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Crop and cattle responses to tillage systems for integrated crop–livestock production in the Southern Piedmont, USA

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Abstract

Integration of crops and livestock has the potential to provide a multitude of benefits to soil and water conservation and nutrient cycling efficiency, while reducing economic risk and increasing profitability. We conducted a field study from May 2002 to October 2005 to determine crop and cattle responses to three management factors on a Typic Kanhapludult in Georgia, USA. Summer grain/winter cover [sorghum (*Sorghum bicolor* L. Moench) or corn (*Zea mays* L.)/rye (*Secale cereale* L.)] and winter grain/summer cover [wheat (*Triticum aestivum* L.)/pearl millet (*Pennisetum glaucum* L. R. Br.)] were managed with either conventional tillage (CT) or no tillage (NT) and with or without cattle grazing of cover crops. All crops were successfully established, irrespective of tillage and cover crop management. Although pearl millet was often lower in the plant stand with NT than with CT, plants compensated with greater biomass on an area basis. Across years, grain yield of sorghum (1.9 Mg ha^{-1} during three seasons) and corn (7.3 Mg ha^{-1} in one season) was 25% greater under NT than under CT when the cover crop was not grazed. Wheat grain yield (2.7 Mg ha^{-1} during three seasons) was unaffected by tillage and cover crop management. Unharvested stover production of summer grain crops was greater with NT than with CT (6.5 versus 4.1 Mg ha^{-1}; $P < 0.001$). Grazing rye rather than allowing it to accumulate as surface residue reduced summer grain yield 23% and reduced standing grain-crop dry matter 26% under NT, but had no effect under CT. In contrast, grazing pearl millet rather than allowing it to accumulate as surface residue increased wheat standing dry matter yield by 25 ± 14% (mean ± standard deviation among 3 years and two tillage systems). Ungrazed cover crop production was greater under NT than under CT for rye (7.0 versus 6.0 Mg ha^{-1}; $P = 0.03$) and pearl millet (10.2 versus 7.6 Mg ha^{-1}; $P = 0.01$). Calf daily gain was either greater or tended to be greater under NT than under CT on rye (2.27 versus 2.09 kg head^{-1} d^{-1}; $P = 0.15$) and pearl millet (2.05 versus 1.81 kg head^{-1} d^{-1}; $P = 0.05$). Total cattle gain per grazing season was either greater or tended to be greater with NT than with CT on rye (350 versus 204 kg ha^{-1}; $P = 0.01$) and pearl millet (324 versus 277 kg ha^{-1}; $P = 0.15$). Net return over variable costs was greater with grazing than without grazing of cover crops (US\$302 versus −US\$63 ha^{-1}; $P < 0.001$). Livestock grazing of cover crops had variable effects on subsequent crop production, but increased economic return and diversity overall. Therefore, an integrated crop–livestock production system with conservation tillage is recommended as a viable option for producers to diversify farming operations to avoid risk, improve ecological production of crops, and potentially avoid environmental damage from soil erosion and nutrient loss.

Key words: cattle production, conservation tillage, corn, cover cropping, pearl millet, rye, sorghum, wheat

Introduction

Integrated crop–livestock production is not common in modern agricultural production systems for a number of reasons. Technological advances in plant genetics, machinery and synthetic chemicals, as well as shifting government policies during the past century are the primary reasons that agriculture has been transformed from small, diversified farming operations to large specialized production

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facilities. Despite this change, a growing awareness is emerging that the stability and resiliency of modern agricultural landscapes are now becoming impaired by this shift to enterprise specialization, concentration of operations, and expansion of scale. Energy and nutrient cycles are becoming spatially and temporally compartmentalized in a manner far removed from natural ecosystem cycling[1]. There is a need to rediscover the mechanisms and attributes of integrated crop–livestock production systems to (1) enable more efficient utilization of natural resources (sunlight, water, biologically fixed N, and recycled nutrients), (2) exploit natural pest control phenomena, (3) reduce nutrient concentration and consequent environmental risk, and (4) improve soil functioning and productivity[2].

Soil organic matter is a critical component in maintaining soil quality[3]. Pastures are known to increase soil organic matter quantity due to large input of residues and lack of disturbance[4], which could lead to retention of organically bound nutrients and improved water relations in soil. Cropping systems under conditions of high soil organic matter have not been evaluated in the Southern Piedmont, USA, because much of the cropland has been degraded by historical cropping that caused excessive soil erosion[5]. Crop responses to tillage management following pasture termination may be significantly different than responses on previously degraded land, because of the presence of a large storage of nutrients, soil biological potential and improved soil physical structure.

Yield of crops as affected by tillage management in the southeastern USA has been investigated previously in several studies. A general recommendation has been hampered by the diversity of yield responses to tillage obtained. Yield reduction with NT compared with CT has been observed for sorghum in Texas[6], wheat stover in Texas[6], and wheat grain in North Carolina[7] and South Carolina[8]. Equivalent yield between conventional tillage (CT) and no tillage (NT) has been observed for wheat grain in Texas[6] and South Carolina[9]. Yield enhancement with NT compared with CT has been observed for sorghum in Georgia[10], for corn in North Carolina[11], Georgia[12], and Alabama[13], and for wheat in South Carolina (when preceded by deep ripping)[11]. The diversity of yield responses to tillage suggests that any NT advantage would be more likely to occur with summer grain crops than with winter grain crops.

The effect of tillage system on cover crop production has been previously investigated to a limited extent. On a Typic Rhodudult in Georgia, rye cover crop production was 5.9 $Mg\,ha^{-1}$ under CT and 8.5 $Mg\,ha^{-1}$ under NT during 2 years[14]. However, crimson clover (*Trifolium incarnatum* L.) cover crop production was lower under NT (3.6 $Mg\,ha^{-1}$) than under CT (5.7 $Mg\,ha^{-1}$). On a Plinthic Paleudult in Georgia, hairy vetch (*Vicia villosa* Roth.) cover crop production was 4.6 $Mg\,ha^{-1}$ under moldboard plowing and 4.8 $Mg\,ha^{-1}$ under NT during 2 years[15]. In this same study, winter annual weed production without a planted cover crop was 1.8 $Mg\,ha^{-1}$ under moldboard plowing and 1.3 $Mg\,ha^{-1}$ under NT. Cover crops have typically been incorporated into contemporary cropping systems only in combination with conservation tillage to obtain surface residue accumulation[16].

Climatic conditions in the Southern Piedmont are characterized by excessive precipitation to potential evapotranspiration during the winter growing season, but during the summer growing season precipitation is similar to potential evapotranspiration. The impact of time of grain cropping (i.e., winter versus summer) on grain yield and forage availability has not been directly evaluated, especially under conditions of initially high soil organic matter. Under a double-cropping environment in the southeastern USA, a cover crop following grain cropping could provide high-quality forage to supplement shortages from potential perennial pasture.

Animals grazing cover crops could compact soil due to excessive animal traffic, especially when the soil is wet. Tollner et al.[17] observed compaction from cattle traffic in a Southern Piedmont soil with low soil organic matter. However, surface residue cover may provide a significant buffer against animal trampling effects, such that NT crop production following long-term pasture could alleviate the negative effects of animal trampling.

We hypothesized that winter grain production would be more reliable than summer grain production due to milder temperature and less risk from drought. It is possible that time of grain production could interact with tillage management, such that NT might have a positive impact on summer grain production, but a negative impact on winter grain production due to lower temperature and excessive soil moisture. It is also more likely that winter grazing of a cover crop could compact soil compared with summer grazing, especially under CT. We conducted this study to assist crop and animal producers in determining the appropriate timing for grazing and tillage management to optimize crop production without degrading soil and water resources.

Materials and Methods

The experiment was located at the US Department of Agriculture (USDA)-Agricultural Research Service J. Phil Campbell Sr. Natural Resource Conservation Center in Watkinsville, GA (33° 62′ N, 83° 25′ W) on Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult). Soil was moderately acidic (pH∼6) and contained moderate total N (1.2 $g\,kg^{-1}$) in the upper 20 cm. The experimental design was a completely randomized arrangement of 16 main plots. Main plots were a factorial arrangement of (a) tillage and (b) time of grain/cover cropping, which were replicated four times. Main plots were split into grazed (0.5 ha) and ungrazed (0.2 ha) cover crop treatments. A total of 16 main plots and 32 split plots were evaluated from May 2002 to October 2005.

Previously, the experimental area was in tall fescue [*Lolium arundinaceum* (Schreb.) S.J. Darbyshire] for 20

years. Unfertilized pasture growth during the three years just prior to the experiment was expected to remove differences in residual inorganic soil N among paddocks. All paddocks received dolomitic limestone ($2.2\,Mg\,ha^{-1}$) immediately prior to termination of the tall fescue. The 16 experimental paddocks were regarded as an excellent starting point for the proposed research, because soil organic matter was at a high level[18] and grazing infrastructure was mostly in place at the site (fencing, gates, shades, mineral feeders, watering troughs, and animal handling facility).

Tillage systems were: (1) conventional disk tillage (CT) following harvest of each grain and cover crop and (2) NT with glyphosate to control weeds prior to planting. Tillage treatments were initiated in May 2002. Initial CT treatment consisted of moldboard plowing to a depth of 25–30 cm. Disk plowing only to a depth of 15–20 cm occurred in subsequent years. Pasture was terminated in the NT treatment with two applications of glyphosate (Table 1).

Cropping systems were: (1) winter grain cropping [wheat (*Triticum aestivum* L.); November planting and May/June harvest] with summer cover cropping {pearl millet [*Pennisetum glaucum* (L.) R. Br.]; June/July planting and September/October termination} and (2) summer grain cropping {grain sorghum [*Sorghum bicolor* (L.) Moench] or corn (*Zea mays* L.); April to June planting and September/October harvest} with winter cover cropping [cereal rye (*Secale cereale* L.); November planting and May termination]. Management details of each crop are reported in Table 1. Sorghum, rye, wheat, and pearl millet were planted with a John Deere grain drill for CT and a Great Plains drill for NT.

Cover crop management was: (1) no grazing and (2) grazing with cattle to consume 90% of available forage produced. Cover crops were stocked with yearling Angus steers in the summer of 2002 and in the spring of 2003 (Table 1). Thereafter, cow/calf pairs were used to simulate a more typical regional management approach. Stocking rates and weights are reported in Table 2. Ungrazed cover crops were grown until approx. 2 weeks prior to planting of the next crop and either (1) mowed prior to CT operations or (2) mechanically rolled to the ground in the NT system[19].

Application of N was relatively low during the first 3 years, but was adequate to assure early plant growth and development with further growth dependent upon the mineralization of stored nutrients in soil organic matter. Extractable P and K concentrations in the surface 7.5 cm of soil were $\geqslant 100\,mg\,P\,kg^{-1}$ soil and $400\,mg\,K\,kg^{-1}$ soil[20]; levels considered adequate for crop production.

Early-season plant population of crops was determined by counting the number of plants in two adjacent rows 1 m long at three locations in ungrazed plots and five locations in grazed plots. Plant populations were not determined during the first year of this study.

Grain yield was determined by weighing the contents of the entire experimental unit harvested with a field combine followed by unloading onto a truck with scales placed under all tires. A subsample of grain was collected for moisture determination and protein concentration (calculated as $6.25 \times N$ concentration). Grain yield was adjusted to an oven-dried basis (55°C, $\geqslant 72$ h). Standing grain-crop dry matter following grain harvest was determined from 0.15×1-m areas (three areas in ungrazed plots and five areas in grazed plots). Cover-crop above-ground dry matter was collected in the same manner. Hand-harvested yield was determined for wheat in 2004 from 0.38-m^2 areas, for sorghum in 2004 from 0.76-m^2 areas, and for corn in 2005 from 4.56-m^2 areas in each plot and separated into grain and stover components. Grain, stover and forage components were weighed before and after oven drying (55°C).

A variable stocking rate was used to consume $\geqslant 90\%$ of available forage from each paddock. Stocking was targeted so that grazing could last for at least a month. Since grazing was initiated when cover crops were 0.3–0.5 m tall and actively growing, stocking estimates from experienced animal scientists were used rather than quantitative measures. Performance and production were determined from periodic weighing of cattle (2.4 ± 1.4 times per grazing season with 20 ± 11 days in each period). Cattle shrunk weight during each handling event was determined by not offering water for 16 h (evening prior to next day handling), herding animals into the nearby handling facility in the morning, and weighing of animals on a balance under a cattle chute. Cattle gain ha^{-1} was calculated as the difference in initial and final weight of all cattle placed on a paddock during a grazing season. Average daily gain was calculated from total weight gain divided by the number of cattle and grazing days in a season.

The general linear model procedure of SAS was used to analyze variances for each of the plant and animal responses during each growing season separately[21]. Means across years were analyzed for variance, with year as a random variable in the error term. Significant differences among means were declared at $P \leqslant 0.05$, unless otherwise indicated. Only a priori contrasts between cover crop treatments within a tillage system and between tillage systems with a cover crop management were considered.

Results and Discussion

Crop establishment

Establishment of most crops was not affected by tillage and cover crop management, except for pearl millet, corn and wheat (Table 3). Pearl millet population under NT was $66 \pm 9\%$ of that under CT during the 3 years of evaluation. One reason for the lower plant population with NT compared with CT may have been due to poorer seed-to-soil contact in the surface residue layer as a result of the need for shallow planting of the small seed. Also, occasional flocks of birds may have consumed seeds or seedlings when foraging in the residue-rich surface soil

Table 1. Crop management inputs and characteristics from 2002 to 2005 at Watkinsville GA.

	Summer grain/winter cover		Summer cover/winter grain	
Property	**Sorghum or corn**	**Rye**	**Pearl millet**	**Wheat**
Cultivar	*Sorghum*—Pioneer 83G66 (2002–2004) *Corn*—Pioneer 31N26 (2005)	Hi-Gainer (2002–2003), Wrens Abruzzi (2004)	Tifleaf 3 (2002–2005)	Crawford (2002), 518W (2003), Coker 9863 (2004)
Row spacing	*Sorghum*—34 cm (CT), 38 cm (NT) *Corn*—76 cm	19 cm	17 cm (CT), 19 cm (NT)	19 cm
Planting date	13–14 Jun 2002, 2–5 Jun 2003, 18–19 May 2004, 11 Apr 2005 (NT), 19 Apr 2005 (CT)	2 Dec 2002, 5 Nov 2003, 10–16 Nov 2004	12 Jun 2002, 26 Jun 2003, 22–23 Jun 2004, 6 Jul 2005 (NT), 28 Jul 2005 (CT)	28 Nov 2002, 4–6 Nov 2003, 10–16 Nov 2004
Harvest/ termination date	15–22 Nov 2002, 17–20 Oct 2003, 5–6 Oct 2004, 26 Sep–3 Oct 2005	7–12 May 2003, 27–28 Apr 2004, 6 Apr 2005	15–25 Nov 2002, 29 Sep 2003, 24–30 Sep 2004, 17–18 Oct 2005	11–19 Jun 2003, 3–4 Jun 2004, 17–20 Jun 2005
Fertilizer applications	*Limestone*—19 Mar 2002 (2.24 Mg ha^{-1}) *NH_4NO_3*—18 Jun 2002 (146 kg ha^{-1}), 12 Jun 2003 (150 kg ha^{-1}), 18 Jun 2004 (142 kg ha^{-1}), 24 May 2005 (325 kg ha^{-1}) *18-9-18(N-P_2O_5-K_2O)*—15–18 Apr 2005 (292 kg ha^{-1})	*NH_4NO_3*—25 Feb 2003 (153 kg ha^{-1}), 20 Feb 2004 (118 kg ha^{-1}), 3 Mar 2005 (147 kg ha^{-1})	*Limestone—19* Mar 2002 (2.24 Mg ha^{-1}) *NH_4NO_3*—18 Jun 2002 (146 kg ha^{-1}), 9 Jul 2003 (132 kg ha^{-1}), 19 Jul 2004 (148 kg ha^{-1}), 17 Aug 2005 (165 kg ha^{-1})	*NH_4NO_3*—25 Feb 2003 (153 kg ha^{-1}), 20 Feb 2004 (118 kg ha^{-1}), 3 Mar 2005 (147 kg ha^{-1})
Herbicide applications	*Glyphosate*—9 May 2002—NT (5.8 l ha^{-1}), 14 Jun 2002—NT (2.3 l ha^{-1}), 2–6 Jun 2003—NT (1.6 l ha^{-1}), 21 May 2004—NT (2.3 l ha^{-1}), 12 Apr 2005—NT (3.5 l ha^{-1}), 19 May 2005—NT (1.6 l ha^{-1}) *Atrazine*—2–6 Jun 2003 (4.7 l ha^{-1}), 6 Jun 2004 (4.7 l ha^{-1}) *Dual*—2–6 Jun 2003 (1.2 l ha^{-1})	*Glyphosate*—2 Dec 2002—NT (2.3 l ha^{-1}), 6 Nov 2003—NT (2.3 l ha^{-1}), 17 Nov 2004—NT (2.3 l ha^{-1})	*Glyphosate*—9 May 2002—NT (5.8 l ha^{-1}), 14 Jun 2002—NT (2.3 l ha^{-1}), 27 Jun 2003—NT (3.5 l ha^{-1})	*Glyphosate*—2 Dec 2002—NT (2.3 l ha^{-1}), 6 Nov 2003—NT (2.3 l ha^{-1}), 17 Nov 2004—NT (2.3 l ha^{-1}) *2,4-D amine*—23 Feb 2004 (2.3 l ha^{-1})
Initial cattle stocking date	13 Oct 2005	25 Mar 2003, 9 Mar 2004, 10 Mar 2005	11 Jul 2002, 6 Aug 2003, 2 Aug 2004, 23 Aug 2005	None
Termination cattle stocking date	27 Oct 2005	6 May 2003, 27 Apr 2004, 5 Apr 2005	26 Sep 2002, 1 Oct 2003, 21 Sep 2004, 4 Oct 2005	None

CT is conventional tillage and NT is no tillage.

Table 2. Cattle stocking characteristics averaged across the entire grazing period in two cropping systems managed with CT and NT.

	Summer grain/winter cover crop				Winter grain/summer cover crop				
Tillage	**2003**	**2004**	**2005**	**Mean**	**2002**	**2003**	**2004**	**2005**	**Mean**
Calf stocking rate (head ha^{-1})									
CT	6.0	3.1	4.4	4.5	6.7	3.3	4.0	4.0	4.5
NT	6.0	5.5	4.6	5.4	5.9	3.4	4.0	4.0	4.3
$LSD_{(P=0.05)}$	NV	2.7	0.9	0.8*	0.7*	0.3	NV	NV	0.2*
Calf head weight (kg $head^{-1}$)									
CT	290	85	69	148	294	182	224	187	222
NT	292	92	73	152	306	206	214	196	231
$LSD_{(P=0.05)}$	14	20	19	9	8*	17*	24	26	8*
Cow head weight (kg $head^{-1}$)									
CT	–	513	525	519	–	508	497	496	500
NT	–	552	490	521	–	513	536	520	523
$LSD_{(P=0.05)}$	–	52	49	32	–	74	52	49	29
Paddock stocking weight (Mg ha^{-1})									
CT	1.74	1.88	2.62	2.08	1.98	2.28	2.89	2.73	2.47
NT	1.75	3.57	2.60	2.64	1.81	2.46	3.00	2.86	2.53
$LSD_{(P=0.05)}$	0.09	1.94	0.68	0.59	0.21	0.44	0.15	0.28	0.12
Days of grazing (days)									
CT	42	49	26	39	77	57	50	31	54
NT	42	49	26	39	77	57	50	41	56
$LSD_{(P=0.05)}$	NV	NV	NV	NV	NV	NV	NV	3*	1*
Animal grazing days [(head d) ha^{-1}]									
CT	252	301	228	260	518	375	400	250	386
NT	252	539	240	344	455	390	400	330	394
$LSD_{(P=0.05)}$	NV	268	45	78*	55*	36	NV	21*	15

NV is no variance.
* Next to LSD value indicates significance between tillage means.

Table 3. Early-season population (plants m^{-2}) of grain and cover crops in two cropping systems varying in tillage system (CT and NT) and cover crop management (with and without cattle grazing).

		Summer grain/winter cover crop				Winter grain/summer cover crop			
Tillage	**Cover crop**	**2003**	**2004**	**2005**	**Mean**	**2003**	**2004**	**2005**	**Mean**
Grain crop		----------------Sorghum or corn---------------				-------------------Wheat-------------------			
CT	Ungrazed	29.6	18.0	5.9	17.8	159	60	–	110
	Grazed	29.3	22.1	6.2	19.2	141	68	–	105
NT	Ungrazed	26.0	13.9	7.2	15.7	136	70	–	103
	Grazed	29.5	15.9	7.7	17.7	180	79	–	129
$LSD_{(P=0.05)}$		5.8	5.1*	1.2*	2.4	18*	26	–	15*
Cover crop		-----------------------Rye-----------------------				------------------Pearl millet--------------			
CT	Ungrazed	146	135	–	141	124	130	102	118
	Grazed	143	141	–	142	125	108	94	109
NT	Ungrazed	150	134	–	142	71	82	77	77
	Grazed	160	143	–	152	68	75	69	70
$LSD_{(P=0.05)}$		30	34	–	22	37*	39*	19*	18*

Populations were determined for sorghum on 28 June 2003 and 18 June 2004, for corn on 29 April 2005, for wheat and rye on 12 December 2003 and 8 February 2005, and for pearl millet on 14 July 2003, 8 July 2004 and 16 August 2005.
A priori mean comparisons are between tillage systems within a cover crop management or between cover crop management within a tillage system. *Next to LSD value indicates significance in at least one of these comparisons.

Table 4. Grain yield, standing grain-crop dry matter, and cover-crop dry matter (Mg ha^{-1}) in two cropping systems varying in tillage system (CT and NT) and cover crop management (with and without cattle grazing).

		Summer grain/winter cover crop					Winter grain/summer cover crop				
Tillage	**Cover crop**	**2002**	**2003**	**2004**	**2005**	**Mean**	**2002**	**2003**	**2004**	**2005**	**Mean**
Grain yield		--------Sorghum (2002–2004) or corn (2005) --------					-----------------Wheat-----------------				
CT	Ungrazed	1.23	4.14	0.46	6.43	3.06	–	2.75	2.62	2.71	2.69
	Grazed	1.48	3.73	0.55	7.46	3.30	–	2.63	3.03	2.67	2.78
NT	Ungrazed	0.83	4.71	1.20	8.63	3.84	–	2.78	2.07	2.85	2.57
	Grazed	0.69	3.77	0.59	6.74	2.95	–	2.65	2.58	2.66	2.63
$LSD_{(P=0.05)}$		0.67*	1.38	0.33*	2.38	0.66*	–	0.51	0.59	1.05	0.41
Grain-crop standing dry matter		--------Sorghum (2002–2004) or corn (2005) --------					------------------Wheat----------------				
CT	Ungrazed	1.89	3.55	4.25	7.24	4.23	–	1.29	0.77	1.28	1.11
	Grazed	1.77	2.84	4.13	7.50	4.06	–	1.41	1.09	1.78	1.43
NT	Ungrazed	2.17	7.31	8.40	11.92	7.45	–	1.47	1.02	1.39	1.29
	Grazed	2.27	5.05	6.50	8.29	5.53	–	1.60	1.24	1.82	1.55
$LSD_{(P=0.05)}$		1.33	1.29*	2.32*	3.97*	1.13*	–	–	0.37	0.42*	0.21*
Cover-crop standing dry matter		------------------------------Rye---------------------------					--------------Pearl millet--------------				
CT	Ungrazed	–	7.21	6.67	4.21	6.03	5.28	7.29	8.72	9.09	7.59
	Grazed	–	0.62	0.18	0.02	0.27	0.40	0.38	0.36	0.58	0.43
NT	Ungrazed	–	8.85	6.95	5.28	7.02	5.89	13.23	7.49	14.13	10.19
	Grazed	–	0.91	0.60	0.04	0.52	0.98	0.90	0.20	1.26	0.83
$LSD_{(P=0.05)}$		–	1.52*	1.12	1.70	0.79*	1.05	4.72*	2.60	4.98*	1.71*

A priori mean comparisons are between tillage systems within a cover crop management or between cover crop management within a tillage system. *Next to LSD value indicates significance in at least one of these comparisons.

immediately following planting. Lower early-season pearl millet population under NT than under CT, however, was not a hindrance to successful cover crop dry matter accumulation (Table 4). These results suggest that pearl millet could possibly be planted at lower density than the 13–17 kg ha^{-1} rate that was targeted in this study.

The only other major tillage effect was that the corn population under NT in 2005 was 23 ± 2% greater than under CT (Table 3). The water conservation benefit of NT compared with CT may have contributed to this effect, as well as the fact that corn was planted a week earlier under NT than under CT (Table 1). The earlier planting date was a consequence of greater preparation time required for CT planting.

The only cover crop management effect on plant population occurred with wheat (Table 3). More plants were established with grazing than without grazing of cover crops under NT in 2003. Inhibition of seedling emergence could have occurred with the large amount of pearl millet residue at the soil surface, because of either a mechanical cause at planting from residue impeding penetration of planting equipment into the soil or from a biochemical cause at seedling emergence due to presence of allelopathic compounds[22].

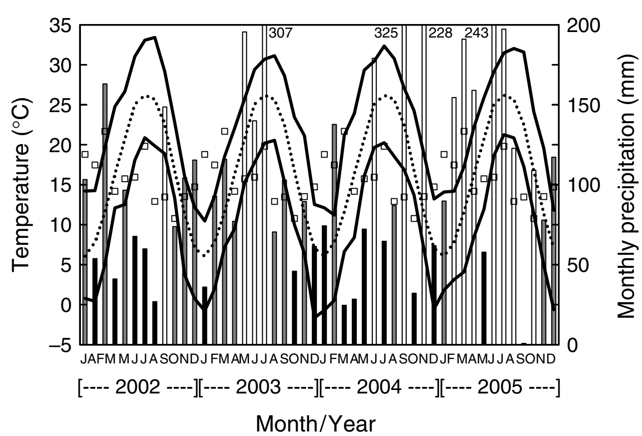

Figure 1. Monthly temperature and precipitation near Watkinsville, GA from 2002 to 2005. Solid lines are observed minimum and maximum temperatures and dotted line is the long-term (1945–2003) mean temperature. Vertical bars are observed monthly precipitation, and squares are long-term mean precipitation. Vertical bars that are gray-shaded are within 75–125% of mean precipitation. Vertical bars that are black are < 75% of mean precipitation. Vertical bars that are unfilled are > 125% of mean precipitation. Data from the Georgia Automated Environmental Monitoring Network (www.georgiaweather.net).

Summer grain-crop production

Summer grain-crop production was highly variable from year-to-year (Table 4). Precipitation from May to September was also highly variable (Figs. 1 and 2). During 2002, precipitation from sorghum planting to grain filling in mid September was only 121 mm, well below that needed to produce a crop. Sorghum production during 2003 was more typical of the regional average, and was not affected by tillage or cover crop management. Sorghum production in 2004 was again very low, because of late-season precipitation in September (Fig. 2), which caused lodging

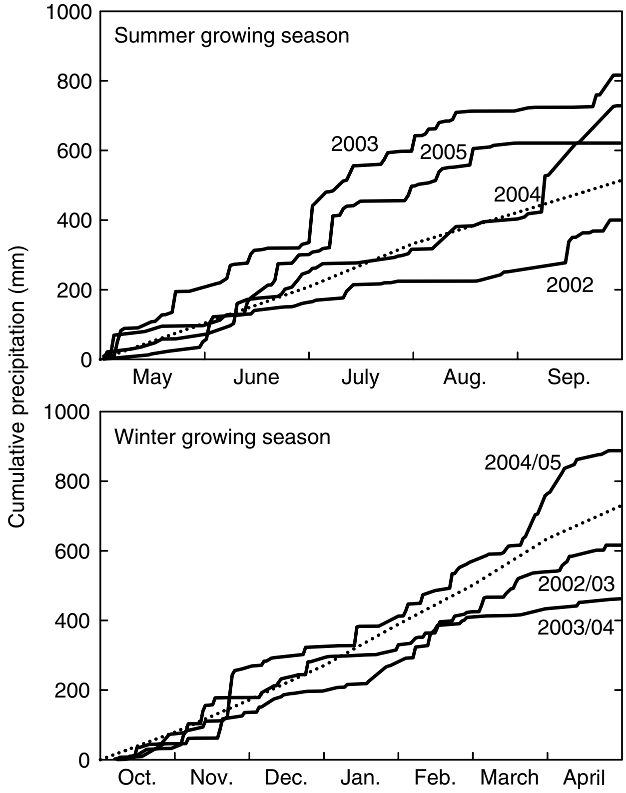

Figure 2. Cumulative precipitation in summer and winter growing seasons from 2002 to 2005 at Watkinsville, GA. Dotted line is long-term mean cumulative precipitation. Data from the Georgia Automated Environmental Monitoring Network (www.georgiaweather.net).

and made it difficult to harvest grain. The switch to corn production in 2005 (because of poor performance of sorghum in previous years) resulted in very good grain yield, but there was no effect of tillage or cover crop management.

The effect of tillage on grain yield was significant in 2 of 4 years (Table 4). Sorghum grain yield was negatively affected by NT compared with CT in 2002, but was positively affected by NT compared with CT when the cover crop was not grazed in 2004. The effect of cover crop management was significant only in 2004 under NT, in which grazing of cover crop led to lower sorghum grain yield than when cover crop was not grazed. The 4-year mean grain yield was greater under NT than under CT when the rye cover crop was not grazed. In addition, the 4-year mean grain yield was lower when rye was grazed than left ungrazed, but only under NT. The accumulation of surface plant residue under NT appears to have been more important for summer grain production than processing of cover crop into animal manure. Soil water conservation under a mulch of surface residues probably benefited plant production during the summer[23]. Further research is needed to better understand the interaction between tillage and cover crop management on summer grain yield.

Hand-harvested sorghum grain yield in 2004 (Table 5) was 8.4 ± 2.4 times greater than grain yield from commercial-sized farm machinery (Table 4). Hand-harvested corn yield in 2005 was $48 \pm 6\%$ higher than by combine. For sorghum, the large discrepancy between hand- and machine-harvested estimates was due to late-season precipitation that flattened the maturing crop. For corn, higher hand-harvested yield than machine yield was due to grain loss through the machine. Grain-to-whole plant ratio of sorghum in 2004 was 0.48 and of corn in 2005 was 0.56 (Table 5).

Hand-harvested yield of sorghum stover in 2004 (Table 5) was very similar in magnitude to the sorghum standing in the field after combine harvest (Table 4). Standing, summer-crop dry matter after harvest averaged 2.0 Mg ha^{-1} in 2002, 4.7 Mg ha^{-1} in 2003, 5.9 Mg ha^{-1} in 2004, and 8.7 Mg ha^{-1} in 2005. Standing summer-crop dry matter was not affected by tillage in 2002, but was significantly greater under NT than under CT in all other years. The 4-year mean values followed the order: NT-ungrazed > NT-grazed > CT-ungrazed = CT-grazed. It appears likely that a soil water conservation effect contributed to higher production with NT compared with CT and, under NT, with surface crop residue accumulation compared with grazed condition.

The results for summer crop grain yield in this study were in general agreement with previous studies, in which grain yield was positively affected by NT compared with CT[10–12]. However, there is little available literature describing the effect of grazing cover crops on subsequent grain yield. Our results indicate that grazing of rye as a winter cover crop negatively affected 4-year mean summer grain and stover production under NT, but not under CT (Table 4).

Winter grain-crop production

Winter wheat production was highly uniform, both among years and within years among treatments (Table 4). Tillage and cover crop management had no effect on wheat grain yield in any year. Precipitation was nearly as variable in winter as in summer (Fig. 2), but the low evaporative demand allowed wheat to develop successfully despite differences in precipitation. Variation in wheat grain yield among years (8%) was much lower than variation in summer grain yield (85%). Mean wheat grain yield averaged 2.7 Mg ha^{-1}, while summer grain yield averaged 3.3 Mg ha^{-1}. These data support the hypothesis that winter grain production would be more uniform, but lower in potential, than summer grain production, as a result of differences in climatic conditions between winter and summer.

Standing wheat dry matter after harvest was greater with grazed than with ungrazed cover crop in 2005 and when averaged across years, independent of tillage system (Table 4). This cover crop management effect may have been due to either (1) enhanced nutrient availability to wheat with processing of summer cover crop dry matter through grazing cattle as manure or (2) inhibition of wheat

Table 5. Hand-harvested yield components of three grain crops managed with either CT or NT and with or without cattle grazing of cover crops.

Tillage	Cover crop	Wheat (28 May 2004)			Sorghum (20 September 2004)			Corn (14 September 2005)				
		Grain	Stover	Grain : Plant	Grain	Stover	Grain : Plant	Grain	Stover	Grain : Plant	Stalks	Ears
		---Mg ha $^{-1}$---		---g g $^{-1}$---	------Mg ha $^{-1}$------		---g g $^{-1}$---	------Mg ha $^{-1}$------		---g g $^{-1}$---	Number m $^{-2}$	
CT	Ungrazed	3.39	3.45	0.50	4.51	5.08	0.46	10.08	7.24	0.60	34	33
	Grazed	3.33	4.08	0.45	3.43	4.80	0.39	10.87	7.50	0.60	37	37
NT	Ungrazed	3.30	4.61	0.42	7.77	7.61	0.49	12.78	11.92	0.51	40	40
	Grazed	3.35	4.24	0.44	6.58	5.16	0.58	9.65	8.29	0.54	40	38
$LSD_{(P=0.05)}$		1.07	1.34	0.04*	3.89	3.43	0.16*	2.25*	3.97*	0.12	11	9

A priori mean comparisons are between tillage systems within a cover crop management or between cover crop management within a tillage system. * Next to LSD value indicates significance in at least one of these comparisons.

growth from unaltered summer cover crop dry matter accumulation. Potential inhibition of wheat stover production could have been from a biochemical cause resulting from either (1) presence of allelopathic compounds in pearl millet or (2) enhanced immobilization of N from mature pearl millet residue straw (although C : N ratio of mature, ungrazed pearl millet residue among years was moderate at 36 ± 15 g g^{-1}; Table 6). Potential inhibition of wheat stover production could have also been physical, at least under NT, resulting from cooler and wetter soil conditions that were likely under heavy mulch residue.

Hand-harvested wheat yield components in 2004 suggested that $32 \pm 20\%$ of wheat grain may have been left in the field, as a result of machine inefficiency (Tables 4 and 5). Standing wheat dry matter (Table 4) would also have to be considered a minimum value, since hand-harvested yield of wheat stover (Table 5) was 4.0 ± 0.5 times greater than machine-harvested stover in 2004 (Table 4). Grain-to-whole plant ratio of wheat averaged 0.45 and was highest under CT when the cover crop was not grazed.

Winter grain crop yields in this study were in general agreement with previous studies, in which grain yield was little affected by tillage system[5,10–12]. There is no known literature describing the effect of grazing summer cover crops on subsequent wheat grain yield. Our results indicate that grazing of pearl millet as a summer cover crop could enhance wheat stover production and have no detrimental effect on wheat grain yield. Tanaka et al.[24] observed that swath grazing by cattle increased forage and grain production compared with cropping systems without cattle during the 4th year of a study in North Dakota. Additional crop responses to grazing of cover crops under different soil and crop management conditions are needed to bolster these results prior to making wide-scale recommendations.

Grain protein

Protein concentration of harvested grain varied from year-to-year and among crops. Across years and crops (wheat, sorghum, and corn), grain protein concentration was 108 ± 16 mg g^{-1}. Grain protein concentration was little affected by tillage and cover crop management, except for wheat in 2004 (Table 6). Wheat grain protein concentration was greater under NT than under CT in 2004 and when averaged across years, perhaps as a result of greater access to soil moisture with surface mulching and preservation of high surface soil organic N with NT (A.J. Franzluebbers, unpublished data). Summarized from a number of studies[25], wheat grain protein concentration varied from 80 to 140 mg g^{-1}. Halvorson et al.[26] reported grain protein concentration of 139 ± 31 mg g^{-1} during 9 years of cropping with wheat–corn–fallow and wheat–sorghum–fallow in Colorado. Sorghum and corn grain protein concentration was 127 ± 11 mg g^{-1} among nine selections in Kansas[27].

Table 6. Grain protein concentration and C : N ratio of plant residues in two cropping systems managed with either CT or NT and with or without cattle grazing of cover crops.

Tillage	Cover crop	Summer grain/winter cover crop 2002	2003	2004	2005	Mean	Winter grain/summer cover crop 2002	2003	2004	2005	Mean
Grain protein ($mg\,g^{-1}$)		Sorghum (2002–2004) or corn (2005)					Wheat				
CT	Ungrazed	124	88	115	93	105	–	121	106	95	108
	Grazed	124	85	143	92	111	–	117	115	98	110
NT	Ungrazed	127	95	107	95	106	–	124	127	100	117
	Grazed	127	93	114	90	106	–	122	130	101	118
$LSD_{(P=0.05)}$		10	11	35	7	9	–	15	11*	6	6*
C : N ratio of grain-crop standing dry matter ($g\,C\,g^{-1}\,N$)		Sorghum (2002–2004) or corn (2005)					Wheat				
CT	Ungrazed	32	61	30	41	41	–	83	100	134	106
	Grazed	31	46	29	39	36	–	71	95	119	95
NT	Ungrazed	34	51	28	48	40	–	68	70	127	88
	Grazed	33	57	31	39	40	–	70	82	127	93
$LSD_{(P=0.05)}$		7	12*	7	12	4*	–	14*	39	32	16*
C : N ratio of cover crop standing dry matter ($g\,C\,g^{-1}\,N$)		Rye					Pearl millet				
CT	Ungrazed	–	45	47	19	37	58	21	33	21	33
	Grazed	–	39	29	8	25	17	18	21	15	18
NT	Ungrazed	–	55	59	17	44	57	26	39	29	38
	Grazed	–	41	50	10	34	23	20	17	20	20
$LSD_{(P=0.05)}$		–	9*	18*	4*	6*	14*	5*	5*	5*	4*

A priori mean comparisons are between tillage systems within a cover crop management or between cover crop management within a tillage system. *Next to LSD value indicates significance in at least one of these comparisons.

Cover crop production

Ungrazed rye cover crop production was significantly greater under NT than under CT in 2003 (Table 4). Although differences were not significant in subsequent years, there was a continuing trend for higher production with NT than with CT. Averaged across years, ungrazed rye cover crop production was 6.0 Mg ha^{-1} under CT and 7.0 Mg ha^{-1} under NT ($P = 0.03$). Cattle grazing rye cover crop were able to consume 95 ± 4% of the forage by the end of the growing season (difference in cover crop standing dry matter between ungrazed and grazed plots). Standing dry matter of rye following grazing did not vary between tillage systems, averaging 0.4 ± 0.4 Mg ha^{-1} across years and tillage systems.

Ungrazed pearl millet cover crop production was significantly greater under NT than under CT in 2003 and 2005 (Table 4). Averaged across years, ungrazed pearl millet cover crop production was 7.6 Mg ha^{-1} under CT and 10.2 Mg ha^{-1} under NT ($P = 0.01$). Cattle grazing pearl millet cover crop consumed 93 ± 4% of the forage produced. Standing dry matter of pearl millet following grazing did not vary between tillage systems, averaging 0.6 ± 0.4 Mg ha^{-1} across years and tillage systems. It is clear from the data in our study that NT was superior to CT for producing cover crop growth.

The C : N ratio of ungrazed cover crops was higher than the remaining cover crop biomass at the end of grazing for both cover crop types and in all years (Table 6). Ungrazed cover crop C : N ratio was often greater under NT than under CT, which may have been due simply to greater biomass accumulation with NT. In contrast, the C : N ratio of wheat stover was lower under NT than under CT when the previous cover crop was ungrazed. The reason for this discrepancy in C : N ratio between cover crops and grain crops with respect to tillage is unclear.

Cover crops grazed by cattle were transformed from (a) raw plant materials that could be used to help conserve soil water and protect the soil surface from erosion into (b) non-uniform animal manure droppings that could contribute to accelerated nutrient cycling and more rapid transformation of crop residue into soil organic matter. Characterizing the benefits of ungrazed and grazed cover crops on ecosystem processes extending beyond the growth of plants needs further investigation.

Greater cover crop production with NT compared with CT suggests that there would be no need to invert crop residues and soil to obtain adequate cover crop growth. Any standing weeds prior to establishment of a cover crop could be controlled with preplant herbicide. Post-planting weeds could be effectively controlled with the development of a vigorous cover crop canopy.

Cattle stocking characteristics

Cattle were stocked on rye for 26–49 days in the spring and on pearl millet for 31–77 days in the summer (Table 2). During the first year of experimentation, yearling steers (5.9–6.7 head ha^{-1}) were stocked on both pearl millet and rye and in subsequent years cow/calf pairs (3.1–5.5 pair ha^{-1}) were stocked on cover crops. Average suckling-calf head weight was lower on rye (69–92 kg $head^{-1}$) than on pearl millet (182–224 kg $head^{-1}$), because all calves were born in January/February of each year and rye was ready for grazing about 2 months after calving whereas pearl millet was ready for grazing about 5 months after calving. Average cow weight was not different between cropping systems (515 ± 19 kg $head^{-1}$).

Total weight of cattle on rye varied from a low of 1.74 Mg ha^{-1} in 2003 to a high of 2.72 Mg ha^{-1} in 2004, averaging 2.36 Mg ha^{-1} across years (Table 2). On pearl millet, stocking weight varied from a low of 1.89 Mg ha^{-1} in 2003 to a high of 2.94 Mg ha^{-1} in 2004, averaging 2.50 Mg ha^{-1} across years. Although no differences occurred between tillage systems in any one particular year, stocking weight tended to be greater under NT than under CT when averaged across years and cover crops ($P = 0.09$), reflecting the greater availability of forage under NT than under CT.

Total number of grazing days was 302 ± 119 (head d) ha^{-1} on rye and 390 ± 79 (head d) ha^{-1} on pearl millet (Table 2). The greater number of grazing days on pearl millet was due to greater forage production (Table 4) and regrowth potential. Number of grazing days was greater under NT than under CT when averaged across years on rye, but was not different between tillage systems on pearl millet. Significant tillage effects did occur in 2002 and 2005 on pearl millet, but they were opposing, resulting in no difference across years.

Cattle performance and production

Calf daily gain was excellent on both forages, but was higher on rye (2.18 ± 0.18 kg $head^{-1}$ d^{-1}) than on pearl millet (1.93 ± 0.17 kg $head^{-1}$ d^{-1}) (Table 7). Calf daily gain tended to be higher under NT than under CT in most years, but differences were not significant for any year. Averaged across years, calf daily gain was significantly higher under NT than under CT on pearl millet (13%) and when averaged across cover crops (2.16 versus 1.95 kg $head^{-1}$ d^{-1}; $P = 0.01$).

Cow daily gain was highly variable among years and tillage systems (0.88 ± 1.16 kg $head^{-1}$ d^{-1}) (Table 7), partly because of variable weather conditions (e.g., 121 ± 36% of normal precipitation during the five growing seasons with cows) and variable length of grazing period (44 ± 12 days during the five seasons). Considering both cows and calves together, average daily gain across years was greater under NT than under CT on rye (36%) and when averaged across cover crops (1.80 versus 1.45 kg $head^{-1}$ d^{-1}; $P = 0.05$). Greater cattle performance under NT was probably related to greater availability of forage, since stocking rate was mostly similar between tillage systems due to the small

Table 7. Cattle performance and production characteristics in two cropping systems managed with either CT or NT.

	Summer grain/winter cover crop—rye				Winter grain/summer cover crop—pearl millet				
Tillage	**2003**	**2004**	**2005**	**Mean**	**2002**	**2003**	**2004**	**2005**	**Mean**
Calf daily gain (kg head^{-1} d^{-1})									
CT	1.90	2.18	2.18	2.09	1.74	1.94	1.75	1.81	1.81
NT	2.25	2.11	2.45	2.27	2.01	2.14	1.89	2.18	2.05
$LSD_{(P=0.05)}$	0.55	0.45	0.50	0.25	0.39	0.67	0.55	0.68	0.25*
Cow daily gain (kg head^{-1} d^{-1})									
CT	–	1.45	−0.95	0.25	–	1.05	−0.55	2.22	0.91
NT	–	2.42	0.27	1.35	–	1.30	−0.08	1.73	0.98
$LSD_{(P=0.05)}$	–	1.76	1.89	1.15	–	1.89	1.27	1.06	0.72
Cow/calf pair daily gain (kg head^{-1} d^{-1})									
CT	1.90	1.81	0.62	1.44	1.74	1.49	0.60	2.01	1.46
NT	2.25	2.26	1.36	1.96	2.01	1.72	0.91	1.95	1.65
$LSD_{(P=0.05)}$	0.55	0.86	0.91	0.39*	0.39	1.20	0.63	0.67	0.33
Calf gain (kg ha^{-1})									
CT	239	165	124	176	452	184	175	113	231
NT	283	285	147	239	456	209	189	181	258
$LSD_{(P=0.05)}$	69	160	34	51*	101	75	55	57*	31
Cow gain (kg ha^{-1})									
CT	–	133	−48	43	–	102	−55	137	61
NT	–	319	16	167	–	126	−8	143	87
$LSD_{(P=0.05)}$	–	203	111	103*	–	184	127	74	66
Cow/calf pair gain (kg ha^{-1})									
CT	239	298	76	204	452	286	120	250	277
NT	283	604	163	350	456	335	181	324	324
$LSD_{(P=0.05)}$	69	348	120	107*	101	240	125	97	64

* Next to LSD value indicates significance between tillage means.

paddock size that limited our ability to make fine-tuned adjustments.

Calf gain ha^{-1} was 207 ± 71 kg ha^{-1} on rye and was 245 ± 132 kg ha^{-1} on pearl millet (Table 7). There was a tendency for greater calf gain ha^{-1} under NT than under CT in most seasons, but this effect was significant only on pearl millet in 2005. Averaged across years, there was significantly greater calf gain ha^{-1} under NT than under CT on rye (36%) and a tendency for greater calf gain ha^{-1} under NT than under CT on pearl millet (12%; $P = 0.08$).

Cow gain ha^{-1} was highly variable (87 ± 113 kg ha^{-1}), but averaged across years was greater under NT than under CT on rye ($P = 0.02$) with a similar tendency averaged across cover crops ($P = 0.08$) (Table 7). Considering cows and calves together, total gain ha^{-1} was greater under NT than under CT on rye (350 versus 204 kg ha^{-1}; $P = 0.01$) and when averaged across cover crops (337 versus 241 kg ha^{-1}; $P = 0.03$).

Integrated economic analysis

Grain-crop costs were US$284 ± 137 ha^{-1} among years in the summer grain/winter cover crop system and US$237 ± 93 ha^{-1} among years in the winter grain/summer cover crop system (Table 8). First-year costs were higher than subsequent years in both systems, due to extra pasture termination costs. Also when corn replaced sorghum in the summer grain/winter cover crop system, higher fertilizer inputs and use of glyphosate-resistant seed resulted in a doubling of input cost. By excluding cover crop input costs from these estimates, net return from grain cropping only over variable costs was US$40 ± 38 ha^{-1} among tillage and cover crop treatments in the summer grain/winter cover crop system and US$8 ± 21 ha^{-1} among treatments in the winter grain/summer cover crop system. When cover cropping costs were included, all systems resulted in a net loss from grain cropping.

The added value of cattle gain from grazing of cover crops was 138 ± 36% of grain cropping only (Table 8). Obviously with different prices of crop and livestock components, shifts in return could be expected. During the seven seasons evaluated in this study, net return over variable costs was not different between tillage systems in either cropping system. Net return over variable costs was highly significant ($P < 0.01$) between cover crop management systems, averaging −US$63 ha^{-1} when not grazed and US$302 ha^{-1} when grazed.

Increased diversity of income and greater magnitude of economic return when cover crops were grazed by cattle should be key drivers for producers considering the adoption of such a management system. However, with multiple enterprises there will be a need for a greater

Table 8. Mean yearly economic inputs and outputs from summer grain/winter cover crop and winter grain/summer cover crop systems as affected by tillage and cover crop management.

	Sorghum (corn)/rye				Wheat/pearl millet			
	Ungrazed		Grazed		Ungrazed		Grazed	
Item	CT	NT	CT	NT	CT	NT	CT	NT
	US$ ha^{-1}							
Grain crop seed	41.84	43.32	41.84	43.32	43.42	49.20	43.42	49.20
Lime	22.95	22.95	22.95	22.95	30.58	30.58	30.58	30.58
Fertilizer	96.63	96.63	96.63	96.63	50.59	50.59	50.59	50.59
Herbicide	21.34	70.99	21.34	70.99	0.00	79.04	0.00	79.04
Fuel	38.61	15.22	38.61	15.22	41.82	13.07	37.37	11.12
Machinery repair and maintenance	51.35	20.23	51.35	20.23	55.62	17.36	49.72	14.80
Drying	12.08	15.14	13.02	11.61	9.90	10.20	9.44	9.66
Total grain crop variable costs	284.80	284.48	285.74	280.95	231.93	250.04	221.12	244.99
Cover crop seed	58.86	61.58	58.86	61.58	20.78	19.36	20.78	19.36
Fertilizer	50.59	50.59	50.59	50.59	50.99	50.99	50.99	50.99
Total cover crop variable costs	109.45	112.17	109.45	112.17	71.77	70.35	71.77	70.35
Total costs	394.25	396.65	395.19	393.12	303.70	320.39	292.89	315.34
Crop value	301.66	378.23	325.42	290.23	247.42	235.89	255.03	241.64
Added calf gain value	0.00	0.00	290.40	394.35	0.00	0.00	381.15	425.70
Total crop and calf value	301.66	378.23	615.82	684.58	247.42	235.89	636.18	667.34
Net return over variable costs	−92.59	−18.42	220.63	291.46	−56.28	−84.50	343.29	352.00

Unit costs of US\$2.65 kg^{-1} sorghum seed, US\$5.86 kg^{-1} corn seed, US\$0.40 kg^{-1} wheat seed, US\$0.49 kg^{-1} rye seed, US\$1.23 kg^{-1} pearl millet seed, US\$33.07 Mg^{-1} lime, US\$1.06 kg^{-1} fertilizer N, US\$0.72 kg^{-1} fertilizer P_2O_5, US\$0.54 kg^{-1} fertilizer K_2O, US\$12.68 l^{-1} glyphosate, US\$3.01 l^{-1} atrazine, US\$31.17 l^{-1} metolachlor, US\$0.59 l^{-1} diesel fuel, and US\$3.94 Mg^{-1} grain to dry three points.
Unit values of US\$98.42 Mg^{-1} sorghum, corn, or wheat grain produced and US\$1.65 kg^{-1} calf gain.
Note: Analysis excludes labor cost, as well as grazing time and gain of cows.

amount of infrastructure, technology, labor and information. The rudimentary economic analysis presented here has not accounted for all of the limitations in an integrated crop–livestock system, but has shown the great potential for economic gain for producers that can effectively optimize such a system within the biophysical and socioeconomic constraints in the southeastern USA. In the Northern Plains region of the USA, winter feeding cost was reduced from US\$0.73 cow^{-1} d^{-1} with baled hay in drylot to US\$0.49 cow^{-1} d^{-1} with swath grazing of crop residues left in the field[28].

Conclusions

As expected, grain production in the summer was greater, but more variable than in the winter (3.3 Mg ha^{-1} with 94% coefficient of variation among years in summer compared with 2.7 Mg ha^{-1} with 3% coefficient of variation among years in winter). Although precipitation varied equally as much in both summer and winter seasons, lack of precipitation with high evaporative demand throughout the summer and excessive precipitation just prior to harvest caused major reductions in summer grain yield. Summer grain and stover production were greater under NT than under CT, but winter grain and stover production were unaffected by tillage system. In addition, both winter and summer cover crops were more productive under NT than under CT. Grazing cover crops with cattle had (1) a positive effect on wheat stover production irrespective of tillage system, (2) no effect on wheat grain and sorghum (or corn) grain and stover production under CT, and (3) a negative effect on sorghum (or corn) grain and stover production under NT. Both rye and pearl millet cover crops provided an abundant and high-quality diet for either yearling calves or cow–calf pairs for 26–77 days. Calf performance on cover crops was 2.15 ± 0.18 kg head^{-1} d^{-1} under NT, which was an average of 11% greater than under CT. These data indicate that integrated crop–livestock production may not necessarily suppress crop yields, but could even enhance yields and net economic return, especially if managed with conservation tillage. Despite current social challenges with integrated crop–livestock production systems, significant agronomic and economic benefits could be expected with adoption.

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