# Integrated Crop–Livestock Systems in the Southeastern USA

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## ABSTRACT

Opportunities to integrate crops and livestock are abundant throughout the southeastern USA due to a mild climate and a rich natural resource base that can produce different crops throughout the year. Although not currently common, integration of forage and grazing animals with cropping systems could benefit both production and environmental goals. This report summarizes research from some of the key components that could produce viable integrated crop–livestock production systems: sod-based crop rotation, cover cropping, intercropping, and conservation tillage. Sod-based crop rotations have been effective in breaking pest cycles and restoring soil organic matter, which critically controls a wide diversity of key soil and plant properties and processes. Cover cropping by itself has many agronomic benefits, but its adoption appears to be limited, because of cost without immediate economic benefit. Grazing of cover crops could provide an immediate economic benefit to producers, especially with the development of conservation tillage technologies to avoid deterioration of soil and water quality. The potential for advancement of integrated crop–livestock systems is exemplified in a few current research projects in the Coastal Plain and Piedmont regions. With greater integration of crops and livestock, new management guidelines and experiences will be needed, but the quantity and quality of production and economic return could increase, while at the same time placing less degrading pressure on soil and water resources.

INTEGRATION OF CROPS AND LIVESTOCK was a common approach to agricultural production throughout the world before modern industrialization in the 20th century. Huge technological advances in plant genetics, machinery, and synthetic chemicals improved agricultural production manyfold, and eventually shifted diverse agricultural enterprises into specialized production facilities. Today, agriculture is faced with challenges and opportunities, not necessarily unique from the past, but melded with a diverse range of societal and ecological concerns about how the world and its people can be sustained. A growing awareness is emerging that the stability and resiliency of agricultural landscapes appear to be impaired by enterprise specialization, concentration of operations, and expansion of scale, which have spatially and temporally compartmentalized and disrupted energy and nutrient cycles in a manner far removed from natural ecosystem cycling (Gates, 2003). Greater integration of crop and livestock enterprises may impart major benefits to the environment and to development of a sustainable agricultural production system by: (i) more efficiently utilizing natural resources, (ii) exploiting natural pest control processes, (iii) reducing nutrient concentration and consequent environmental risk, and (iv) improving soil structure and productivity.

Ruminant livestock should be considered an important part of an integrated approach, because these animals can convert cellulosic feedstuffs from traditional pastures and crop residues into high-value meat and milk products (Oltjen and Beckett, 1996). However, a number of concerns with integrated crop–livestock systems have been identified and will need to be addressed (Hardesty and Tiedeman, 1996): (i) large volume of information needed for sophisticated production systems; (ii) lack of infrastructure; (iii) lack of information on how chemical usage could affect crop, animal, and human health, as well as food safety; (iv) need to balance year-round forage supplies and labor for crop and livestock requirements; and (v) need to develop a market for alternative meat production (consumer preference for grain-fed vs. pasture-fed beef may be changing).

The focus of this paper is to explore the scientific basis for integrated crop–livestock production in the warm, humid regions of the world, and specifically for the southeastern USA. Socioeconomic aspects of integrated crop–livestock systems cannot be adequately addressed in this paper. However, to change agricultural production from its current state of specialization to one of integrated crop–livestock production will require major changes in: (i) farming attitudes and how farmers might utilize relevant scientific information, (ii) agribusiness developments and marketing, and (iii) government support to balance agricultural production with natural resource conservation.

## CHARACTERISTICS OF THE SOUTHEASTERN USA

The warm, humid region was defined for the purposes of this paper based on mean annual air temperature $\geq 12°C$ and mean annual precipitation $\geq 750$ mm, but excluded the Tropics. In the USA, this area is represented primarily in the southeastern region, but also includes a small portion of California (Fig. 1). Around the world, significant areas meeting these climatic criteria also occur in South America (northern Argentina, southern Brazil, Paraguay, and Uruguay), Europe (southern France, Italy, Slovenia), Asia (eastern China and Japan), Africa (South Africa), and Oceania (southeastern Australia and New Zealand).

In many parts of the southeastern USA, precipitation typically is abundant in the winter and spring, but is nearly sufficient to deficient in summer and autumn. Variations in monthly mean precipitation and potential evapotranspiration among several locations are depicted in Fig. 2. Matching cropping and grazing cycles to coincide with climatic conditions is important for reliable production. However, this becomes difficult due

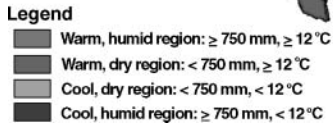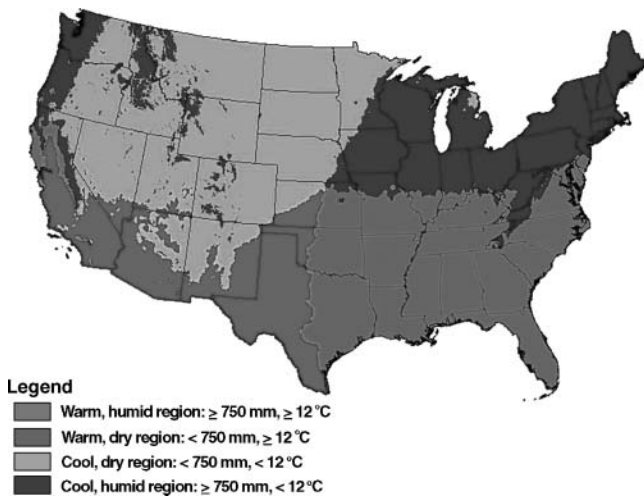USDA-ARS, 1420 Experiment Station Rd., Watkinsville, GA 30677-2373. Received 14 Mar. 2006. *Corresponding author (afranz@uga.edu).

**Fig. 1. Delineation of major climatic zones in the USA based on mean annual temperature (cool, <12°C; warm, ≥12°C) and mean annual precipitation (dry, <750 mm; humid, ≥750 mm). Produced by H.J. Causarano using the Spatial Climate Analysis Service (www.ocs. orst.edu/prism/).**

to significant weather variation from year to year in the region. The advantage that the region has over other temperate regions is the long growing season that extends into winter with cool-season crops.

Soils of the southeastern USA are diverse, because of the complexity of factors contributing to their formation, i.e., climate, topography, vegetation, parent material, and time (Jenny, 1941; West, 2000). The majority of land in the region is composed of Ultisols (strongly leached with low native fertility) and Alfisols (moderately leached with high native fertility) (Table 1). Other major soils in the region include Mollisols (highly fertile, dark surface horizon), Entisols (undeveloped structure), and Inceptisols (relatively undeveloped structure). Smaller areas can also be found of Histosols (organic soils), Vertisols (clay-rich with shrink-swell characteristics), and Spodo-

sols (subsurface accumulation of humus that is complexed with Al and Fe).

The southeastern USA occupies approximately 200 Mha (20% of land in the entire USA). From state-level data in the 2002 Census of Agriculture (USDA-National Agricultural Statistics Service, 2004), the 11-state region (AL, AR, FL, GA, KY, LA, MS, NC, SC, TN, and VA) occupies 12% of the total farmland area and has 26% of the total number of farms in the USA (Table 2). Therefore, farms in the region were generally smaller (mean area of 81 ha) than in the rest of the country (mean area of 213 ha). In the region in 2002, 80% of the farms had cropland (mean area of 55 ha), 55% of the farms had woodland (mean area of 39 ha), 41% of the farms had pasture (mean area of 30 ha), and 53% of the farms had cattle. Dividing the total number of animals by the number of farms in the region, each farm would have had 10 sheep, 22 cattle, 402 hogs, 1643 layers, and 24 823 broilers (these figures are for comparative purposes only and do not accurately reflect typical farms). As a percentage of the inventory in the entire USA, the region carried 3% of the sheep, 16% of the cattle, 20% of the hogs, 26% of the layers, and 75% of the broilers in 2002. Of the major crop commodities, the region produced 50% of the cotton (*Gossypium hirsutum* L.) lint and 80% of the peanut (*Arachis hypogaea* L.) seed in 2002. Average yield of crops in 2002 was 0.7 Mg ha$^{-1}$ for cotton lint, 2.0 Mg ha$^{-1}$ for soybean [*Glycine max* (L.) Merr.] seed, 2.7 Mg ha$^{-1}$ for peanut seed, 4.1 Mg ha$^{-1}$ for wheat (*Triticum aestivum* L.) grain, 4.9 Mg ha$^{-1}$ for harvested hay, and 6.4 Mg ha$^{-1}$ for corn (*Zea mays* L.) grain. Cotton farms in the region tended to be larger (mean of 201 ha cotton farm$^{-1}$) than other types of farms (mean of 118 ha soybean farm$^{-1}$, 66 ha wheat farm$^{-1}$, 56 ha corn farm$^{-1}$, 52 ha peanut farm$^{-1}$, and 19 ha forage farm$^{-1}$). Land areas were specific to a crop, but individual farms would typically have a diversity of agricultural enterprises within the farm.
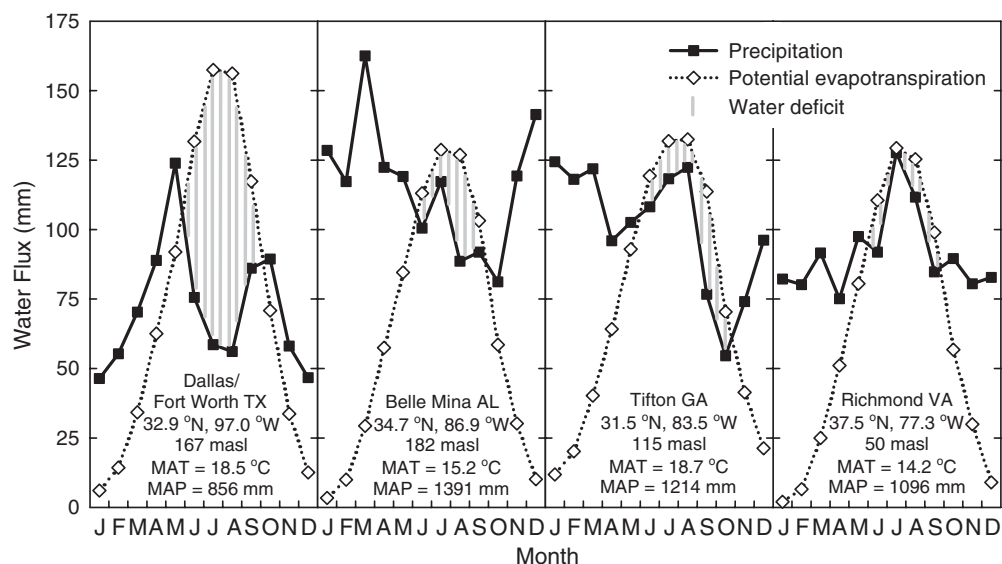


**Fig. 2. Mean monthly climatic conditions at four different locations within the southeastern USA. MAT is mean annual temperature and MAP is mean annual precipitation. Potential evapotranspiration was calculated using the Thornthwaite equation (Thornthwaite et al., 1957). Data from 1961 to 1990 (National Climatic Data Center, www.ncdc.noaa.gov/oa/ncdc.html).**

**Table 1. Major land resource areas and soil types within the south-eastern USA (USDA-SCS, 1981).**

| Major land resource area | Typical soil suborders |
|---|---|
| 156, Florida everglades and southern lowlands | Aqualfs, Aquents, Fibrists, Hemists, Saprists, Aquolls, Aquods |
| 155, Southern Florida flatwoods | Aquents, Aquolls, Aquods, Aquults |
| 154, Southcentral Florida ridge | Psamments, Aquults, Udults |
| 153, Atlantic coast flatwoods | Psamments, Histosols, Aquods, Orthods, Aquults, Udults |
| 152, Gulf coast flatwoods | Aqualfs, Udalfs, Udults |
| 151, Gulf coast marsh | Aquents, Histosols, Aquolls |
| 150, Gulf coast prairies | Aqualfs, Aquents, Psamments, Aquolls, Aquerts, Uderts |
| 149, Northern coastal plain | Alfisols, Udults |
| 148, Northern Piedmont | Udalfs, Ochrepts, Udults |
| 138, Northcentral Florida ridge | Psamments, Udults |
| 137, Carolina and Georgia sandhills | Psamments, Udults |
| 136, Southern Piedmont | Udalfs, Udults |
| 135, Alabama and Mississippi blackland prairies | Udalfs, Udepts, Aquerts, Uderts |
| 134, Southern Mississippi valley silty uplands | Aqualfs, Udalfs, Udults |
| 133, Southern coastal plain | Alfisols, Udults |
| 132, Eastern Arkansas prairies | |
| 131, Southern Mississippi valley alluvium | Aqualfs, Udalfs, Histosols, Aquepts, Udolls, Aquerts |
| 129, Sand mountain | Udepts, Udults |
| 128, Southern Appalachian ridges and valleys | Udepts, Udults |
| 125, Cumberland plateau and mountains | Udepts, Udults |
| 123, Nashville basin | Udalfs, Udults |
| 122, Highland rim and pennyroyal | Udalfs, Aquults, Udults |
| 121, Kentucky bluegrass | Udalfs |
| 120, Kentucky and Indiana sandstone and shale hills and valleys | Udalfs, Aquents, Aquepts, Udepts, Udolls |
| 119, Ouachita mountains | Udepts, Udults |
| 118, Arkansas valley and ridges | Udalfs, Udolls, Udults |
| 117, Boston mountains | Udults |
| 116, Ozark highland | Udalfs, Udults |
| 112, Cherokee prairies | Aqualfs, Aquolls, Udolls |
| 87, Texas claypan area | Ustalfs |
| 86, Texas blackland prairie | Orthents, Ustolls |
| 85, Grand prairie | Ustepts, Ustolls |
| 84, Cross timbers | Ustalfs, Psamments, Ustults |
| 82, Texas central basin | Ustalfs, Ustepts |
| 80, Central rolling red prairies | Ustepts, Ustolls |
| 76, Bluestem hills | Ustolls |
| 75, Central loess plains | Ustolls |

Changes in how crops and pasture are managed on a farm would have a number of implications on overall costs and on production levels. Stuedemann et al. (2003) estimated that if 10% of cropland were converted to grazed pasture, there would be an increase of about 367 000 beef cows in the Southern Coastal Plain (40% greater than in 1997) and an increase of about 59 000 beef cows in the Southern Piedmont (7% greater than in 1997). Although crop production from the region would decline initially, these authors predicted that the apparent loss of total production could be regained with higher productivity on remaining land through positive rotation benefits. Total input cost of crop production also would decline, yet additional profit could be attained through animal sales.

## AGRICULTURAL MANAGEMENT APPROACHES

Relatively recent agricultural production systems in the southeastern USA have had a specialized focus, based on optimization of management using four primary factors: climate, socioeconomics, infrastructure, and markets. Specialization in crop and animal production has led to high-technology systems that can be viewed as most profitable when implemented with a single goal of maximizing output per unit of technological input. Synthetic chemical inputs are often used to overcome a growing number of threats from pests. Since this approach relies on large crop production equipment and a relatively simple recipe for obtaining high yield with synthetic inputs and pest protection, large land areas are often necessary to optimize economic return. A similar emphasis on large confined animal production facilities has been the focus for obtaining the highest economic return in animal production systems. These specialized systems have been successful, because they have created opportunities for high economic return, while maintaining or reducing the cost of food available to consumers. Economics tend to drive these systems apparently with less regard for other factors. Integration of agricultural enterprises is often viewed positively from the standpoint of vertical integration, where a producer or company controls most of the inputs and outputs of a particular system. Integration across agricultural enterprises may or may not be considered economically valid, depending on the amount of distraction from the primary economic investment and its potential to provide return.

Social tradition also has had a large role in determining whether technological advances are adopted or not. Aside from the technologically advanced producers, there also are producers that cling to tradition as a protocol for agricultural production. These producers often continue a traditional system that fits their climate and infrastructure without regard for other factors.

For agricultural systems to become sustainable with time there are considerations beyond profitability that need to be incorporated. These considerations are: (i) maximizing investment in natural capital, (ii) reducing environmental impacts, and (iii) considering social values of animal treatment and human exposure to synthetic chemicals. These additional factors are the foundation of successful integrated crop–livestock production system in the warm, humid regions of the world. Natural capital is derived from a wide array of naturally occurring properties and processes that are often overlooked in a more assembly-line approach to agriculture (Gliessman, 1998), including solar radiation, precipitation, wind, landscape formations, biological control of pests, symbiotic associations, soil biology and their processes, adaptation and/or recycling of machinery, locally produced seeds, and family involvement. Environmental impacts of agriculture are numerous (e.g., nitrate and pesticides in groundwater, eutrophication of lakes from P runoff, siltation of water bodies, dust storms, potential pesticide residues on food products, etc.) and these impacts need to be minimized for agriculture to function effectively in the future, especially with the growing wealth of society and repopulation of the rural landscape with people relatively unknowledgeable about food production.

**Table 2. Agricultural production characteristics of the southeastern USA (AL, AR, FL, GA, KY, LA, MS, NC, SC, TN, and VA) in comparison with those of the entire USA (USDA-NASS, 2004).**

| Component | Farm number | | | Farm area | | | Farm production | | |
|---|---|---|---|---|---|---|---|---|---|
| | Region | USA | Region share of USA | Region | USA | Region share of USA | Region production | USA production | Region share of USA |
| | Thousands of farms | | % | Mha | | % | Tg | | % |
| Total area | NA† | NA | NA | 140.5 | 966.6 | 15 | NA | NA | NA |
| Farm | 555.8 | 2129.0 | 26 | 45.2 | 379.9 | 12 | NA | NA | NA |
| Cropland | 443.2 | 1751.5 | 25 | 24.3 | 175.8 | 14 | NA | NA | NA |
| Woodland | 303.5 | 818.1 | 37 | 11.8 | 30.7 | 38 | NA | NA | NA |
| Pasture | 227.6 | 850.9 | 27 | 6.8 | 160.0 | 4 | NA | NA | NA |
| Other | 288.2 | 1165.6 | 25 | 2.4 | 13.3 | 18 | NA | NA | NA |
| Corn | 33.1 | 348.6 | 10 | 1.8 | 27.6 | 7 | 11.6 | 218.8 | 5 |
| Wheat | 16.5 | 169.5 | 10 | 1.1 | 18.4 | 6 | 4.5 | 42.9 | 11 |
| Soybean | 33.0 | 317.6 | 10 | 3.9 | 29.3 | 13 | 7.9 | 73.7 | 11 |
| Cotton | 12.5 | 24.8 | 50 | 2.5 | 5.0 | 50 | 1.8 | 3.7 | 49 |
| Forages | 236.1 | 884.8 | 27 | 4.4 | 25.9 | 17 | 21.5 | 140.6 | 15 |
| Peanut | 6.9 | 8.6 | 80 | 0.4 | 0.5 | 73 | 1.0 | 1.4 | 68 |
| | Thousands of farms | | % | Millions of animals | | % | | | |
| Cattle | 296.3 | 1018.4 | 29 | 6.4 | 38.7 | 16 | NA | NA | NA |
| Hogs | 12.5 | 78.9 | 16 | 5.0 | 24.5 | 20 | NA | NA | NA |
| Layers | 21.0 | 98.3 | 21 | 34.6 | 135.4 | 26 | NA | NA | NA |
| Broilers | 17.0 | 37.9 | 45 | 421.6 | 562.5 | 75 | NA | NA | NA |
| Sheep | 8.4 | 73.8 | 11 | 0.1 | 2.6 | 3 | NA | NA | NA |

† NA is not applicable and/or available.

Some of the reasons for shifting from a specialized production system to an integrated crop–livestock production system are: (i) specialized farms operating on marginal profit, (ii) economic vulnerability with specialized production, (iii) high cost of fuel and nutrients, (iv) pests (i.e., weeds, insects, nematodes, and pathogens) becoming more damaging with monocultures, (v) yield decline due to long-term management-induced constraints on soil chemical and physical characteristics and biological diversity, (vi) spatially and temporally improved nutrient cycling on a field and landscape level with integration of enterprises, and (vii) conservation of soil and water resources with greater adoption of sod-based management approaches.

Although contemporary research documenting the characteristics of integrated crop–livestock production is limited, there are examples from historical and recent research on key potential components of an integrated approach that should provide insights as to how such systems might be developed. A greater research effort is required to investigate the responses of integrated crop–livestock production.

## Crop Rotation

Across the southeastern USA, soil loss calculated from the Universal Soil Loss Equation was estimated at $5.4 \pm 3.2$ Mg ha$^{-1}$ yr$^{-1}$ (weighted mean ± standard deviation among 19 Major Land Resource Areas) (Langdale and Moldenhauer, 1995). Minimizing soil loss in agriculture is of utmost importance in sustaining soil and environmental quality. In the Southern Piedmont region, "the most promising answer to the persistent row-crop erosion hazard on sloping land has been the increasing use of the highly protective grass-based crop rotation" (Hendrickson et al., 1963a). This research demonstrated that water runoff could be reduced from 20% of precipitation with land under continuous cotton

to 10% of precipitation with land under perennial grass. Even more dramatically, soil loss could be reduced from 45 Mg ha$^{-1}$ under cotton to <1 Mg ha$^{-1}$ under perennial grass (Hendrickson et al., 1963a). Soil loss from 1940 to 1944 at Watkinsville, GA, averaged 65 Mg ha$^{-1}$ under continuous cotton, but only 10 Mg ha$^{-1}$ under a 3-yr rotation of oat (*Avena sativa* L.)/annual lespedeza [*Kummerowia stipulacea* (Maxim) Makino]–lespedeza–cotton (Carreker, 1946). Within individual phases of the rotation, soil loss was 10 Mg ha$^{-1}$ from oat–lespedeza, 1 Mg ha$^{-1}$ from lespedeza, and 20 Mg ha$^{-1}$ from cotton. Soil loss from 1945 to 1952 in Watkinsville, GA, averaged 30 Mg ha$^{-1}$ under continuous cotton and 4 Mg ha$^{-1}$ under a 3-yr rotation of oat–lespedeza–lespedeza–cotton (Hendrickson et al., 1963b). In the same report, soil loss under continuous peanut was 13 Mg ha$^{-1}$ but was only 3 Mg ha$^{-1}$ under a 2-yr rotation of oat–vetch (*Vicia sativa* L.)–crotalaria (*Crotalaria retusa* L.)–peanut.

Following plowing and disking of 5-yr-old stands of either 'Kentucky-31' tall fescue [*Lolium arundinaceum* (Schreb.) Darbyshire] or 'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers.] at 14 Southern Piedmont locations in Georgia and South Carolina, corn grain yield averaged 3.6 Mg ha$^{-1}$ without N fertilizer input and 22% higher at maximum yield with an average of 128 kg N ha$^{-1}$ (Parks et al., 1969). Corn yield response to N fertilizer following sod was relatively low compared with more typical severalfold responses in continuous cultivation. From 1958 to 1964 in Watkinsville, GA, continuous corn grain yield increased nearly fourfold with N fertilizer (Fig. 3). Corn grown in rotation with perennial sods responded far less to N fertilizer than continuous corn and attained 11 to 24% greater yield than under continuous cultivation (Adams et al., 1970a).

Sod-based rotation effects on subsequent crop yield can last for several years. With moderate N fertilization (90 kg N ha$^{-1}$), corn grain yield averaged 4.2 Mg ha$^{-1}$ under continuous corn and was 47, 59, 62, and 32%
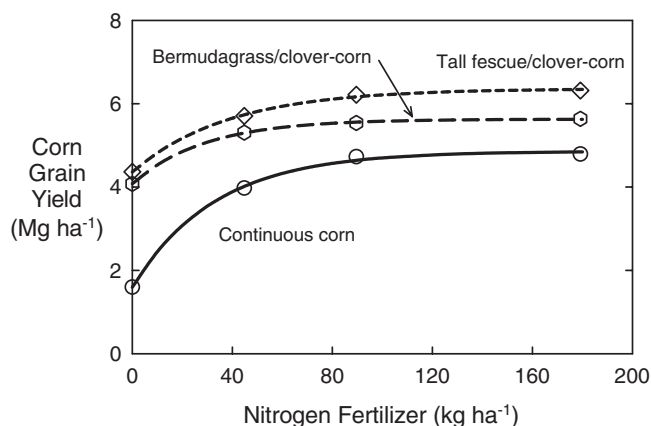
**Fig. 3. Corn grain yield response to N fertilizer as affected by previous cropping. Perennial grass phase was 3 yr. Data from 1958 to 1964 near Watkinsville, GA (Adams et al., 1970a).**

**Fig. 5. Relationship of peanut yield to incidence of stem rot (*Sclerotinium rolfsii*) as influenced by crop rotation system in Georgia. Mean yield of the four treatments within each year was set as 100% yield. Data from 1993 to 1999 near Tifton, GA (Brenneman et al., 2003).**

greater in the 2nd, 3rd, 4th, and 5th years following termination of sod (Adams et al., 1970a). Relative corn grain yield with optimum fertilization in the 1st, 2nd, and 3rd years following termination of perennial sod averaged 100, 97, and 92%, respectively (Parks et al., 1969).

Some of the reasons for long-lasting effects of sod rotation on crop yield might be soil organic matter accumulation, better soil physical condition, and disease suppression (Barber, 1972; Crookston, 1984; Jawson et al., 1993). In Georgia, Giddens et al. (1971a, 1971b) demonstrated that a significant quantity of soil organic N accumulated after establishment of tall fescue and was subsequently slowly released to cereals in rotation (Fig. 4).

Peanut seed yield was often greater following 2 yr of bahiagrass (*Paspalum notatum* Fluegge) than following annual crops, and was much greater than in continuous peanut, as a result of a reduction in stem rot (*Sclerotinium rolfsii* Cattaneo) (Fig. 5). Rotation with bahiagrass has controlled other diseases of peanut (Johnson et al., 1999; Brenneman et al., 2003) and vegetables (Sumner et al., 1999), as well as root-knot nematode
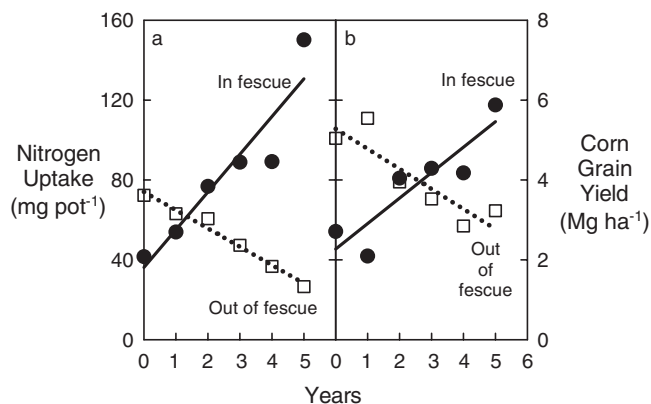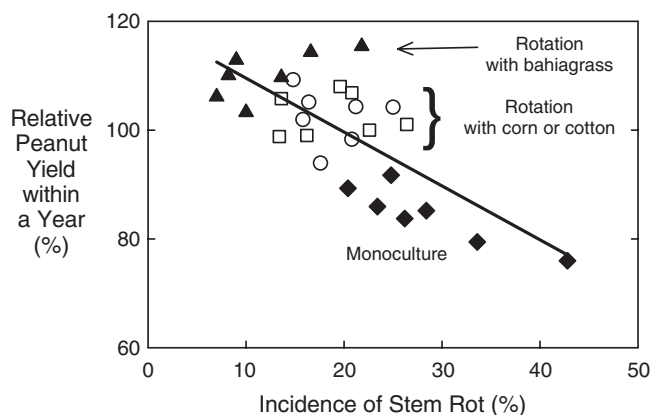
(*Meloidogyne* sp.) infection in peanut and soybean (Rodriguez-Kabana et al., 1988, 1989a, 1989b).

Establishment of perennial forage on previously eroded cropland can lead to significant improvement in soil organic matter, nutrient cycling, and biological and physical conditions of soil. For example, during the first 5 yr of bermudagrass management, soil organic C increased in all systems, but more so with grazing than without (Fig. 6). Greater accumulation of soil organic C with grazing was due to fecal return directly on the paddock, rather than application elsewhere with hay harvest. Summarized across 10 studies in the southeastern USA, soil organic C accumulation following grass establishment was $1.0 \pm 0.9$ Mg ha$^{-1}$ yr$^{-1}$ during $15 \pm 17$ yr (Franzluebbers, 2005). Accumulation of soil organic C with pasture development was also associated with changes in organic N, where the equivalent of about 90% of applied N accumulated as soil organic N with grazing and 26 to 53% of applied N accumulated as soil organic N with unharvested or hayed management (Franzluebbers and Stuedemann, 2003b). With the additional OM resources at the soil surface, soil under
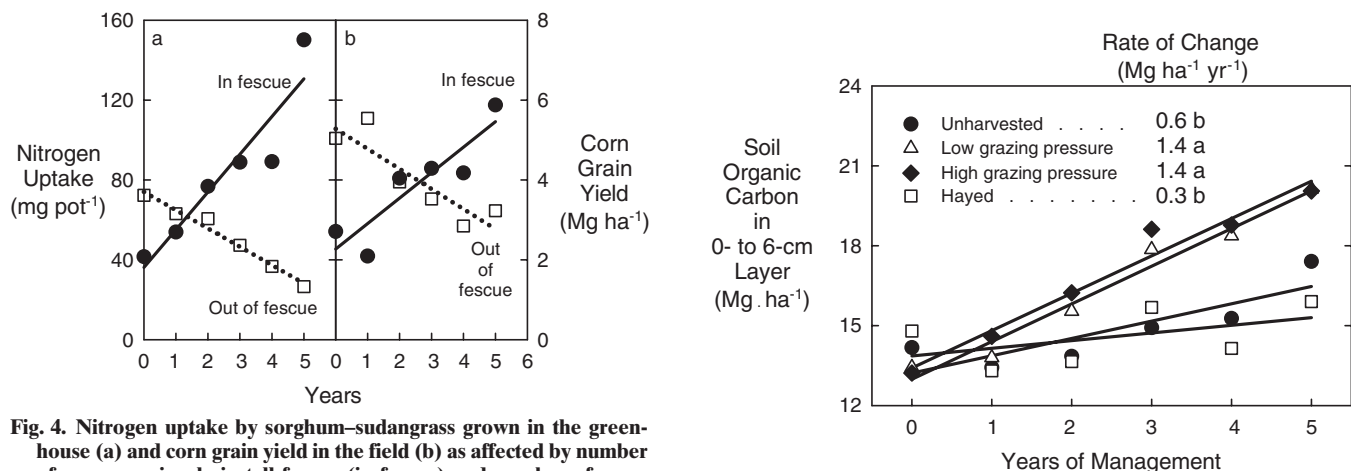
**Fig. 4. Nitrogen uptake by sorghum–sudangrass grown in the greenhouse (a) and corn grain yield in the field (b) as affected by number of years previously in tall fescue (in fescue) and number of years since tall fescue terminated (out of fescue). Data collected near Watkinsville, GA (Giddens et al., 1971a, 1971b).**

**Fig. 6. Change in soil organic C during 5 yr of management of bermudagrass near Watkinsville, GA (Franzluebbers et al., 2001).**

pasture also accumulated soil microbial biomass at an equivalent rate of 19 to 24% $yr^{-1}$ with grazing and 10 to 15% $yr^{-1}$ without cattle grazing (Franzluebbers and Stuedemann, 2003a). Since more opportunities exist throughout the year to spread manure on pastures than on cropland, deficiencies in secondary nutrients can be corrected before cropping with application of animal manure to pasture (Franzluebbers et al., 2004).

Cropping systems that include perennial grass phases rotated with annual crops are currently more common in other regions of the world. Crop–pasture rotation is a common practice in New Zealand, in which arable crops (cereals, brassicas, and legumes) are grown for 2 to 5 yr in rotation with 2 to 5 yr of grazed grass–legume pastures (Haynes and Francis, 1990). Energy output to input ratio from three pairs of conventional and alternative farms in New Zealand was relatively high at 13 ± 3, suggesting high efficiency with the inclusion of legume-based pastures (Nguyen and Haynes, 1995). Labor productivity tended to be greater in conventional (1.3 ± 0.2 Mg grain yield $h^{-1}$ labor) than in biodynamic or organic systems (0.7 ± 0.3 Mg grain yield $h^{-1}$ labor).

In Argentina, all soil quality indicators decreased with conventional-tillage cropping and increased with perennial pasture in long-term rotations (Studdert et al., 1997). Rotations with ≤7 yr of conventional cropping alternated with ≥3 yr of pasture maintained soil properties within acceptable limits to avoid degradation. Cattle grazing in crop–pasture rotations compacted surface soil only under conventional tillage, but not under no-tillage (Diaz-Zorita et al., 2002). The ability of soil to resist compaction under no-tillage was attributed to higher structural stability. These data suggested that crop residues could be grazed without inducing significant soil compaction if crops were established following pasture without tillage.

In Uruguay, soil erosion averaged 19 Mg $ha^{-1}$ under conventional-tillage continuous cropping, 7 Mg $ha^{-1}$ under conventional-tillage crop–pasture rotation, 3 Mg $ha^{-1}$ under no-tillage continuous cropping, and <2 Mg $ha^{-1}$ under no-tillage crop–pasture rotation or perennial natural pasture (Garcia-Prechac et al., 2004). Soil organic C could be maintained or increased compared to natural pasture with crop–pasture rotation, but declined with time with continuous cropping, especially with conventional tillage. Crop yield was also enhanced with crop–pasture rotation, more so in the long-term with concomitant management with no-tillage, rather than with conventional tillage.

## Cover Cropping

Cover crops provide a viable short-rotation opportunity for almost any cropping sequence in the southeastern USA. Even though most previous research has been with ungrazed cover crops or green manures, adding a cover crop component can improve productivity potential and reduce environmental threats from erosion (Langdale et al., 1991) and nutrient loss (Meisinger et al., 1991; Sharpley and Smith, 1991). Despite the plethora of research conducted with cover crops (Hargrove, 1991; Sustainable Agriculture Network, 1998), and in-

creasingly in combination with conservation tillage systems during the past two decades, there remains a paucity of information on how cover crops have been successfully integrated into crop–livestock systems (Gardner and Faulkner, 1991). Benefits from cover crops in cropping systems are numerous, including: (i) controlling soil erosion; (ii) reducing water and nutrient runoff; (iii) improving soil tilth, structure, water infiltration, and nutrient cycling; (iv) modifying soil moisture, by increasing uptake and reducing evaporation at different times of the year; (v) contributing to soil organic C sequestration and soil biological diversity; (vi) controlling weeds through competition, allelopathy, and microclimatic alteration; (vii) controlling insect and disease pressures ecologically; (viii) serving as a nutrient trap in high-fertility systems; and (ix) if leguminous, providing biologically fixed N to the cropping system.

As summarized by Gardner and Faulkner (1991), having ruminant livestock utilize cover crops in a crop production system could increase the value of cover crops, because "planting and caring for a crop that apparently serves no immediate economic and harvestable purpose is both a foreign and unknown practice in much of the world... details, time, and skill required to manage both crops and livestock are obvious adoption barriers to seeing cover crops as pasture." Installation of fencing, access to water, and continued availability of land for tenants are further considerations. Gardner and Faulkner (1991) also stated that the most basic barrier to adoption of integrated crop–livestock systems today is that many producers are reluctant to obtain or manage grazing livestock, because of a lack of experience and/or time during critical crop management periods. Livestock increased labor required on an average North Dakota farm by about 50%, but only about 30% of the additional time competed directly during critical crop management (Gardner and Faulkner, 1991). Net economic return attributed to livestock increased whole farm income by about 20%.

Plant species that have been investigated as cover crops in conjunction with conservation tillage systems and that have potential for providing sufficient forage for grazing animals in integrated crop–livestock systems for the southeastern USA include wheat, rye (*Secale cereale* L.), oat, barley (*Hordeum vulgare* L.), annual ryegrass [*Lolium multiflorum* (Lam.) Husnot], hairy vetch (*Vicia villosa* Roth), common vetch, crimson clover (*Trifolium incarnatum* L.), orchardgrass (*Dactylis glomerata* L.), bluegrass (*Poa pratensis* L.), tall fescue, bermudagrass, and bahiagrass (Sojka et al., 1984). Other plants evaluated for various agronomic and ecological purposes in the region include arrowleaf clover (*Trifolium vesiculosum* Savi), bigflower vetch (*Vicia grandiflora* Scop.), caley pea (*Lathyrus hirsutus* L.), subterranean clover (*Trifolium subterraneum* L.), winter pea (*Pisum sativum* L.) (Duck and Tyler, 1991), annual lespedeza (Rao and Phillips, 1999), white lupin (*Lupinus albus* L.), sunnhemp (*Crotalaria juncea* L.) (Reeves and Delaney, 2002), pigeonpea [*Cajanus cajan* (L.) Millsp.] (Rao et al., 2003), and balansa clover (*Trifolium michelianum* Savi) (Tillman et al., 2004).

Cover crops can either increase yield potential or reduce the amount of additional N fertilizer required by a succeeding crop, depending on the type of cover crop and rotation system (Reeves et al., 1995). In Georgia, corn yield was either enhanced with rye as a cover crop or required less N fertilizer to achieve optimal yield using hairy vetch as a cover crop (Fig. 7). In North Carolina, legume cover crops provided both N and enhanced yield to corn planted with no-tillage (Fig. 7). Under no-tillage cropping from 1981 to 1983 near Griffin, GA, sorghum [*Sorghum bicolor* (L.) Moench] grain yield without additional N fertilizer averaged 3.9 Mg ha$^{-1}$ with cover crops of either crimson clover, subterranean clover, hairy vetch, or common vetch, and averaged 2.7 Mg ha$^{-1}$ with winter fallow or rye as cover crop (Hargrove, 1986). With 112 kg N ha$^{-1}$, grain yield averaged 3.9 Mg ha$^{-1}$ across treatments. In Maryland, corn grain yield without cover crop and no additional fertilizer averaged 5.2 Mg ha$^{-1}$, with hairy vetch only as a cover crop averaged 7.7 Mg ha$^{-1}$, and with a gradient of hairy vetch and rye mixture averaged 5.9 to 6.7 Mg ha$^{-1}$ (Clark et al., 1994).

Legume cover crops can supply sufficient N for succeeding crops to achieve maximum yield, especially if aboveground residues are returned to the soil. The amount and rate of nutrient release from decomposing cover crop residue depend primarily on growth stage, N concentration, and phenolic compounds (Buchanan and King, 1993; Ranells and Wagger, 1996). Corn grain yield without N fertilizer was 5.0 Mg ha$^{-1}$ when crimson clover or hairy vetch residues were removed as hay and was 37% higher when cover crop residues were returned to the soil (Hargrove, 1982). In this same comparison with 120 kg N ha$^{-1}$ applied, corn grain yield was 7.4 Mg ha$^{-1}$ with cover crop residue removed, but only 9% higher when cover crop residue was retained. Touchton et al. (1982) found a 12 ± 15% increase in corn grain yield with crimson clover residue returned to soil compared with removal before planting corn across a range of N fertilizer inputs during 2 yr. Crop residue removal, however, should not be considered a proxy

to that of grazing, as grazing returns partially digested materials and a majority of the nutrients contained in cover crops back to the land via feces and urine (Follett and Wilkinson, 1995).

Plant-parasitic nematodes, which affect many of the dominant crops in the southeastern USA, can be controlled without chemicals using resistant cultivars, crop rotation, cover crops, destruction of weeds, organic amendment, tillage, solarization, and flooding (Trivedi and Barker, 1986). Some cover crops that showed reasonable success in controlling nematodes include rye, narrow-leafed lupin (*Lupinus angustifolius*), sunnhemp (Wang et al., 2002), velvetbean [*Mucuna pruriens* (L.) DC.], cultivars of cowpea [*Vigna unguiculata* (L.) Walp.], and sorghum (McSorley and Gallaher, 1997).

Small grains, either managed purely as cover crops or for harvesting of grain, have been utilized for winter pasture in several areas of the southeastern USA. Beef steer performance on winter wheat pasture in Oklahoma was 0.96 kg head$^{-1}$ d$^{-1}$, stocked at 1.2 head ha$^{-1}$ for 84 to 115 d during three winters (Horn et al., 1995). Redmon et al. (1995) reviewed the extensive research conducted on grazing of wheat. With high fertility and precipitation, grazing until joint stage of tall winter wheat cultivars often increased grain yield when compared with ungrazed wheat, because of reduced lodging. With semidwarf cultivars, maximum leaf area at anthesis is needed to maximize yield, suggesting that grazing must cease earlier than for taller varieties to avoid yield reduction. Grazing of winter cover crops could also affect soil compaction, which occurred with extended grazing of conventionally tilled wheat in South Carolina (Worrell et al., 1992). At three sites in Oklahoma, soil strength increased from wheat planting to joint stage with cattle grazing (Krenzer et al., 1989). Soil compaction responses in wheat planted with low surface soil organic matter following conventional tillage practices, however, may not be applicable to responses using conservation tillage and high surface soil organic matter (Franzluebbers and Stuedemann, 2005). The accumulation of surface soil organic C can buffer against potential soil compaction resulting from cattle traffic (Fig. 8).
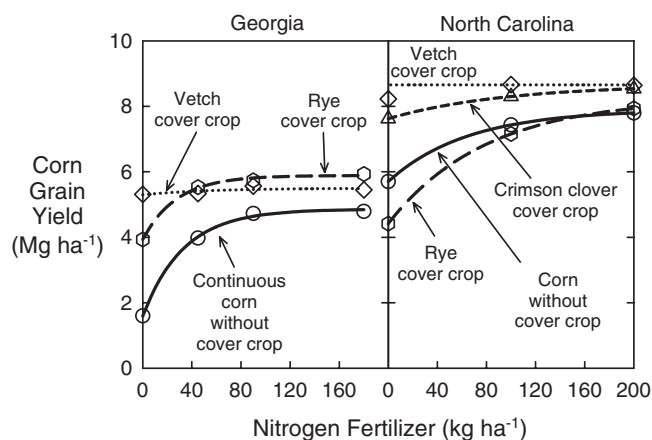


**Fig. 7. Corn grain yield response to N fertilizer as affected by cover crop management. Georgia data from 1958 to 1964 near Watkinsville (Adams et al., 1970a). North Carolina data from 1984 (McLeansville) and 1985 (Reidsville) (Wagger, 1989).**
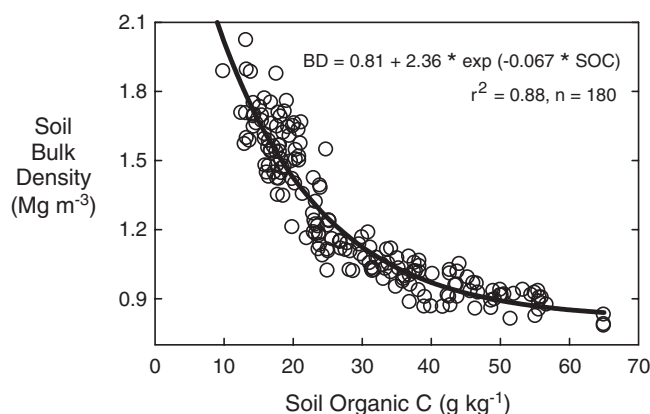


**Fig. 8. Relationship of soil bulk density with soil organic C concentration from a pasture experiment near Watkinsville, GA. Data from 0- to 2-cm depth (Franzluebbers et al., 2001).**

## Sod-Based Intercropping

The warm, humid region offers a unique climatic opportunity to capitalize on annual–perennial rotations in time, but occupying the same space. Several examples have been investigated that offer possibilities for crop–livestock integration in the future. Bermudagrass is a widely disseminated perennial pasture grass that grows primarily from May through September in the southeastern USA. Overseeding of bermudagrass (hay or grazing land) with annual grasses or legumes (e.g., ryegrass, rye, and crimson clover) is common for beef producers and provides an opportunity to extend the forage growing season on the same land area. It is also possible to overseed bermudagrass with winter cereals for grain harvest. Grain yield of rye interseeded into a dormant stand of Coastal bermudagrass was equivalent to rye seeded alone (1.5 Mg ha$^{-1}$) during 1964 and 1965 near Watkinsville, GA (Welch et al., 1967). Grain production of wheat interseeded into dormant bermudagrass from 1966 to 1968 near Watkinsville, GA, was successful ($\geq$1.5 Mg ha$^{-1}$) only with high N application (>135 kg N ha$^{-1}$) (Carreker et al., 1977), but these authors cautioned about the increasing pressure from weed development with the relatively late harvest of wheat, which could reduce the yield of first-cut bermudagrass hay. Adequate wheat silage ($\geq$5 Mg ha$^{-1}$) could be produced with N application >90 kg N ha$^{-1}$.

Another opportunity, albeit riskier due to dependence on weather, would be to interseed crops into perennial forages during summer. Supplemental irrigation would reduce the risk of stand establishment failure. Grain production of corn interseeded into bermudagrass or tall fescue sods was successful, depending on forage base and seedbed preparation (Table 3). Corn grain yield was maximized with plow tillage, because of reduction in grass competition, but forage recovery was greatest with the least soil disturbance (Adams et al., 1970b). With supplemental irrigation, maximum grain yield production of corn no-till planted into strip-killed tall fescue sod could be attained by optimizing corn population at 75 000 $\pm$ 25 000 plants ha$^{-1}$ (Fig. 9). Greatest total dry matter production (corn grain + stover + tall fescue recovery) also occurred at 75 000 plants ha$^{-1}$, but greatest forage production (corn stover + tall fescue recovery) occurred at the lowest plant population (~20 000 plants ha$^{-1}$) (Harper et al., 1980). When
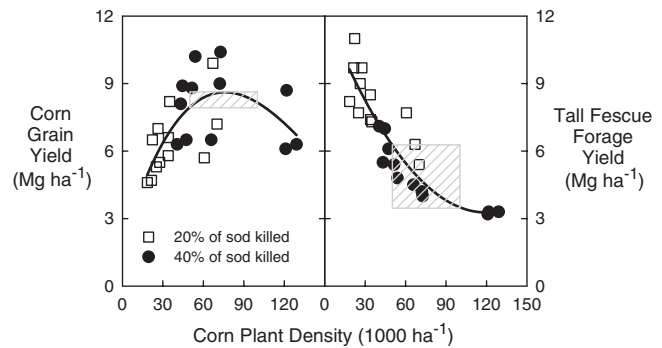


**Fig. 9. Corn grain yield and tall fescue forage yield components in response to corn planting density when strip-killed into living tall fescue sod from 1972 to 1973 with supplemental irrigation to maintain high soil water availability near Watkinsville, GA (Harper et al., 1980). Shaded areas correspond to the zone of maximum corn grain yield production (centered at 75 000 plants ha$^{-1}$).**

no-till planting corn into strip-killed tall fescue sod, corn grain yield from 1973 to 1976 near Watkinsville, GA, averaged 5.5 Mg ha$^{-1}$ under nonirrigated conditions and 8.5 Mg ha$^{-1}$ with supplemental irrigation (Box et al., 1980). Tall fescue forage yield when strip-killed averaged 6.0 and 4.7 Mg ha$^{-1}$ under dryland and irrigated conditions, respectively. Grain yield in completely killed sod with rye as a cover crop averaged 8.4 and 10.0 Mg ha$^{-1}$ under dryland and irrigated conditions, respectively. Rye forage yield averaged 6.0 Mg ha$^{-1}$, irrespective of water regime. These studies with corn planted into tall fescue sod illustrate a multitude of opportunities available to producers, depending on irrigation availability and their need to balance grain and forage production. Missing from most of these reports is the altered nutrient cycling that will occur when one or more phases of the rotation are grazed.

## Conservation Tillage

Refinement of conservation tillage technologies during the past several decades has greatly improved opportunities to successfully integrate crops and livestock (Southern Extension and Research Activity–Information Exchange Group 20, 2002). Along with improved weed control, fertilization, seed sources, and planting technologies, great potential exists to make integrated crop–livestock production systems more economically successful and ecologically responsible than they were before the post–World War II adoption of the fossil fuel-derived paradigm.

Establishment of annual crops into living, partially killed, or completely killed perennial sods is becoming increasingly possible with a combination of ecological strategy, conservation tillage, and herbicide-resistant plant varieties. The benefits of conservation tillage in agriculture are numerous, including: (i) reduction in fuel, time, and labor necessary to manage crops; (ii) reduction in machinery wear; (iii) more timely planting of crops even under wetter soil conditions; (iv) improvement in soil and water quality; (v) reduction in soil erosion; (vi) reduction in water runoff and more effective use of precipitation; and (vii) improvement in wildlife habitat.

**Table 3. Corn grain yield and forage recovery as affected by forage base and tillage treatment from 1961 to 1963 near Watkinsville, GA (Adams et al., 1970b).**

| Tillage system | Corn grain yield (Mg ha$^{-1}$) | | Forage yield (Mg ha$^{-1}$) |
|---|---|---|---|
| | Dryland | Irrigated | |
| **Grown on Coastal bermudagrass sod** | | | |
| Plow–disk–cultivate | 5.1 | 7.9 | 1.5 |
| Lister–cultivate | 4.2 | 6.2 | 4.4 |
| No-till + maleic hydrazide | 2.2 | 4.8 | 7.0 |
| **Grown on tall fescue sod** | | | |
| Plow–disk–cultivate | 5.6 | 9.3 | 0 |
| Lister–cultivate | 4.8 | 8.9 | 0.5 |
| No-till + maleic hydrazide | 1.0 | 7.6 | 2.0 |

Some barriers to overcome with conservation tillage are: (i) high bulk density and compaction, especially if traffic is uncontrolled; (ii) dependence on herbicides for weed control; and (iii) nutrient accumulation at the soil surface that may be susceptible to runoff loss or that may not feed roots during drought periods.

Yield of crops under conservation tillage in the southeastern USA is often similar to or greater than with traditional inversion tillage, as reviewed by Franzluebbers (2005). From 50 pairs of observations, yield of corn and cotton was $7 \pm 4\%$ greater under conservation tillage than under conventional tillage. Yields of other crops were statistically not different between tillage systems.

Adoption of conservation tillage also improves soil organic matter content, the accumulation of which helps to build a healthy soil biological community, improves aggregation and water infiltration, and increases the efficiency of nutrient cycling within the soil–plant domain. In cropping systems throughout the southeastern USA, multiple-year studies have indicated the potential for significant soil organic C sequestration with conservation tillage. From 40 paired observations, soil organic C sequestration was 0.28 Mg ha$^{-1}$ yr$^{-1}$ greater under conservation tillage than with conventional tillage in cropping systems without a cover crop (Franzluebbers, 2005). In cropping systems with a cover crop, soil organic C sequestration was 0.53 Mg ha$^{-1}$ yr$^{-1}$. During a period of ~10 yr with conservation tillage, soil organic C to a depth of ~20 cm was increased by 11% without and 20% with cover cropping. There is great potential to increase adoption of integrated crop–livestock production systems in the southeastern USA, especially with conservation-tillage management that protects the surface soil with plant residues and minimizes preparation time between crops.

## Integrated Crop–Livestock Production in the Southern Coastal Plain USA

An average farm in the Southern Coastal Plain in 1997 (total farmland of 8.5 Mha) was composed of 114 ha, although 64% of farms had <73 ha (Stuedemann et al., 2003). Cropland was present on 84% of farms, 46% of farms had beef cows, and 3% of farms sold broiler chickens. Only 43% of the farm operators in 1997 considered farming their principal occupation.

A research and extension project was developed at the Sunbelt Agricultural Exposition near Moultrie, GA, in autumn 2000 to integrate cattle during winter onto traditional cropland (Hill et al., 2004). Cotton and peanut were grown in rotation during the summer with rye or ryegrass as cover crop in the winter. Treatments imposed were conventional and strip tillage (two replications, each 1 ha) and grazed and ungrazed cover crop (small ungrazed exclosures). A total of 10 steers or heifers ($235 \pm 12$ kg initial weight) grazed the entire 4-ha area for 57 to 84 d beginning in mid-January. Cotton lint yield in 2001 and 2003 averaged 1.2 Mg ha$^{-1}$ under conventional tillage and 1.3 Mg ha$^{-1}$ under strip tillage. Peanut seed yield in 2002 was 4.0 Mg ha$^{-1}$ under conventional tillage and 4.4 Mg ha$^{-1}$ under strip tillage.

Cotton lint yield in 2001 and 2003 averaged 1.2 Mg ha$^{-1}$ without grazing and 1.3 Mg ha$^{-1}$ with grazing. Peanut seed yield in 2002 was 4.1 Mg ha$^{-1}$ without grazing and 4.2 Mg ha$^{-1}$ with grazing. Yields were statistically not different with and without grazing. However, since cattle could be stocked on the winter cover crop, the equivalent of $\$311 \pm 62$ ha$^{-1}$ greater gross income was generated in the value of animal gain (assuming $\$1.75$ kg$^{-1}$ animal gain). Stocker performance averaged $0.86 \pm 0.10$ kg head$^{-1}$ d$^{-1}$ among years.

A 3-yr experiment was conducted at Headland, AL, to compare the effect of oat and ryegrass winter cover crops under cattle grazing on cotton and peanut production managed under different tillage systems (Siri-Prieto et al., 2005; Gamble et al., 2005). Cotton and peanut plant populations were greater following oat rather than following ryegrass. Noninversion deep tillage (paratillage) following oat resulted in the highest seed cotton yield (4.0 Mg ha$^{-1}$), whereas strict no-tillage produced the lowest seed cotton yield (3.7 Mg ha$^{-1}$). Peanut seed yield under strict no-tillage (2.3 Mg ha$^{-1}$) was 42% less than under all other tillage systems. Net return from winter grazing of cover crops (5 head ha$^{-1}$ for 80 d) was $\$185$ to $200$ ha$^{-1}$ yr$^{-1}$, which represented 40% of the total system return. Noninversion deep tillage was necessary to alleviate a rooting depth restriction in this loamy sand that had high soil strength in the argillic subsoil.

A tristate sod-based project to study the effects of bahiagrass rotation with cotton and peanut was initiated at the turn of the millennium among researchers in Alabama, Florida, and Georgia (Hartzog and Balkcom, 2003). The justification for this project (http://nfrec.ifas. ufl.edu/sodrotation.htm) was:

> Main production limitations in the Southeast are infertile, compacted, droughty soils and pests. There is a low cost way to markedly reduce the impact of each of these limitations, and that is using a sod based rotation of bahia or bermuda grass in the cropping system. Bahia or bermuda grass adds organic matter to infertile soils for better nutrient and water holding capacity, while grass roots grow through the compacted soil layer allowing subsequent row crop roots to move through the compacted layer for access to more water and nutrients. These grasses also reduce nematode populations and other pests. Water in the soil profile is conserved and utilized by subsequent crops, since rooting depth of row crops is often 10 times deeper following bahia or bermuda grass as in conventional cropping systems. This could result in as little as one-tenth the current water use for irrigation, alleviating some of the water problems currently being debated in Tri-state water talks. Most growers will agree that sod based rotations with bahia or bermuda grass will increase yield of crops by 50 to 100%. State average yield of peanut in the Southeast is about 2500 pounds per acre (2.8 Mg ha$^{-1}$) and is often increased to 3500–4500 pounds per acre (3.9–5.0 Mg ha$^{-1}$) after bahiagrass. When economic analyses are done on cotton and peanut in a sod based rotation, profits are about 4 times greater than in a conventional peanut-cotton rotation. The increased farm profitability would create jobs in smaller rural towns making them a viable place for young people to stay and live and work.

Using an economic model comparing a conventional system (53 ha cotton, 27 ha peanut) with a sod-based rotation system (20 ha cotton, 20 ha peanut, 40 ha bahiagrass) on a typical small farm in Florida, net profit

was expected to be \$15 689 yr$^{-1}$ on a conventional farm, \$35 552 yr$^{-1}$ on a sod-based farm with hay harvest only, and \$44 840 yr$^{-1}$ on a sod-based farm with cattle grazing 2nd year bahiagrass (Marois et al., 2002). Detailed responses from several field experiments in the project are expected in coming years pertaining to agronomy, entomology, soil science, weed science, plant pathology, nematology, animal science, and economics.

## Integrated Crop–Livestock Production in the Southern Piedmont USA

An average farm in the Southern Piedmont in 1997 (total farmland of 4.3 Mha) was composed of 67 ha, and 76% of farms had <73 ha (Stuedemann et al., 2003). Cropland was present on 86% of farms, 55% of farms had beef cows, and 5% of farms sold broiler chickens. As in the Coastal Plain region, only 43% of the farm operators in 1997 considered farming their principal occupation. In both the Coastal Plain and Southern Piedmont regions, integration of crop and livestock operations currently is typified by large confined broiler chicken operators that have the need to spread floor litter onto their own or neighboring pasture and crop lands.

A fully replicated field experiment investigating crop, animal, and soil responses to three management factors was initiated in 2002 near Watkinsville, GA. Land previously in 20 yr of grazed tall fescue was converted to two cropping systems (sorghum grain + rye cover crop and wheat grain + pearl millet [*Pennisetum glaucum* (L.) R. Br.] cover crop) managed under two tillage systems (no-tillage and conventional with initial moldboard plow followed by disk tillage) and two cover crop scenarios (cover crop left ungrazed and grazed by cattle). During the first 1.5 yr of production, total aboveground biomass of sorghum averaged 5.9 Mg ha$^{-1}$ under ungrazed, and 5.1 Mg ha$^{-1}$ under grazed condition of previous rye cover crop; whereas that of wheat averaged 3.6 Mg ha$^{-1}$ under ungrazed, and 3.8 Mg ha$^{-1}$ under grazed condition of previous pearl millet cover crop (Franzluebbers and Stuedemann, 2004). Ungrazed cover crop biomass was greater under no-tillage (8.8 Mg ha$^{-1}$ of rye, and 6.2 Mg ha$^{-1}$ of pearl millet) than under conventional tillage (7.2 Mg ha$^{-1}$ of rye, and 4.5 Mg ha$^{-1}$ of pearl millet), with a similar tillage trend occurring for grain crop biomass. Cattle liveweight gain was not affected by tillage system, but averaged 287 kg ha$^{-1}$ on rye and 419 kg ha$^{-1}$ on pearl millet. With the neutral effect of cattle on grain crop biomass production and the additional cattle production on grazed cover crops, total system productivity and diversification in opportunities for economic return were greatly enhanced with the presence of grazing cattle in these two cropping systems.

The effect of grazing cattle on soil properties was variable. Soil penetration resistance tended to be higher under grazed than ungrazed condition, but values depended largely on antecedent soil water content at the time of measurement (Franzluebbers and Stuedemann, 2005). Soil organic C concentration was initially highly stratified with depth and remained so with no-tillage, but
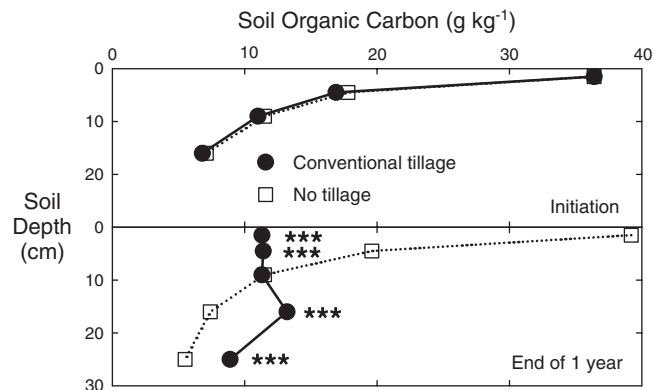


**Fig. 10. Soil organic C concentration with depth as affected by tillage management and year of sampling (Franzluebbers and Stuedemann, 2005). \*\*\* Denotes significance between tillage means within a depth at $p \leq 0.001$.**

became uniform with depth following termination of perennial pasture with moldboard plowing (Fig. 10). A change in soil organic C due to the presence of grazing cattle was not evident. With time, this study will be able to evaluate the relative impact of how conventional and no-tillage might alter the response of soil surface properties to grazing cattle. Initial soil responses to grazing appear to be minimal, suggesting that the greater economic return and diversity by grazing of cover crops could benefit production and economics without damage of the environment. This research needs to be continued to validate this suggestion.

## SUMMARY AND CONCLUSIONS

Opportunities for greater integration of crops and livestock on farms in the southeastern USA are abundant. Integrated crop–livestock production systems could increase crop health and productivity, reduce external input requirements, increase economic stability and diversity, and reduce environmental pollution from agriculture. Further research is needed to establish the production, logistical, and environmental limitations and consequences of integrated crop–livestock production systems, as well as to understand the multitude of potential interactions among various components. Barriers to adoption of integrated crop–livestock production systems are considered to be derived more from social influences than from biophysical limitations, but these social dimensions could be overcome with education and experience with time.

# REFERENCES

Adams, W.E., H.D. Morris, and R.N. Dawson. 1970a. Effect of cropping systems and nitrogen levels on corn (*Zea mays*) yields in the Southern Piedmont region. Agron. J. 62:655–659.

Adams, W.E., J.E. Pallas, Jr., and R.N. Dawson. 1970b. Tillage methods for corn–sod systems in the Southern Piedmont. Agron. J. 62:646–649.

Barber, S.A. 1972. Relation of weather to the influence of hay crops on subsequent corn yields on a Chalmers silt loam. Agron. J. 64:8–10.

Box, J.E., Jr., S.R. Wilkinson, R.N. Dawson, and J. Kazachyn. 1980. Soil water effects on no-till corn production in strip and completely killed mulches. Agron. J. 72:797–802.

Brenneman, T.B., P. Timper, N.A. Minton, and A.W. Johnson. 2003. Comparison of bahiagrass, corn, and cotton as rotational crops for peanut. p. 59–65. *In* F.M. Rhoads (ed.) Proc. Sod Based Cropping Syst. Conf., Quincy, FL. 20–21 Feb. 2003. Inst. Food and Agric. Sci., Univ. of Florida.

Buchanan, M., and L.D. King. 1993. Carbon and phosphorus losses from decomposing crop residues in no-till and conventional till agroecosystems. Agron. J. 85:631–638.

Carreker, J.R. 1946. Proper cropping practices strengthen terraces on sloping ground. Agric. Eng. 27:311–313.

Carreker, J.R., S.R. Wilkinson, A.P. Barnett, and J.E. Box. 1977. Soil and water management systems for sloping land. ARS-S-160. USDA-ARS, Washington, DC.

Clark, A.J., A.M. Decker, and J.J. Meisinger. 1994. Seeding rate and kill date effects on hairy vetch–cereal rye cover crop mixtures for corn production. Agron. J. 86:1065–1070.

Crookston, R.K. 1984. The rotation effect: What causes it to boost yields? Crops Soils 36:12–14.

Diaz-Zorita, M., G.A. Duarte, and J.H. Grove. 2002. A review of no-till systems and soil management for sustainable crop production in the subhumid and semiarid Pampas of Argentina. Soil Tillage Res. 65:1–18.

Duck, B.N., and D.D. Tyler. 1991. Adaptation of legume species as cover crops in no-till systems. p. 130–131. *In* W.L. Hargrove (ed.) Cover crops for clean water. Soil and Water Conserv. Soc., Ankeny, IA.

Follett, R.F., and S.R. Wilkinson. 1995. Nutrient management in forages. p. 55–82. *In* R.F. Barnes et al. (ed.) Forages. Vol. 2. Iowa State Univ. Press, Ames, IA.

Franzluebbers, A.J. 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. Soil Tillage Res. 83:120–147.

Franzluebbers, A.J., and J.A. Stuedemann. 2003a. Bermudagrass management in the Southern Piedmont USA: III. Particulate and biologically active soil carbon. Soil Sci. Soc. Am. J. 67:132–138.

Franzluebbers, A.J., and J.A. Stuedemann. 2003b. Bermudagrass management in the Southern Piedmont USA: VI. Soil-profile inorganic nitrogen. J. Environ. Qual. 32:1316–1322.

Franzluebbers, A.J., and J.A. Stuedemann. 2004. Crop management and animal production in yearly rotation under inversion and no tillage. p. 231–238. *In* D. Jordan and D. Caldwell (ed.) Proc. 26th South. Conserv. Tillage Conf., Tech. Bull. 321, Raleigh, NC. 8–9 June 2004. North Carolina Agric. Res. Serv.

Franzluebbers, A.J., and J.A. Stuedemann. 2005. Soil responses under integrated crop and livestock production. p. 13–21. *In* W. Busscher et al. (ed.) Proc. 27th South. Conserv. Tillage Conf., Florence, SC. 27–29 June 2005. Clemson Univ.

Franzluebbers, A.J., J.A. Stuedemann, and S.R. Wilkinson. 2001. Bermudagrass management in the Southern Piedmont USA: I. Soil and surface residue carbon and sulfur. Soil Sci. Soc. Am. J. 65:834–841.

Franzluebbers, A.J., S.R. Wilkinson, and J.A. Stuedemann. 2004. Bermudagrass management in the Southern Piedmont USA: VIII. Soil pH and nutrient cations. Agron. J. 96:1390–1399.

Gamble, B.E., G. Siri-Prieto, D.W. Reeves, and R.L. Raper. 2005. Forage and tillage systems for integrating winter-grazed stocker cattle in peanut production. p. 162–164. *In* W. Busscher et al. (ed.) Proc. South. Conserv. Tillage Conf., Florence, SC. 27–29 June 2005. Clemson Univ.

Garcia-Prechac, F., O. Ernst, G. Siri-Prieto, and J.A. Terra. 2004. Integrating no-till into crop-pasture rotations in Uruguay. Soil Tillage Res. 77:1–13.

Gardner, J.C., and D.B. Faulkner. 1991. Use of cover crops with integrated crop–livestock production systems. p. 185–191. *In* W.L. Hargrove (ed.) Cover crops for clean water. Soil and Water Conserv. Soc., Ankeny, IA.

Gates, R.N. 2003. Integration of perennial forages and grazing in sod based crop rotations. p. 7–14. *In* F.M. Rhoads (ed.) Proc. Sod Based Cropping Syst. Conf., Quincy, FL. 20–21 Feb. 2003. Inst. Food and Agric. Sci., Univ. of Florida.

Giddens, J., W.E. Adams, and R.N. Dawson. 1971a. Nitrogen accumulation in fescuegrass sod. Agron. J. 63:451–454.

Giddens, J., R.D. Hauck, W.E. Adams, and R.N. Dawson. 1971b. Forms of nitrogen and nitrogen availability in fescuegrass sod. Agron. J. 63:458–460.

Gliessman, S.R. 1998. Agroecology: Ecological processes in sustainable agriculture. Sleeping Bear Press, Chelsea, MI.

Hardesty, L.H., and J.A. Tiedeman. 1996. Integrating crop and livestock production in Inland Northwest farming systems. Am. J. Altern. Agric. 11:121–126.

Hargrove, W.L. 1982. Proceedings of the minisymposium on legume cover crops for conservation tillage production systems. Spec. Publ. 19. Univ. of Georgia College Agric. Exp. Stn., Athens.

Hargrove, W.L. 1986. Winter legumes as a nitrogen source for no-till grain sorghum. Agron. J. 78:70–74.

Hargrove, W.L. (ed.) 1991. Cover crops for clean water. Soil and Water Conserv. Soc., Ankeny, IA.

Harper, L.A., S.R. Wilkinson, and J.E. Box, Jr. 1980. Row-plant spacing and broiler litter effects on intercropping corn in tall fescue. Agron. J. 72:5–10.

Hartzog, D.L., and K. Balkcom. 2003. Initiation of the tri-state sod-based rotation project, an overview. p. 17–20. *In* F.M. Rhoads (ed.) Proc. Sod-Based Cropping Syst. Conf., Quincy, FL. 20–21 Feb. 2003. Inst. Food and Agric. Sci., Univ. of Florida.

Haynes, R.J., and G.S. Francis. 1990. Effects of mixed cropping systems on changes in soil properties on the Canterbury Plains. N.Z. J. Ecol. 14:73–82.

Hendrickson, B.H., A.P. Barnett, and O.W. Beale. 1963a. Conservation methods for soils of the Southern Piedmont. Agric. Inf. Bull. 269. USDA-ARS, Washington, DC.

Hendrickson, B.H., A.P. Barnett, J.R. Carreker, and W.E. Adams. 1963b. Runoff and erosion control studies on Cecil soil in the Southern Piedmont. Tech. Bull. 1281. USDA-ARS, Washington, DC.

Hill, G.M., R.K. Hubbard, R.C. Lacy, and C. Blalock. 2004. Integration of winter grazing and irrigated cotton production. p. 40–45. *In* 2003 Georgia Cotton Research and Extension Reports. UGA/CPES Res.-Ext. Publ. 6. Univ. of Georgia CAES and USDA-ARS, Athens.

Horn, G.W., M.D. Cravey, F.T. McCollum, C.A. Strasia, E.G. Krenzer, Jr., and P.L. Claypool. 1995. Influence of high-starch vs high-fiber energy supplements on performance of stocker cattle grazing wheat pasture and subsequent feedlot performance. J. Anim. Sci. 73:45–54.

Jawson, M.D., A.J. Franzluebbers, D.K. Galusha, and R.M. Aiken. 1993. Soil fumigation within monoculture and rotations: Response of corn and mycorrhizae. Agron. J. 85:1174–1180.

Jenny, H. 1941. Factors of soil formation. McGraw-Hill, New York.

Johnson, A.W., N.A. Minton, T.B. Brenneman, G.W. Burton, A.K. Culbreath, G.J. Gascho, and S.H. Baker. 1999. Bahiagrass, corn, cotton rotations, and pesticides for managing nematodes, diseases, and insects on peanut. J. Nematol. 31:191–200.

Krenzer, E.G., Jr., C.F. Chee, and J.F. Stone. 1989. Effects of animal traffic on soil compaction in wheat pastures. J. Prod. Agric. 2:246–249.

Langdale, G.W., R.L. Blevins, D.L. Karlen, D.K. McCool, M.A. Nearing, E.L. Skidmore, A.W. Thomas, D.D. Tyler, and J.R. Williams. 1991. Cover crop effects on soil erosion by wind and water. p. 15–22. *In* W.L. Hargrove (ed.) Cover crops for clean water. Soil and Water Conserv. Soc., Ankeny, IA.

Langdale, G.W., and W.C. Moldenhauer (ed.) 1995. Crop residue management to reduce erosion and improve soil quality: Southeast. Rep. 39. USDA-ARS, Washington, DC.

Marois, J.J., D.L. Wright, J.A. Baldwin, and D.L. Hartzog. 2002. A multi-state project to sustain peanut and cotton yields by incorporating cattle in a sod based rotation. p. 101–107. *In* E. van Santen (ed.) Proc. 25th Ann. South. Conserv. Tillage Conf. Sustain. Agric.,

Auburn, AL. 24–26 June 2002. Alabama Agric. Exp. Stn. and Auburn Univ.

Meisinger, J.J., W.L. Hargrove, R.L. Mikkelsen, J.R. Williams, and V.W. Benson. 1991. Effects of cover crops on groundwater quality. p. 57–68. *In* W.L. Hargrove (ed.) Cover crops for clean water. Soil and Water Conserv. Soc., Ankeny, IA.

McSorley, R., and R.N. Gallaher. 1997. Methods for managing nematodes in sustainable agriculture. p. 75–79. *In* R.N. Gallaher and R. McSorley (ed.) Proc. 20th Ann. South. Conserv. Tillage Conf. Sustain. Agric., Gainesville, FL. 24–26 June 1997. Inst. Food and Agric. Sci., Univ. of Florida.

Nguyen, M.L., and R.J. Haynes. 1995. Energy and labour efficiency for three pairs of conventional and alternative mixed cropping (pasture-arable) farms in Canterbury, New Zealand. Agric. Ecosyst. Environ. 52:163–172.

Oltjen, J.W., and J.L. Beckett. 1996. Role of ruminant livestock in sustainable agricultural systems. J. Anim. Sci. 74:1406–1409.

Parks, C.L., L.F. Welch, H.D. Morris, G.R. Craddock, G.A. Hillsman, and C.B. Elkins, Jr. 1969. Corn yields as affected by soil slope, fertilization, year from sod, and rainfall. South Carolina Agric. Exp. Stn. Bull. 1032. South Carolina Agric. Exp. Stn.

Ranells, N.N., and M.G. Wagger. 1996. Nitrogen release from grass and legume cover crop monocultures and bicultures. Agron. J. 88:777–782.

Rao, S.C., and W.A. Phillips. 1999. Forage production and nutritive value of three lespedeza cultivars intercropped into continuous no-till winter wheat. J. Prod. Agric. 12:235–238.

Rao, S.C., W.A. Phillips, H.S. Mayeux, and S.C. Phatak. 2003. Potential grain and forage production of early maturing pigeonpea in the southern Great Plains. Crop Sci. 43:2212–2217.

Redmon, L.A., G.W. Horn, E.G. Krenzer, Jr., and D.J. Bernardo. 1995. A review of livestock grazing and wheat grain yield: Boom or bust? Agron. J. 87:137–147.

Reeves, D.W., and D.P. Delaney. 2002. Conservation rotations for cotton production and carbon storage. p. 344–348. *In* E. van Santen (ed.) Proc. 25th Ann. South. Conserv. Tillage Conf. Sustain. Agric., Auburn, AL. 24–26 June 2002. Alabama Agric. Exp. Stn. and Auburn Univ.

Reeves, D.W., D.D. Tyler, and W.L. Hargrove. 1995. Winter cover crops. p. 27–30. *In* G.W. Langdale and W.C. Moldenhauer (ed.) Crop residue management to reduce erosion and improve soil quality: Southeast. Conserv. Res. Rep. 39. USDA-ARS, Washington, DC.

Rodriguez-Kabana, R., C.F. Weaver, R. Garcia, D.G. Robertson, and E.L. Carden. 1989a. Additional studies on the use of bahiagrass for the management of root-knot, and cyst nematodes in soybean. Nematropica 21:203–210.

Rodriguez-Kabana, R., C.F. Weaver, R. Garcia, D.G. Robertson, and E.L. Carden. 1989b. Bahiagrass for the management of root-knot, and cyst nematodes in soybean. Nematropica 19:185–193.

Rodriguez-Kabana, R., C.F. Weaver, D.G. Robertson, and H. Ivey. 1988. Bahiagrass for the management of *Meloidogyne arenaria* in peanut. Ann. Appl. Nematol. 2:110–114.

Sharpley, A.N., and S.J. Smith. 1991. Effects of cover crops on surface water quality. p. 41–49. *In* W.L. Hargrove (ed.) Cover crops for clean water. Soil and Water Conserv. Soc., Ankeny, IA.

Siri-Prieto, G., D.W. Reeves, R.L. Raper, and B.E. Gamble. 2005. Forage and tillage systems for integrating winter-grazed stocker cattle in cotton production. p. 160–161. *In* W. Busscher et al. (ed.) Proc. South. Conserv. Tillage Conf., Florence, SC. 27–29 June 2005. Univ. of Florida.

Sojka, R.E., G.W. Langdale, and D.L. Karlen. 1984. Vegetative techniques for reducing water erosion of cropland in the southeastern United States. Adv. Agron. 37:155–181.

Southern Extension and Research Activity–Information Exchange Group 20. 2002. 25 Years: Proceedings of the Southern Conservation Tillage Conference for Sustainable Agriculture—1978 to 2002 [CD-ROM]. SERA-IEG-20, Auburn, AL.

Studdert, G.A., H.E. Echeverria, and E.M. Casanovas. 1997. Crop-pasture rotation for sustaining the quality and productivity of a Typic Argiudoll. Soil Sci. Soc. Am. J. 61:1466–1472.

Stuedemann, J.A., A.J. Franzluebbers, D.H. Seman, and D.W. Reeves. 2003. Potential outcomes of integrating cattle and cropping systems in southeastern Major Land Resource Areas. p. 81–103. *In* F.M. Rhoads (ed.) Proc. Sod-Based Cropping Syst. Conf., Quincy, FL. 20–21 Feb. 2003. Inst. Food and Agric. Sci., Univ. of Florida.

Sumner, D.R., N.A. Minton, T.B. Brenneman, G.W. Burton, and A.W. Johnson. 1999. Root diseases, and nematodes in bahiagrass–vegetable rotations. Plant Dis. 83:55–59.

Sustainable Agriculture Network. 1998. Managing cover crops profitably. 2nd ed. Sustain. Agric. Network Handb. Ser. 3. Sustainable Agric. Network, Beltsville, MD.

Thornthwaite, C.W., J.R. Mather, and D.B. Carter. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. p. 181–311. *In* Publication in climatology, Vol. 10, Issue 3. Drexel Inst. Technol., Lab. Climatol., Centerton, NJ.

Tillman, G., H. Schomberg, S. Phatak, and S. Lachnicht. 2004. Influence of cover crops on insect pests and predators in conservation-tillage cotton. p. 320–329. *In* Proc. 26th South. Conserv. Tillage Conf., Raleigh, NC. 8–9 June 2004.

Touchton, J.T., W.A. Gardner, W.L. Hargrove, and R.R. Duncan. 1982. Reseeding crimson clover as a N source for no-tillage grain sorghum production. Agron. J. 74:283–287.

Trivedi, P.C., and K.R. Barker. 1986. Management of nematodes by cultural practices. Nematropica 16:213–236.

USDA-National Agricultural Statistics Service. 2004. 2002 Census of Agriculture, United States Summary and State Data, Vol. 1, Geographic Area Series, Part 51, AC-02-A-51. Available at www.nass.usda.gov/census/census02/volume1/us/index1.htm (accessed 20 Oct. 2005; verified 21 Nov. 2006). USDA-NASS, Washington, DC.

USDA-SCS. 1981. Land resource regions and major land resource areas of the United States. Agric. Handb. 296. USDA-SCS, Washington, DC.

Wagger, M.G. 1989. Cover crop management and nitrogen rate in relation to growth and yield of no-till corn. Agron. J. 81:533–538.

Wang, K.-H., R. McSorley, R.N. Gallaher, and R.S. Tubbs. 2002. Effects of winter and fall cover crops on plant–parasitic nematode population development. p. 152–155. *In* E. van Santen (ed.) Proc. 25th Ann. South. Conserv. Tillage Conf. Sustain. Agric., Auburn, AL. 24–26 June 2002. Alabama Agric. Exp. Stn. and Auburn Univ.

Welch, L.F., S.R. Wilkinson, and G.A. Hillsman. 1967. Rye seeded for grain in Coastal bermudagrass. Agron. J. 59:467–472.

West, L.T. 2000. Soils and landscapes in the southern region. Section IV. *In* H.D. Scott (ed.) Water and chemical transport in soils of the southeastern USA. Southern Coop. Ser. Bull. 395. Available at http://soilphysics.okstate.edu/S257/index.html (accessed 15 May 2006; verified 21 Nov. 2006). Oklahoma State Univ., Stillwater.

Worrell, M.A., D.J. Undersander, and A. Khalilian. 1992. Grazing wheat to different morphological stages for effects on grain yield and soil compaction. J. Prod. Agric. 5:81–85.