Tillage Requirements for Integrating Winter-Annual Grazing in Cotton Production: Plant Water Status and Productivity

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Integrating livestock with cotton (*Gossypium hirsutum* L.) offers profitable alternatives for producers in the southeastern USA, but could result in soil water depletion and soil compaction. We conducted a 3-yr field study on a Dothan loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) in southern Alabama to develop a conservation tillage system for integrating cotton with winter-annual grazing of stocker cattle under rainfed conditions. Winter annual forages and tillage systems were evaluated in a strip-plot design where winter forages were oat (*Avena sativa* L.) and annual ryegrass (*Lolium mutiflorum* L.). Tillage systems included moldboard and chisel plowing and combinations of noninversion deep tillage (none, in-row subsoil, or paratill) with or without disking. We evaluated forage dry matter, N concentration, average daily gain, net returns from grazing, soil water content, and cotton leaf stomatal conductance, plant populations, and yield. Net returns from winter-annual grazing were between US$185 to US$200 ha^{-1} yr^{-1}. Soil water content was reduced by 15% with conventional tillage or deep tillage, suggesting that cotton rooting was increased by these systems. Oat increased cotton stands by 25% and seed-cotton yields by 7% compared with ryegrass. Strict no-till resulted in the lowest yields—30% less than the overall mean (3.69 Mg ha^{-1}). Noninversion deep tillage in no-till (especially paratill) following oat was the best tillage system combination (3.97 Mg ha^{-1}) but deep tillage did not increase cotton yields with conventional tillage. Integrating winter-annual grazing can be achieved using noninversion deep tillage following oat in a conservation tillage system, providing producers extra income while protecting the soil resource.

Abbreviations: AAES, Alabama Agricultural Experiment Station; ACES, Alabama Cooperative Extension System; DOY, day of year.

Soil management practices that maintain or increase soil C and improve soil physical properties include conservation tillage, cropping intensification, and inclusion of sod-based rotations (Varvel, 1994; Reeves, 1997; Bayer et al., 2000). Although 69% of the cotton acreage in the USA grown with conservation tillage was in the Southeast (Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee), only 40% of the cotton in the region was grown with this best management practice in 2004 (Conservation Technology Information Center, 2005). Crop rotation is generally recognized as being economically and agronomically beneficial due to the potential for increased yields, reduced pest and disease control inputs, and more flexible marketing opportunities (Bayer et al., 2000; Reeves, 1994), but modern production systems and farm policies favor specialization and monocropping. This is especially true for cotton: in the Delta or mid-South states, between 87 and 92% of cotton is grown in monoculture (Padgitt et al., 2000. The record is better in the southeastern states: 48 to 63% of cotton is grown in rotation (Padgitt et al., 2000). Even when produced with rotation practices, cotton is rotated with a limited number of crops, usually corn (*Zea mays* L.) or peanut (*Arachis hypogaea* L.). Integrating animal production with row cropping systems, e.g., cotton production, may offer economic and conservation benefits; however, it presents an even greater challenge to diversification than rotation with other row crops.

Recent research in Alabama has shown that contract grazing of stocker cattle in winter to early spring (100–140 d grazing) offers returns from US$170 to US$560 ha^{-1} (Bransby et al., 1999). In those studies, conducted during five site-seasons, the mean stocking rate was 4.4 head ha^{-1}, the mean contract price was US$0.77 kg^{-1}, and the mean gain was 777 kg ha^{-1}. This system diversifies market opportunities and offers potential for extra revenue for producers double-cropping following winter grazing. Winter-annual grazing, however, can result in excessive soil compaction, which can severely limit yields of double-cropped cash crops (Touchton et al., 1989; Mullins and Burmester, 1997). The degree of soil compaction can vary with soil texture, soil water, grazing intensity, vegetation type, and climate regime (Greenwood and McKenzie, 2001). Mullins and Burmester (1997) found that cattle could compact the soil surface to a depth of 15 cm on a silt loam soil in northern Alabama; however, other research on Coastal Plain soils reported cattle compacting soil to the 40-cm depth (Touchton et al., 1989; Miller et al., 1997). Additionally, little is known about the direct impact of short-term grazing on soil properties. Several studies have revealed that cotton is especially susceptible to soil compaction (Mullins et al., 1994;

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Reeves and Mullins, 1995). In-row subsoiling at planting can be used to alleviate soil compaction for cotton grown on sandy Coastal Plain soils (Busscher et al., 1988; Reeves and Mullins, 1995; Schwab et al., 2002). Tillage to alleviate soil compaction for cotton has generally been limited to monoculture systems; with the exception of the study by Touchton et al. (1989), we found no other research that identified a tillage requirement for cotton following grazing.

The objectives of this study were to determine the feasibility of double-cropping cotton following winter-annual grazing of stocker cattle in the southeastern Coastal Plain and to identify an optimal choice of forage and tillage system combination for animal performance, cotton productivity, soil conservation, and profitability. The results presented here emphasize cotton productivity and system profitability.

MATERIALS AND METHODS

Site Description

Our experiment began in October 2000 and was conducted for 3 yr at the Alabama Agricultural Experiment Station's (AAES) Wiregrass Research and Extension Center (31°24′ N, 85°15′ W) in the Coastal Plain of southeastern Alabama. The soil was a well-drained Dothan sandy loam. The site had been cropped previously in a cotton–peanut rotation managed according to recommendations of the Alabama Cooperative Extension System (ACES). The climate for this area is humid subtropical, with a mean annual air temperature of 18°C and 1400-mm annual precipitation.

Winter forages and summer tillage practices were evaluated in a strip-plot design with four replications. Two winter-annual forages (oat and annual ryegrass) served as horizontal treatments and eight tillage systems served as vertical treatments.

Cultural Practices

Forage plots were 100 m long by 61 m wide. At the beginning of the experiment (October 2000), all plots were disked and seeded with oat and ryegrass with a no-till drill (Great Plains Manufacturing, Salina, KA). Phosphorous, K, and lime applications for forages and cotton were based on ACES soil test recommendations (Adams and Mitchell, 2000).

The winter annual forages were fertilized with an average of 140–40–40–20 kg ha^{-1} of N–P–K–S; P and K applications varied somewhat each year based on soil test results and resultant ACES recommendations. All winter annual forages were terminated before summer tillage with application of 0.9 kg a.i. ha^{-1} glyphosate approximately 4 to 6 wk before cotton planting (Table 1).

Yearling Angus × Simmental steers (initial weight = 260 kg, averaged across years) supplied by independent cattle owners were stocked on a contract-grazing basis at a rate of 1.3 Mg ha^{-1} (five head) for winter grazing lasting >70 d (Table 1). All steers received commercial growth-promoting implants. Gain per hectare was determined by multiplying the average daily gain by the stocking rate.

The entire grazed experimental area was divided in half for planting peanut and cotton and imposing tillage treatments. One half of the area was planted to peanut, and the other half was planted to cotton. The peanut and cotton areas were rotated each year (2000–2003), allowing cropping of both phases of the peanut–cotton rotation each year. The experimental design and tillage treatment plot arrangement was identical for both areas each year, and each experimental tillage treatment unit (plot) in both cropping areas received the same tillage treatment each year of the study. Tillage plots within these areas were 15.2 m long and 7.3 m wide with eight, 0.92-m rows. The eight summer tillage practices were: (i) moldboard plowing to a depth of 30 cm and disking or leveling (10–15-cm depth); (ii) disking or leveling only; (iii) chisel plowing to a depth of 20 cm and disking or leveling; (iv) in-row subsoiling with a narrow-shanked subsoiler (KMC, Kelley Manufacturing Co., Tifton, GA) to a depth of 35 to 40 cm and disking or leveling; (v) no-till with in-row subsoiling; (vi) under-the-row Paratilling with a bent-leg subsoiler (Paratill, Bigham Brothers, Lubbock, TX) to a depth of 45 to 50 cm and disking or leveling; (vii) no-till with Paratilling; and (viii) no-till. Treatments 1 through 4 and 6 are forms of conventional tillage and result in a smooth, bare soil surface. Treatments 5, 7, and 8 are all variations of conservation tillage. The KMC narrow-shanked subsoiler is equipped with a coulter to cut residue ahead of the shank, and with pneumatic closing wheels following the shank. When used alone, it disrupts a narrow strip 10 to 16 cm wide at the soil surface, directly in the seeding zone, with very little residue disturbance. The Paratill bent-leg subsoiler shanks also are equipped with a coulter to cut residue but the shanks operate offset at a 45° angle to lift the soil beneath the row. The vertical portion of the shank operates offset from the row area, resulting in a narrow (10–16-cm) zone of surface soil disruption about 30 cm from the row. The Paratill was equipped with a smooth metal drum-type roller to level the soil surface. All tillage operations were performed after the removal of cattle from the winter annual forages. Planting dates, densities, and varieties for forages and cotton, as well as grazing times, are listed in Table 1. Tillage and planting equipment were guided using a tractor equipped with a Trimble AgGPS Autopilot automatic steering system (Trimble, Sunnyvale, CA), capable of centimeter-level precision, which reduced equipment-induced compaction near the cotton row. A four-row John Deere Maxi-Emerge planter (Deere

Table 1. Cultural practices used in evaluation of two forage species and eight tillage systems for integrating winter-annual grazing with cotton production on a Dothan loamy sand in southeastern Alabama (2001–2003).

Species	Cultivar	Seeding rate	Planting date	Row spacing	Tillage	Grazing initiated	Grazing terminated
		ha^{-1}					
Oat	Harrison	160 kg seed	20 Oct. 2000	17 cm	Conventional	31 Jan. 2001	11 Apr. 2001
Ryegrass	Marshall	35 kg seed	20 Oct. 2000	Broadcast	Conventional	31 Jan. 2001	11 Apr. 2001
Cotton	Suregrow 125B/R	110 000 seed	25 May 2001	91 cm	Treatment variable	_	_
Oat	Mitchell	160 kg seed	10 Nov. 2001	17 cm	No-till	22 Jan. 2002	15 Apr. 2002
Ryegrass	Marshall	35 kg seed	10 Nov. 2001	Broadcast	No-till	22 Jan. 2002	15 Apr. 2002
Cotton	Suregrow 501B/R	115 000 seed	24 May 2002	91 cm	Treatment variable	_	_
Oat	Mitchell	160 kg seed	18 Oct. 2002	17 cm	No-till	9 Jan. 2003	10 Apr. 2003
Ryegrass	Marshall	35 kg seed	18 Oct. 2002	Broadcast	No-till	9 Jan. 2003	10 Apr. 2003
Cotton	Suregrow 501B/R	115 000 seed	30 Apr. 2003	91 cm	Treatment variable	_	_

& Co., Moline, IL) was used to plant cotton. Three to four weeks following cotton planting each year, 97–55–19 kg ha^{-1} of N–P–K fertilizer was applied in a band over the row. In all years, a harvest aid (defoliant) was applied at 60% open boll. Alabama Cooperative Extension System recommendations were used to apply all insecticides and defoliants. The center two rows were harvested with a spindle picker equipped with a sacking unit for determination of seed cotton yields on 23 Oct. 2001, 9 Oct. 2002, and 3 Oct. 2003.

Data Collection

Dry matter samples of winter annual forages were collected from each replication in the area to be planted to cotton the following spring, using three animal-exclusion cages (0.81 m^2). Samples were taken three to four times throughout each grazing season, starting when cattle entered the experiment. Sampling dates were 2 Feb., 8 Mar., and 11 Apr. 2001; 22 Jan., 21 Feb., 21 Mar., and 15 Apr. 2002; and 13 Jan., 11 Feb., 11 Mar., and 10 Apr. 2003. After each forage harvest, the three cages were moved to another location within the plot that was grazed. A subsample (0.275 m^2) was taken from each cage, dried at 55°C until all moisture was removed, and weighed to determine dry matter. The sample was ground to pass a 2-mm sieve. Total N was determined by dry combustion from the mean of three subsamples from each ground subsample using a Fisons 1500 NCS nitrogen/carbon analyzer (Fisons Instruments, Beverly, MA) (Jones, 2001). Beef cattle performance was measured by weighing animals at the same time that forage samples were collected. Pasture cost values were estimated assuming application of recommended management practices (Agricultural Economics and Rural Sociology Department–Auburn University, 2004). For informational (nonstatistical) comparisons between cotton following integrated winter-annual grazing vs. the conventional practice of annual cotton cropping, we used the mean yield of the top five performing varieties from the AAES unirrigated cotton variety trials at the location of our study (Wiregrass Research and Extension Center in Headland, AL) during the experiment (Alabama Agricultural Experiment Station, 2003). The soil type for the variety trials was the same as in our experiment. The tillage system used in the AAES cotton variety trials was chisel plus disk tillage without a cover crop, the standard practice by most producers in the region. Cotton plant populations (∼2 wk after sowing) were determined in all years. Plants were counted along 10-m lengths of randomly selected rows (three sections per plot in all treatments).

Soil Water Content

Within the eight tillage and residue management systems tested, we selected four tillage systems (chisel plus disk, paratill plus disk, paratill plus no-till, and no-till), following both forage species, for more intensive data collection, including soil water content. A Tektronix 1502 C (Tektronix, Beaverton, OR) cable tester was used to measure soil water by time-domain reflectrometry (Topp, 1980). Parallel-paired stainless steel rods, 300 mm by 6.4-mm diameter, were installed 10 cm away from the row in a trafficked and an untrafficked interrow, and connected to the cable tester with coaxial cables. Soil water content for this well-drained sandy loam ranges between 0.209 m^3 m^{-3} at field capacity to 0.059 m^3 m^{-3} at the permanent wilting point in the 30-cm depth, indicating an available water holding capacity of 0.150 m^3 m^{-3} in the upper 30 cm of soil (Quisenberry et al., 1987). Average volumetric water content was determined in the top 30-cm soil depth from first bloom to peak bloom in 2001 and 2002. In 2001, measurements were taken seven times, beginning 21 July (day of year [DOY] 202) and finishing 20 August (DOY 232). In 2002, six measures were taken, beginning on 24 July (DOY 205) and finishing 15 August (DOY 227). Row position (sub-subplots) was analyzed as an expansion of the original design (strip-plot) to a strip-split-plot model.

Stomatal Conductance

A Li-1600 steady-state porometer (LI-COR, Lincoln, NE) was used to measure cotton leaf stomatal conductance from the abaxial side of unshaded, uppermost fully expanded leaves in the canopy, in the same plots used for soil water content measurement. Measurements were taken in 2001 and 2002 from single leaves of four different plants per plot from the middle two rows of the plot. They were taken on uncloudy days from 1200 to 1500 h when solar radiation and plant transpiration were maximized. In 2001, measures were taken during cotton bloom seven times, beginning 21 July (DOY 202) and ending 23 August (DOY 235) and six times in 2002, beginning 24 July (DOY 205) and ending 10 August (DOY 222).

Data Analysis

Forage species and tillage system effects on crop and soil indicators were evaluated using the appropriate strip-plot design using the PROC MIXED procedure of the Statistical Analysis System (SAS; Littell et al., 1996). Replication and its interactions were considered random effects and treatments as fixed effects. Analyses across years were made for forage dry matter, N concentration, cotton plant population, and cotton yield, with year treated as a fixed effect to determine interactions involving years. Year × treatment interactions occurred for all variables except for forage dry matter and N concentration. Therefore data were additionally analyzed by year, and treatment effects and data are presented and discussed by year. Soil water content and stomatal conductance were analyzed as a split plot in time; spatial correlation was accounted for each measurement day (Littell et al., 1996). Least square means comparisons were made using Fisher's protected least significant differences (LSD) with a significance level of $P \leq 0.05$ established a priori.

RESULTS AND DISCUSSION

Forages Dry Matter and Nitrogen Concentration

No significant forage × year interactions were observed for dry matter and N concentration; therefore these data are presented averaged across years. A harvest day × forage species interaction was observed between dry matter and N content (Table 2). Oat produced more dry matter than ryegrass at grazing initiation (1.27 vs. 1.03 Mg ha^{-1}, $P \leq 0.05$), but ryegrass produced slightly more dry matter at the end of grazing (1.86 vs. 1.74 Mg ha^{-1}, not significant). These results agree with others who report that oat has a shorter

Table 2. Forage dry matter and N concentration (averaged across years) by harvest dates (month) in an evaluation of two forage species and eight tillage systems for integrating winter-annual grazing with cotton production on a Dothan loamy sand in southeastern Alabama (2001–2003).

Forage species	Dry matter					N concentration			
	Jan.	Feb.	Mar.	Apr.	Total	Jan.	Feb.	Mar.	Apr.
	Mg ha^{-1}					g kg^{-1}			
Oat	1.27	1.58	1.89	1.74	6.47	38.6	29.8	27.9	21.9
Ryegrass	1.03	0.98	1.70	1.86	5.57	36.6	26.7	28.1	29.9
LSD(0.05) (forage × month)			0.18		0.54		2.1		

Table 3. Animal gain at different dates by forage species in an evaluation of two forages and eight tillage systems for integrating winter-annual grazing with cotton production on a Dothan loamy sand in southeastern Alabama (2001–2003).

Forage species	Weight gain per hectare† Feb.	Mar.	Apr.
	——— kg d^{-1} ———		
	2001		
Oat	8.28	7.14	4.29
Ryegrass	8.71	6.60	6.71
LSD(0.05)	NS‡	NS	1.54
	2002		
Oat	8.01	6.53	6.80
Ryegrass	7.92	6.53	7.14
LSD(0.05)	NS	NS	NS
	2003		
Oat	5.22	7.46	5.85
Ryegrass	4.51	7.17	7.03
LSD(0.05)	NS	NS	NS

† Gain per hectare based on average daily gain × stocking rate (five animals ha^{-1}).

‡ NS indicates forage term was not significant ($P \leq 0.05$).

growth cycle than annual ryegrass, and consequently produces less dry matter in late spring (Ball et al., 2002). Oat produced significantly more total dry matter than ryegrass (6.47 vs. 5.57 Mg ha^{-1}, $P \leq 0.05$). Differences among years occurred for forage dry matter production (data not shown). In 2002, total forage dry matter was 48 and 34% higher than in 2001 and 2003, respectively. Fewer growing degrees, calculated with 4.4 and 0°C base for oat and annual ryegrass, respectively (Colville and Frey, 1986; Griffith and Chastain, 1997), accumulated through the season in 2001 and 2003, with decreased production. The 2002 season (November–April) accumulated 357 and 323 more growing degree days than the 2001 and 2003 seasons, respectively.

Nitrogen concentration of forage species duplicated dry matter trends (Table 2). A harvest day × forage species interaction occurred. Oat had a tendency for higher N concentration in the beginning of the season (not significant) but ryegrass had a higher N concentration at the end of the season (29.9 vs. 21.9 g kg^{-1}, $P \leq 0.001$). As indicated above, annual ryegrass has a longer cycle of production and subsequently provides more sustained nutritional pastures for grazing than oat. This is one reason that, in a wide range of grazing experiments that evaluated different winter-annual pastures for stocker production, ryegrass was considered better than small grains (Ball et al., 2002; Bransby et al., 1999). In our study, however, we found no practical differences between forage species for total dry matter production, suggesting that both forages responded to the established grazing pressure in a similar fashion. Total N uptake by forage species was similar among years (data not shown); however, ryegrass N uptake was increased at the end of the season compared with oat. For a following summer crop like cotton, this has implications regarding N availability. Ryegrass has been shown to have negative effects on following crops by increasing N fertilizer needs and by using more water than oat in late spring (Evers et al., 1997).

Table 4. Estimated total gain, gross income, total expenses, net returns and cost per kilogram of animal gain by forage species in an evaluation of two forage species and eight tillage systems for integrating winter-annual grazing with cotton production on a Dothan loamy sand in southeastern Alabama (2001–2003).

Parameter	Oat	Ryegrass
Grazing time, d	81	
Total gain ha^{-1}, kg†	541	561
Gross income, US$ ha^{-1}‡	378	393
Total expenses, US$ ha^{-1}§	193	
Net returns, US$ ha^{-1}	185	200
Cost kg^{-1} of gain, US$	0.36	0.34

† Total gain ha^{-1} = cumulative difference in animal mass per stocked experimental unit during grazing period; calculated as average daily gain × stocking rate (five animals ha^{-1}) × days of grazing.

‡ Based on price under contract: avg. US$0.70 kg^{-1}.

§ Total expenses do not include fences, water facilities, and land cost.

Average Daily Gain and Economic Return

Only in the last grazing period in 2001 (April), did annual ryegrass provided higher gain per hectare than oat (Table 3); however, there was a tendency in all years for ryegrass to have better average daily gain than oat at the end of the season. This information agrees with the results found with respect to dry matter production and N concentration at the end of the grazing period (Table 2). Total gain per hectare averaged 551 kg for 81 d of grazing (Table 4). Recent studies with ryegrass grazing at three locations in Alabama established an average daily gain of 6.5 kg for stocker cattle in winter to early spring averaged across 122 d of grazing (Bransby et al., 1999). In our experiments, the average daily gain per hectare was 6.8 kg, which was similar to the results reported by Bransby et al. (1999), demonstrating the potential of this system.

According to the Auburn University Department of Agricultural Economics and Rural Sociology (Agricultural Economics and Rural Sociology Department–Auburn University, 2004), the total cost of winter annual grazing in our experiment was US$193 ha^{-1} (does not include fences, water facilities, or land cost), leaving a net return from the inclusion of winter-annual grazing of ~US$185 to US$200. Another criterion used to compare systems for livestock production is cost per kilogram of gain, which is dependent on input costs, production levels per animal per hectare, and length of the grazing season. Ball et al. (2002) stated that winter annual pastures are comparatively expensive and must be well managed to produce profits. They reported costs per kilogram of gains of ~US$0.55 to US$0.88. In our experiment, the cost per kilogram of gain (averaged across years and forage species) was US$0.35. This demonstrates, under current economic conditions, that it is possible to achieve weight gains grazing oat or annual ryegrass profitably.

Cotton Population

Due to interactions (i.e., year × forage species × tillage system), plant population data are presented separately by year (Table 5). Plant population was affected by forage species (25% more cotton plants following oat compared with ryegrass). Differences in plant stands associated with forage residues appeared to be partially due to mechanical problems that prevented good seed–soil contact; however, no soil strength or water content measurements were taken at planting. Annual ryegrass produced more dry matter, and N uptake was increased by the end of the season (45%

greater N uptake with ryegrass than oat in the last month of grazing). We speculate that this resulted in soil water depletion and potential short-term N immobilization by ryegrass, which might have impaired cotton plant stand and seedling growth. Stand reduction might also be associated with allelopathic exudates from ryegrass residues (Burgos and Talbert, 1996). In all tillage systems, the best cotton stands followed oat, indicating no interaction between forage species and tillage systems in two of the three year (2001 and 2003). In 2002, a forage species × tillage systems interaction occurred. Plant populations were similar between both forage species with the moldboard plus disk treatment; however, plant populations for the other seven tillage systems were higher following grazed oat than grazed ryegrass. For this warm spring (2002), both forage species had the highest dry matter production among years, which might explain the differences in cotton plant stands between these two forage species (Bauer and Reeves, 1999).

No-till without in-row deep tillage (i.e., Paratilling or subsoiling) had the lowest plant population in all years (significant in 2002 and 2003), but the magnitude of this difference among tillage systems varied among forage species and years (Table 5). Averaged across years and forage species, no-till had the lowest cotton plant stand (28% less than the overall mean), but noninversion deep tillage alleviated this problem. There was no difference between the two noninversion deep tillage methods (in-row subsoil or Paratill) used in conjunction with no-till, but there was a consistent trend toward increased plant stands with in-row subsoiling compared with Paratilling following ryegrass (16% greater plant stands). The in-row subsoiler disrupts the seed zone before planting, while the Paratill lifts the soil surface under the seed zone without disrupting it. We speculate that the Paratill failed to fracture surface soil compaction in the seeding zone compared with the in-row subsoiler, which resulted in poorer seed–soil contact with the Paratill.

Table 5. Cotton plant populations as affected by forage species and tillage system in an evaluation of two forages and eight tillage systems for integrating winter-annual grazing with cotton production on a Dothan loamy sand in southeastern Alabama (2001–2003).

Tillage system	2001		2002		2003	
	Oat	Ryegrass	Oat	Ryegrass	Oat	Ryegrass
	1000 plants ha^{-1}					
Moldboard + disk	83.6	77.6	93.4	84.2	84.2	78.8
Disk	82.7	75.7	90.7	68.0	83.5	60.2
Chisel + disk	78.0	76.2	89.7	66.8	76.1	52.9
In-row subsoil† + disk	93.5	79.1	83.9	68.2	73.4	58.4
In-row subsoil + no-till	85.4	76.4	83.9	65.6	71.8	59.2
Paratill‡ + disk	84.7	84.1	100.6	67.4	81.4	66.7
Paratill + no-till	86.6	72.2	88.8	50.7	64.4	50.2
No-till	80.3	56.9	68.8	30.7	61.0	33.1
Least square mean	84.4	74.8	87.4	62.7	74.5	57.5
LSD(0.05) for year × forage			7.6			
LSD(0.05) for year × tillage			9.3			
LSD(0.05) for forage	5.4		7.8		9.4	
LSD(0.05) for tillage	NS§		9.0		8.4	
LSD(0.05) for tillage × forage	NS		11.1		NS	

† Noninversion deep tillage using a "narrow-shanked" subsoiler in row.
‡ Noninversion deep tillage using a "bent-leg" subsoiler.
§ NS indicates not significant at P≤ 0.05.

Soil Water Content

Rainfall quantity and distribution were different among years (Fig. 1). Four tillage systems were selected (chisel plus disk, paratill plus disk, paratill plus no-till, and no-till) to monitor soil water content during bloom. These represented the standard conventional tillage practice (chisel plus disk) with and without noninversion in-row deep tillage, and no-till with and without noninversion deep tillage. Row position, forage species, and tillage system affected soil water content averaged during the 30-d period in 2001 and the 22-d period in 2002 in which measurements were taken (Table 6). Since no row position × tillage system or row position × forage species interactions occurred for soil water content (0–30-cm depth) for any of the years, only main effects are shown. The main difference in soil water content was found between the trafficked and nontrafficked positions in both years (Table 6). The trafficked position presented higher soil water contents than the nontrafficked position (16 and 12% greater soil water contents in 2001 and 2002, respectively). This is consistent with reduced root growth and consequent reduced water uptake in trafficked interrows compared with nontrafficked interrows as a result of greater compaction by equipment traffic (Touchton et al., 1989; Reeves et al., 1992; Schwab et al., 2002). In 2002, soil water following oat during cotton bloom averaged less than following ryegrass (0.101 vs. 0.121 m^3 m^{-3}). As shown in Fig. 1, in the period that measurements were taken, 2002 was a dry year. Ryegrass has a fibrous root system and greater rates of

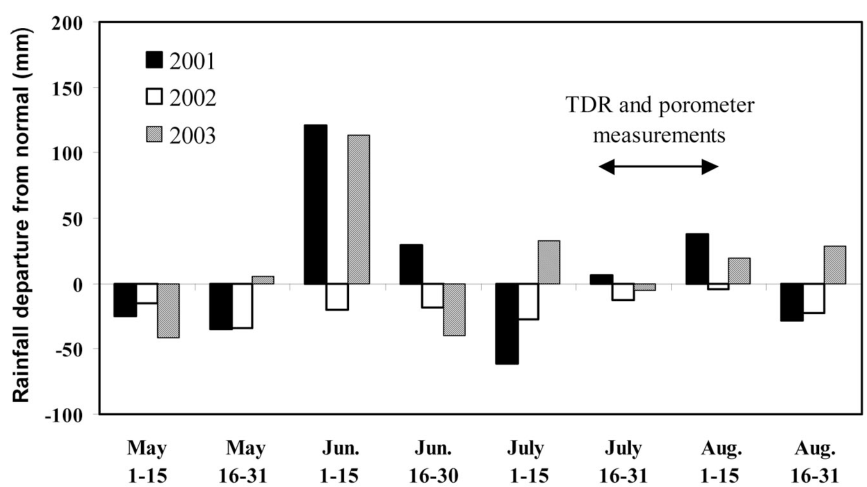

Fig. 1. Biweekly departure from long-term average rainfall (1938–2003) for the 3 yr under study on a Dothan loamy sand in southeastern Alabama (2001–2003). Soil water determination by time domain reflectometry (TDR), stomatal conductance determined using a porometer.

Table 6. Averaged soil volumetric water content during cotton bloom (2001–2002) as affected by row position, forage species, and selected tillage systems in an evaluation of two forages and eight tillage systems for integrating winter-annual grazing with cotton production on a Dothan loamy sand in southeastern Alabama.

Parameter	Soil water content		
	2001	2002	
		Oat	Ryegrass
	$m^3\ m^{-3}$		
Row position			
Untrafficked	0.126	0.105	
Trafficked	0.146	0.118	
LSD(0.05)	0.011	0.004	
Forage species			
Oat	0.137	0.101	
Ryegrass	0.136	0.121	
LSD(0.05)	NS†	0.013	
Tillage system			
Chisel + disk	0.126	0.088	0.130
Paratill‡ + disk	0.127	0.084	0.119
Paratill + no-till	0.133	0.109	0.116
No-till	0.157	0.123	0.120
LSD(0.05) for tillage	0.010		
LSD(0.05) for forage × tillage	NS	0.022	

† NS indicates not significant ($P \leq 0.05$).

‡ Noninversion deep tillage using a "bent-leg" subsoiler.

root growth in relation to shoot growth compared with temperate cereals such as oat (Troughton, 1957). Our results suggest that the aggressive root system of ryegrass impairs cotton root growth, and that subsequently, cotton extracted less water during the drought year of 2002. We speculated that several factors are acting in concert: more soil water depletion, N immobilization during residue decomposition, and allelopathic effects that consequently hinder cotton growth (Troughton, 1957; Weston, 1993).

The no-till without Paratilling system resulted in higher soil water contents than the other tillage systems. Paratill in no-till, averaged across years and forage species, reduced soil water content by 13% compared with strict no-till (Table 6). We speculate that this response can be credited to greater soil water extraction from increased root growth at deeper depths (Reeves and Mullins, 1995; Schwab et al., 2002). Conventional tillage systems (chisel plus disk and Paratill plus disk) resulted in the lowest soil water contents during cotton bloom, except in 2002, when an interaction of forage species × tillage system occurred. In this year, there was no difference in soil water content among tillage systems following annual ryegrass. In contrast, following oat, conservation tillage systems averaged 35% higher soil water content than the mean of the conventional tillage systems (Table 6). Within the no-till systems (with or without Paratilling), soil water content was similar regardless of preceding grazed winter forage species, but conventional tillage systems (with or without Paratilling) resulted in lower soil water contents following oat vs. following ryegrass.

Daily soil water contents averaged across row position and forage species in 2001 and across row position in 2002 are shown in Fig. 2. Even though variations occurred during the measurement periods due to differences in rainfall distribution and cotton water needs for different phenological stages, strict no-till always resulted in higher soil water contents in 2001 (six of seven measurement days). An interaction among forage species × tillage systems existed for soil water content in 2002 ($P \leq 0.01$). This interaction may be explained by the differences in rainfall between 2001 and 2002 plus the differences among forage dry matter production between these 2 yr. Assuming that this sandy loam soil has 0.150 $m^3\ m^{-3}$ of available water in the top 30 cm (Quisenberry et al., 1987), all tillage systems had very low soil available water for plant growth during cotton bloom. Half of the period (DOY 217–227) had <25% of available soil water for cotton growth, demonstrating that water stress was severe for this particular year. Soil water stress in 2002 was confirmed by significantly lower stomatal conductance measurements (discussed below) and seed cotton yield in 2002 than 2001.

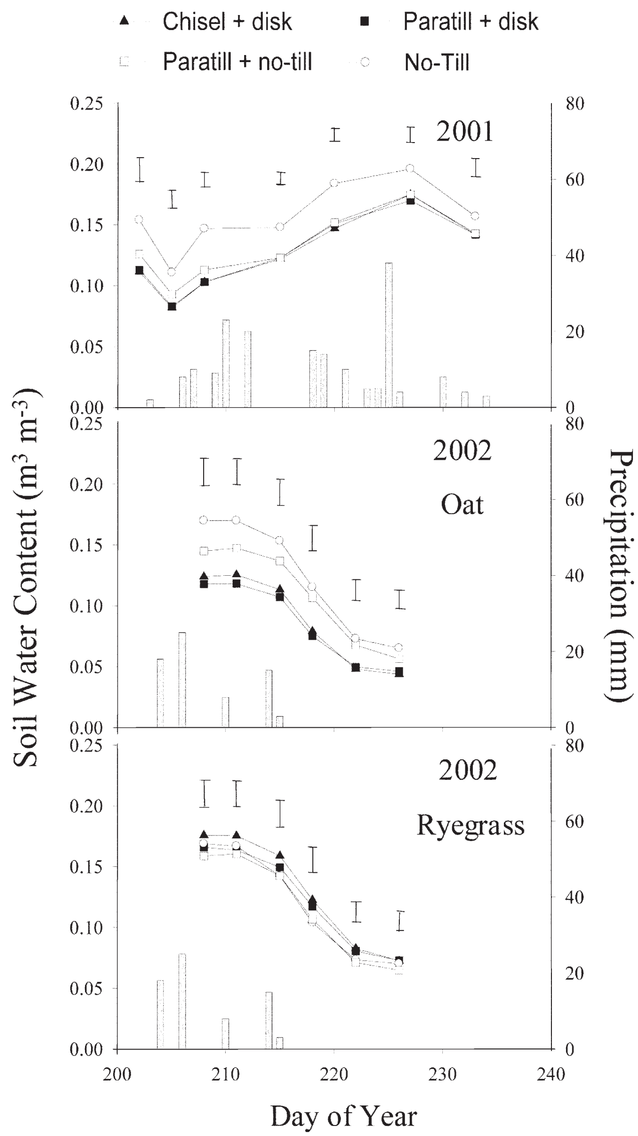

Fig. 2. Precipitation and volumetric soil water content during cotton bloom (averaged across row positions) as affected by selected tillage systems (2001) and forage × tillage system interaction (2002) in an evaluation of two forages and eight tillage systems for integrating winter-annual grazing with cotton production on a Dothan loamy sand in southeastern Alabama. Vertical bars indicate LSD at the 0.05 level of significance.

Table 7. Averaged cotton stomatal conductance (2001–2002) as affected by forage species and selected tillage systems in an evaluation of two forages and eight tillage systems for integrating winter-annual grazing with cotton production on a Dothan loamy sand in southeastern Alabama.

Tillage system	Cotton stomatal conductance 2001	2002 Oat	2002 Ryegrass
	——— mmol m^{-2} s^{-1} ———		
Chisel + disk	669	447	450
Paratill† + disk	695	397	476
Paratill + no-till	677	473	451
No-till	687	470	450
LSD(0.05) for forage	NS‡	NS	
LSD(0.05) for tillage	20		
LSD(0.05) for tillage × forage	NS	26	

† Noninversion deep tillage using a "bent-leg" subsoiler.

‡ NS indicates not significant ($P \leq 0.05$).

Stomatal Conductance

Cotton leaf stomatal conductance measurements were taken in the same tillage systems selected for soil water content measurements. There was no difference between forage species for stomatal conductance between years (data not shown). A forage species × tillage system interaction occurred for cotton leaf stomatal conductance in 2002, while only tillage system main effects were significant in 2001 (Table 7). In 2002, averaged across 33 d, the chisel plus disk systems resulted in the lowest average stomatal conductance (669 mmol m^{-2} s^{-1}), with no differences among the other tillage systems. The chisel plus disk treatment also resulted in the lowest soil water contents measured in 2001.

For 2002, averaged across 17 d, both conventional tillage systems resulted in the lowest mean stomatal conductances following oat (397 and 447 mmol m^{-2} s^{-1} for Paratill plus disk and chisel plus disk, respectively), while there were no significant differences between the no-till systems (470 and 473 mmol m^{-2} s^{-1} for strict no-till and Paratill plus no-till, respectively). These two tillage systems resulted in the highest average soil water contents following oat for this particular year (0.120 and 0.116 m^3 m^{-3} for strict no-till and Paratill plus no-till, respectively). Following ryegrass, only the Paratill plus disk system resulted in increased average stomatal conductance (476 mmol m^{-2} cm^{-1}) compared with the other three systems, which had similar average stomatal conductances. Averaged across forage species, both no-till systems resulted in higher stomatal conductances and higher soil water contents during flowering (Table 6). Daily leaf stomatal conductance for four tillage systems in 2001 (averaged across forage species) and four tillage systems × forage species in 2002 are shown in Fig. 3. In 2002 following oat, at DOY 222 during a period without significant rain, there were significant differences in stomatal conductance between conventional tillage (chisel plus disk and Paratill plus disk) and no-till systems (no-till and Paratill plus no-till; Fig. 3). Stomatal conductance response through first bloom to peak bloom (DOY 205–227) followed the same trend as soil water content (Fig. 2). Stomatal conductance and photosynthesis are considered to be important in regulating yield; however, the use of deep tillage has been reported to result in decreased

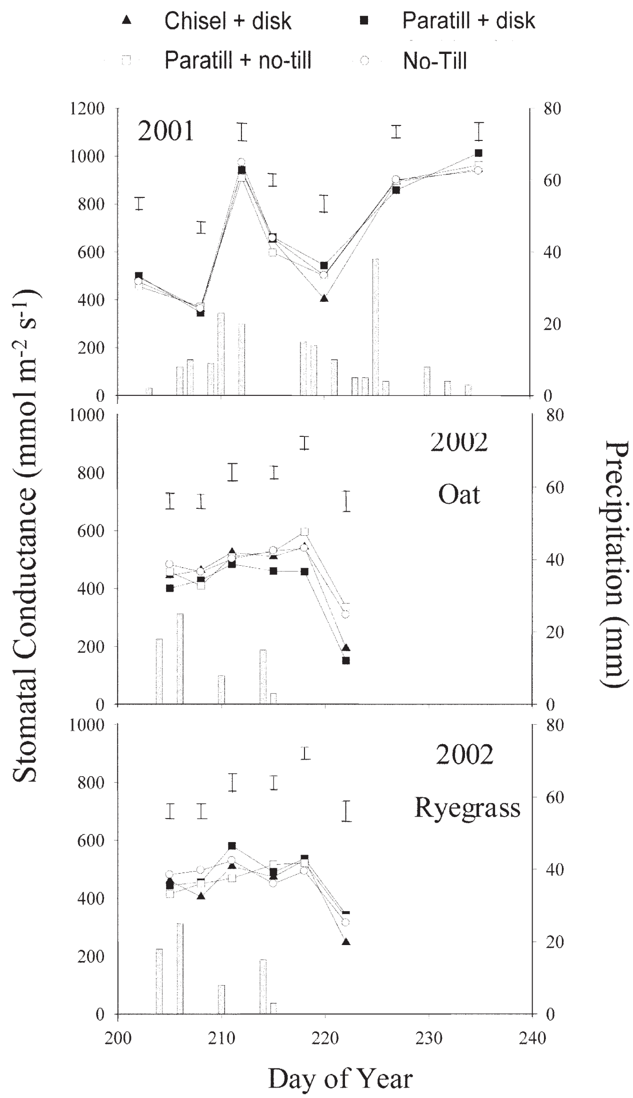

Fig. 3. Precipitation and stomatal conductance during cotton bloom as affected by selected tillage systems (2001) and forage × tillage system interaction (2002) in an evaluation of two forages and eight tillage systems for integrating winter-annual grazing with cotton production on a Dothan loamy sand in southeastern Alabama. Vertical bars indicate LSD at the 0.05 level of significance.

soil water contents (increased soil water extraction) concurrently with reductions in stomatal conductance without reducing cotton yields (Young and Browning, 1977; Reeves and Mullins, 1995).

Seed Cotton Yield

Interactions among year × forage species and year × tillage system occurred for cotton yields (Table 8). Cotton yield averaged 3.85, 3.16 and 4.08 Mg ha^{-1} for 2001, 2002, and 2003, respectively. In 2003, cotton following oat had a higher yield than the same crop following ryegrass (4.33 vs. 3.83 Mg ha^{-1}, $P \leq 0.025$), and a similar nonsignificant trend for higher cotton yields following oat than following annual ryegrass was found in 2001 and 2002 (3.89 vs. 3.81, $P \leq 0.22$, and 3.22 vs. 3.09, $P \leq 0.12$ Mg ha^{-1}, respectively). Although cotton plant populations were affected by forage species, they had no significant impact on yield in 2001 and 2002. In 2003, however, grazed oat resulted in higher cotton plant

Table 8. Seed cotton yields as affected by forage species and tillage system in an evaluation of two forages and eight tillage systems for integrating winter-annual grazing with cotton production on a Dothan loamy sand in southeastern AL (2001–2003).

	Seed cotton yield			
	2001	2002	2003	
	Mg ha^{-1}			
Forage species				
Oat	3.89	3.22	4.33	
Ryegrass	3.81	3.09	3.83	
LSD(0.05) for forage	NS†	NS	0.28	
LSD(0.05) for year × forage	0.25			
Tillage system			Oat	Ryegrass
Moldboard + disk	3.66	2.96	4.76	4.48
Disk	3.90	3.23	4.53	3.88
Chisel + disk	4.08	3.13	4.78	3.50
In-row subsoil‡ + disk	4.00	3.34	4.25	4.07
In-row subsoil + no-till	3.92	3.30	4.20	3.95
Paratill§ + disk	4.02	3.28	4.39	4.24
Paratill + no-till	3.91	3.33	4.62	4.49
No-till	3.29	2.69	3.08	2.04
LSD(0.05) for tillage	0.29	0.41		
LSD(0.05) for forage × tillage	NS	NS	0.41	
LSD(0.05) for year × tillage		0.40		

† NS indicates not significant ($P \leq 0.05$).

‡ Noninversion deep tillage using a "narrow- shanked" subsoiler in row.

§ Noninversion deep tillage using a "bent-leg" subsoiler.

density than grazed annual ryegrass (74 500 vs. 57 000 plants ha^{-1}, $P \leq 0.025$). This may have positively impacted cotton yields. In 2003, there was a forage species × tillage system interaction on seed cotton yields. Averaged for the 3 yr, strict no-till resulted in the lowest seed cotton yields: 2.85 Mg ha^{-1} averaged across forages and 30% less than the overall mean. Paratill and in-row subsoiling, however, maximized seed cotton yield in no-till systems, and yields were highly competitive using noninversion deep tillage in combination with no-till. Similar results have been found in the literature, indicating that subsoiling is necessary for maximum cotton yields in Coastal Plain soils with root-restricting soil layers (Busscher et al., 1988; Reeves and Mullins, 1995). Following ryegrass, there was a trend for Paratilling to increase seed cotton yield compared with in-row subsoiling: 3.88 Mg ha^{-1} vs. 3.63 Mg ha^{-1} ($P \leq 0.12$). Yields were similar for Paratilling and in-row subsoiling following oat: 3.97 Mg ha^{-1} vs. 3.90 Mg ha^{-1}, $P \leq 0.92$). By comparison, the 2001 to 2003 average seed cotton yield of the best five varieties in the full-season unirrigated cotton variety trials at this experiment station was 2.93 Mg ha^{-1} (Alabama Agricultural Experiment Station, 2004). Average yield for cotton following winter-annual grazing in our experiment was 3.69 Mg ha^{1}.

CONCLUSIONS

Our results indicate that integrating winter-annual grazing with cotton provided producers additional income (range: US$185–200) without sacrificing cotton yield. Cotton plant populations following annual ryegrass were lower than following oat. Additionally, in 1 of 2 yr, stomatal conductance and soil water extraction data suggested that cotton rooting and water availability were enhanced following oat compared with ryegrass. Thus, cotton following grazed oat appears to be a better choice than grazed ryegrass: average yields were 3.81 Mg ha^{-1} following oat vs. 3.58 Mg ha^{-1} following ryegrass. In general, soil water content and cotton stomatal conductance were lower with conventional tillage, or noninversion Paratill in no-till systems, suggesting improved rooting and less water stress with these tillage systems.

Strict no-till resulted in the lowest cotton yields (30% less than the overall mean), and noninversion deep tillage was necessary in no-till systems. Within no-till systems, there was a tendency for better cotton yields with Paratilling than in-row subsoiling using a narrow-shanked subsoiler. Our results suggest that the best forage–tillage system combination for integrating winter-annual grazing was Paratilling following oat in a conservation tillage system. This practice can reduce erosion potential, provide a much needed source of additional revenue, and still sustain competitive cotton yields.

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