VEGETATIVE TECHNIQUES FOR REDUCING WATER EROSION OF CROPLAND IN THE SOUTHEASTERN UNITED STATES[1]

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I. INTRODUCTION

Tillage and erosion have been intimately involved in the evolution of cropping systems in the southeastern United States. The region encompasses several physiographic zones, dropping from the foothills of the Blue Ridge and Appalachian mountains across the broad-sloping land of the

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Piedmont and sandhills and finally out over the rolling topography of the coastal plains to the coastal flatwoods (Buol, 1973; Fiskell and Perkins, 1970). Much of the land has been under cultivation for over 250 years. The natural fertility of the land was largely exhausted during the pre-1920 corn–cotton era. Southern agriculture since about 1920 has been forced to turn to alternative crops because of the incursion of the boll weevil and other insect pests, introduction of synthetic fibers and inexpensive western cotton, abandonment of draft animals for mechanized agriculture, and the perennially intense weed and disease pressures. Even though tillage systems have changed dramatically since 1920, predominantly clean-tilled cultural practices have continued to be used to cope with weed, disease, and insect pressures, despite the severe erosion associated with this practice.

In the 1940s, when 2,4-D[4] and DDT were widely introduced, E. H. Faulkner (1943) published one of the first significant challenges to conventional tillage farming. In this era (McCalla and Army, 1961) reduced tillage farming was far more successful in the Midwest and upper Great Plains due to the less severe weed, pest, and disease control problems of those regions compared to the humid South. Two decades of experimentation with tillage systems, cover cropping, and green manure crops ensued. The results of this period were reviewed by McCalla and Army (1961) and (Hendrickson *et al.*, 1963a,b). Significantly, McCalla and Army's review considered only three papers from the humid South (Beale *et al.*, 1955; Nutt and Peele, 1947; Peele *et al.*, 1946). These reviews, and the introduction of the highly effective contact herbicide paraquat stimulated a new round of research. During this period both implement configuration and herbicide technology were arrived at by trial and error and were not well documented. One particular implement innovation was the use of the fluted coulter on cool-season sods (Bandel *et al.*, 1975; Blevins *et al.*, 1971; Box *et al.*, 1980; Harold and Edwards, 1972). This became the first true no-tillage work applicable to the southern region.

Until the oil embargoes of the early 1970s, however, there was little economic incentive to explore alternative tillage practices. As long as petroleum and its derivatives were inexpensive, tillage and fertilizer remained an inexpensive means of maintaining the effective productivity of the land, even against severe erosion losses. In the 1970s petroleum products became expensive and were sometimes simply unavailable. In addition, public pressure to eliminate agricultural pollution of the nation's

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water supply helped stimulate the search for new economical farming methods that simultaneously satisfied the demands of productivity, fuel conservation, and pest, erosion, and pollution control. Research from diverse environments has shown that vegetation or crop residue covering the soil is the most effective means of controlling soil loss across an extremely wide range of soil textures and slopes (Heinemann and Whitaker, 1974; Langdale *et al.*, 1983a,b; Larson *et al.*, 1978). In the Southeast, progress in erosion control has been accomplished by an expansion of expertise in the use of cover crops and residue management practices that minimize tillage of the soil.

The objective of this article is to evaluate new cover cropping technology for limiting soil erosion and to summarize the literature since McCalla and Army's (1961) review, works that quantify the effect of these practices on measured amounts of erosion. Because the technology of this recent period has become more and more specific to individual physiographic regions, this article focuses primarily, though not exclusively, on the southeastern United States.

II. CROP RESIDUES AND COVER CROP MANAGEMENT

A. Crop Residues

Since McCalla and Army's (1961) review, several national and regional conferences, symposia, other recurring meetings, and reports in the general area of conservation tillage have helped accelerate the development of its technology (American Society of Agricultural Engineers, 1967, 1981; Great Plains Agricultural Council, 1968; Ohio State University *et al.*, 1972; Soil Conservation Society of America, 1973, 1977; Halliday, 1975; Oschwald *et al.*, 1978; Larson *et al.*, 1981). Chepil *et al.* (1963) published a detailed review of various mulching techniques developed prior to the early 1960s. Of particular interest to the southern region have been the combined proceedings of the Annual Southeastern No-Tillage Conferences since their formal inauguration in 1978 (Touchton and Cummins, 1978; Gallaher, 1980; Lewis, 1981) and the proceedings of other informational exchange groups spawned by the Southeastern No-Tillage Conference (National Fertilizer Development Center/TVA, 1981; Hargrove, 1982). Publication of three popular books (Phillips and Young, 1973; Phillips *et al.*, 1981; Turner and Rice, 1983) on no-till farming have accelerated information transfer to extension agents and farmers.

Two broad technological breakthroughs have made it possible to produce crops successfully in the South while leaving essentially all existing plant residues on the soil surface. The first breakthrough came with development of commercially successful in-row subsoil-planting equipment (Harden *et al.,* 1978). Subsoiling has been necessary even in otherwise untilled soil in the South because of the extensive acreages of soils with genetic or traffic-induced subsoil "hardpans" (Campbell *et al.,* 1974; Langdale *et al.,* 1981). The second breakthrough was the development of several improved weed control options including new herbicides and new applicators. These herbicides include preemergence surface-applied residuals, nonselective contacts and systemics, and highly specific grass or broadleaf postemergence over-the-top herbicides. New application technologies include rope-wick applicators, recirculating sprayers, fine-mist atomizers, and controlled droplet applicators. These new weed control technologies have made it possible to control most weeds in most forms of conservation tillage, while in many instances minimizing cost of materials. Additionally, some attention is now being directed at "mechanical" weed control in otherwise untilled systems both alone and in combination with directed spraying.

A third, less tangible factor has also had a significant impact. This factor is the realization of the distinctly different nature of conservation tillage in southern agriculture. Conservation tillage in the South is confronted with a mild overwintering period which results in significant weed establishment in undisturbed surface residues, provides habitats for pests, and increases the likelihood of pathogen vectors in the residue. Also, in many systems crops are planted into living vegetative cover. Furthermore, conservation tillage in the South has been shown to be suited to defined physiographic limitations on the basis of the severity of slope of the specific land to be managed (Campbell *et al.,* 1979a,b, 1981). Recent work has suggested that slope affects not only the severity of erosion hazard of the land in question but also the efficacy of the various cropping systems chosen (Campbell *et al.,* 1983, 1984a,b).

The South can be broadly subdivided on the basis of slope into two physiographic areas. The first consists of the sloping lands of Appalachia and the Piedmont. The second consists of the flatter lands of the coastal plains, delta regions, and interior low plateaus (Buol, 1973). The Piedmont and Appalachia have slightly more temperate climates and have few coarse-textured soils. The coastal plains and delta regions are generally warmer, more humid, and more diverse in their soil types. The coastal plains are dominated by coarse-textured soils with very low water- and nutrient-holding capacities, whereas the delta areas have diverse but predominantly heavy clay soils. Certainly if soil factors per se were used as additional criteria for subdivision, numerous other distinct physiographic regions could be identified.

Maintenance of plant residues on the soil surface results in both beneficial and detrimental consequences. Benefits include greater retention of fertilizers, pesticides, and soil in place; increased infiltration; less frequent crusting; reduced soil–water evaporation; early suppression by residues of weed establishment, and, therefore, reduced early nutrient and water competition by weeds. Among the negative consequences are increased full-season insect, weed, and pest pressure; greater traffic-lane compaction; poorer vertical fertilizer placement and distribution; more variable (in time and space) stand establishment—because of seed placement and pathogen problems; increased dependence on chemical weed control; adsorption of soil-targeted chemicals on crop residues; acidification of surface soil; and consequent deactivation of some soil-applied chemicals. Perhaps the most important finding is that when these crop residues are the result of vegetative growth of cool-season cover crops, they can, in some years, result in serious depletion of soil water for the succeeding warm-season crop (Campbell *et al.*, 1984a,b; Hargrove, 1982).

When slopes are significant, the benefits of surface residues tend to outweigh the disadvantages when comparing crop performance with conventional tillage (Sheng, 1982). On nearly level ground, the degree of benefit is reduced and, in some instances, benefits are overridden by disadvantages. Corn in the South seems particularly prone to slope-determined response-reversal when comparing conservation tillage systems (particularly no-till) with conventional systems, whereas southern soybean cultivars, probably because of their determinancy, respond positively to residues in most years even on nonsloping land (Campbell *et al.*, 1984a,b).

B. VEGETATIVE COVER CROPPING

The particular benefit of maintaining a living vegetative cover to reduce soil erosion has been recognized for many years in southern agriculture, particularly in the Piedmont. Moody *et al.* (1961) planted corn directly in mixed sod of orchard grass, fescue, and clover that had been killed with atrazine. They reported yields comparable to those of conventionally grown corn. Free *et al.* (1963) obtained similar results when planting corn in alfalfa sod killed with a mixture of atrazine and aminotriazole. McAlister (1962) grew corn, soybean, sorghum, millet, and other crops in fields of sod, grain stubble, and weeds using a modified Lister[4] planter with mixed results. Beale *et al.* (1955) obtained slight yield increases with corn planted into various mulches and markedly reduced soil loss and runoff while increasing soil nitrogen, organic matter content, and aggregation. Beale and Langdale (1964), however, working in the coastal plain, observed a 9% yield reduction over 3 years in corn that was Lister-planted in Bermuda grass sod killed with aminotriazole. They further observed that although leaf nitrogen content was unaffected and soil moisture content remained higher in the Lister-planted corn, the root systems were less extensive in the Lister-planted corn than under conventional tillage. During the years these studies were conducted, "conventional" tillage practices involved moldboard plowing, disking, and bedding (Goolsby and Seigler, 1975). Later studies would reveal that the primary reason Lister-planting was less successful in the coastal plains was the high soil strength of the undisturbed soils beneath the corn plant (Kashirad *et al.*, 1967; Campbell *et al.*, 1974; Stitt *et al.*, 1982). Long-term observation of soil properties has frequently shown improved soil physical condition on loam and silt-loam soils. Positive effects include increase in aggregation and increase in the surface 5-cm organic matter content, increase in soil moisture retention, and no increase in bulk density (Moschler *et al.*, 1974; Thomas *et al.*, 1975; Smith and Lillard, 1976).

Reicosky *et al.* (1977) described the potential for conservation tillage in the Southeast, suggesting that it could benefit more from conservation tillage than any other region in the United States. They addressed the problems of water and soil conservation in a region where low soil-water storage capacity and high intensity rainfall often resulted in runoff, soil loss, and drought, despite favorable annual precipitation totals. Maintaining surface residues increases infiltration, reduces evaporation, minimizes soil strength (by maintaining favorable water contents), and increases multicropping (more than one harvestable crop per year) potential by compressing the timetable of field operations.

Soil water management becomes more complex for double-crops or cover crops compared to conventional tillage. When rainfall patterns are favorable, double-cropping winter wheat with grain sorghum has been shown to be feasible as far north and west as Bixby, Oklahoma (Crabtree and Makonnen, 1981). In their study, the sorghum crop, grown on a Wynona silt loam soil (Cumulic Haplaquolls), failed in 1 of the 4 years, and mean double-cropped wheat yields were reduced 22% compared to monocropped wheat. Double cropping throughout the rest of the South is generally more favorable, although a major management problem has focused on how best to handle residues of the cool-season crop. The stubble of winter-grown wheat until recently has been burned in most of the South before double-cropping to soybean or sorghum (Beale and Langdale, 1967; Hinkle, 1975; Campbell *et al.*, 1984a,b). Experience with double cropping has shown, however, that the surface residue can significantly conserve soil water by reducing evaporation (Jones *et al.*, 1969;

Blevins *et al.*, 1971; Van Doren and Triplett, 1973) in addition to preventing erosion.

Part of the increase in soil water content under residue results from improved infiltration and reduced runoff (Triplett *et al.*, 1968). These factors are more significant on sloping land and are affected by the presence or absence of subsoils restrictive to root growth (Campbell *et al.*, 1974; Doty *et al.*, 1975; Doty and Reicosky, 1978). Deep tillage to disturb subsoil horizons restrictive to root growth has also been shown to benefit both the primary warm-season crop and the subsequent cool-season crop (Touchton and Johnson, 1982). Recent work suggests that for clay-matrix traffic pans, only a thin slit needs be cut through the pan to promote adequate subsoil root proliferation (Elkins and Hendrick, 1983; Elkins *et al.*, 1983). When infiltration is improved, loss of fertilizer and soil-applied chemicals is also minimized. Since potential runoff and erosion are less on level land, maintenance of residues in this manner contributes less to yield enhancement in the coastal plains than in the Piedmont and Appalachia (Campbell *et al.*, 1984a,b). This is not to say that erosion per se has not been a problem on conventionally tilled land in the coastal plain (Thomas *et al.*, 1969; Sheridan *et al.*, 1982). Similarly, water-conserving properties of surface residues on level land can result in negative consequences on inadequately drained land (Costamagna *et al.*, 1982).

III. USE OF *C*-FACTORS IN CROP RESIDUE MANAGEMENT

The *C*-factor was developed by Wischmeier and Smith (1965) to serve as a cropping management factor in their universal soil loss equation (USLE) (Beasley, 1972; Peterson and Swan, 1979). More than 10,000 plot-years of natural runoff and soil-loss data were assembled from 49 research stations in 26 states to derive empirical crop stage *C* values (Wischmeier, 1955; Wischmeier and Smith, 1965, 1978). It is defined in the USLE as the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow (Wischmeier and Smith, 1978). To derive site values of *C*, soil loss ratios for individual crop stage periods (defined by Wischmeier and Smith, 1965, 1978) must be combined with erosion-index distribution data. Ratios of soil losses in each crop stage period (usually five each) of specified cropping and management systems to corresponding losses from the the basic long-term fallow condition are used to compute an empirical measure of the erosion-control effectiveness of a given crop grown in various sequences.

The erosion index (EI) is a statistical interaction term (or product term) that reflects how total energy and peak rainfall intensity are combined in a particular rainfall event. Summation of individual storm EI values during 1 year gives an annual EI value (Wischmeier and Smith, 1965). The R value used in the USLE is the average EI expected for a particular location. This rainfall factor, R, is also partitioned by crop stage periods. Crop stage EI distribution differs depending on location; thus, the value of C for a particular cropping system will not be the same in all geographic regions. In fact, some researchers (McGregor, 1978; Murphree and Mutchler, 1980) show considerable C-factor variation from year to year on the same runoff plots and watersheds.

In addition to C values developed by Wischmeier and Smith (1965, 1978) generalized C values covering a wide range of row cropping systems are presented by Siddoway and Barnett (1976), Hayes and Kimberlin (1978), and Mannering and Fenster (1977). Generalized C-values are also published in Soil Conservation Service Technical Guides (U.S. Department of Agriculture, 1982). Important modifications of C-subfactors to meet local needs are given by Murphree and Mutchler (1980), Laflen *et al.* (1981, 1983), and Mutchler *et al.* (1982). Most of this accumulated crop residue literature has related C-factors to monocropped–conventional tillage systems. Much of this literature is published by crop stage and as soil loss ratios, thereby making general comparisons from site to site difficult. These C-factors also appear to decrease drastically as conservation tillage evolves.

This discussion will deal primarily with "annual" C-factors. Recently researched annual C-factors for conservation tillage systems will be compared with those reported earlier for conventional tilled systems. McGregor (1978) computes these values from plot data using the following equation:

$$\text{Annual } C = \frac{\sum_{t=1}^{n} C_t R_t}{\sum_{t=1}^{n} R_t} \qquad (1)$$

where n is the number of crop stage periods, C_t is the cropping management factor for period t, and R_t is the number of EI units in period t. Equation (2) (Wishmeier and Smith, 1978) was used to calculate C_t values:

$$C_t = A_t/R_tKLSP \qquad (2)$$

Here A is soil loss in tons per acre, R is a rainfall factor, K is a soil erodibility factor, L is a slope length factor, S is a slope gradient factor, and P is an erosion control practice factor. Observed soil loss and rainfall energy were used to calculate A_t and R_t, respectively. Annual C-factors shown in Table I were determined experimentally by McGregor (1978) and other researchers (Murphree and Mutchler, 1980; Thomas *et al.*, 1969) and were all derived in a similar manner. These values were determined on silt loam soils (Alfisols) of Mississippi and fine loamy sand soils (Ultisols) of Georgia. They range from 0.003 for no-tilled double-cropped wheat–soybean to 0.78 for conventional tilled, monocropped peanuts. Desirable annual *C*-factors for cotton and peanut production, even in rotation with meadow, appear difficult to achieve. Extensive soil erosion in the Southeast during the nineteenth and twentieth centuries may be attributed, in part, to high *C*-factors related to conventionally tilled cotton and associated crops (Trimble, 1974). The *C*-factors for these tillage–cropping systems usually exceed 0.50.

When fluted-coulter no-tillage emerged in the 1970s (Moldenhauer *et al.*, 1983), *C*-factors dropped from tenth's to thousandth's (Tables I and II). However, cropping systems have also shifted. Cotton hectareage dramatically decreased as double-cropped small grain/soybean–grain sorghum emerged in the Southeast. In the corn belt of the north central region, meadow has disappeared from the corn/soybean rotation, and no-tillage of summer annuals in the crop residue of the previous year is rapidly expanding. These cropping systems of both regions improve the *C*-factor over conventional tillage systems. At least 50% land cover or a 0.010 *C*-factor is usually possible during the vulnerable high-energy spring rainfall period. When *C*-factors decrease to or go below 0.010, soil erosion of the Southeast and Midwest is well within soil loss tolerances (*T*-value) (Larson, 1981) on land capability classes I through IV. Conservation tillage research accomplished during the 1970s supports this hypothesis (Harold and Edwards, 1972, 1974; McGregor *et al.*, 1975; Langdale *et al.*, 1979, 1983a,b; Laflen *et al.*, 1981).

Table I

Experimentally Determined Annual *C* Values from Watersheds and Runoff Plots

Tillage	Cropping system	*C*-factors	Reference
Conventional	Continuous cotton (5 yr)	0.58	Murphree and Mutchler (1980)
Conventional	Continuous corn (11 yr)	0.40	Thomas *et al.* (1969)
Conventional	Continuous soybean (4 yr)	0.12	McGregor (1978)
Conventional	Peanuts following Bahia–clover/corn (4 yr)	0.53	Thomas *et al.* (1969)
Conventional	Peanuts following oats–rye (2 yr)	0.78	Thomas *et al.* (1969)
No-till	Continuous soybean (4 yr)	0.006	McGregor (1978)
No-till	Soybean following corn (4 yr)	0.009	McGregor (1978)
No-till	Corn following soybean (4 yr)	0.013	McGregor (1978)
No-till	Wheat–soybean (double crop)	0.003	McGregor (1978)

Table II

Crop Residue Cover Influence on Generalized Annual *C*-Factor of Important Tillage-Cropping Systems

		Percentage of ground cover after planting								
Tillage	Cropping sequence	0	20	30	40	50	60	70	80	90
		Iowa								
Spring plow	Continuous corn	0.29	—	—	—	—	—	—	—	—
Spring plow	Corn (1st yr) following meadow	0.13	—	—	—	—	—	—	—	—
Spring plow	Continuous soybean	0.39	—	—	—	—	—	—	—	—
No-till	Corn following soybean	—	0.24	0.18	0.14	—	—	—	—	—
No-till	Soybean following corn	—	—	—	—	0.12	0.11	0.08	0.05	—
No-till	Corn following small grain	—	—	—	—	0.10	0.09	0.06	0.04	—
No-till	Corn following meadow	—	—	—	—	0.03	0.03	0.01	0.01	—
No-till	Continuous corn	—	—	—	—	0.06	0.05	0.04	0.03	—
No-till	Continuous soybean	—	—	—	—	0.25	0.20	0.16	—	—
No-till	Soybean following small grain (2 yr)	—	—	—	—	0.13	0.12	0.08	0.05	—
		Georgia								
Spring plow	Continuous corn	0.31	—	—	—	—	—	—	—	—
Spring plow	Corn (1st yr) following meadow	0.17	—	—	—	—	—	—	—	—
Spring plow	Continuous soybean	0.46	—	—	—	—	—	—	—	—
No-till	Corn following soybean	—	0.28	0.23	0.17	—	—	—	—	—
No-till	Soybean following corn	—	—	—	—	0.16	0.14	0.10	0.08	—
No-till	Corn following small grain	—	—	—	—	0.16	0.13	0.10	0.08	—
No-till	Corn following meadow	—	—	—	—	—	—	—	0.02	0.01
No-till	Continuous grain sorghum	—	—	0.22	0.18	0.13	0.11	0.07	0.05	—
No-till	Continuous soybean	—	—	—	0.19	—	—	—	—	—
No-till	Soybean following small grain (1 yr)	—	—	—	—	0.13	0.12	0.10	0.09	—

Conservation tillage expansion in the northcentral and southeastern states is also reflected in generalized *C*-factors published in Soil Conservation Service technical guides (U.S. Department of Agriculture, 1982). Their generalized *C*-factors are computed from USDA Handbooks 282 and 537 (Wischmeier and Smith, 1965, 1978). Examples of annual *C*-factors for important tillage–cropping systems in Iowa and Georgia are presented in Table II. A cursory view of these technical guides (usually by states) suggests that estimated annual *C*-factors from states within the same broad geographical areas, or states dominated by the same soil orders, do not differ appreciably. The larger values reported for Georgia are associated with rapid crop decomposition due to long duration of higher ambient temperatures. However, tillage and cropping systems provide even greater differences, with *C*-factors ranging from 0.010 for continuous cover to 0.46 for monocropped conventional tillage. Generally, the *C*-factors in Table II may be bracketed into three categories: 0.010 to 0.100 with ≥50% groundcover associated with double crop no-tillage in small grain or meadow; 0.14 to 0.24 with groundcover between 20 and 30% associated with monocrop no-tillage; and 0.13 to 0.46 for monocropped conventional tillage. The estimated *C* values for double-crop no-tillage (with small grain or meadow) exceed most observed values.

Short duration rainulator runs have been made on conservation tillage crop stages to test the validity of generalized *C* values (Meyer *et al.*, 1970; Meyer and Ports, 1976; Langdale *et al.*, 1978; Laflen and Colvin, 1981). Duration of rainulator runs are usually equal to or less than 2 hours; however, the rainfall kinetic energy (KE) is usually very high. Results from these rainulator studies fill data gaps and support the findings of natural rainfall studies previously discussed. Results of a sample rainulator study are presented in Table III. These values, which represent segments of crop stages 1 and 2 (Wischmeier and Smith, 1978), are for periods when the soil is vulnerable to water erosion in the humid southeastern United States. Double cropping rye and soybean permitted these *C*-factors to exceed 0.010 only in the absence of any soybean canopy in combine-removed straw. Only the chaff and the partially standing stubble remained on the soil surface. Although both increasing rye residues and soybean canopy coverage on this rainulator study decreased the *C*-value range from 0.010 to 0.006, Wischmeier and Smith (1978) and Laflen *et al.* (1983) suggested that the effects of crop residue and canopy are not fully additive. This interaction is complex because both crop residues and canopies reduce rain-drop impact energy, while crop residue also reduces rill erosion and transport capacity of runoff water. The *C*-factors discussed and presented herein suggest that soil erosion control is possible within *T*-tolerances under appropriate conservation tillage practices even

Table III

Experimentally Determined *C*-Factors on Double-Cropped, No-Till, Simulated Rainfall Plots[a]

Rye mulch[b] (Mg ha^{-1})	Soybean canopy (%)	*C* values
2.5	0	0.012
2.5	50	0.008
2.5	100	0.003
3.5	0	0.008
3.5	50	0.006
3.5	100	0.002
4.5	0	0.006
4.5	50	0.004
4.5	100	0.001

[a] Plots 10.7 m, 6% slope, on Cecil sl soil (Langdale *et al.*, 1978).

[b] Combined straw was removed at the 2.5 Mg ha^{-1} rate, no straw was removed or added at the 3.5 Mg ha^{-1} rate, and 1.0 Mg ha^{-1} of combined straw was added at the 4.5 Mg ha^{-1} rate.

while increasing row-crop acreage. In conventional tillage systems, the period most vulnerable to soil erosion by water occurs between primary tillage and near-closure of the crop canopy (Wischmeier and Smith, 1978; Langdale *et al.*, 1979; Laflen and Moldenhauer, 1979; Laflen *et al.*, 1981; McGregor and Greer, 1982). This period usually occurs during crop stages SB (seedbed period), Period 1 (establishment, SB to 50% canopy) and Period 2 (development, Period 1 to 75% canopy). Crop stage *C* values presented in Table IV illustrate probably the most intrinsic long-term worth of no-tillage for soil erosion control. These data suggest, as Lowdermilk (1953) stated 30 years ago, that management of crop residues on soil surfaces through no-tillage may be one of the greatest accomplishments of modern American agriculture. Only *C* values or soil-loss ratios shown for no-till corn following previous-year soybean approach those shown for any conventional tillage systems.

IV. EROSION REDUCTION UNDER CONSERVATION TILLAGE AND COVER CROPPING

Plant residues maintained on the soil surface in conservation tillage dissipate most of the kinetic energy in each centimeter of rainfall

Table IV

Efficiency of Crop Residues with Respect to Tillage during Vulnerable Soil Erosion Crop Stage Periods

Tillage system	Cropping system	Spring residues[a] (Mg ha^{-1})	Crop stage *C* values			Reference
			SB[b]		2	
Conventional	Corn following corn/grain sorghum	5.04	0.55[c]	0.48[c]	0.38[c]	Wischmeier and Smith (1978)
	Continuous cotton	HP	1.01	0.68	0.50	Murphree and Mutchler (1980)
	Continuous corn	HP	—	0.26	0.25	Thomas *et al.* (1969)
	Continuous soybean	HP	—	0.28	0.23	McGregor (1978)
	Soybean following wheat	HP–DC	—	0.099	0.070	Hayes (1973)
No-tillage	Corn following rye grass	4.48	0.07[c]	0.07[c]	0.07[c]	Wischmeier and Smith (1978)
	Corn following row crops	5.04	0.05[c]	0.05[c]	0.05[c]	Wischmeier and Smith (1978)
	Corn following soybean	HP	0.25[c]	0.20[c]	0.19[c]	Wischmeier and Smith (1978)
	Soybean following wheat	HP–DC	—	0.004	0.003	McGregor (1978)
	Soybean following wheat	HP–DC	—	0.010	0.009	Hayes (1973)
	Continuous corn	5.50	—	0.070	0.070	Hayes and Kimberlin (1978)

[a] HP, High production; DC, double cropped.

[b] SB, Seedbed period.

[c] Soil-loss ratios.

(Wischmeier and Smith, 1958). A universal relationship between crop residue rates and percentage surface cover was developed by Wischmeier (1973). Generally, 5 to 7 Mg ha^{-1} of most crop residues used as a surface mulch will provide 80–100% surface cover. This surface cover range will provide a mulch factor (soil loss ratio) less than 0.10 (Wischmeier, 1973). These values are well within the potential of current high production conservation tillage systems. McCalla and Army (1961) summarized mulch use and its beneficial effects up through 1960. Since then, original research dealing with residue types, rates, and effects have been summarized by Siddoway and Barnett (1976), Mannering and Fenster (1977), Oschwald *et al.* (1978), Wischmeier and Smith (1978), and the Soil Conservation Society of America (1979). Such work was stimulated in the late 1970s by the intense evolution of conservation tillage and the potential of increased demand for crop residues as an energy source. The demand for crop residues in conservation tillage systems is also stressed because permanent *in situ* conservation tillage practices, such as terracing, are rapidly becoming too expensive for farm producers. Using crop residues to provide adequate cover on sloping landscapes also permits the farmer to orient row direction for more efficient maneuverability and protection of vegetative waterways (Langdale *et al.*, 1979), and use wide (6–8 rows) equipment without having to reconfigure old terraces.

Runoff and sediment data (Langdale *et al.*, 1979) for the conventional

Table V

Crop Residue Rates Associated with Tillage Systems and Their Control of Runoff and Soil Erosion on a 2.71-ha Piedmont Watershed in Watkinsville, Georgia[a]

Tillage system	Crop sequence	Crop residues (Mg ha^{-1})	Rainfall (ave/crop) (mm)	Runoff (%)	Sediment (Mg ha^{-1})
Conventional tillage (2 yr)	Fallow		787	9.0	3.136
	Soybean	1.64	508	33.0	23.072
	Annual average	1.64	1295	18.4	26.218
Coulter tillage (2 yr)	Barley	3.32	889	8.5	0.134
	Grain sorghum	6.25	356	5.7	0.009
	Annual average	9.57	1245	7.7	0.143
Coulter in-row chisel tillage (4 yr)	Wheat	5.59	711	2.4	0.029
	Soybean	2.98	483	2.7	0.000
Coulter in-row chisel tillage (2 yr)	Clover	4.27	610	1.6	0.004
	Grain sorghum	6.44	330	0.0	0.000

[a] Only coulter and chiseling (18–23 cm deep) on 762-mm centers were performed during the last 8 years.

tillage period on a 2.71-ha Southern Piedmont watershed (Table V) clearly show that terracing should accompany this tillage procedure. However, multiple crop conservation tillage eliminates the necessity for intensive terracing on a sloping landscape. The 26.2 Mg ha^{-1} yr^{-1} sediment yield shown for conventional tillage represents flume-measured sediment only. Equal quantities of sediment did not pass through the flume (Langdale *et al.*, 1979). Similar soil losses from runoff plots have been observed during the cotton production era on Southern Piedmont soils (Hendrickson *et al.*, 1963b). Double-crop fluted-coulter tillage controls soil erosion equally as well as coulter in-row chisel tillage (Table V). However, runoff is more than 2-fold greater for fluted-coulter tillage than coulter in-row chisel tillage. Soil losses resulting from similar tillage practices, cropping systems, and slopes in southern Illinois were essentially equal to those of north Georgia (Siddoway and Barnett, 1976; Langdale *et al.*, 1979). Runoff on the Illinois study was not controlled as well with no-tillage. The last tillage-cropping system shown in Table V deals with coulter in-row chisel planted grain sorghum in crimson clover (Langdale *et al.*, 1983a). The objective of this study was to control soil erosion and biologically fix nitrogen (N) for grain sorghum production. Average annual nonirrigated grain sorghum yields (1981–1982) were 5.02 to 7.53 Mg ha^{-1} without applied N fertilizer (G. W. Langdale, unpublished data). This system also produces 10.71 Mg ha^{-1} of crop residues annually to recycle plant nutrients and provide runoff and soil erosion protection. Presently no row-crop vegetative system provides better land protection than this system on land capability land classes II to IV in the Southern Piedmont. The only runoff studies in the Southern Piedmont that challenge the conservation tilled crimson clover–grain sorghum for runoff control was continuous sericea lespedeza (Pieters *et al.*, 1950) and kudzu (Hendrickson *et al.*, 1963a). When crimson clover begins volunteer reseeding the clover plus grain sorghum potentially provides an effective live canopy up to 10 months per year. It is also one of the least difficult conservation tillage systems to manage for the Southern Piedmont and serves as a good rotation system for soybean production (G. W. Langdale, unpublished data). However, during the soybean phase of the rotation, conventional fall tillage is recommended (Thomas *et al.*, 1982) during this low-energy rainfall period in the Southern Piedmont (Wischmeier and Smith, 1965). If fall plowing is performed, a winter crop should be planted to protect the land against soil erosion during winter and early spring months.

Vegetative control of soil erosion on row-crop land has been amply cited herein. Conservation tillage technologies on the horizon also support the concept of vegetative control of soil erosion, particularly on sloping landscapes with a water erosion hazard. An outstanding recent example of no-till soil erosion control in North America comes from a

20.7% sloping research watershed at Coshocton, Ohio (Harrold and Edwards, 1972). A severe July 1969 storm with an expected frequency of less than once each 100 years (127 mm of rain in 7 hr) generated only 0.071 Mg ha^{-1} sediment yield. The protective vegetation was corn following 30 years of bluegrass and clover. On a nearby 6.6% sloping conventionally tilled watershed also planted to corn, 50.736 Ma ha^{-1} of sediment was eroded during this storm. Obviously, vegetation for protecting row cropland is one of our most natural resources.

American Society of Agronomy publications (Schmidt *et al.*, 1982; Larson *et al.*, 1981) suggest that agricultural production may be forced to grow considerable quantities of our food and fiber on nonprime farmland beginning early in the twenty-first century. Significant hectareage of nonprime cropland has already experienced accelerated water erosion. It is imperative during the next two decades that appreciable research resources be devoted to improving vegetative techniques to control soil erosion on row cropland. Research areas should include tillage equipment design, soil-water management, and germplasm, disease, insect, and allelopathic effects.

V. THEORETICAL ASSESSMENT OF EROSION CONTROL THROUGH RESIDUE MANAGEMENT ON ERODIBLE LANDS IN THE SOUTHEAST

Campbell *et al.* (1979a,b) assessed erosion potential of cropland in six southern states by calculating $A:T$ ratios where A is USLE calculated soil loss and T is the maximum soil erosion allowable without affecting long-term crop productivity. They evaluated 33 major land resource areas (MLRA) (Austin, 1965) in this region and found that A exceeded T by a factor of 1.8 on 15% of the area, by a factor of 3 in 36%, and by factors of 4 to 9 in 36%. These calculations indicate that soil erosion is a major problem in many of the MLRAs in Alabama, Georgia, Mississippi, North Carolina, South Carolina, and Virginia.

Potential benefits of vegetative erosion control techniques were also evident from their calculations of $A:T$ ratios for continuous soybean compared to a small grain/soybean cropping system. In MLRA 153, where slopes are generally less than 2%, approximately 99% of land in small grain/soybean rotation had an $A:T$ ratio of less than 1 compared with 55% of the land in continuous soybean. Similar results were found in Virginia on MLRA 136 and in Mississippi on MLRA 134, where slopes generally ranged from 2 to 5 and 5 to 8%, respectively. In MLRA 134, the

$A:T$ ratio for a small grain/soybean cropping sequence was less than 1 on 41% of the land compared with being less than 1 on only 3% of the land producing continuous soybean. Although the values are extreme, they do emphasize the benefits and importance of maintaining vegetative cover on the soil surface and demonstrate its potential for reducing soil erosion.

VI. EFFECTS OF VEGETATIVE SOIL EROSION CONTROL ON NUTRIENT CYCLING

One major consequence of soil erosion is loss of plant nutrients. On a national scale, Larson *et al.* (1983) calculated that annual losses of nitrogen, phosphorus, and potassium have estimated values of $677, $17, and $382 million per year, respectively. These values are exclusive of any downstream impacts or loss of those nutrients for subsequent recycling. Adoption of conservation tillage practices can reduce soil erosion losses and downstream pollution, but some technical obstacles must be eliminated through research and extension (Ritchie and Follett, 1983) so that those tillage systems are economically competitive with conventional farming systems. Conservation tillage hectareage is projected to rise from 20% in 1982 (No-Till Farmer, 1982) to a projected 50–90% by 2010 (Crosson, 1981). Two of the technical problems that must be resolved for these projections to be achieved are the development of better cover crop technology and development of increased understanding of the complex nutrient cycling associated with cover cropping.

Barrows and Kilmer (1964) reviewed pertinent data relating to water erosion losses of organic matter and plant nutrients from cultivated soils. They found that early studies of nutrient loss through runoff were often complicated by analytical techniques but could show that significant losses of organic matter along with nitrogen and phosphorus did occur. Data which they reviewed showed large total potassium loss but only a small percentage of the potassium lost was exchangeable or available to plants. Calcium and magnesium losses were generally of minor importance; and, although sulfur data were meager at that time, there was an indication that losses were relatively significant.

McCalla and Army (1961) reviewed fertility effects of stubble mulch farming and identified depressed nitrification as one major chemical effect of those management systems. They reviewed data showing that depression of nitrate formation by crop residues was delayed and less intense in stubble mulch systems than when plowed down, but was longer in duration. Among the factors contributing to this effect were aeration differences between the two tillage systems and release of soluble organic compounds. They cited reports that stubble mulching often increased extractable phosphorus and soluble potassium but also found that available potassium was frequently lower with stubble mulching. Manganese availability was reduced by stubble mulching, a condition that would reduce potential toxicities of this nutrient but could also induce more severe manganese deficiency on soils where this nutrient was deficient. Mulches appeared to have no significant effect on soluble calcium concentrations in what they reviewed.

Power and Legg (1978) reviewed nutrient cycling in alternative crop residue management practices. They noted that the basic framework of nutrient cycling (Delwiche, 1970) involves assimilation of inorganic chemicals by plants. The soil, water, and air with which the plant is in contact is the reservoir for these chemicals. When harvested, some constituents are removed from the system, while those in residues or cover crops are recycled. Through decomposition those nutrients are released into the immediate environment of subsequent crops.

Nutrient cycling influences all plant nutrients, but nitrogen, phosphorus, and sulfur cycles are most evident because these nutrients form an integral part of soil organic matter and because microbial transformations are involved. Few long-term comparisons of conventional and reduced tillage systems have been made in the southeastern United States, but long-term crop rotation studies (Thompson and Robertson, 1959) have shown that organic matter greatly influences cation exchange capacity (CEC) and water retention in these sandy-textured soils where the clay content is low and predominantly Kaolinitic. Long-term no-tillage studies in Kentucky (Blevins *et al.*, 1983), Virginia (Shear and Moschler, 1969; Moschler *et al.*, 1975), and Ohio (Van Doren and Triplett, 1973; Dick, 1983) have shown that no-tillage significantly influences profile distribution of organic carbon, nitrogen, and phosphorus. These changes in distribution occur because decomposition rates within the nutrient cycles are influenced by placement and surface area of the residues.

Accumulation of surface residues, because of slower decomposition, influences fertilizer application methods. Nitrogen use efficiencies have often been reduced by surface residues because of increased NH_3 volatilization losses (Volk, 1959, 1966; Ernst and Massey, 1960; Hargrove *et al.*, 1977; Terman, 1979). Surface placement of ammonia nitrogen sources also reduces soil pH in the upper few centimeters (Blevins *et al.*, 1983; Dick, 1983). This can subsequently increase aluminum and manganese concentrations to toxic levels and also significantly influence the efficiency of several herbicides. For these reasons and others, subsurface placement of sidedress nitrogen has been found to be acceptable and more efficient (Fox and Hoffman, 1981; Mengel *et al.*, 1982; Touchton and Hargrove, 1982; Campbell *et al.*, 1984a,b).

In addition to reducing soil erosion, surface vegetation and reduced tillage systems usually improve water conservation by increasing infiltration and reducing evaporation (Jones *et al.*, 1969; Blevins *et al.*, 1971; Gallaher, 1977; Phillips *et al.*, 1980). These beneficial aspects with regard to water management, however, can complicate nitrogen management if greater leaching loss results.

Phosphorus is relatively immobile and generally accumulates in surface soils even under conventional tillage. Therefore, when vegetative covers and reduced tillage systems are used, stratification is often increased. This was expected to be a significant problem for no-tillage production, but results of several experiments (Singh *et al.*, 1966; Triplett and Van Doren, 1969; Lutz and Lillard, 1973; Lal, 1974) show that crop needs were adequately met by surface application of phosphorus in reduced tillage systems. This may occur because of an increased amount of organic phosphorus compounds (Dick, 1983), which are more mobile than inorganic phosphorus compounds (Pinck *et al.*, 1941).

Exchangeable potassium, calcium, and magnesium will also tend to stratify in high CEC soils, but in coastal plain soils leaching can be observed because of the low CEC (Rhoads, 1970; Karlen *et al.*, 1984). Increased water infiltration because of vegetative covers may also increase movement of these nutrients.

Use of vegetative covers and reduced tillage to control soil erosion will probably not influence micronutrient availability, provided soil pH and extractable levels are monitored and adjusted routinely. Increased water infiltration because of vegetative covers, however, may influence boron requirements because of its mobility in coastal plain soils (Langdale *et al.*, 1981; Rhoads, 1981; D. L. Karlen, unpublished data).

VII. SELECTION OF VEGETATIVE COVERS

Several types of vegetation can be used in conjunction with conservation tillage practices to reduce soil erosion and subsequent nutrient loss. The types of vegetative covers which can be used include (1) residues from previous crops, (2) living nonleguminous plant species, and (3) living legumes. All of these vegetative sources can reduce wind and water erosion, but their role and function will vary with regard to nutrient cycling.

Recent interest in utilizing crop residues as an alternative bioenergy source was one impetus for reviewing the impact of crop residues on nutrient cycling (Larson, 1979; Campbell *et al.*, 1979a,b; Holt, 1979). This interest resulted in studies such as those by Karlen *et al.* (1984), which quantified crop residue production in various physiographic regions and evaluated effects of alternative management practices on soil physical, biological, and chemical processes. Erosion losses from studies on soils representing the southeastern Atlantic Coastal Plain were not measured. Nonetheless, surface cover exceeded 80% even when 6.5 Mg ha^{-1} of corn stover was harvested. Removing crop residues did influence nutrient balances, but fertilization practices corrected and compensated for the changes.

In the southeastern United States, several plant species have been used to provide vegetative cover in conjunction with minimum tillage systems (Gallaher, 1980; Hargrove, 1982). These include small grains such as wheat (*Triticum astivium* L.), rye (*Secale cereale* L.), oat (*Avena sativa* L.), or barley (*Hordeum vulgare*); winter annuals including ryegrass (*Lolium multiflorum* L.), hairy vetch (*Vicia villosa*) or common vetch (*Vicia sativa*), lupin (*Lupinus alba*), or crimson clover (*Trifolium incarnatum*); and perennial sod crops such as orchard grass (*Dactylis glomerata* L.), bluegrass (*Poa pratensis* L.), tall fescue (*Fetuca arundinacea* Schreb), Bermuda grass (*Cyndon dactylon*), or Bahia grass (*Paspalum notatum*).

Utilizing nonleguminous cover crops in conjunction with conservation tillage practices has probably received the greatest attention as a vegetative technique to control erosion, conserve water, and increase row-crop yields in physiographic regions where terrains are undulating (Elkins *et al.*, 1979; Box *et al.*, 1980; Phillips *et al.*, 1980; Langdale *et al.*, 1983b).

The particular plant species used for vegetative cover will influence each nutrient cycle. For nitrogen, the species selected will determine (through its C : N ratio) whether there will be net mineralization or immobilization during early stages of decomposition (Tisdale and Nelson, 1975). As an example, when corn is no-till planted into high C : N crop residues, more fertilizer nitrogen is frequently required to compensate for immobilization of nitrogen (Bandel *et al.*, 1975; Phillips *et al.*, 1980). Conversely, when legumes are used as vegetative covers, nitrogen fixation reduces C : N ratios of the residues and nitrogen is subsequently made available to subsequent crops through mineralization (Ebelhar and Fry, 1981; Fleming *et al.*, 1981; Hargrove, 1982). Phosphorus and sulfur are subject to similar cycles involving plant residues, microbes, and soil organic matter, but, in general, if crop residues contain 1.5% N, 0.3% P, and 0.3% S, immobilization processes will be minimized (Tisdale and Nelson, 1975).

Interest in using legumes as cover crops in the Southeast has increased in recent years because they can reduce soil erosion and generally add nitrogen to the system rather than immobilize it. Leguminous species being studied and utilized vary with physiographic region (Power *et al.*, 1983). In the southeastern United States, crimson clover, hairy vetch, and common vetch appear to be adapted for use as winter cover crops (Hargrove, 1982). Currently, these crops can provide 90–120 kg ha^{-1} of nitrogen to subsequent grain crops in addition to controlling erosion and limiting winter runoff (Touchton *et al.*, 1982).

Use of leguminous cover crops in conjunction with conservation tillage techniques such as slot or strip tillage probably has the most optimistic future for vegetative control of soil erosion because of the projected increase in cost for nitrogen fertilizers. These practices are not new. Prior to the development of the Haber process for NH_3 production, legumes generally supplied most nitrogen for subsequent row crops (Thompson and Robertson, 1959; Larson and Beale, 1961; Hargrove, 1982). However, production demands and yield goals have increased so much that, before legumes can be used as cover crop and nitrogen sources again, new system-oriented research is needed. Power *et al.* (1983) concluded that water requirements and nitrogen-fixing efficiency of legume cultivars grown in various climates, soils, and cropping systems are among the highest priority research needs for this technology (Larson *et al.*, 1981).

If nutrient cycles are considered in the choice of vegetative cover crops for erosion control, plant nutrition problems can be minimized. Factors that will need consideration are (1) decomposition rates and immobilization and mineralization reactions; (2) changed soil-water contents due to the progressive effects of increased infiltration, reduced evaporation, and spring extraction of water by the transpiration of living mulch; (3) nutrient stratification because of reduced soil mixing; and (4) yield potential of all crops in the sequence. Recognizing potential effects of these factors on nutrient cycling can influence and will determine the acceptance or rejection of vegetative erosion control techniques.

VIII. SUMMARY

Because of the combined effects of slope and rainfall intensity, erosion continues to be a serious problem throughout much of the South. Although maintenance of crop residues or the growing of cover crops on the soil surface is the best available means of controlling erosion, it has been recognized that the problems of southern reduced-tillage agriculture are unique to the region. Mild winters and prevalence of soil hardpans have required specific management to overcome the disease, pest, weed, and root penetration problems that result from these regional characteristics. It has been shown that a cover crop helps recharge soil profiles on sloping land during the cool winter months when precipitation exceeds potential evapotranspiration. Cover crops can, however, remove water needed by the primary spring-planted crop if the cover crop is not controlled several weeks before planting. The yield advantages of conservation tillage compared to conventional tillage dissipate with reduction of slope.

Comparison of nutrient cycles in different tillage or residue management systems has been shown to be highly complex. Cropping systems must be adjusted to account for the impact of cover cropping for erosion control on nutrient cycles. Factors affected include decomposition rates, immobilization and mineralization reactions, greater leaching and denitrification resulting from increased profile water contents, nutrient stratification because of reduced mixing, and final yield potential of all crops in the cropping system.

Recognition and accommodation of all the soil physical and fertility considerations described in this article are necessary to design and achieve successful cropping systems that limit soil erosion.

Erosion studies have been conducted on natural watersheds and on rainulator plots. They have confirmed the beneficial effect of maintaining crop residues or a living mulch crop on the soil surface to reduce erosion. Erosion is reduced through dissipation of raindrop kinetic energy by surface residues or growing vegetation. Lower raindrop kinetic energy results in less dislodging of soil particles. This erosion reduction occurs through attainment of smaller *C*-factors in the USLE.

Since fewer particles are dislodged in the presence of a mulch, fewer soil pores are blocked as a result of particle reorientation, and therefore infiltration rates remain high in the presence of a mulch. The higher infiltration rates in the presence of mulch allow more efficient profile recharge when rainfall exceeds potential evapotranspiration. Differences in recharge are less between conservation tillage and conventional tillage on nearly level ground. Water conservation in the presence of crop residues on level ground is accomplished primarily through suppression of soil evaporation.

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