SEDIMENT LOSS AND RUNOFF FROM CROPLAND IN A SOUTHEAST ATLANTIC COASTAL PLAIN LANDSCAPE

D. M. Endale, D. D. Bosch, T. L. Potter, T. C. Strickland

ABSTRACT. *Widespread implementation of conservation tillage systems during cotton (*Gossypium hirsutum *L.) and peanut (*Arachis hypogea *L.) production in the Atlantic Coastal Plain region of the U.S. has substantially reduced erosion and sediment loss. However, the benefits of conservation tillage in these cropping systems are being threatened by weather shifts that include increased frequency of high-intensity rainfall, policies that encourage the removal of crop residues as cellulosic feedstocks for energy production, and increased herbicide resistance in weeds. Long-term integrated studies are needed to quantify potential impacts. We evaluated runoff and sediment loss from six 0.2 ha fields located on a gently sloping hillslope in a Southern Atlantic Coastal Plain landscape over ten years (2000-2009) during rotational cotton-peanut production, with a rye (*Secale cereale*) winter cover crop. Half of the fields were in conventional tillage (CT; inversion tillage with cover crop residue incorporation prior to planting), and half were in strip tillage (ST), which is a commonly used conservation tillage practice in the region. Fields were laid out as contrasting tillage pairs at upper, middle, and lower landscape positions and irrigated as needed. Runoff and sediment load from CT fields was significantly greater than from ST fields at each landscape position. Over the 10-year study period, mean annual total sediment load was 1823 kg ha^{-1} year^{-1} from CT fields and 237 kg ha^{-1} year^{-1} from ST fields (an 87% difference), and runoff was reduced by 41%. A soil tolerance value (T) of 2,200 kg ha^{-1} year^{-1} was exceeded in three out of ten years in CT fields and never exceeded in ST fields. On a monthly basis, extreme events (>90th percentile; 10%) accounted for 61% to 72% of the 10-year total sediment load for the CT system (341 to 2,828 kg ha^{-1} month^{-1}) and 73% to 84% for the ST system (49 to 593 kg ha^{-1} month^{-1}). The rainfall and irrigation total was above the normal monthly rainfall in 83% of these extreme monthly periods (mean 179 mm, range 81 to 316 mm). Sediment load was greatest in summer and spring, and during cotton production. The study results improve estimates of the increase in rainfall event size tolerated by CT vs. ST cropping systems, demonstrate the benefits of conservation tillage management during cotton and peanut production, and are expected to guide management decisions that focus on reducing sediment loss in this landscape. Specifically, the results point to the use of cover crops and strip tillage as essential best management practices for this purpose.*

Keywords. *Biofuel, Climate change, Cotton, Crop residue, Crop rotation, Peanut, Soil erosion, Water quality.*

The Atlantic Coastal Plain of the southeastern U.S. is the nation's largest major land resource area (MLRA), covering 276,000 km^2 extending from Virginia to Mississippi (USDA-NRCS, 2006). Croplands cover 17% of the MLRA, grasslands cover 8%, and forestlands cover 61% (USDA-NRCS, 2006). Agriculture plays a prominent role in the economy of the region. Irrigated and non-irrigated cotton, peanuts, corn, and soybeans are major row crops, with about 50% of the planted hectares under conventional tillage (CT) practices such as moldboard plowing, chiseling, disking, and harrowing (CTIC, 2009). Ultisols, the predominant soil group, are highly weathered, low in organic matter, weak in structure, and have highly erodible sandy surfaces (West et al., 1997). Intense spring and summer storms come at a time when the soil is likely to have the least vegetative cover under CT. As a result, erosion and sediment loss due to runoff are persistent natural resource concerns (Langdale et al., 1992; NRC, 1993; Bruce and Langdale, 1996; Reeves, 1997; Pieri et al., 2002; Schnepf and Cox, 2006; FAO, 2008; Towery and Werblow, 2010). Lowrance et al. (1986) estimated annual average sediment deposition rates ranging from 35 to 52 Mg ha^{-1} year^{-1} in riparian zones of a 1,736 ha subwatershed of the Little River watershed near Tifton, Georgia, during 100 years since settlement began in 1880.

Numerous studies have shown that conservation tillage practices have the potential to substantially reduce runoff, erosion, and sediment loss in the region (Langdale et al., 1992; Fawcett et al., 1994; Gilley, 1995; Bruce and Langdale, 1996; Reeves, 1997; Allmaras et al., 2000; Endale et al., 2000, 2002; Schomberg et al., 2003; Schnepf and Cox, 2006; FAO, 2008). Conservation tillage is an umbrella term encompassing four interlinked management practices: min-

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The authors are **Dinku M. Endale**, **ASABE Member,** Agricultural Engineer, **David D. Bosch**, **ASABE Member,** Research Hydraulic Engineer, **Thomas L. Potter**, Research Chemist, and **Timothy C. Strickland,** Research Leader, USDA-ARS Southeast Watershed Research Laboratory, Tifton, Georgia. **Corresponding author:** Dinku M. Endale, USDA-ARS SWRL, 2316 Rainwater Road, P.O. Box 748, Tifton, GA 31793; phone: 229-386-3893; e-mail: Dinku.Endale@ars.usda.gov.

imum or no soil disturbance, permanent residue cover on 30% or more of the surface partly achieved by growing cover crops, direct sowing, and sound crop rotation (Schnepf and Cox, 2006; FAO, 2008). The residue cover buffers the erosive energy of raindrops, facilitates infiltration, and reduces runoff, an agent for transport of sediment and agrichemicals from farm fields. Conservation tillage practices are credited with decreasing soil erosion on U.S. cropland by 43% from 1982 to 2007, preventing close to 0.7 billion Mg of soil from leaving croplands and entering wetlands and waterways (USDA-NRCS, 2010). There are notable geographical differences in the reductions due to differences in climate, soil and landscape characteristics, and cropping and management practices.

After a surge starting in the 1980s, the conservation tillage adoption rate in the U.S. leveled off in the late 1990s but appears to have picked up again in recent years. For example, the 2012 U.S. Census of Agriculture (USDA-NASS, 2014) found that 45% of all U.S. cropland (~70 million ha) was planted in conservation tillage, of which ~56% (~39 million ha) was in no-till. Adoption rates in the southeastern U.S. are comparable. For example, the 2008 crop residue management survey by the Conservation Technology Information Center (CTIC, 2009) found that Alabama, Georgia, South Carolina, and North Carolina had, respectively, 48.5%, 34.1%, 48.3%, and 43.3% of their total planted hectares under conservation tillage. This also means that at least 50% of the cropland remained under CT management.

Conservation tillage practices in the southeastern U.S. are threatened by the development of herbicide-resistant weeds, in particular glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) (Price et al., 2011; Aulakh et al., 2013). This has led some growers to revert from conservation tillage to CT practices in which residue cover is not maintained on soil surfaces (Price et al., 2011; CAST, 2012; Aulakh et al., 2013). Renewable energy initiatives, which aim to utilize cellulosic feedstocks by removing crop residues from croplands, also have potential to increase soil erosion and sediment loss (Blanco-Canqui, 2010; Delgado et al., 2013). Finally, implications of recent shifts in regional weather patterns on runoff and sediment loss are a concern. The increased rainfall intensities predicted by climate change models are expected to lead to higher soil erosion and sediment loss rates (Delgado et al., 2013; Ingram et al., 2013). Using various global circulation models and the Water Erosion Prediction Project (WEPP; Flanagan and Nearing, 1995) model, Nearing et al. (2004) examined trends in precipitation, rainfall erosivity, runoff, and soil erosion across the U.S. in the coming century. Scenarios examined for Atlanta, Georgia, in the southeastern U.S. point to increases in precipitation, rainfall erosivity, runoff, and soil erosion for corn and wheat cropping on a Tifton soil series.

To guide decisions on residue harvesting and other practices and determine the value of conservation tillage practices, long-term data are needed that take into account temporal changes in the matrix of components that make up agricultural production systems (Delgado et al., 2013). Ingram et al. (2013) argued that, to engage decision makers, scientific information should be provided at the time scale relevant to their needs, and they noted that decision makers in the southeast have an interest in seasonal and decadal time scales. Data on sediment loss from cropland at such scales are not readily available in the southeast. Furthermore, common models used for assessment of regional and national soil loss, such as the empirical Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978), the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997), RUSLE2 (USDA-ARS, 2008), and the physically based WEPP model, continue to need improvements to allow better event-based and spatial and temporal predictions for better assessment of soil loss in light of changing climate and land use (Kinnell, 2010; USDA-NRCS, 2010; Hawkins et al., 2012). As options for switching back and forth between tillage systems arise in response to national initiatives, weed management, or market and other forces, it is important to establish, from long-term field studies, the spectrum of sediment losses and environmental risk that may result from the combination of management practices and extreme weather events. The objective of this study was to directly compare runoff and sediment loss for fields under CT and a commonly used conservation tillage practice, strip tillage (ST), using ten years (2000 to 2009) of runoff and sediment loss data from six fields in a Southeast Atlantic Coastal Plain landscape during rotational cotton-peanut cropping with rye used as a winter cover crop. Strip tillage is a popular conservation practice applied throughout the southeastern U.S. and advocated by the USDA-NRCS as a best management practice (BMP). Strip tillage creates a residue-free tilled seed bed that is 15 to 30 cm wide and 10 to 20 cm deep while leaving the soil and residue between rows undisturbed. Strip tillage implements, while showing some variation depending on the manufacturer, can generally include row markers, coulters, row cleaners, tillage shanks, covering disks, and packing wheels or conditioning baskets mounted on a heavy tool bar and matching the number of rows and spacing of the planter.

Materials and Methods

Site and Treatment

The study was conducted from 2000 to 2009 at the University of Georgia Gibbs Farm located in Tift County, Georgia (31° 26′ 13″ N, 83° 35′ 17″ W). The specific site, soils, hydrologic infrastructure, and farming practices have been described in detail by others (Bosch et al., 2005, 2012; Potter et al., 2004, 2008). Briefly, the experimental site (fig. 1) is a 1.4 ha, gently sloping (3% to 5%) parcel of land divided into two blocks running down the prevailing slope. Three 0.2 ha fields were established in each block, with each field surrounded by a 0.6 m high berm constructed from soil brought to the site.

Tillage was randomly assigned to the blocks, with CT on the northern block (fields 1, 3, and 5) and ST on the southern block (fields 2, 4, and 6), prior to planting the first cotton crop in May 1999. Mean field slopes vary slightly from 3% to 4% (fig. 1). At the upper landscape position, field slopes in the two blocks are similar. At the middle and

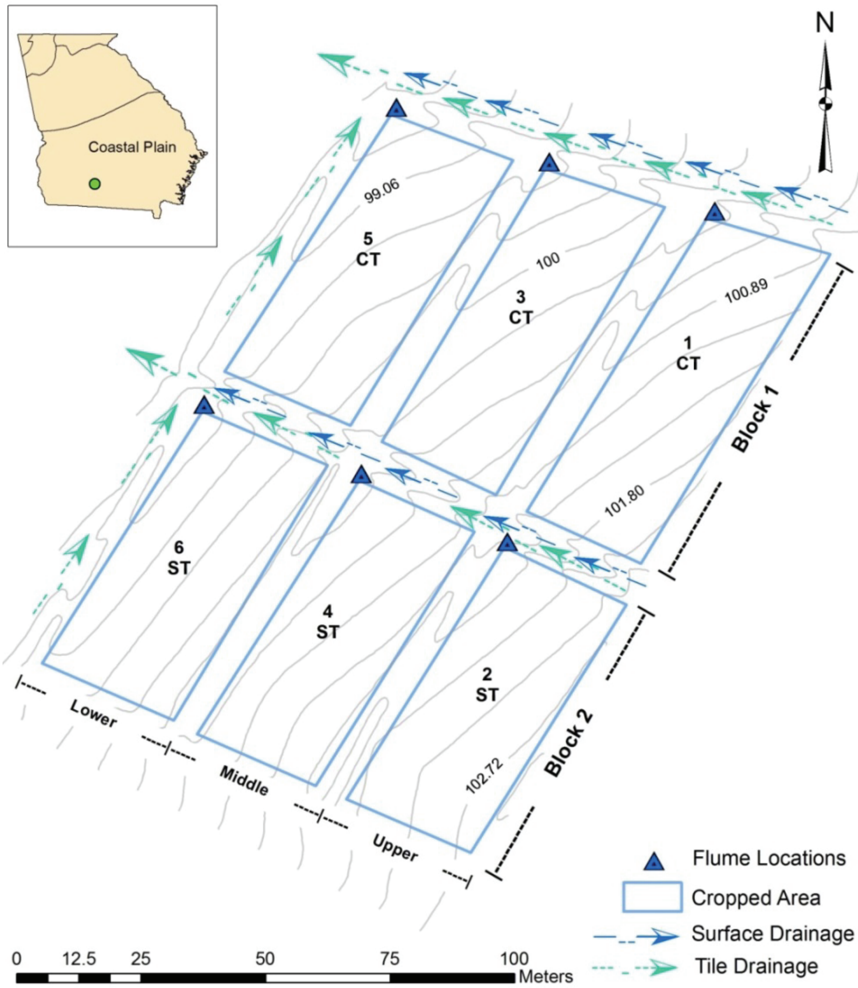

Figure 1. Layout of the Gibbs Farm experimental site: block 1 is conventional tillage (CT) fields 1, 3 and 5; block 2 is strip tillage (ST) fields 2, 4, and 6; and upper, middle and lower are landscape positions. The inset map shows the site location within the Coastal Plain in Georgia.

lower landscape positions, fields in block 2 have slightly greater slope (up to 0.5% greater) than fields in block 1 (fig. 1). The field divisions and tillage assignments established paired fields (CT-ST) at each of the upper, middle, and lower landscape positions to be used for comparison of hydrologic response, sediment, and agrichemical loss at each position between tillage treatments (Bosch et al., 2012).

SOILS

The official USDA Tift County soil survey map shows two soil series at the research site: Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) and Carnegie sandy loam (fine, kaolinitic, thermic Plinthic Kandiudults) (Bosch et al., 2012). Detailed site-specific delineation of soil series within the six fields has not been performed. However, particle size data indicate Carnegie at the upper, Tifton at the middle, and Fuquay loamy sand (loamy, kaolinitic, thermic arenic Plinthic Kandiudults) at the lower landscape positions. The Tifton series occurs on gently sloping ridge tops and hillsides (0% to 8% slope) and is deep and well drained. Soil profiles are characterized by loamy sand or sandy loam A and E horizons over sandy clay loam Bt, Btv, and BC horizons that extend to 200 cm. Tifton soils typically contain an argillic horizon within 50 cm of the soil surface. The Carnegie soil is morphologically similar to the Tifton except that the A and E horizons have a sandy loam texture, are often thinner, and the series has more than 35% clay in the upper 50 cm of the Bt horizon. Particle size analysis from soil samples collected at the study site in 1999, 2001, and 2010 indicated differences in the texture of surface soils between the upper and lower landscape positions, likely attributed to soil erosion at the upper position and deposition at the lower position due to prior farming, which was in evidence when research started at the site in 1998 (Bosch et al., 2012). The lower landscape position had a sandier surface and deeper Bt horizons, hence the Fuquay loamy sand designation. Textural differences existed within a given landscape position but were small (<4.0% above 15 cm), with the ST fields having slightly coarser surface texture than the CT fields.

HYDROLOGY AND WATER SAMPLE COLLECTION

The hydrologic infrastructure was designed to monitor subsurface flow from each 0.6 ha block and surface runoff from each 0.2 ha field (Bosch et al., 2012). The berm and slope configuration directed surface runoff to the northwest corner of each 0.2 ha field (fig. 1), where it was measured with an integrated combination of a 0.46 m metal H-flume, Druck pressure transducer, and CR10X data logger (Campbell Scientific, Inc., Logan, Utah). Runoff flow rate data were compiled at 1 min intervals from the depth measurements and flume calibration curves, downloaded into a computer, and summarized as daily, monthly, and annual runoff amounts. Missing and erroneous runoff data over the study period were <1% of the total (Bosch et al., 2012). Climatic data, including 1 min rainfall amounts, were collected from a weather station erected 10 m away from the northeastern border of field 1. A solid-set irrigation system with stationary risers and sprinkler heads provided water during plant water stress periods and helped to activate weed, insect, and disease controlling chemicals. Irrigation amounts were determined with stationary rain gauges placed across the fields. Some of these irrigation events generated runoff. Rainfall and irrigation amounts were summarized on a daily, monthly, and annual basis.

Runoff sample collection procedures are described by Potter et al. (2004). Automated ISCO samplers (Lincoln, Neb.) integrated with data loggers were programmed to sample 50 mL for every 520 L of runoff and directed to 9 L glass jars representing flow-proportional composite samples. Physical limitations of the sample intake prevented sample collection from flow depths less than 2 cm. In addition, some samples were missed due to equipment and instrument issues. In some cases, samples collected after periods when personnel were not available for immediate sample collection represented multiple events. In total, over the 10-year period, water samples were collected during plot runoff that represented 88% to 95% of the total flow. Sediment mass was determined gravimetrically by vacuum filtration of runoff samples using 0.7 μm nominal size GFF filters, (Whatman, Maidstone, U.K.) followed by drying overnight at 105°C. Sediment concentration was determined from sediment mass and filtered runoff volume.

MANAGEMENT

A summary of the 2000-2009 cropping schedule and activities is shown in table 1 (Bosch et al., 2005, 2012; Potter et al., 2004, 2008). Cotton was grown in 2000 and subsequent odd years and peanuts in even years. Planting was in May, and harvesting was in September or October. A rye grain cover crop was drilled (see below regarding tillage) in all fields in October through mid-December and was seeded with crimson clover (*Trifolium incarnatum*) in 2004 and Austrian winter pea (*Pisum sativum*) in 2009. Glyphosate application in late March through mid-April killed the cover crop. Fertilization and pesticide treatments were identical for all fields and followed the Extension Service recommendations from the University of Georgia (e.g., Jost et al., 2005; Prostko et al., 2007). Poultry litter was applied at 4.5 Mg ha^{-1} on all plots in 2002 and during the cotton years (except in 2003 and 2009) with mean N, P_2O_5, and K_2O contents of 2.8%, 2.4%, and 2.7%, respectively. Starter fertilizer and side-dress fertilizer were also applied during the cotton years in granular (34-0-0) and/or liquid (28-0-0-5) form. Mean annual N and elemental P and K applications from all sources during the cotton years were approximately 169, 74, and 112 kg ha^{-1}, respectively. No additional fertilizer was applied during peanut years.

Tillage in CT fields consisted of fall chisel plowing (2000-2003, 2005, and 2006 only) followed by spring disking (2×) to 20 cm depth up to three weeks before planting. This was followed by 8 cm deep harrowing and cultivator leveling to form the seedbed just before planting, except in 2002, 2004, and 2009 when a moldboard plow was used to turn the soil 30 cm deep followed by an 8 cm deep harrowing and leveling with a cultivator. In ST fields, an in-row shank subsoiler was used to create 15 cm wide strips in the desiccated cover crop mulch, and the tillage depth was 20 cm. To reduce soil compaction, non-inversion plowing was completed on all fields using a paratill plow in November 2002. The ST fields were also paratilled in October 2004 and 2007. All cotton stalks were mowed to 5 cm following cotton harvest. Peanut harvesting caused some soil disturbance due to mechanical digging. All crop residue was left on the fields, but residue in CT fields was incorporated 10 to 15 cm deep into the soil.

DATA PROCESSING AND ANALYSIS

Daily runoff amount and sediment concentration were

Table 1. Summary of cropping schedule and activities at the Gibbs Farm experimental site with dates as month/day for 2000-2009.[a]

Activity		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Summer crop		Cotton	Cotton	Peanuts	Cotton	Peanuts	Cotton	Peanuts	Cotton	Peanuts	Cotton
First disking[b]		3/15	3/26	3/21	4/1	3/31	4/29	4/10	4/17	4/18	4/20
Bedding[b]		4/17	5/3	4/22	5/1	4/28	5/9	5/2	4/24	5/9	4/30
Fertilize	Poultry litter	4/12	4/19	4/16	NA	NA	4/19	NA	4/17	NA	NA
	Inorganic	NA	NA	NA	4/21	NA	NA	NA	5/1	NA	4/21
Plant		5/1	5/7	5/9	5/12	5/10	5/23	5/9	5/1	5/12	5/4
N side-dress		6/1	6/18	NA	6/25	NA	6/22	NA	NA	NA	6/19
Defoliate		8/28	9/20	NA	10/8	NA	9/29	NA	9/25	NA	10/8
Harvest		9/14	10/5	9/10	10/22	9/21	11/1	9/28	10/10	10/16	10/23
Mow		10/1	11/1	10/25	11/3	NA	11/2	NA	10/10	NA	10/26
Chisel/harrow[c]		11/30	11/1	10/25	11/3	NA	11/2	10/19	NA	NA	NA
Paratill[d]		NA	NA	11/1	NA	10/5	NA	NA	10/10	NA	NA
Cover crop		Rye	Rye	Rye	Rye	Rye	Rye	Rye	Rye	Rye	Rye
Spray/mow		3/24	4/10	4/3	4/1	4/15	4/11	4/6	4/4	3/31	3/30
Plant		12/1	12/11	11/25	11/25	10/5	11/16	10/31	10/15	10/29	11/4

[a] NA = not applicable.
[b] Disking and bedding operations in conventional tillage fields only.
[c] Fall chisel/harrow ended in 2006 and was performed in conventional tillage plots only.
[d] Fall paratill in all plots (2002) and in strip tillage plots only (2004 and 2007).

used to estimate daily sediment load as kg ha^{-1}. To account for temporal variability of rainfall and spatial runoff, normalized runoff and sediment data (using a runoff coefficient for runoff as a percentage of rainfall plus irrigation, and a sediment loss coefficient for runoff-normalized sediment loss as kg ha^{-1} mm^{-1} runoff) were used to test for statistical differences between CT and ST fields at each landscape position on a monthly, annual, seasonal, and crop period basis. Seasons were taken as three-month periods for spring, summer, fall, and winter. Crop periods were those of cotton, peanuts, rye, and fallow. For cotton and peanuts, the crop period was from planting until harvest. For rye, the crop period was from planting until chemical application to kill the crop. Fallow was considered as the period between chemical application to kill the cover crop in the fall and planting of the summer crop in spring. Statistix 9.0 (Analytical Software, Tallahassee, Fla.) was used to first test the data for normality using the Shapiro-Wilk test. Depending on the test outcome, either paired t-tests or nonparametric Wilcoxon signed rank tests were used to compare results. Data were also examined using cumulative and exceedance probability curves and linear and nonlinear regression (TableCurve 2D, V5.01 for Windows, Systat Software, Inc., Richmond, Cal.). In the following discussions, when differences are stated as significant, this implies a p-value of 0.05 or less, or as given.

RESULTS

RAINFALL AND IRRIGATION

Out of the total 3,653 days of the study period, 69.3% had no rainfall (period A), 15.9% had 0 to ≤5 mm daily rainfall (period B), 7.6% had 5 to ≤15 mm daily rainfall (period C), 3.8% had 15 to ≤25 mm daily rainfall (period D), 2.6% had 25 to ≤50 mm daily rainfall (period E), 0.6% had 50 to ≤75 mm daily rainfall (period F), 0.1% had 75 to ≤100 mm daily rainfall (period G), and 0.2% had >100 mm daily rainfall (period H). Of the total applied irrigation amount, 78% occurred during period A and 18.2% occurred during period B. According to Ingram et al. (2013), a variety of weather systems with seasonality characteristics cause heavy rainfall events in the southeast, such as those during periods F, G, and H. Slow-moving extratropical cyclones cause such events over large areas in winter and spring. Such events occur over more localized areas during the late spring and summer due to slow-moving thunderstorms. Tropical cyclones (tropical storms and hurricanes) in the late summer and fall can cause heavy rainfall locally and regionally. Out of the seven rainfall days associated with period H, four were caused by hurricanes or associated tropical storms or depressions (Dennis in July 2005, Fay in August 2008, and Francis and Jeanne in September 2004). Two were caused when a weak frontal boundary stalled across north Georgia (March and April 2009). The seventh in early January 2006 was likely caused by a similarly stalled system. Out of four rainfall days associated with period G, one was caused by a tropical storm associated with Hurricane Alberto (June 2006); the others occurred in March 2001, March 2005, and October 2008. Seven of the top ten costliest hurricanes in the U.S. since 1900 occurred in the active Atlantic hurricane seasons of 2004 and 2005, and the 2001-2010 decade was the warmest on record (Ingram et al., 2013).

Mean annual rainfall over the study period was 1,165 ±62 mm (± standard error) and varied from 886 mm in 2001 to 1,487 mm in 2005 (table 2). Mean monthly rainfall varied from 45 mm in May to 141 mm in August with distribution as 64 to 87 mm in October, November, January,

Table 2. Monthly and annual rainfall and irrigation amounts at the Gibbs Farm experimental site for 2000-2009.[a]

Year	Parameter	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
2000	Rainfall	92	56	131	34	6	50	110	67	281	21	103	90	1042
	Irrigation	-	-	-	-	29	-	76	-	-	-	-	-	105
2001	Rainfall	47	13	267	35	39	155	97	61	100	35	19	20	886
	Irrigation	-	-	-	-	76	51	51	51	-	-	-	-	229
2002	Rainfall	89	43	113	80	18	72	196	74	92	130	140	99	1145
	Irrigation	-	-	-	-	25	51	25	76	-	-	-	-	178
2003	Rainfall	8	106	242	85	32	154	152	249	71	75	29	42	1246
	Irrigation	-	-	-	-	25	-	-	-	-	-	-	-	25
2004	Rainfall	72	142	10	68	31	153	58	112	316	21	81	68	1131
	Irrigation	-	-	-	-	13	-	64	51	-	-	-	-	127
2005	Rainfall	52	90	218	186	89	248	240	101	45	16	86	117	1487
	Irrigation	-	-	-	-	10	16	25	-	-	-	25	-	77
2006	Rainfall	166	102	6	43	92	123	62	195	70	28	79	143	1113
	Irrigation			19	25	25	25	25	25	-	-	-	-	146
2007	Rainfall	91	62	32	14	1	112	79	182	72	88	25	143	903
	Irrigation	-	-	25	58	83	25	25	72	-	-	-	13	302
2008	Rainfall	90	214	77	89	10	65	144	269	52	129	117	81	1337
	Irrigation	-	-	-	19	38	51	76	-	-	25	-	-	210
2009	Rainfall	51	44	198	211	137	77	187	96	13	100	61	184	1360
	Irrigation	-	-	-	-	19	38	25	-	-	-	-	-	83
Mean	Rainfall	76	87	129	84	45	121	132	141	111	64	74	99	1165
	Irrigation	-	-	4	10	34	26	39	28	-	3	3	1	148
LTM[b] (95% CL)	Rainfall	112 (17)	107 (15)	122 (17)	89 (17)	84 (15)	110 (15)	124 (15)	111 (17)	89 (18)	59 (14)	66) (11)	92 (13)	1165 (52)

[a] All values are in mm; dash indicates no irrigation.

[b] LTM = long-term mean rainfall from 61 years (1950 to 2010) of records at the University of Georgia's Coastal Plain Experimental Station located approximately 9 km northeast of the study site; 95% CL = 95% confidence limit for the LTM.

and February; 99 and 111 in December and September; and 121 to 141 mm in March and summer months. Mean monthly irrigation was 38 ±3 mm (*n* = 39; range 10 to 83 mm; table 2), with 80% in summer and 13% in spring months. Annual irrigation amounts varied from 5% of annual rainfall in 2005 to 33% in 2007. Over the 10-year study period, the total irrigation amount was 13% of the total rainfall. Weather records from 1950 to 2010 at the University of Georgia's Coastal Plain Experiment Station (CPES), approximately 9 km northeast of the study site, indicated that annual rainfall varied from 613 mm in 1954 to 1,748 mm in 1964 with a mean of 1,165 ±26 mm. At CPES, the years 2001, 2000, 2007, 2006, and 2002 were the 5th, 7th, 8th, 10th, and 12th driest, respectively, in 61 years (890 to 976 mm). On the other hand, 2009 and 2004 were the 3rd (1,512 mm) and 7th (1,404 mm) wettest, respectively. In total, 54% of months from 2000 to 2009 had below-normal rainfall, 14% had normal rainfall, and 32% had above-normal rainfall.

RUNOFF

Bosch et al. (2012) previously presented results for runoff variability. A summary is presented here, supplemented with results from additional analyses. Of the total 10-year runoff, the across-tillage mean runoff percentage for rainfall periods A, B, C, D, E, F, G, and H (as described above) was, respectively, 2.0% (from irrigation), 2.2%, 5.7%, 15.5%, 29.4%, 18.5%, 4.7%, and 22.0%. Further aggregating the rainfall data into fewer rainfall classes, ~1% of the study period had >50 mm daily rainfall, from which the across-tillage mean runoff percentage was ~45% (±3%). Similarly, ~4% of the study period had daily rainfall from 20 to ≤50 mm, from which the across-tillage mean runoff percentage was ~38% (±1%).

Monthly and annual runoff volumes from CT fields significantly exceeded those from ST fields at all landscape positions (figs. 2a to 2c). The p-values were <0.001 at all landscape positions for monthly runoff comparisons and 0.006, 0.019, and 0.06 at the upper, middle, and lower landscape positions, respectively, for annual runoff comparisons.

The CT:ST ratio for monthly mean runoff values was 2.3, 1.5, and 1.7 at the upper, middle, and lower landscape positions, respectively. Respective ratios for annual mean

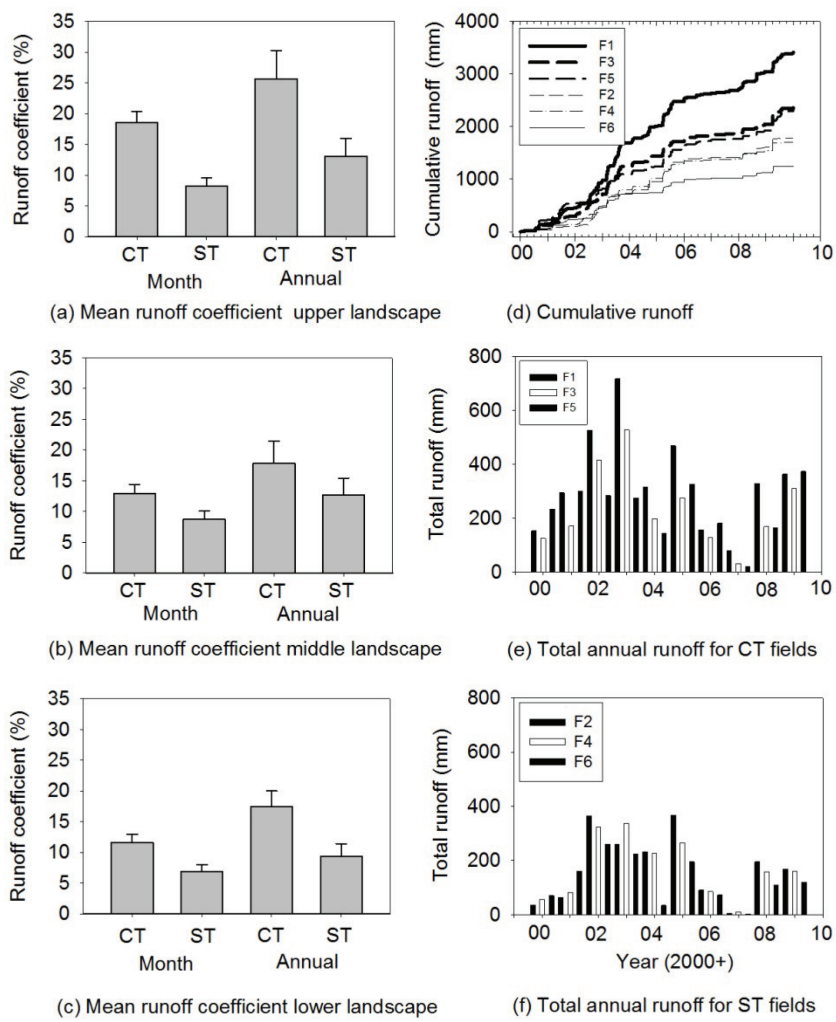

Figure 2. (a, b, c) Mean monthly and annual runoff coefficient by landscape position and tillage with error bars, (d) cumulative runoff by field, (e) total annual runoff for CT fields, and (f) total annual runoff for ST fields from 2000 to 2009 (F1 to F6 signify fields 1 to 6).

runoff values were 2, 1.4, and 1.9. Over the 10-year period, the runoff coefficient was 25.9%, 17.9%, and 17.5% for CT fields 1, 3, and 5, respectively (CT mean of 20.5%) and 13.6%, 13%, and 9.5% for ST fields 2, 4, and 6, respectively (ST mean of 12%). Differences were greatest in summer and during the cotton cropping period. Periods of above-normal rainfall (some with irrigation) contributed to greater runoff response than other periods. Daily extreme runoff events from ST can equal and in some cases exceed those observed from CT under certain hydrologic conditions, as similarly observed by Yoo et al. (1987) and Bosch et al. (2005). Yoo et al. (1987) compared no-till and conventional tillage. Over the 10-year period, runoff from <10% of the total months accounted for >50% of the total runoff.

Deviation in cumulative runoff between the field with the most runoff (the CT field at the upper landscape position, field 1) and the field with the least runoff (the ST field at the lower landscape position, field 6) increased over time (fig. 2d). Over the 10-year period, total runoff from the three ST fields was ~41% less than from the three CT fields (4,731 vs. 8,059 mm). Variability in total annual runoff by tillage and within tillage is shown in figures 2e and 2f. In CT fields, total annual runoff varied from a mean of 79 mm in 2007 to 718 mm in 2003. In ST fields, total annual runoff varied from a mean of 5 mm in 2007 to 364 mm in 2002. The tillage mean total annual runoff was least in the four driest years (2000, 2001, 2006, and 2007; see above) and was <300 mm in CT and <100 mm in ST during these dry years.

Sediment

For total 10-year sediment load (kg ha^{-1}), the across-tillage mean sediment loss percentage for rainfall periods A, B, C, D, E, F, G, and H was, respectively, 1.3% (from irrigation), 2.2%, 5.1%, 20.4%, 30.6%, 22.3%, 1.7%, and 16.6%. Based on further aggregated rainfall classes, the across-tillage mean sediment loss percentage was 41% (±9%) for days with >50 mm daily rainfall, representing ~1% of the study period. Similarly, the across-tillage mean sediment loss percentage was 40% (±5%) for the ~ 4% of the study period with daily rainfall from 20 to ≤50 mm.

Daily Sediment Load and Runoff Correlation

Linear regression using natural log (ln) transformed data indicated a correlation between daily sediment load (kg ha^{-1}) and runoff (mm) for all fields with a coefficient of determination (R^2) of 0.44 to 0.58 except for the ST field at the upper landscape position, which had R^2 of 0.08 (table 3). The likely explanation regarding the poor correlation for this field is that it had better cover crop growth than the other ST fields (4 and 6), which provided more residue cover and protection from rainfall impact. Correlations of monthly sediment loads were higher within individual tillage treatments across landscape positions (R^2 = 0.47 to 0.80) than across tillage treatments within a landscape position (R^2 = 0.35 to 0.48) (table 3).

Sediment Loss Comparisons by Month, Year, Season, and Crop Period

Mean and median sediment loss coefficient values by landscape position and by month, year, season, and crop period are summarized in table 4. Monthly and annual sediment loss coefficients were significantly different for CT fields compared to ST fields at each landscape position. The CT:ST ratio for the monthly mean sediment loss coefficient was 2.2, 5.4, and 4.3 at the upper, middle, and lower landscape positions, respectively. Similarly, the CT:ST ratio for annual mean sediment loss coefficient was 3.3, 3.7, and 3.6 at the respective landscape positions. For the total 10-year sediment loss coefficients, the CT:ST ratio was 5.9, 3.9, and 3.8 at the upper, middle, and lower landscape position, respectively. Seasonal differences were significant at each landscape position in winter (CT:ST ratio of means 1.2 to 4.5) and summer (CT:ST ratio of means 1.8 to 8.3). In the fall, significant differences only occurred at the middle landscape position (CT:ST ratio of means 5.2), while in the spring they occurred at the upper and middle landscape positions (CT:ST ratio of means 15.3 and 4.6, respectively). Considering crop period, differences were significant at each landscape position during the peanuts and rye periods (CT:ST ratio of means 6.1 to 11.0 for peanuts and 1.2 to 3.4 for rye). During the cotton period, significant differences were limited to the middle and lower landscape positions (CT:ST ratio of means 5.3 and 7.9, respectively). During the fallow period, significant differences were limited to the upper and middle landscape positions (CT:ST ratio of means 15.8 and 8.4, respectively). Differences were thus greatest in spring through summer, and in fallow plus peanuts periods.

Table 3. Parameters for linear regression for natural log-transformed daily sediment load versus runoff for fields 1 to 6 and natural log-transformed monthly sediment loads between pairs of fields.

			Slope		Intercept	
Tillage	Field	R^2	Value	Pr > F	Value	Pr > F
Field daily[a]						
CT	1	0.538	0.993	<0.001	1.518	<0.001
	3	0.477	0.919	<0.001	1.672	<0.001
	5	0.443	0.996	<0.001	1.297	<0.001
ST	2	0.082	-0.222	0.003	2.800	<0.001
	4	0.504	0.843	<0.001	0.337	0.127
	6	0.576	1.010	<0.001	0.171	0.247
Field pair monthly[b]						
CT	1 & 3	0.724	0.842	<0.001	-0.204	0.292
	1 & 5	0.655	0.792	<0.001	-0.224	0.295
	3 & 5	0.803	0.886	<0.001	0.101	0.473
ST	2 & 4	0.537	0.734	<0.001	0.125	0.343
	2 & 6	0.474	0.691	<0.001	0.370	0.009
	4 & 6	0.670	0.820	<0.001	0.375	0.001
CT-ST	1 & 2	0.348	0.401	<0.001	-0.051	0.801
	3 & 4	0.447	0.461	<0.001	-0.115	0.487
	5 & 6	0.376	0.428	<0.001	0.235	0.169

[a] Model: $\ln(Y) = a \times \ln(X) + b$, where Y is daily sediment load (kg ha^{-1}), X is daily runoff (mm), a is slope, and b is intercept.

[b] Model: $\ln(Y+1) = a \times \ln(X+1) + b$, where Y and X are monthly sediment loads per field (kg ha^{-1}), a is slope, and b is intercept.

Cumulative Sediment Load

The cumulative sediment load data (kg ha^{-1}) showed temporal changes in sediment loss during the study period (fig. 3a). Divergence between the curves increased after the first quarter of 2001 and grew over time between the CT and ST fields and within the CT fields. This suggests that the positive effect of ST in reducing runoff and sediment loss increased over time. The curves for the ST fields

Table 4. Statistical summary for sediment loss coefficient for conventional tillage (CT) and strip tillage (ST) fields at the upper, middle, and lower landscape positions by monthly, annual, seasonal, and crop periods.[a]

		Upper		Middle		Lower	
Period	Statistic	CT	ST	CT	ST	CT	ST
Monthly	Mean (SE)	6.0 (0.9)	2.8 (0.8)	4.2 (0.6)	0.8 (0.2)	4.0 (0.7)	0.9 (0.2)
	Median	2.3	0.0***	0.8	0.0***	0.6	0.0***
Annual	Mean (SE)	6.9 (1.5)	2.1 (0.9)	5.7 (1.2)	1.5 (0.4)	5.8 (1.6)	1.6 (0.3)
	Median	5.4	0.9*	4.5	1.5**	4.3	1.5*
Fall	Mean (SE)	2.6 (1.1)	2.7 (1.9)	1.7 (0.7)	0.3 (0.2)	0.7 (0.5)	0.5 (0.3)
	Median	0.4	0.0	0.0	0.0**	0.0	0.0
Winter	Mean (SE)	3.3 (0.6)	2.8 (1.7)	3.3 (0.7)	0.7 (0.2)	3.1 (0.8)	1.1 (0.4)
	Median	2.5	0.0*	1.2	0.0***	1.2	0.0***
Spring	Mean (SE)	8.8 (2.5)	0.6 (0.4)	3.8 (1.5)	0.8 (0.6)	3.2 (1.6)	1.0 (0.3)
	Median	2.1	0.0***	0.0	0.0**	0.0	0.0
Summer	Mean (SE)	9.3 (2.1)	5.1 (2.1)	8.1 (1.7)	1.3 (0.6)	8.9 (2.1)	1.1 (0.3)
	Median	6.2	0.04*	7.1	0.0***	4.2	0.5***
Cotton	Mean (SE)	6.5 (2.1)	5.1 (1.9)	5.4 (1.6)	1.1 (0.5)	6.7 (2.1)	0.8 (0.3)
	Median	2.3	0.0	1.2	0.0***	1.7	0.0***
Peanut	Mean (SE)	5.1 (1.5)	0.8 (0.4)	4.9 (1.4)	0.5 (0.4)	3.5 (1.3)	0.6 (0.2)
	Median	3.2	0.0**	1.6	0.0**	0.9	0.2*
Rye cover	Mean (SE)	4.1 (1.1)	3.4 (1.8)	3.5 (0.7)	1.1 (0.4)	2.6 (0.6)	1.1 (0.3)
	Median	2.1	0.0**	1.2	0.0***	0.8	0.0***
Fallow	Mean (SE)	8.7 (2.4)	0.6 (0.4)	3.7 (1.5)	0.4 (0.3)	3.4 (1.7)	0.9 (0.3)
	Median	2.2	0.0***	0.0	0.0***	0.0	0.0

[a] Values are kg ha^{-1} mm^{-1} runoff. SE = standard error of the mean. Asterisks indicate significant differences between CT and ST fields at each landscape position at 0.05 (*), 0.01 (**), and 0.001 (***) probability levels. When shown for the median, asterisks indicate that the data were non-normally distributed.

tracked very closely. At the end of the study period (31 December 2009), total sediment load was lowest from the ST fields, with a mean of 2,372 kg ha^{-1} and range of 2,165 to 2,676 kg ha^{-1}. In comparison, the mean from the CT fields was 18,227 kg ha^{-1} with a range of 14,726 to 24,160 kg ha^{-1}. The CT:ST total sediment load ratio was 11.1, 5.5, and 7 at the upper, middle, and lower landscape positions, respectively.

Cumulative sediment load curves also showed distinct periods of varying sediment loss. Six periods were identified in which soil loss rates were elevated compared with the rest of the study period (fig. 3a, table 5). Rainfall (plus irrigation) was greater than the long-term monthly mean rainfall most of the time during these periods (table 5). The time span per period varied from 27 days for period 2 to 400 days for period 4; the latter had a steady increase in soil loss throughout the time span. Most of these periods occurred during cotton production. Soil loss per period varied from 194 to 6935 kg ha^{-1} in CT fields and from 2 to 1146 kg ha^{-1} in ST fields. A combination of several field cultivations, including moldboard plowing, from 20 April 2009 until cotton planting on 4 May 2009, and above-normal rainfall in March through May and July, likely contributed to the high sediment load from CT during period 6 (table 5). Monthly rainfall amounts in April, May, March, and July 2009 were the 4th, 5th, 6th, and 7th highest, respectively, in 61 years (1950 to 2010).

Mean total annual sediment load varied from approximately 161 kg ha^{-1} in 2007 to 5,914 kg ha^{-1} in 2009 from the three CT fields (overall mean 1,823 kg ha^{-1} $year^{-1}$) and from 3 kg ha^{-1} in 2007 to 696 kg ha^{-1} in 2002 from the three ST fields (overall mean 237 kg ha^{-1} $year^{-1}$) (figs. 3b and 3c). The mean annual CT:ST field sediment load ratio was between 2 and 7 for 2000-2003 and 2008, and between 11 and 18 for 2004-2006 and 2009. The very small sediment load in 2007 from ST fields resulted in a ratio of 53 for that year.

Extreme Events

We evaluated extreme events, which were defined as those greater than the 90th percentile, on a daily and monthly basis. Approximately 10% of the monthly sediment loss data fell in this category for each field and accounted for 60.8%, 62.7%, and 71.8% of the 10-year total sediment loss from CT field 1 (552 to 2,828 kg ha^{-1}), field 3 (467 to 1,116 kg ha^{-1}), and field 5 (341 to 2,499 kg ha^{-1}), respectively, and for 73.6%, 84.4%, and 72.8% of the 10-year total sediment loss from ST field 2 (73 to 360 kg ha^{-1}), field 4 (49 to 593 kg ha^{-1}), and field 6 (53 to 393 kg ha^{-1}), respectively. Rainfall (plus irrigation) was above the normal monthly rainfall in 83% of the monthly periods (mean 179 mm, range 81 to 316 mm). A quarter of the 10-year total sediment loss was accounted for by the top two or three extreme month periods, and half was accounted for by the top six to nine extreme month periods. In the CT fields, extreme months were distributed as 67% in summer, 19% in spring, 8% in winter, and 6% in fall. In the ST fields, the distribution was 36% in summer, 25% in spring, 20% in winter, and 19% in fall. Thus, the risk for sediment loss was highest in summer and spring (fig. 4).

There were 47 dates on which extreme daily sediment losses, as defined above (>90th percentile), occurred from a single field up to all fields (table 6). For these dates, rainfall plus irrigation varied from 10 to 124 mm with a mean of 47 and median of 40 mm. In addition, up to 70 mm rainfall and/or up to 30 mm irrigation had occurred in the previous one to three days. Truman et al. (2011) pointed out the importance of antecedent water content in runoff and sediment generation. The largest single sediment load of 1,545 kg ha^{-1} occurred from the CT field at the upper landscape position (field 1) on 28 March 2009 as a result of the largest daily rainfall of 124 mm of all the extreme daily events, which was preceded by 20 mm of rainfall in the previous two days. The sediment load was 217 to 595 kg

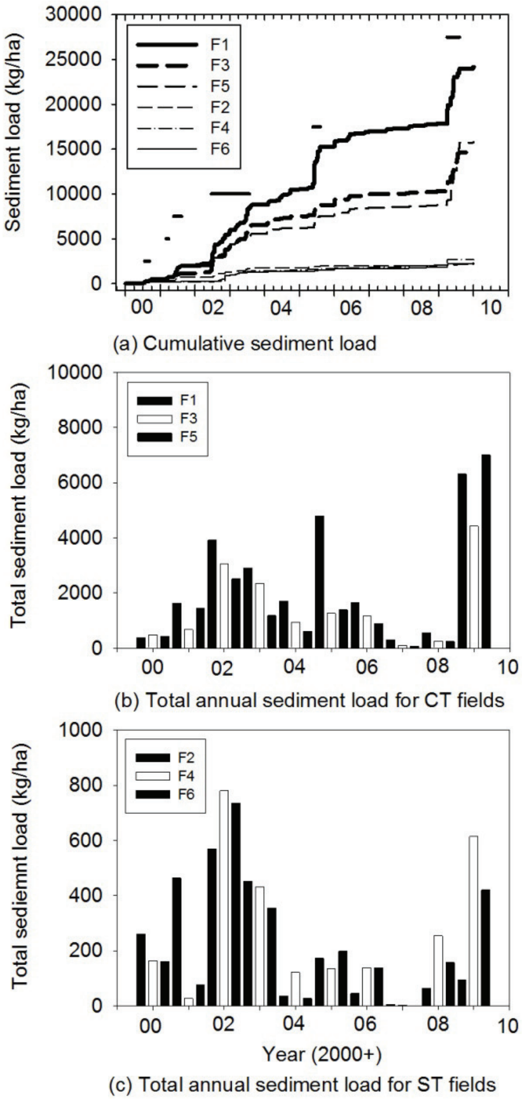

Figure 3. (a) Cumulative sediment load from 2000 to 2009 by field, (b) total annual sediment load for CT fields, and (c) total annual sediment load for ST fields (F1 to F6 signify fields 1 to 6). The six short lines above the graph for F1 in (a) indicate the time span of periods 1 to 6 (in sequence starting from year 2000) identified in table 5.

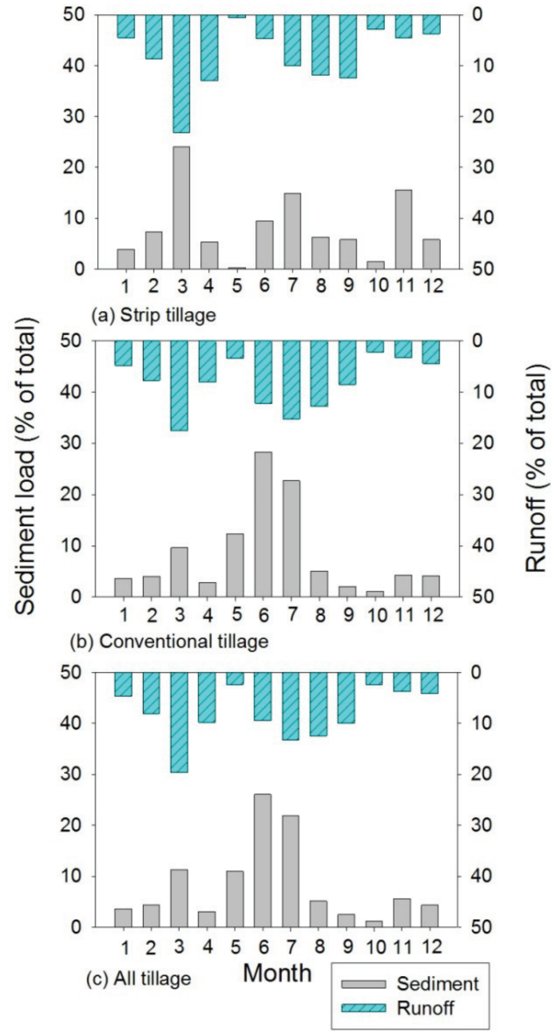

Figure 4. Monthly distribution of sediment load (kg ha^{-1}) and runoff (mm) as a percentage of the 10-year total for (a) strip tillage, (b) conventional tillage, and (c) all tillage for 2000-2009.

ha^{-1} in four of the remaining five fields on this date, indicating that sediment loss risk was also tillage and landscape dependent. The fields were under mature rye.

The next six largest extreme daily events (913 to 1,495 kg ha^{-1}; field 1 or 5) all occurred under cotton production, with field 5 at 1 to 31 days after planting and field 1 at 71 days after planting (table 6). In a cotton study conducted in 1997 and 1998 in north Alabama, Nyakatawa et al. (2001) found that cotton canopy cover was approximately 10%, 30%, 50%, and 75% at 6, 8, 9.5, and 11.5 weeks after planting, respectively, in a 128-day (1998) and 185-day (1997) cotton crop. Cotton was at less than four weeks after planting for five of the six extreme daily

Table 5. Range of soil losses during six relatively elevated soil loss periods with details per period for the duration, crop, days after planting, and rainfall plus irrigation amount, and how that compares with the long-term monthly mean rainfall.[a]

Period	From (m/d/y)	To (m/d/y)	Duration (days)	Crop	Days after Planting[b]	Rainfall + Irrigation (mm)	Range of Soil Loss (kg ha^{-1}) CT	ST	Rainfall + Irrigation Compared with Long-Term Mean
1	7/21/00	9/7/00	48	Cotton	81 to 129	321	250 to 387	69 to 143	Above normal for July
2	3/2/01	3/29/01	27	Rye	91 to 118	260	194 to 378	26 to 48	Above normal for March
3	5/21/01	8/12/01	83	Cotton	14 to 97	445	462 to 1198	2 to 102	Above normal for May to August
4	6/19/02	7/24/03	400	Peanut/rye/ cotton	-	1687	3390 to 6171	921 to 1146	Above normal 50% of the time
5	5/19/05	8/6/05	79	Cotton	-4 to 87	634	1127 to 4546	67 to 169	Above normal for June and July
6	3/27/09	8/3/09	129	Rye/cotton	-	889	4343 to 6935	42 to 607	Above normal for March to May and July

[a] The duration of each of the six periods is also shown as short line above the graph for F1 (field 1) in figure 3a.
[b] Dash indicates multiple crops, so days after planting is not shown.

Table 6. Extreme daily sediment loss events and amounts (>90th percentile) from conventional tillage (CT) and strip tillage (ST) fields for 2000 to 2009. Included for each event are the date, crop, number of days after disking and planting and before harvest of summer crop, and amount of rainfall and irrigation.

Date (m/d/y)	No. of Fields with Extreme Events CT	ST	Crop	Days After Spring Disking	Days After Planting Crop	Days Before Summer Harvest	Sediment Load[a] kg ha^{-1}	Field	% of Total	Rainfall + Irrigation (mm)	Remarks
3/28/09	3	2	Rye	-23	-37	209	1545	1	6.4	124	20 mm rain 3/27
7/14/09	3	0	Cotton	85	71	101	1495	5	9.5	58	-
6/4/09	3	0	Cotton	45	31	141	1340	1	5.5	31	-
6/3/05	2	0	Cotton	35	11	151	1228	1	5.1	43	-
5/5/09	3	0	Cotton	15	1	171	1038	5	6.6	61	13 mm irrigation
5/27/09	3	0	Cotton	37	23	149	976	5	6.2	33	43 mm rain 5/21 to 5/23
6/6/05	3	0	Cotton	38	14	148	913	1	3.8	40	-
11/12/02	3	3	Fallow	236	187	-63	875	5	5.5	57	-
7/10/05	3	1	Cotton	72	48	114	733	1	3.0	122	18 mm rain 7/9
8/3/09	1	0	Cotton	105	91	81	602	5	3.8	18	63 mm rain 7/31 to 8/2
1/2/06	3	2	Rye	-116	-127	268	573	3	3.9	107	-
4/2/09	2	1	Rye	-18	-32	204	463	1	1.9	108	66 mm rain 3/31+4/1
6/16/03	2	1	Cotton	76	35	128	451	1	1.9	51	-
5/20/05	1	0	Fallow	21	-3	165	448	1	1.9	41	10 mm rain 5/19
7/29/05	1	0	Cotton	91	67	95	439	1	1.8	60	25 mm rain 7/28
7/31/09	2	0	Cotton	102	88	84	431	5	2.7	43	26 mm rain 7/29
7/1/03	2	1	Cotton	91	50	113	400	1	1.7	31	-
7/21/02	2	1	Peanut	102	73	51	397	1	1.6	51	32 mm rain 7/20
7/3/02	3	0	Peanut	104	55	69	392	1	1.6	38	-
6/29/05	2	0	Cotton	61	37	125	357	1	1.5	49	9 mm rain 6/18
2/6/04	3	0	Rye	-54	-94	228	355	3	2.4	41	17 mm rain 9/26
9/27/04	1	1	Fallow	180	140	-6	341	1	1.4	115	-
7/8/09	2	0	Cotton	79	65	107	328	3	2.2	18	42 mm rain 7/5 to 7/7
6/25/02	1	0	Peanut	96	47	77	267	3	1.8	18	25 mm irrigation 6/10
6/30/02	1	0	Peanut	101	52	72	266	1	1.1	16	-
7/22/00	2	2	Cotton	129	82	54	263	3	1.8	58	25 mm irrigation 7/21
11/11/02	2	3	Fallow	235	186	-62	251	5	1.6	48	-
5/28/06	2	0	Peanut	30	19	122	229	1	0.9	31	-
12/31/02	1	0	Rye	285	236	-112	225	1	0.9	24	-
3/20/03	0	2	Rye	-12	-53	216	221	4	8.3	56	-
6/13/06	2	0	Peanut	46	35	106	219	5	1.4	82	-
6/6/09	1	0	Cotton	47	33	139	216	1	0.9	10	-
5/10/06	1	0	Peanut	12	1	140	214	1	0.9	22	20 mm rain 5/8
7/26/02	1	0	Peanut	127	78	46	214	1	0.9	23	-
10/15/02	1	0	Fallow	208	159	-35	209	1	0.9	28	19 mm irrigation 10/13
6/29/01	1	1	Cotton	95	53	98	202	5	1.3	19	35 mm rain 6/27 to 6/28
2/22/08	0	2	Rye	-56	-80	237	128	4	4.8	63	40 mm rain 2/21
6/9/01	0	1	Cotton	75	33	118	115	2	5.3	22	-
6/10/01	0	1	Cotton	76	34	117	115	2	5.3	18	22 mm rain 6/9/01
4/7/05	0	1	Rye	-22	-46	208	89	2	4.1	49	-
6/18/03	0	1	Cotton	78	37	126	62	2	2.8	18	60 mm rain 6/17
2/14/00	0	1	Rye	-30	-77	213	62	6	2.7	25	6 mm rain 2/13
9/14/02	0	1	Peanut	177	128	-4	58	6	2.6	32	-
12/25/09	0	1	Rye	249	235	-63	52	2	2.4	30	30 mm irrigation
8/23/08	0	1	Peanut	127	103	54	51	6	2.3	120	69 mm 8/22
9/15/02	0	1	Fallow	178	129	-5	51	6	2.3	28	-
10/13/02	0	1	Fallow	206	157	-33	45	6	2.0	19	-

[a] Sediment loads (kg ha^{-1}) are arranged in descending order; % of total = percentage of the 10-year total sediment load.

events just discussed and at ten weeks after planting for the sixth event. The cotton season (plant to harvest) lasted 136 to 172 days.

Overall, 20 single extreme daily events occurred during cotton production, with 11 at <40 days after planting, six at 40 to 71 days after planting, and three at 82 to 91 days after planting. Ten extreme daily events occurred during peanut production, with three at <40 days after planting, five at 40 to 80 days after planting, and two at 100 to 128 days after planting. Seven extreme daily events occurred under fallow, with six in September through November and one in May. Ten extreme daily events occurred during a rye cover crop, with eight in January through March and two in December. Rye biomass is low in fall through early March, creating high risk for soil loss. The largest numbers of single extreme daily events occurred in 2002 (12 events) and 2009 (11 events). In 2002, six events occurred during peanut production, with five at 46 to 77 days after planting and one four days after harvest. Of the remaining six events in 2002, five occurred during fall fallow, and one occurred at the end of December (rye). Each extreme daily event accounted up to 10% of the total 10-year sediment load for the fields (table 6). These data point to the high risk of sediment loss in CT cotton or peanut production before canopy closure, and during very large rainfall events in fall through early spring when residue cover is low.

Rainfall-Sediment Loss Thresholds and Exceedance Frequency

Even moderate soil loss can reduce the soil's capacity to absorb water, ultimately increasing surface runoff and reducing crop productivity (Pimentel et al., 1995). Soil tolerance (T) values generally vary from 2,200 to 11,200 kg ha^{-1} year^{-1} (1 to 5 tons acre^{-1}) (Wischmeier and Smith, 1978; Delgado et al., 2013). For the Tifton loamy sand, a T value of 2,200 kg ha^{-1} year^{-1} was considered appropriate, given the high sand content of the surface horizons and the highly eroded hillslopes that typify this region of the Coastal Plain. In the current study, the mean annual sediment load from the ST fields was much lower than the T value each year; the largest load was ~696 kg ha^{-1} in 2002. On the other hand, the mean annual sediment load from the CT fields exceeded the T value in 2002 (3,167 kg ha^{-1}), 2005 (2,481 kg ha^{-1}), and 2009 (5,914 kg ha^{-1}). In 2003, the mean annual sediment load was 2,143 Mg ha^{-1}, close to the T value.

Exceedance probability curves are useful tools for examining risk and thresholds for a given parameter. We developed such curves for monthly runoff and sediment loss coefficients for individual fields and across fields for CT and ST (fig. 5). We found that five equations defined the various relationships well for all conditions:

$$Y = a + bX + cX^{1.5} + dX^{0.5} \quad (1)$$

where Y is the monthly runoff coefficient and X is the exceedance probability.

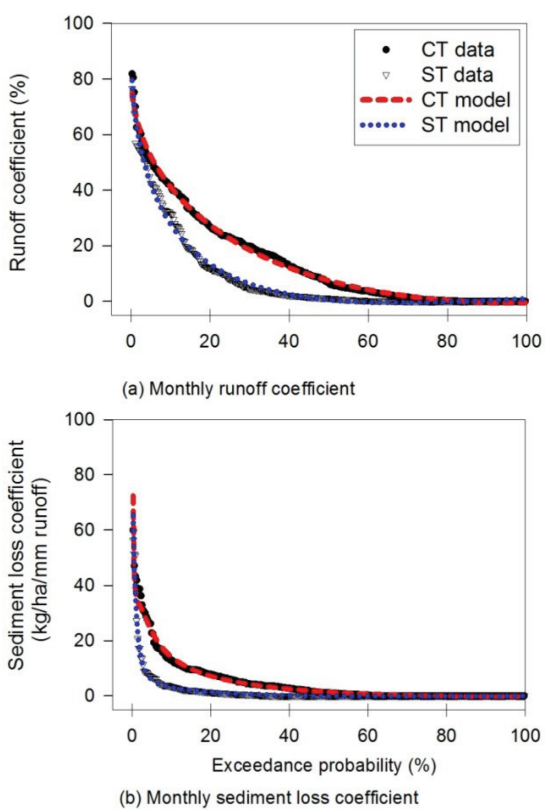

Figure 5. Exceedance probabilities for (a) monthly runoff coefficient and (b) monthly sediment loss coefficient (data) and models derived from nonlinear regression for the data combined by tillage (CT = conventional tillage and ST = strip tillage).

$$Y = a + bX^2 + c(X^{0.5})^{-1} + d(e^{-X}) \quad (2)$$

where Y is the monthly sediment loss coefficient and X is the exceedance probability.

$$\ln(Y) = a + bX + c(e^{-X}) \quad (3)$$

where Y is the exceedance probability and X is the monthly runoff coefficient.

$$Y = (a + cX^{0.5})\,(1 + bX^{0.5} + dX)^{-1} \quad (4)$$

where Y is the exceedance probability and X is the monthly sediment loss coefficient.

$$Y = a + bX^{1.5} + cX^2 + dX^{0.5} \quad (5)$$

where Y and X are monthly sediment loss and runoff coefficients, respectively, with both at the same exceedance probability.

Model parameters were established for each field and are summarized by tillage in table 7. The coefficient of determination (R^2) was >0.9 for all equations except for equation 4 as applied to ST (R^2 = 0.7). It is not clear why R^2 was lower for ST in equation 4 than in other cases. The data and equation model curves (fig. 5 for CT and ST) generally show that, between the lower and upper threshold coefficient values, exceedance probabilities for both the monthly runoff coefficient and the monthly sediment loss coefficient were greater for CT compared with ST, with differences getting larger as the monthly coefficients got smaller. Above and below the coefficient threshold values, the exceedance probability curves merged. This implies, for example, that exceedance probabilities were similar for relatively high runoff or sediment loss coefficients, suggesting that the ST fields had no more buffering capacity to provide for runoff or sediment loss reduction.

Table 7. Parameters for nonlinear regression for relationships among monthly runoff coefficient (%), monthly sediment loss coefficient (kg ha^{-1} mm^{-1} runoff), and exceedance probabilities for CT (fields 1, 3, and 5 combined) and ST (fields 2, 4, and 6 combined).[a]

	Model		Coefficients[b]			
Tillage	R^2	Pr > F	*a*	*b*	*c*	*d*
Eq. 1: Monthly runoff coefficient (Y) versus exceedance probability (X)						
CT	0.996	<0.001	82.446	0.376	0.024	-14.477
ST	0.991	<0.001	94.034	2.931	-0.094	-29.276
Eq. 2: Monthly sediment loss coefficient (Y) versus exceedance probability (X)						
CT	0.982	<0.001	-9.788	0.0002	75.449	-80.648
ST	0.969	<0.001	-2.921	0.0001	19.032	42.469
Eq. 3: Exceedance probability (Y) versus monthly runoff coefficient (X)						
CT	0.991	<0.001	4.226	-0.044	0.277	NA
ST	0.960	<0.001	3.647	-0.048	0.787	NA
Eq. 4: Exceedance probability (Y) versus monthly sediment loss coefficient (X)						
CT	0.937	<0.001	79.709	0.175	-11.816	0.116
ST	0.746	<0.001	67.878	1.185	-8.327	0.52
Eq. 5: Sediment loss coefficient (Y) versus runoff coefficient (X), both at same exceedance probability level.						
CT	0.981	<0.001	-0.178	-0.011	0.009	0.400
ST	0.926	<0.001	-0.491	-0.191	0.029	1.363

[a] Equation 1: $Y = a + bX + cX^{1.5} + dX^{0.5}$
Equation 2: $Y = a + bX^2 + c(X^{0.5})^{-1} + d(e^{-X})$
Equation 3: $\ln(Y) = a + bX + c(e^{-X})$
Equation 4: $Y = (a + cX^{0.5})\,(1 + bX^{0.5} + dX)^{-1}$
Equation 5: $Y = a + bX^{1.5} + cX^2 + dX^{0.5}$.

[b] NA = not applicable. Coefficients for individual fields are available but are not shown in this table.

Given the monthly mean sediment loss coefficient for each tillage and landscape position in this study (table 4), and assuming an equal distribution among months of the *T* value of 2,200 kg ha^{-1} $year^{-1}$ and mean annual rainfall of 1,165 mm (table 2), it was possible to estimate the runoff coefficient and corresponding exceedance probability that would be required to exceed the *T* value. The assumed monthly *T* value divided by the monthly mean sediment loss coefficient gives a runoff amount, which when divided by the assumed monthly mean rainfall converts into the runoff coefficient. The corresponding exceedance probability was then determined using equation 3. The analysis suggests that the required monthly runoff coefficients are 40% for CT (across all CT fields) and >100% for ST (across all ST fields), the latter suggesting that the *T* value would not be exceeded in ST since the monthly runoff coefficient cannot exceed 100%. In addition, the analysis suggests that the *T* value would be exceeded ~12% of the time for CT (from eq. 3). For ST, even taking the monthly runoff coefficient as 100% (all rain becoming runoff), the *T* values would be exceeded only ~0.3% of the time. Breaking down the analysis by landscape position suggests that the required runoff coefficients are 32%, 46%, and 49% for the upper, middle, and lower landscape positions of the CT fields, respectively, and 70% for the upper landscape position of the ST fields. Finally, the analysis suggests that the *T* values would be exceeded 22%, 9%, 6%, and 2% of the time, respectively (from eq. 3). Runoff coefficients sufficient to cause soil loss greater than the *T* value were never reached at the middle and lower landscape positions of the ST fields during the study period.

DISCUSSION

Adoption of conservation tillage by U.S. farmers is credited for the large drop in soil erosion in the U.S. since 1982 (Fawcett and Towery, 2003; USDA-NRCS, 2010). However, Fawcett and Towery (2003) pointed out that approximately 29% of U.S. cropland still suffered excessive erosion rates. There are approximately 4.7 million ha of cropland in the Southern Coastal Plain MLRA (USDA-NRCS, 2006), over half utilizing CT methods. Among the major resource concerns listed for the MLRA are water erosion and maintenance of soil organic matter and fertility (USDA-NRCS, 2006). Lecce et al. (2006) pointed out that, despite the perception of lack of significant erosion in the Coastal Plain because of the gentle topography and sandy permeable soils, evidence has accumulated showing erosion to be more rapid and extensive than previously thought.

Soil erosion models are useful tools for estimating soil erosion rates across landscapes (Wischmeier and Smith, 1978; Laflen et al., 1991, 1997; Renard et al., 1997; Merritt et al., 2003). Sheridan et al. (1982) estimated upland erosion rates from a 639 ha cropped portion of a 1736 ha mixed land use watershed (Watershed K, close to the current study site) as 18,000 kg ha^{-1} $year^{-1}$. The estimate covered the period from September 1974 through December 1976 and used the USLE with a soil erodibility factor experimentally determined by Thomas et al. (1967). Rainfall for 1975 and 1976 was approximately 20% greater than the long-term average, and watershed runoff was approximately 24% greater than the nine-year average for these two years. For the same watershed, Lowrance et al. (1986) estimated the erosion rate over a century (1880 to 1979) as 15,000 kg ha^{-1} $year^{-1}$ based on sediment deposition measurements in the riparian area, and as 10,000 kg ha^{-1} $year^{-1}$ based on the USLE from all but the riparian area (the estimate from the cultivated part of the watershed would be expected to be greater). Lowrance et al. (1986) noted that using average values for USLE parameters could underestimate soil erosion because larger events account for a greater percent of the total erosion. Nearing (1998) pointed out that several soil erosion models, including the empirical USLE and the physically based WEPP model, tend to overpredict small measured values and underpredict large values. It appears that an erosion rate estimate between that of Sheridan et al. (1982) and the upper limit of Lowrance et al. (1986) might serve as a reasonable average estimate for Watershed K. Sheridan et al. (1982) and Lowrance et al. (1986) both predicted much larger erosion rates than those observed from the 10-year CT tillage cropping in our study (1,823 kg ha^{-1} $year^{-1}$). However, those previous studies were watershed-scale estimates that included both runoff and sediment loss from the upland, whereas our study used winter covers on fields that were artificially constrained to a slope length of 23 m using berms. Historically, winter covers have not been part of the typical row-crop management in the region. The use of winter covers, even in the CT system, is expected to reduce erosion rates by providing soil cover during erosion-susceptible months early in the year.

The Tifton loamy sand was one of the benchmark soils used for rainfall-runoff studies beginning in late 1940s that eventually produced part of the datasets that were used in the development of the USLE. Thomas et al. (1967) summarized results from a 16-year (1951 to 1966) study on 18 experiment plots on Tifton loamy sand, each approximately 8 m wide by 25 m long on a 3% slope, located <10 km from the current study site. Seven of these plots would fit into one of the fields in the current study. In seven years (1960 to 1966) of tilled continuous fallow, the average annual rainfall, percent runoff, and soil loss were 1,233 mm, 24.4%, and 11,524 kg ha^{-1}, respectively. This experimental setup was the unit plot equivalent of the USLE and was tilled up and down the slope but under fallow, which explains the high runoff and erosion rate. In eight years (1951 to 1958) of continuous CT peanut production with non-tilled fallow in fall and winter, the equivalent average annual values were 1,091 mm, 6.7%, and 2,758 kg ha^{-1}, respectively. Tillage was close to the contour lines. Rainfall in 1954, 1955, and 1956 was 50%, 26%, and 12% below the annual average, which would have contributed to the comparatively lower runoff percent compared with the fallow system. In the current study, equivalent annual average values from the four years (even years from 2002) of peanut production with cover crop under CT were 1,347 mm (with 165 mm irrigation), 18.7%, and 1,461 kg ha^{-1}, respectively. The somewhat lower sediment losses observed in this study under higher rainfall conditions may have resulted from cover crop usage, which keeps the soil protected during the late winter to early spring period. The introduction of ST as a BMP reduced mean annual surface runoff by 41% (2,686 vs. 1,577 mm) and mean annual sediment losses by 87% (1,823 vs. 237 kg ha^{-1}) over the 10-year study period.

Using a survey of the literature and their own experiments, Leys et al. (2010) concluded that differences in runoff and erosion rates between conventional and conservation tillage practices are strongly scale-dependent. Data from the literature were grouped into three plot lengths along the slope as <2 m (n = 57), 2 to 30 m (n = 120), and >30 m (n = 40). Leys et al. (2010) generally found that the conservation tillage to CT ratio exponentially decreased with increasing slope length for runoff and soil loss, asymptotically approaching a somewhat constant value at slope length >100 m. The scale effect was stronger for soil loss than for runoff. Differences in transmission losses along slopes partly explained this difference. Mean soil loss ratios for the above slope lengths were, respectively, 0.52, 0.33, and 0.14 and were significantly different from each other. For runoff, mean ratios for the slope lengths were 0.94, 0.80, and 0.65, respectively, which were also significantly different from each other. Leys et al. (2010) argued that the effectiveness of conservation tillage in reducing runoff and soil loss at the field or watershed scale might be underestimated from data obtained from plots or small fields with limited slope length, and further noted that erroneous management decisions may follow from this. The average slope length of the six fields in the current study was 23 m, which would place them in the second group of the Leys et al. (2010) study. Therefore, the measured ratios in the current study would be expected to decrease, perhaps up to half, in larger fields with slope length >100 m, thus showing greater impact of ST in reducing runoff and soil loss than was measured.

Gonzalez-Hidalgo et al. (2012) analyzed the effect of large daily storm events on soil erosion using daily erosion data from 594 USLE database erosion plots compiled from 35 agricultural field sites across the east central U.S. The data fitted an empirical power law, showing a reduction of the percent contribution of the n-largest daily events as a function of the number of daily events per plot. The data from 189 plots from the southeast had an R^2 of 0.59 when examined for the five largest daily events ($p < 0.05$). The curve stabilized to an approximately constant value for >200 daily events. Aggregation of the daily events into monthly and annual time periods was not covered. In the current study, the mean number of analyzed daily soil loss events was 230 for CT and 107 for ST. To evaluate erosion rates, Gonzalez-Hidalgo et al. (2012) suggested considering the minimum number of daily events that correspond to chosen values for the percentage of total soil loss from the n-largest daily events rather than a minimum number of years of research, thus avoiding bias from considering large events in short records.

A suite of soil conservation technologies has been developed over the years to effectively reduce soil erosion, including terracing, contour plowing, residue cover, cover crops, crop rotation, conservation tillage, ridge planting, agroforestry, and wind breaks (Pimentel et al., 1995). The results of the current study show that some of these technologies have proven to be effective in the Coastal Plain. For example cover crops in CT systems can be considered as the first and most convenient BMP for reducing erosion. However, the adoption rate by farmers has been limited, due perhaps to economic considerations and lack of experience with residue management. Strip tillage systems have been used by farmers and supported by the USDA-NRCS for several decades. Despite the widespread support for and benefits of strip tillage, approximately half of the cropped area in the Coastal Plain continues to be managed under CT systems (USDA-NASS, 2014). Our research has shown that landscape position in the Coastal Plain is a parameter of influence on erosion rates. Minimizing or avoiding cropping in the most erosion-prone landscape positions, or choosing a cropping system that has potential for fuller canopy cover at critical times of the cropping year, is an option that can be considered. Contour cultivation (plowing and/or planting) is another BMP that should be encouraged with or without others mentioned above. Reducing slope length using berms (terracing) is also a best management option that can be considered. In ST systems, slope lengths should be >100 m, as recommended by Leys et al. (2010), whereas slope lengths likely would be less in CT systems. In either case, accommodation for mobility of farm machinery needs to be taken into account. The USDA-NRCS has developed conservation practice standards for runoff and erosion reduction technologies that also can be consulted (USDA-NRCS, 2011).

In a recent report, published as one of a series of technical inputs to the Third National Climate Assessment report, Ingram et al. (2013) characterized the climate of the southeast U.S. in terms of variability, change, impacts, and vulnerability. Among aspects of the Ingram et al. (2013) report relevant to the current study, two are of particular interest: weather changes observed during the 20th century and model predictions for the coming decades. In this regard, the Ingram et al. (2013) report has drawn on many recently published studies, including Groisman and Knight (2008), Keim et al. (2011), Kunkel et al. (2013), Li et al. (2012), Seager et al. (2009), Solomon et al. (2007), and Wang et al. (2010). Model projections were based on regional downscaling of the National Climate Assessment under two Intergovernmental Panel for Climate Change (IPCC) scenarios (Solomon et al., 2007): under the A2 scenario, little or no national response is assumed to mitigate human impact, including population growth, on adverse climate change; under the B1 scenario, the opposite is assumed. The Ingram et al. (2013) report (chapter 10) indicates that some parts of the southeast observed an increase in annual rainfall of 20% to 30% or more during the 20th century, while others observed a decline. From 1958 to 2007, there was a 15% to 20% increase in the amount of heavy rainfall, given as >50 mm per event. There was also a doubling of abnormally wet and dry summers over the last few decades. Even with uncertainty due to inadequacies in model resolutions, the IPCC precipitation simulations (Solomon et al., 2007) under the A2 scenario project increases of up to 6% in annual rainfall in the southeast through the mid-21st century (Ingram et al., 2013, chapter 2). Seasonally, most of the region is expected to experience precipitation increases of 5% to 20% in fall, spring, and winter, and decreases of 5% to 20% in summer. The number of days per year with precipitation >25 mm is expected to increase by up to 10% in most of the region and up to 20% in some areas, such as southern Georgia. In addition, tropical storms are expected to be stronger. If these projections are realized, then, based on our results, more runoff and sediment loss will be expected from agricultural fields, with a greater percentage coming from CT systems.

SUMMARY AND CONCLUSIONS

Results from the 10-year field-based research, with some very wet and dry years, highlighted the potential for ST management to reduce sediment loss during rotational cotton and peanut production in the Atlantic Coastal Plain region of southern Georgia. Residue cover from a desiccated rye cover crop in ST protected fields and reduced sediment loss by 87% when compared to CT fields (1,823 kg ha^{-1} $year^{-1}$ for CT fields vs. 237 kg ha^{-1} $year^{-1}$ for ST fields). This was due primarily to a reduction in runoff with ST. The 10-year annual average partitioning of the total annual rainfall and irrigation into runoff was 20.5% for CT and 12% for ST, a reduction of 41%. The *T* value of 2,200 kg ha^{-1} $year^{-1}$ was exceeded in three out of ten years in the CT fields and never exceeded in the ST fields.

A small number of the largest daily events contributed disproportionately to greater runoff and sediment totals in both CT and ST. Approximately 1% of the study period had >50 mm daily rainfall, from which the across-tillage mean runoff percentage was 45% (±3%) of the total runoff, and the across-tillage mean sediment loss (kg ha^{-1}) was 41% (±9%) of the total. Similarly, 4% of the study period had daily rainfall from 20 to ≤50 mm, from which the across-tillage mean runoff percentage was 38% (±1%) of the total, and the across-tillage mean sediment loss was 40% (±5%) of the total.

Runoff and sediment loss from higher landscape positions were greater than those from lower landscape positions. This was likely due to the fact that clay-rich subsoils were closer to the soil surface in fields at upper landscape positions. Under CT, the month of June, followed by July, posed the most risk for high runoff and sediment loss, particularly under cotton production. However, high runoff events and sediment loss occurred throughout the year in response to rainfall, high antecedent soil water content, and cover conditions. Five equations were derived that effectively described the relationship between runoff and sediment loss coefficients and corresponding exceedance probabilities.

Long-term research and experimental data, as presented here, are critical for generating the scientifically based information needed to make wise management decisions that sustain the integrity of natural resources. The study results point to the need to consider a combination of best management practices in the form of cover crops, strip tillage, and others such as contour cultivation and reduced slope length to consistently reduce soil loss below tolerance levels for the Atlantic Coastal Plain. This will be critical in view of expected climate change for this region in the coming decades in the form of increased rainfall amounts and intensity, which, based on the results of this study, will imply more runoff and sediment loss from agricultural fields, with a greater percentage coming from CT systems.

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