated erosion and surface runoff by vegetated field-edge buffers and elevated maintenance roads along the banks of the drainage ditches. Where such linkages do exist, rates of ditch sedimentation may be considerably higher. The results from Littlefield are consistent with the results of Slattery et al. (2002), who contended that low-order watersheds on the Coastal Plain might lack a strong direct linkage between hillslopes and stream channels. Phillips et al. (1999a,b) also provided compelling evidence that much of the eroded soil remains on individual fields, deposited in rill fans at slope bases and as aeolian deposits at field edges.

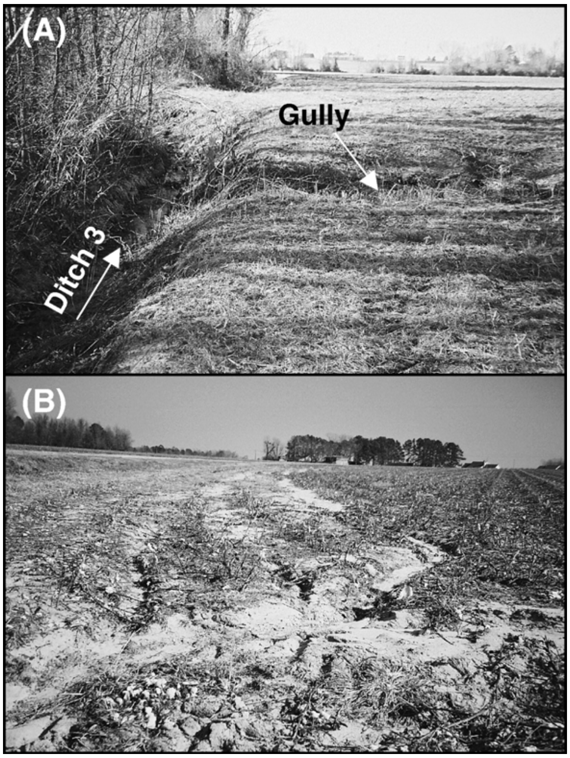

Fig. 7. Gullies and rill networks: (A) gullies supplying sediment to the headwaters of Ditch 3; (B) rill network on field south of Ditch 1.

4.5. Contingency and unpredictability

The results reported in this paper suggest that sediment loads and concentrations may be difficult to predict, in part because of local and seasonal factors associated with vegetation. This view is supported by recent arguments, both implicit (e.g., Lane and Richards, 1997; Russell et al., 2001; Miller et al., 2003) and explicit (e.g., Phillips, 2001, 2004) involving historical and spatial contingency. Phillips (2001) has suggested that environmental systems may be inherently unpredictable because of the influence of conditions that are historically or spatially contingent, and therefore unique. Historical contingency exists where the state of an environmental system is dependent on one or more previous states, or on past events or a past sequence of events (Phillips, 2001). Spatial contingency exists where the state of an environmental system is dependent on other linked locations or is sensitive to local controls that are unlikely to be duplicated elsewhere (Phillips, 2001). Vale (2003) argued that the finer the scale (whether spatial, temporal, or the degree of resolution) the more likely it is that satisfactory explanations will require the invocation of historical contingency. Gould (1986, p. 69) even went so far as to suggest that “everything, ultimately, may be a product of history.”

Several processes may be reasonably viewed as contingent at Littlefield. Soil moisture is spatially contingent in that it is dependent on local conditions that are unlikely to be duplicated elsewhere. It can be highly variable over short distances because of variations in topography, vegetation, soil organic matter, and soil texture. The effect of soil moisture on runoff and erosion is also a historically contingent process in that a local sequence of rainfall events (which may be highly complex spatially and temporally) produces antecedent moisture conditions that exhibit a high degree of spatial variability. Spatial variations in the soil's physical and hydrological properties (as reflected in soil moisture) may produce a mosaic of areas with contrasting hydrologic responses and discontinuous, isolated hydrologic pathways (e.g., Fitzjohn et al., 1998). Russell et al. (2001) showed that estimates of the contribution from individual sediment sources concealed significant seasonal and intrastorm variability from changes in soil moisture and groundwater levels. Such variability is a manifestation of historical and spatial contingency that may require a synoptic approach to obtain meaningful generalizations and/or predictions (Phillips, 2001).

The development of gullies that transport sediment to the ditches is a local, contingent process. Whether, when, and where a gully network develops depends on factors such as soil moisture, crop coverage, cultivation practices, season, etc. Although soil erosion can be predicted in a general sense at larger and longer spatial and temporal scales (e.g., using the USLE), the development of the gullies that connect the fields to the ditches and supply much of the sediment transported to the basin outlet may be largely unpredictable.

Significant sediment transporting events can also be associated with a particular combination of seasonal phenomena. Just as Miller et al. (2003) found that the sequence of fires and storms influenced the sequence of sediment inflow and transport events in western Oregon, the sequence of vegetation change and the seasonality of storm characteristics affect sediment dynamics at Littlefield. This is similar to wind erosion in the region (Pease et al., 2002a), which is strongly associated with seasonal climatology (late winter/early spring wind regimes), climate synoptics (dry southwesterly winds, low soil moisture), and agricultural operations (spring tillage). Although seasonality in the fluvial system is less pronounced, similar conclusions have been reached regarding the geomorphic effect of floods, which show that initial conditions, seasonal timing, and event sequencing may be as important, or even more important, than event magnitude. For example, Magilligan et al. (1998) argued that timing and event sequences were the primary explanation for the lack of floodplain sedimentation associated with the 1993 flood on the Mississippi River.

5. Conclusions

Suspended sediment transport at Littlefield is influenced by seasonal differences in crop coverage on agricultural fields, the growth of vegetation in drainage ditches, and the intensity/duration characteristics of storm systems. The harvesting of crops and mowing of drainage ditches in late autumn produces conditions conducive to soil erosion and sediment transport in winter and early spring. Although these storms may not be very intense or have large rainfall totals and runoff volumes, they may transport significant sediment loads. As field crops and ditch vegetation matures during the growing season, erosion and sediment transport are curtailed, but not to the point that intense thunderstorms cannot mobilize and move significant amounts of sediment. Large runoff volumes dilute sediment concentrations, whereas the highest concentrations are experienced during events that generate low runoff volumes but are still capable of mobilizing available sediment.

The computed sediment yield of 0.11 Mg/ha/yr represents a minimum approximation that may underestimate yields by two to three times. Nevertheless, this estimate is more than two orders of magnitude lower than the high rates of soil loss (9–30 Mg/ha/yr or more) reported in other investigations of soil erosion on Coastal Plain croplands. Measurements of sediment storage in drainage ditches are an order of magnitude higher than the sediment yield, but an order of magnitude lower than estimated rates of soil erosion. These results are consistent with several recent studies suggesting that slopes and tributary channels are effectively decoupled. Much of the eroded soil is stored within small watersheds rather than being transported out of the basin. If Littlefield is representative of other agricultural watersheds in the region, and we have no reason to believe that it is not, then suspended sediment loads in headwater channels on the Coastal Plain can be expected to be low unless gullies or other means of channel-slope coupling (e.g., ineffective field-edge buffers) act to link channels to areas with high rates of soil loss on fields.

The results of this study confirm previous observations that artificial drainage ditches may be a significant sediment sink (Phillips et al., 1999a,b; Slattery et al., 2002). However, the role that bedload transport plays in the transfer of sediment through these ditches remains unclear. Phillips et al. (1993) suggested the possibility that a large percentage of the fluvial sediment transport occurs as sandy bedload. Our observations suggest that seasonal variations in vegetation in ditches and on fields play an important role influencing the movement of sandy bedload through these ditches. The transport of sandy bedload in drainage ditches warrants further study.

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