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A conservation tillage research update from the Coastal Plain Soil and Water Conservation Research Center of South Carolina: A review of previous research

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ABSTRACT

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In the U.S. Southeastern Coastal Plains conservation tillage (CT) became useful as a management system with the development of in-row subsoiling systems capable of planting into heavy residues. Research priorities associated with the development of CT included: reducing cover crop water loss, improving stand establishment, assessing nutrient and water management requirements, determining optimal subsoiling strategies, understanding long-term conservation tillage effects on soil properties, evaluating the interaction of crop residue removal with tillage systems, and documenting tillage impact on pests and beneficial organisms. Since the late 1970s the Coastal Plains Soil and Water Conservation Research Center in Florence, SC has made a concerted effort to study these interactions and alleviate them as obstructions to the use of CT management. These studies showed that for Coastal Plain soils such as Norfolk sandy loam (fine-loamy, siliceous thermic, Typic Paleudults) winter cover crops such as rye (*Secale cereale* L.) desiccated the soil profile by evapotranspiration in the spring. This delayed emergence and early season growth of corn (*Zea mays* L.) but not full-season soybean (*Glycine max* (L.) Merr.). Conservation tillage helped manage soil strength by gradually increasing soil organic matter content, restricting traffic patterns and maintaining higher soil water contents. Laboratory studies demonstrated a negative correlation ($R^2=0.85$) between proctor soil strength and organic matter content. Conservation tillage affected nematode, *Bradyrhizobium japonicum* and *Heliothis* species populations. Alternate cropping systems using rapeseed (*Brassica napus* L.) as a winter crop or sunflower (*Helianthus annuus* L.) either before soybean or after corn provided crop cover against potential soil loss from late autumn through early spring, when bare soil is exposed to intense rainfall. Water quality questions associated with CT have been raised but remain unanswered. Although CT can reduce runoff and erosion, the crop residues can support higher insect populations and pathogen inoculum levels, and thus prompt greater pesticide use. Quantifying relationships between soil strength, macropore formation and persistence, and water infiltration with surface and subsurface

water quality is the focus of new long-term evaluations. The findings of these studies, published to date, are summarized in this paper.

INTRODUCTION

The Coastal Plain Soil and Water Conservation Research Center in Florence, SC celebrated its 25th anniversary in the fall of 1989. This federally funded laboratory, administered under the Agricultural Research Service of the U.S. Department of Agriculture, has focused its research on pressing soil and water management problems germane to the Coastal Plain of the S.E. U.S.A. This laboratory conducts cropping systems research in a physiographic area characterized by flat sandy infertile soils with poorly drained acid subsoils. Those characteristics limit the production potential of the long mild growing season and high annual precipitation levels. Among the laboratory's primary research objectives has been development of innovative management systems that preserve and protect soil and water resources of the physiographic region. Research on conservation tillage (CT) and tillage-related problems has been a key focus of that effort.

Healy and Sojka (1985) concluded that CT will be a key component of continued southern agricultural expansion. However, numerous obstacles have hindered the shift to CT systems on sandy textured soils of the Coastal Plain. Initial adoption of CT was impeded primarily by problems associated with root penetration of the dense eluviated E soil horizons (Campbell et al., 1974) common to most of the Paleudult soils that predominate in the Coastal Plain. These eluviated E horizons were often further compacted by traffic and tillage. Resting bulk densities of the Ap, E and B horizons of these soils commonly reach values of 1.45, 1.65 and 1.55 Mg m^{-3}, respectively, and are easily compacted to higher bulk densities with traffic or tillage. Furthermore, promotion of CT systems to Coastal Plain farmers was difficult because dramatic increases in water infiltration, soil conservation and fertilizer retention, seen with CT in the southern Piedmont or on silt loam soils of the upper South were not as evident in the flat sandy Coastal Plain. This occurred because despite mean annual precipitation for the region in excess of 1250 mm, the predominant soil map units in the lower Coastal Plain (Norfolk, Noboco, and Goldsboro loamy fine sands and fine sandy loams) have universal soil loss equation "K" values that range from 0.17 to 0.20. By comparison the upper Coastal Plain and Piedmont soils such as Emporia fine sandy loam and Cecil sandy clay loam have "K" values of 0.24–0.28. Furthermore, slope length and steepness in the Piedmont, upper Coastal Plain, and upper South are generally much greater than in the lower Coastal Plain where our investigations were focused (Sojka et al., 1984). Initial adoption of CT practices was further impaired by inadequate residue management technology. Residue levels in southeastern cropping systems vary from 1.6 to 9.6 Mg ha^{-1} depending on cropping sequence and tillage practices (Sojka et al., 1984).

Conservation tillage became a practical possibility in the late 1970s with the development of integral subsoil-tillage/planting systems capable of planting crops into heavy plant residues (Harden et al., 1978). Several such systems are now available (Fig. 1). The SuperSeeder* (one of the earliest successful commercial implements) allowed planting into crop residues or living mulches that were controlled with broad spectrum herbicides (e.g. paraquat or glyphosate, which became widely available in the late 1970s). The term "no-till plus" was coined by implement dealers in the Coastal Plain to describe the use of subsoiling into residue at planting to break up subsoil barriers to rooting which had made earlier efforts at no-till on these soils unsuccessful.

A number of additional problems associated with further development of CT systems were quickly recognized. These included reducing water loss from cover crops, improving stand establishment, assessing nutrient and water management requirements, determining optimal subsoiling strategies, understanding long-term effects of CT on soil properties, effects of crop residue removal (for on-farm energy production), and determining the interaction of CT tillage systems with pests and beneficial organisms. While wind erosion is an occasional problem on some bare conventionally tilled fields the combination of frequent rain and low prevailing wind velocities in the southeast has not yet sustained an interest in wind-erosion abatement. Therefore, with ini-

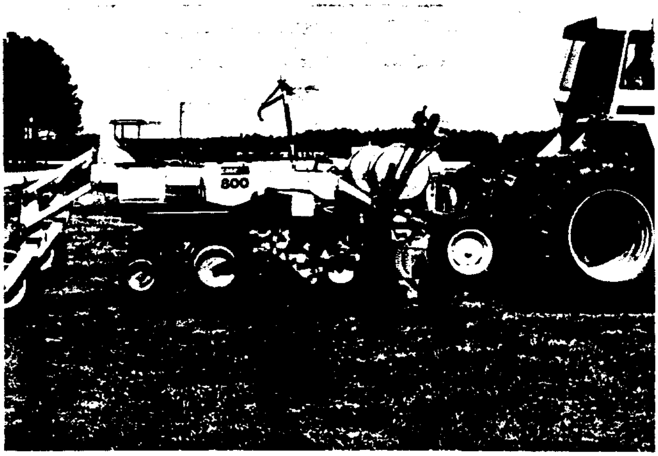

Fig. 1. An in-row subsoiling system for conservation tillage produced by the Kelley Mfg Co (KMC) utilizing Case-IH series 800 early-riser planters.

*Names of trademarks are provided for the benefit of the reader and do not imply endorsement by the Department of Agriculture.

tial rooting and weed-control problems largely solved, extensive applied and basic research was initiated in 1979 at the USDA-ARS Coastal Plains Research Center in Florence, SC, to extend the understanding of CT principles and their applications in the region. This paper synthesizes and interprets much of the Center's published findings related to CT from then until the present.

Soil water

Because the first CT system that was actively promoted consisted of spring planting of corn (*Zea mays* L.) or soybean (*Glycine max* (L.) Merr.) into a fall-planted rye (*Secale cereale* L.) cover crop, initial work focused on cover-crop water use. The rye, whose grain had little cash value, was often grazed by livestock over the winter and then killed with paraquat at spring planting. Although the rye canopy reduced soil loss from intense late-winter and early spring rain, it often desiccated the soil profile by evapotranspiration (ET) in late spring during planting and early corn or soybean crop development. This usually reduced corn yield, but had no negative effect on full-season, determinate soybean yield (Campbell et al., 1984a,b). The more frequent occurrence of problems with CT in corn than in soybean had not been anticipated from research in other regions (Sojka et al., 1984) but was a consistent year-to-year response in the Coastal Plain (Campbell et al., 1984a,b; Sojka and Busscher, 1989). Results from a long-term tillage study (Sojka and Busscher, 1989) demonstrated that corn yields were always slightly greater in tillage systems that had some form of surface tillage.

Poor corn yield in CT plots was attributed by Karlen and Sojka (1985) to erratic emergence and slow early season growth. In their study, stand count of CT 7 days after planting was half that of conventional tillage, and although counts were not statistically different by 17 days after planting, plant size of CT plants remained smaller and more variable in size. Late-emerged CT plants remained stunted but continued to grow, although ultimately producing little or no grain. These retarded corn plants robbed water and nutrients from their productive neighbors and were termed "corn weeds". Low soil temperature in CT systems had caused similar stand problems at northern latitudes (Gupta et al., 1983), but Karlen and Sojka (1985) showed this was not the case in the Coastal Plain, where temperatures at 5 and 15 cm depths were never more than 1°C (2°F) different for conventional and CT seedbeds (Table 1). Water was thought to be the most limiting factor for Coastal Plain soils. In later work, Karlen (1989) confirmed that erratic seedling emergence in his no-till system was the result of poor placement and coverage of the seed using conventional John Deere Flexi planters behind the subsoiling implement in heavy residue. This resulted in soil and seed desiccation in some parts of the CT seedbed. An additional water-related consideration was the fact that most

TABLE 1

Influence of pre-plant disk and conservation (non-disk) tillage on 08:00 h and 15:00 h soil temperatures (°C) at depths of 5, 15 or 30 cm during the 28 days after planting corn on Norfolk loamy sand near Florence, SC in 1981, 1982 and 1983 (adapted from Karlen and Sojka, 1985)

Preplant[1] surface tillage operation	Growth period after planting (days)	08:00 h Depth in cm			15:00 h Depth in cm		
		5	15	30	5	15	30
1981							
Disked	0–14	15	16	16	25	23	19
Non-disked	0–14	14	15	16	24	21	20
Disked	15–28	18	18	19	33	27	22
Non-disked	15–28	17	18	18	31	26	21
1982							
Disked	0–14	13	14	16	23	19	16
Non-disked	0–14	13	14	16	23	19	17
Disked	15–28	16	18	20	34	28	23
Non-disked	15–28	16	17	19	32	26	22
1983							
Disked	0–14	14	16	18	29	25	22
Non-disked	0–14	14	16	18	26	22	19
Disked	15–28	19	20	21	29	26	23
Non-disked	15–28	18	19	20	27	24	21

[1]Soil temperatures were not significantly different between tillages at $P \geq 0.05$.

Coastal Plain Ultisols are sandy textured and frequently retain less than 10 cm of plant-available water per meter of profile (Beale et al., 1966). Furthermore, even though surface residues can conserve several days' equivalent ET by reducing soil evaporation during the growing season, this gradual benefit does not accrue rapidly enough to overcome early season profile depletion by a cover crop and growth retardation in corn resulting from competition between productive plants and "corn weeds".

Where full canopy coverage had been achieved by the time of flowering, determinate soybean yields were not reduced by cover cropping or CT. An effective management solution to the problem of cover crop water use was to kill the cover crop 2–3 weeks before planting corn or soybean. This halted soil water extraction, providing an opportunity for soil profile recharge (Campbell et al., 1984a,b; Karlen, 1989). In studies where prolonged drought occurred in soybean during the reproductive period, CT increased yields slightly compared with conventional tillage. The magnitude of yield increases depended upon the timing of the dry period relative to the length of the reproductive period.

A long-term comparison of results from several variations of possible CT systems for corn, soybean, and double-cropped wheat showed mixed results (Sojka and Busscher, 1989). Soybean yields were favored by CT in row cropping configurations, but were reduced by drilling. Corn yields were slightly reduced by CT systems in which residues were left standing at planting. Double-crop wheat yields were increased by deep primary tillage, and burning of double-crop small grain residues showed no yield advantage for the subsequent soybean crop.

Soil strength

One approach to eliminating high soil strength involves managing soil water content. At a given bulk density, soil strength generally increases as a log, parabolic, or similarly shaped function as water content or potential decreases (Fig. 2). The problem of root restriction due to high soil strength can be avoided by conserving soil water, by timing planting so that early root growth occurs when the subsoil is moist, or by applying water to keep soils "soft". However, at high bulk densities most Coastal Plain soils have limited porosity. Overcoming strength limitations for the dense Coastal Plain soils by maintaining high water contents risked restricting oxygen availability (Campbell and Phene, 1977). Recent work with buried trickle irrigation tubing in sweet corn showed that manipulating soil water to control soil strength can be made to work, but only with a high level of management (Camp et al., 1989). Furthermore, the cost of such management and hardware could be limiting for all but high value crops. One novel experiment explored the possibility of improving rooting and water availability by mixing the A and B horizons. This improvement was expected to result from increasing the water-holding capacity of the surface soils and E horizon and, in so doing, enabling lower strengths to be maintained. However, complete mixing of the A and B horizon exacerbated both of these problems because of the extremely low void ratio of the resulting media (Campbell et al., 1988). In addition the lower fertility and pH limited root growth and caused nutritional problems.

Another applied CT study showed that for South Carolina Coastal Plain soils, soil strength management through a combination of deep tillage, to loosen the subsoil zone of high strength, and water content management was superior to either approach alone. In-row subsoiling with irrigation resulted in additive yield benefits for corn (Camp et al., 1984). This occurred because the sandy surface of Coastal Plain Ultisols allowed N, K, S and B to leach to the Bt horizon (Karlen et al., 1984). Subsoiling promoted deeper and earlier root penetration (Fig. 3) allowing more efficient use of these nutrients from the B horizon where they occur in greater abundance than the eluviated E horizon. In-row subsoiler shanks also facilitated direct fertilizer placement behind the shanks (Fig. 4) without requiring separate shallow knives or disks on which surface trash entangled (Karlen and Zublena, 1986). Deep subsoil fertilization at planting with a complete N, P, K fertilizer produced yields equivalent to traditional 5 cm by 5 cm banded placement. Starter rates of N,

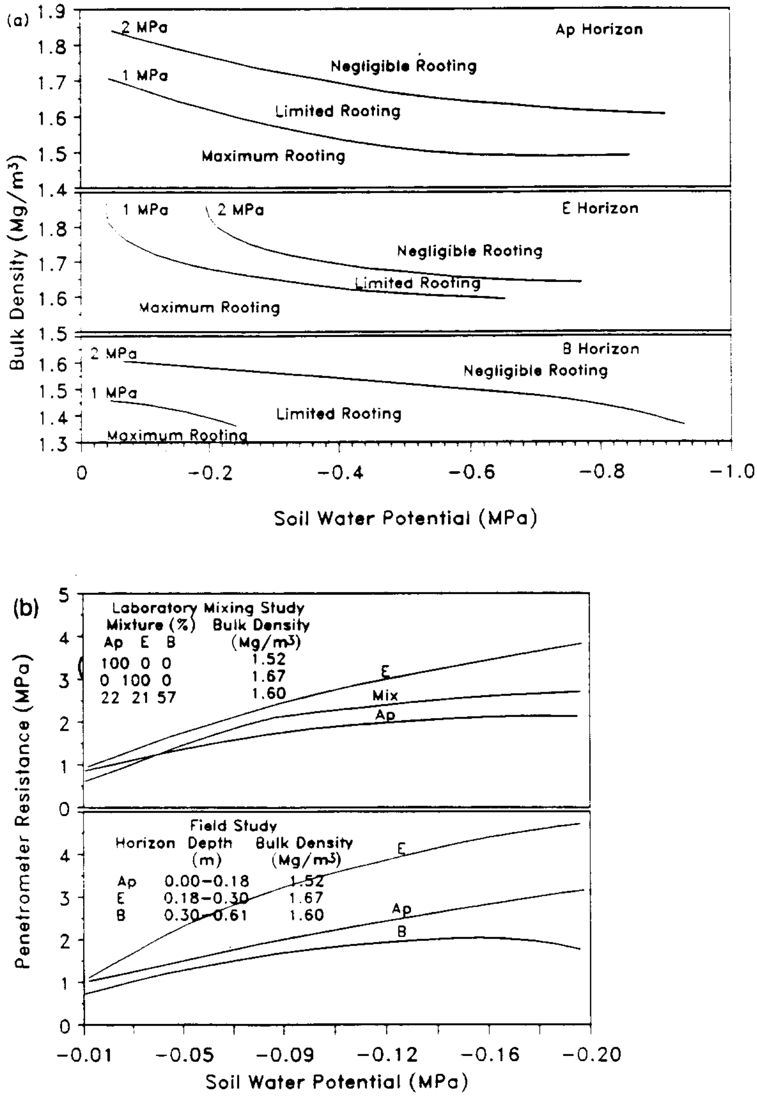

Fig. 2. The effect of soil water potential (a) related to rooting for the A, E and B horizons for the naturally occurring Norfolk soil and (b) on soil strength of natural and mixed soil horizons at several bulk densities for a Norfolk soil (adapted from Campbell et al., 1988).

P and K were determined by standard soil test recommendations for the soil and were followed by nitrogen side-dressing with anhydrous ammonia when corn plants were 0.5 m in height. Related studies support this finding and demonstrate that placement of fertilizer below the seed with subsoil shanks could significantly improve nutrient uptake if optimal depth of the placement was determined for the specific soil (J. Zublena, unpublished data, 1987).

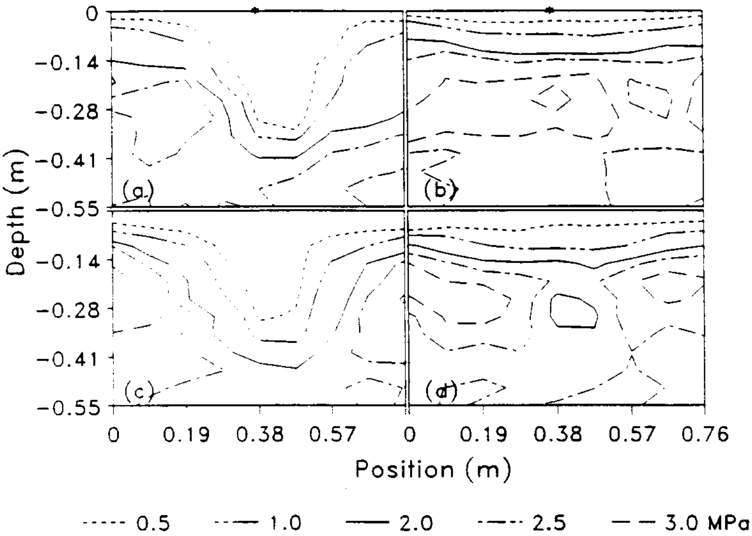

Fig. 3. Soil strength contours that show breaking up of the 15–36 cm deep E horizon by the Superseeder in April (a) soon after the deep tillage and in August (c), compared with disked plots in April (b) and August (d). Some remnants of deep tillage from previous years can be seen in the disked plot. * Indicates the row position. (Busscher and Sojka, unpublished data.)

Fig. 4. Pressurized spray nozzle for deep fertilizer placement behind coulter and subsoil shank of a subsoil planter used for CT.

Even though the most widely accepted practice to combat compaction in CT became the use of in-row subsoil/planting systems, energy costs in the late 1970s caused farmers and researchers to question the need for annual subsoiling (Threadgill, 1982). The persistence of subsoil disruption in Coastal Plane soils was evaluated for several deep-tillage methods (Busscher et al., 1986). In-row subsoiling in this and subsequent studies reduced soil strength more effectively than disking, chiselling, and mold-board plowing, thereby providing root access to the B horizon with its higher clay content and water-holding capacity. This could be seen dramatically in two-dimensional contour plots of soil profile penetration resistance (Fig. 5). Although the location of a subsoiling operation was still identifiable after 2 years by probing with a penetrometer, none of the implements maintained cone indices below recognized limits to rooting for more than 1 year (Busscher et al., 1986). Furthermore, without precise traffic control, aligning planting over the previous season's subsoiling was not possible.

As in-row subsoiling became widely adopted in the Coastal Plain, several implements became available for use in CT. Although the deep disruption patterns for the Brown–Harden Superseeder, the Tye Paratill, and the Kelly

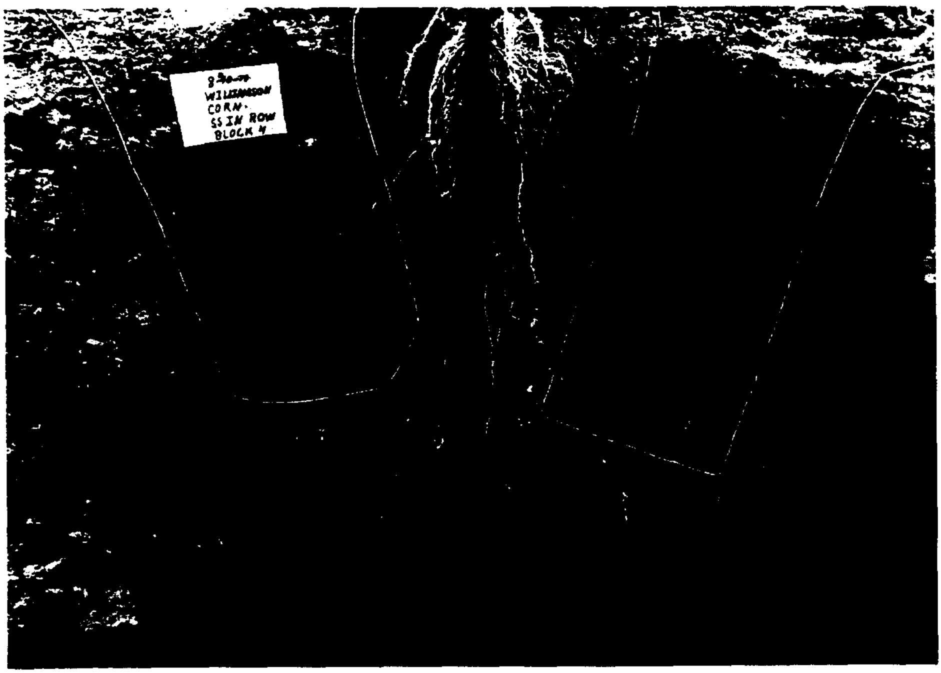

Fig. 5. Rooting pattern of corn in a Norfolk soil which was planted using in-row subsoiling, and showing root proliferation in the B horizon. The area inside the strings had no roots because of higher soil strength (R.B. Campbell, unpublished data).

No-till System varied (Busscher et al., 1988) as well as their draft requirements (T.H. Garner, personal communication, 1986), they all shattered the E horizon to non-restricting cone indices and provided seedling root access to the less restrictive B horizon. Despite producing differences in the overall soil profile strengths, yields produced did not differ significantly among implements. The yields did, however, drop in proportion to mean profile soil strength (Fig. 6). This can be demonstrated by regressing the 2-year mean treatment yields against the 2-year mean soil strength measured at planting in April and at harvest in August each year at the prevailing soil profile water content distributions. As explained in their publication (Busscher et al., 1988) soil water content differences could explain only a fraction of the plant response.

Another promising subsoiler design has been described which slits shallow tillage pans (Elkins and Hendrick, 1983). Here, a thin blade cuts a 3–4 mm wide slit (about the size of a large macropore) through the hard layer to the less restrictive underlying soil. Crop roots stabilize the slit and maintain it for several years. Where the layer of high strength is deep in the profile, the blade is attached as an inverted fin to the underside of a short subsoil shank. This combination uses 4.9 kJ (6.6 hp) less than deeper parabolic shanks alone. These slits have persisted for 3 years after they were initially cut. After 2 years of slitting, grain sorghum (*Sorghum bicolor*) plots that were annually slit outyielded standard in-row subsoiled plots 4.30 Mg ha^{-1} compared with 3.60 Mg ha^{-1} (Karlen et al., 1991). The 3-year mean comparison produced 3.12, 2.89 and 2.45 Mg ha^{-1} for slit tilled, parabolic subsoiled, and non-subsoiled treatments, respectively.

As appreciation of the need for a better understanding of soil strength management considerations has grown (Fig. 7) work has been undertaken to develop the relationship of other soil properties to soil strength. Relating strength

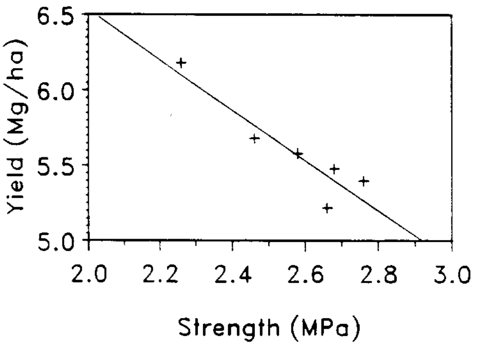

Fig. 6. The negative correlation (R^2=0.85, $P \geq 0.01$) of corn grain yield and soil strength (yield= $-1.67\times+9.87$) as demonstrated by 2-year mean yields and 2-year mean profile strengths on a Norfolk soil (adapted from Busscher et al., 1988).

Fig. 7. Deformation of an ASAE standard cone-tipped penetrometer, hydraulically driven into a Norfolk sandy loam soil.

to bulk density and water content were found to depend also on texture and organic matter. Coarse textured Ultisols with low organic matter required less compactive force to produce high bulk densities and high probe resistances (Spivey et al., 1986; Busscher et al., 1987) than the same soils with higher organic matter levels. These studies also showed a negative correlation ($R^2=0.85$) between Proctor soil strength and organic matter content. The textural component was also important with a positive correlation ($R^2=0.85$) between increasing silt content and flat-tipped probe strength of soils with $<1\%$ organic matter. Making soil strength comparisons in the field is complicated by water content and bulk density variability. Statistical and mathematical techniques were developed to assess absolute strength differences (Busscher and Sojka, 1987, 1990; Sojka and Busscher, 1988) reducing treatment-confounding effects such as strength dependence on measurement date, treatment location, or water regime. These techniques were ultimately utilized to show that in-row subsoiling was more effective when combined with CT than with conventional tillage (Busscher and Sojka, 1987). In these comparisons disking between seasons contributed to greater subsoil compaction, whereas these compactive episodes were eliminated from the CT systems.

Soil biota

Initially, very little was known about the interaction of CT with soil organisms. Crop residue level and tillage affected four nematode species (*Meliodogyne incognita, Scutellonema brahyurum, Pratylenchus scribneri* and *Paratrichodorus christiei*) differently (Fortnum and Karlen, 1985). *Meliodogyne incognita* and *P. christiei* populations did not change significantly with tillage, but *S. brachyurum* populations were significantly higher in CT treatments where crop residue remained on the surface. In contrast, *S. brachyurum* populations were lowest in CT plots where 90% of the crop residues were removed or were incorporated. The study of crop residue removal was prompted by the search for on-farm renewable energy sources following the oil embargo of the mid 1970s. As concern for global climate change creates new interest in renewable carbon sources, and as world oil reserves drop, this concern is resurfacing. These studies identified a high value of preserving soil organic matter despite residue effects on nematode populations.

Organic matter content is an indicator of the long-term accumulation and decomposition of substrate by the resident soil microbial population. For sandy Coastal Plain soils, increased organic matter can eventually enhance productivity by improving both water and nutrient retention and ameliorating strength problems. Long-term CT effects on several soil-test parameters in one study were examined after 8 years. In the upper 20 cm, there was a trend toward, but not a significant increase of organic matter (Mehlich I soil test values) of CT over disked treatments. Organic carbon over the 8 years increased from 0.5 to 1.0% for the disked treatment and from 0.5 to 1.2% for CT (Karlen et al., 1989).

Conservation tillage also affected the environment of beneficial organisms. Profitable soybean production depends greatly on providing a favorable environment for the symbiotic interaction of soybean and *Bradyrhizobium japonicum*. Yield was not affected despite subtle tillage × strain × cultivar interactions that altered nodular occupancy, N_2 fixation by specific cultivar and strain combinations, and plant N distribution (Hunt et al., 1985). In a related greenhouse experiment in which understory surfaces were varied independently from soil properties, early stem growth was greater for a straw-covered surface than for a bare surface, but nodulation was unaffected (Hunt et al., 1989).

Insect pressure in southern agricultural systems is significantly greater than in more temperate climates, and particular concern has been focussed on the need to understand CT impacts on insect dynamics. Tillage reduced emergence of *Heliothis* species in insect studies. Compaction without tillage stabilized insect burrows; compaction after tillage sealed the burrows and damaged the pupae (Roach, 1981; Roach and Campbell, 1983). Therefore, less intensive tillage treatments resulted in greater emergence of *Heliothis*.

Alternative cropping systems

Because the growing season of the South Atlantic Coastal Plain is long and winters are mild (in excess of 300 frost-free days throughout the region) new crops could be grown if an appropriate niche existed in the region's cropping practices. The periods of greatest potential soil loss for the region occur from late fall through early spring when bare soil is exposed to high intensity rainfall. One approach to soil conservation during this period is to maintain crop residues on the surface. Another approach is to maintain a live vegetative cover. The most widespread expression of this practice in the region has been the production of double-crop (i.e. winter grown) small grains, primarily wheat (*Triticum aestivum*). However, other cropping alternatives also exist which provide a significant extension of the period of effective vegetative cover. Sojka and Karlen (1988) reported on the potential for winter production of rapeseed (*Brassica napus* L.) for which demand is rapidly increasing in the American oilseed market. In addition to being economically competitive with wheat production, the rapeseed crop was shown to provide effective ground cover up to 2 months earlier than any of the small grains, while still allowing harvest in late May for double-crop soybean production. Existing herbicides can control volunteer rapeseed in the following soybean crop. Sojka et al. (1989, 1990) explored a similar strategy for the production of sunflower (*Helianthus annuus* L.) either before soybean, planting as early as March, or following corn, planting as late as mid-August. Yields and quality were highly dependent on planting date, but both early spring and mid-summer planting allowed production potentials on a par with or exceeding more northerly growing regions. Again because of rapid canopy coverage, double-cropped sunflower has the potential to extend significantly the period of vegetative soil cover for the region.

Water quality

Many leading scientists see water quality as one of the greatest concerns of civilization as we approach the new millennium. Development of farming practices that preserve or improve groundwater quality and limit erosion and surface-water pollution will be a major component of water-quality research. Use of CT poses new questions and offers potential for new solutions to water-quality concerns. Experts disagree as to whether CT introduces fewer or more agricultural chemicals into the environment. Although CT holds chemicals against runoff and erosion, the presence of crop residues usually creates environments that support higher insect populations and pathogen inoculum levels. This could prompt greater use of pesticide chemicals. In all the studies reported in this paper weed control for both conventional and CT systems used pre-emergence surface-applied herbicides that relied on activation by irrigation or rainfall. Pre-emergence chemicals had the same formulation and rate among tillages. Tillage regimes differed in the use of mechanical cultivation for conventional treatments and contact or systemic directed sprays for CT treatments prior to canopy closure. No comparisons of differing formulations or rates were conducted in these studies.

Another unresolved issue is whether the stimulation of macropore formation and stabilization by CT systems positively or negatively affects groundwater quality. Macropores more easily transmit surface waters to the Vadose zone, but also allow more prolific root penetration and resulting soil solute uptake. Water moving rapidly through macropores also has less contact opportunity to leach chemicals held in micropores. In the South Atlantic Coastal Plain soil strength could have a major impact on water quality because of its effects on water infiltration, rooting, and required amelioration practices, such as increased nitrate additions in the absence of subsoiling, or increased transmission of nitrate to groundwater resulting from subsoiling, which is a necessary component of CT on most Coastal Plain soils. Resolution of these unanswered questions is a major new focus of the programs of the Coastal Plain Soil and Water Conservation Research Center.

CONCLUSIONS

The Coastal Plains Soil and Water Conservation Research Center in Florence, SC, has made a concerted effort to understand the advantages and shortcomings of CT for the South Atlantic Coastal Plain. This has included the interaction of CT with water loss from cover crops, stand establishment, water and nutrient management, soil strength management through deep tillage or intensively managed irrigation, crop residue removal, long-term effects on soil properties, and pests and beneficial organisms. The complex nature of these interacting factors and the diversity of specific conservation systems has resulted in both positive and negative impacts of CT within the scope of the many parameters studied. Nonetheless, understanding these effects on conservation tillage has improved the viability of CT as a management alternative in the SC Coastal Plain and surrounding states within the physiographic region.

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