Bermudagrass Management in the Southern Piedmont USA: X. Coastal Productivity and Persistence in Response to Fertilization and Defoliation Regimes

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ABSTRACT

Productivity, quality, and persistence of 'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers.] pastures are affected by fertilization, but possible interactions with defoliation regime including animal grazing are not fully known. We evaluated three sources of fertilization with equivalent N rates [inorganic, crimson clover (*Trifolium incarnatum* L.) cover crop plus inorganic, and chicken (*Gallus gallus*) broiler litter] factorially arranged with four defoliation regimes [unharvested, cattle (*Bos taurus*) grazing to maintain high (4.5 ± 1.6 Mg ha^{-1}) and low (2.5 ± 1.1 Mg ha^{-1}) forage mass, and hayed monthly] on estimated forage dry matter production, forage and surface residue C/N ratio, and ground cover of pastures on a Typic Kanhapludult in Georgia during 5 yr. Mean annual forage dry matter production was 7.5 ± 0.7 Mg ha^{-1} with hay harvest but declined (1.3 Mg ha^{-1} yr^{-1}) significantly with time as a result of lower precipitation. With grazing, estimated production was 8.3 ± 1.0 Mg ha^{-1} and did not change with time, suggesting that grazing cattle sustained forage productivity by recycling nutrients and creating better surface soil conditions. Coastal bermudagrass as a percentage of ground cover (initially 81%) declined 5 ± 2% yr^{-1} with unharvested and grazing to maintain low forage mass, declined 3 ± 1% yr^{-1} with haying, and remained unchanged (−1 ± 1% yr^{-1}) with grazing to maintain high forage mass. Pastures with high forage mass were more productive than with low forage mass (9.2 ± 1.6 vs. 7.5 ± 1.1 Mg ha^{-1}) from a forage sustainability perspective, primarily by avoiding encroachment of undesirable plant species.

Hybrid bermudagrass, of which Coastal represents a long-term performance standard, is an important warm-season component of pastures in the southeastern USA. The effect of fertilizer rate and defoliation frequency on bermudagrass production and quality has been extensively studied (Holt and Lancaster, 1968; Monson and Burton, 1982; Wood et al., 1993; Evers, 1998). Bermudagrass hay yield and quality are maximized when N is applied frequently at levels > 400 kg ha^{-1} yr^{-1} (Overman et al., 1992). Although production is maximized with long defoliation intervals, it comes at the expense of lower forage quality (Monson and Burton, 1982; Holt and Conrad, 1986).

Nitrogen fertilizer is a necessary agronomic input for high forage productivity and quality (Wilkinson and Langdale, 1974). It is also a monetary input for producers (Hoveland, 1992), a costly energy input for society (Lockeretz, 1980), and a possible source of surface and ground water pollution from excessive application, especially in humid regions with abundant precipitation (Russelle, 1992). Optimum N fertilization of Coastal bermudagrass depends upon a variety of producer goals, socioeconomic constraints, and environmental factors. Maximum conversion efficiency of applied N to dry matter was estimated at ≈200 kg N ha^{-1} yr^{-1} for Coastal bermudagrass (Overman and Wilkinson, 1992), which was also the approximate breakpoint for susceptibility to N leaching loss (Wilkinson and Frere, 1993). The rising cost of inorganic N fertilizer has prompted the need to look for alternatives for supplying pastures with N. Overseeding of bermudagrass with the winter annual, crimson clover, has been shown to produce equivalent hay yield with half the inorganic N input required for bermudagrass alone (Adams et al., 1967). Broiler litter is a locally abundant resource that can supply sufficient N at a reasonable cost with many opportunities for application throughout the year in the southeastern USA (Wood et al., 1993; Evers, 1998).

Most of the studies that have determined defoliation effects on bermudagrass productivity and quality have focused on frequency or timing of mechanical defoliation. Frequency and clipping height of mechanical defoliation are sometimes used to simulate animal grazing pressure, but plants are known to respond differently to animal grazing compared with mechanical defoliation (Matches, 1992). Animal grazing not only alters the structure and quality of pastures in the short term (Roth et al., 1990) but may also affect long-term pasture productivity (Matches, 1992) and environmental quality (Russelle, 1992). For many forages, maintenance of low forage mass leads to a reduction in plant productivity although the threshold to induce this decline may vary considerably depending upon plant species and environmental conditions (Matches, 1992). In contrast, maintaining moderate forage mass can lead to enhanced plant productivity compared with ungrazed pasture (Hodgkinson and Mott, 1986). Matches (1992) presented a review of a wide diversity of plant responses to grazing and concluded that no single plant response to grazing was applicable to all pastures under all environments.

Available literature on forage responses to fertilization and defoliation regimes is fragmented and not always integrated into a continuum of information relating plant, animal, and environmental responses (Coleman, 1992). We began a long-term study focusing primarily on the effects of fertilization and defoliation regimes on soil properties under bermudagrass-based pasture (Franzluebbers et al., 2001, 2002; Stuedemann et al., 2002; Franzluebbers and Stuedemann, 2003b). Forage mass, forage and surface residue C and N concentration, and ground cover of pastures were also determined as part of a holistic approach to assess soil and water quality within the context of forage and cattle production.

Our objective in this portion of the experiment was to assess forage productivity, forage and surface residue

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N content and C/N ratio, and persistence of Coastal bermudagrass–based pastures under a factorial arrangement of three sources of N fertilization and four defoliation regimes during the initial 5 yr of management.

MATERIALS AND METHODS

Site Characteristics

A 15-ha upland field (33°22′ N, 83°24′ W) near Farmington, GA, in the Southern Piedmont resource area had previously been conventionally cultivated with various row crops for several decades before grassland establishment by sprigging of Coastal bermudagrass in 1991. Long-term mean annual conditions were 16.5°C air temperature, 1250 mm precipitation, and 1560 mm potential pan evaporation. Precipitation at the site was recorded at least twice each week throughout the study. Sampled on a 30-m grid, the frequency of soil series was 46% Madison, 22% Cecil, 13% Pacolet, 5% Appling, 2% Wedowee (fine, kaolinitic, thermic Typic Kanhapludults), 11% Grover (fine-loamy, micaceous, thermic Typic Hapludults), and 1% Louisa (loamy, micaceous, thermic, shallow Ruptic-Ultic Dystrudepts). Soil textural frequency of the Ap horizon (21 ± 12 cm) was 75% sandy loam, 12% sandy clay loam, 8% loamy sand, and 4% loam.

Experimental Design

The experimental design was a randomized complete block with treatments in a split-plot arrangement in each of three blocks, which were delineated by landscape features (i.e., slight, moderate, and severe erosion classes). Main plots were fertilization regime ($n = 3$), and split plots were defoliation regime ($n = 4$) for a total of 36 experimental units. Individual paddocks were 0.69 ± 0.03 ha. Each paddock contained a 3- by 4-m shade, mineral feeder, and water trough placed in a line 15 m long at the highest elevation. Unharvested and hayed exclosures (100 m^2 each) were placed side-by-side in paired low- and high-forage-mass paddocks of each fertilization regime.

Fertilization was targeted to supply 200 kg total N ha^{-1} yr^{-1} in one of three manners: (i) inorganic only as NH$_4$NO$_3$ broadcast in equally split applications in May and July, (ii) crimson clover cover crop plus supplemental inorganic fertilizer with half of the N assumed supplied by decomposing clover biomass derived from biological N fixation and half as NH$_4$NO$_3$ broadcast in July, and (iii) broiler litter broadcast by commercial truck spreader in split applications in May and July. A 3-yr evaluation at a site near our study suggested that hay yield (12.7 Mg dry matter ha^{-1} yr^{-1}) from Coastal bermudagrass overseeded with crimson clover and supplied with 110 kg N ha^{-1} yr^{-1} was similar (13.0 Mg dry matter ha^{-1} yr^{-1}) to that of Coastal bermudagrass supplied with 220 kg N ha^{-1} yr^{-1} (Carreker et al., 1977). Details of fertilizer applications each year are reported in Table 1. Diammonium phosphate and potash were applied based on soil-testing recommendations while excess P and K were applied with broiler litter as a result of meeting N requirements. Crimson clover 'AU Robin' seed was direct-drilled into dormant bermudagrass at 10 kg ha^{-1} in October each year for the clover + inorganic treatment only. All grazed paddocks were mowed in late April immediately following collection of initial forage and surface residue samples and estimation of ground cover, and residue was allowed to decompose (i.e., clover biomass in clover plus inorganic treatment and winter annual weeds in other treatments). Paddocks were tedded occasionally to evenly distribute residue and avoid smothering the emerging bermudagrass.

Defoliation regime mimicked a gradient in forage utilization consisting of (i) unharvested or simulated conservation reserve with biomass cut and left in place at the end of the growing season, (ii) grazing to maintain high forage mass at a target of 3.0 Mg ha^{-1}, (iii) grazing to maintain low forage mass at a target of 1.5 Mg ha^{-1}, and (iv) haying monthly during the summer to remove aboveground forage mass at 5-cm height. Grazed paddocks were stocked with Angus steers (initially 15 mo old weighing 257 ± 32 kg) during a 140-d period from mid-May until early October each year, except during the first year of treatment implementation (1994) when grazing began in July due to repairs to infrastructure following a tornado. No grazing occurred in the winter. At 28-d intervals, forage mass was determined, cattle were weighed following 16 h without access to water while on pasture, and paddocks restocked to achieve target forage mass levels. The grazing method was put-and-take (Bransby, 1989) to achieve targeted forage mass with stocking density at 5.9 ± 2.1 head ha^{-1} with high forage mass and 8.4 ± 2.8 head ha^{-1} with low forage mass (mean ± standard deviation among fertilization regimes, years, and stocking periods).

Sampling and Analyses

Forage mass was determined by hand from multiple 0.25-m^2 subsampling locations within experimental units by collecting all aboveground forage and drying at 55°C for several days. Samples were collected during the middle of each month from April to October. Subsampling locations within grazed paddocks were within a 3-m radius of points on a 30-m grid.

Table 1. Characteristics and rates of fertilizer sources applied to Coastal bermudagrass.

Variable	1994	1995	1996	1997	1998	5-yr mean
			Inorganic			
N, kg ha^{-1}	211	202	250	238	224	225
P, kg ha^{-1}	0	24	24	24	7	16
K, kg ha^{-1}	0	47	93	93	28	52
			Clover + inorganic†			
N, kg ha^{-1}	211	101	132	120	111	135
P, kg ha^{-1}	0	33	49	24	7	23
K, kg ha^{-1}	0	62	93	93	28	55
			Broiler litter‡			
Dry mass, Mg ha^{-1}	5.22	6.50	5.19	5.02	5.04	5.39
N, kg ha^{-1}	195	216	164	223	172	194
P, kg ha^{-1}	119	141	112	69	179	124
K, kg ha^{-1}	169	243	168	115	140	167

† An additional 110 kg N ha^{-1} yr^{-1} was assumed to be released from biologically fixed N in clover cover crop biomass produced from 1995 to 1998.

‡ Broiler litter contained 26 ± 4% moisture on a gravimetric basis.

Due to the nonuniform dimensions of paddocks, subsampling locations within a paddock varied from four to nine, averaging 7 ± 1. Two points were established in each unharvested and hayed exclosure, around which samples were collected. At the initial and final sampling of each season, surface residue was collected from the same 0.25-m^2 subsampling locations by removing all surface litter to mineral soil with the aid of battery-powered hand shears. Forage and surface residue samples at the initial and final sampling times were oven-dried (55°C for several days) and ground to <1 mm, and a subsample was analyzed for organic C and total N with dry combustion at 1350°C (Leco CNS-2000, St. Joseph, MI).[1]

Forage was harvested from hayed exclosures at 5-cm height each month from April to October with a vacuum mower. A 1- by 10-m strip was cut from the center of each hayed exclosure, wet forage weighed on a portable balance, and a 0.5- to 1.0-kg subsample weighed before and after drying at 55°C for several days. Dry matter yield was calculated from dry and wet weights and area harvested. The entire hayed exclosure was mowed and forage removed following subsampling.

Basal ground cover of grazed paddocks and exclosures was evaluated at monthly intervals immediately before forage mass determinations within each of the 0.25-m^2 sampling areas. All visual estimates of basal ground cover were made by the same experienced technician. Percentages (with separations in multiples of five) were calculated for the following six classes: (i) Coastal bermudagrass, (ii) crimson clover, (iii) common bermudagrass, (iv) winter annual grass [primarily Italian ryegrass (*Lolium multiflorum* Lam.) and rescuegrass (*Bromus catharticus* Vahl.)], (v) broadleaf weeds {primarily henbit (*Lamium amplexicaule* L.), chickweed (*Cerastium nutans* Raf.), shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.], and horsenettle (*Solanum carolinense* L.)}, and (vi) bare ground.

Forage productivity was calculated differently for each defoliation regime. For hayed exclosures, annual forage productivity was measured from cumulative monthly machine harvests (10 m^2) throughout the year. For unharvested exclosures, annual forage productivity was calculated from a yearly peak using linear + quadratic regression of monthly harvests of forage mass against day of year. Monthly harvests were by hand from two 0.25-m^2 areas within each exclosure. Only on 1 July 1994, the unharvested exclosures were machine-harvested for hay (before finalization of treatment designation), and this hayed forage mass was added to the calculated peak forage mass that occurred later in 1994. Peak forage mass usually occurred in August with subsequent decline later in the year due to deterioration of unharvested biomass. For high- and low-forage-mass treatments with grazing, annual forage productivity was calculated from the sum of final forage mass in October and an estimate of forage intake by grazing cattle. Forage intake was estimated based on equations established by the National Research Council using measured cattle live-weight gain specific to each experimental unit of this study and assuming 9.6 kJ of metabolizable energy g^{-1} of bermudagrass forage (National Research Council, 1996, p. 116). We did not determine metabolizable energy of the forage produced in this study, so we could not verify the validity of this assumed value, nor determine whether this value might need to be seasonally adjusted. Since pastures were continuously stocked in summer, it is unlikely that seasonal differences in metabolizable energy would have been nearly as large as accumulated forage with haying or unharvested management. Sampled at 14-d intervals from grazed bermudagrass in North Carolina, in vitro dry matter digestibility declined from 54% in early June to 52% at the end of August while crude protein declined from 17.7 to 14.3% (Harvey et al., 1996). We also could not account for trampling and spoilage losses of forage by cattle, and therefore, forage productivity under grazed systems would likely have been underestimated although the relative change in productivity with time in any particular management system would be valid.

Data from multiple samples collected within an experimental unit were averaged and not considered as a source of variation in the analysis of variance using the general linear models procedure (SAS Inst., 1990). Mass, N content, C/N ratio of forage and surface residue components, and percentage ground cover were analyzed within each sampling date of each year separately according to the split-plot design with three blocks. When analyzed across years, treatment means of these same response variables were analyzed with year as an additional blocking effect. Annual changes in ground cover were analyzed using linear regression with a common intercept for all treatments to evaluate a single variable, the slope coefficient. Annual changes in forage productivity among fertilization and defoliation regimes were analyzed by linear regression of actual values and treatment residuals from an overall annual mean, in which the slope represented a management-induced difference against a normalized yearly effect, since climatic differences among years were expected to alter absolute productivity. All effects were considered significant at $P \leq 0.1$.

RESULTS AND DISCUSSION

Precipitation

During the 5 yr of this study, annual precipitation was at or above normal each year (Fig. 1). However,

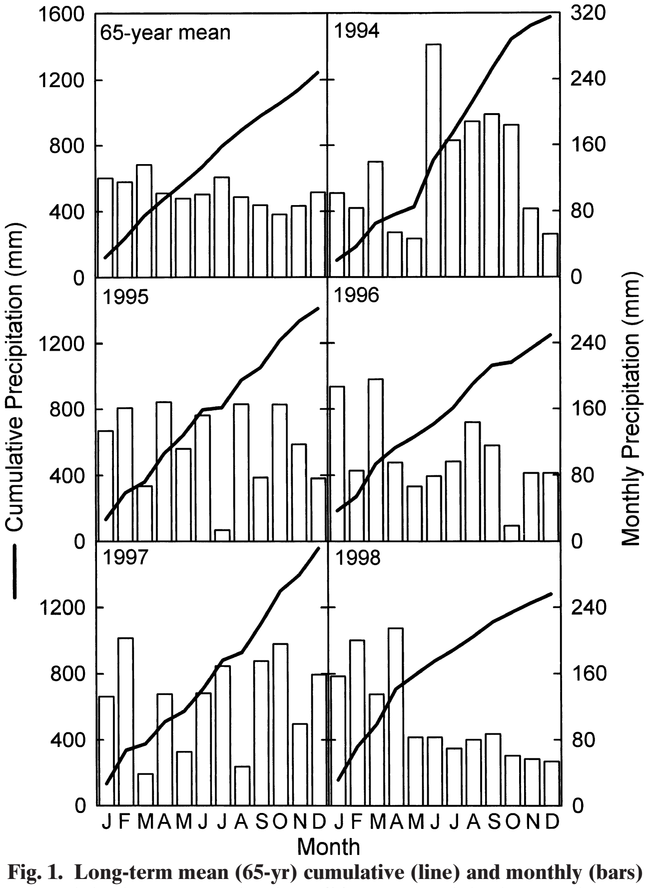

Fig. 1. Long-term mean (65-yr) cumulative (line) and monthly (bars) precipitation at Watkinsville, GA, and precipitation received at the site during 1994 to 1998.

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[1] Trade and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the USDA.

deviations from long-term monthly means occurred, especially regarding the consistently wetter-than-normal summer months in 1994, the alternating drier- and wetter-than-normal spring and summer months in 1997, and the consistently drier-than-normal summer months in 1998.

Precipitation had an effect on forage mass. Mean annual hay yield and peak unharvested forage mass were related to annual precipitation ($r = 0.63$ and $r = 0.36$, respectively) but were more related to precipitation during May to September ($r = 0.74$ and $r = 0.75$, respectively). The better relationship of forage yield with May to September precipitation would have been expected based on the warm-season growth period of bermudagrass. May to September precipitation declined with time in this study ($r = -0.77$, $P = 0.13$), suggesting that the apparent forage productivity decline with time was more likely a function of water availability and not cumulative management effects.

Forage and Surface Residue Carbon and Nitrogen

Forage C/N ratio was positively related to forage maturity. Average forage C/N ratio was 22 at the beginning of the season and 29 at the end of the season (Table 2). Forage N concentration was 20 ± 2 mg g^{-1} (mean ± standard deviation among fertilization and defoliation regimes) at the beginning of the growing season and 16 ± 2 mg g^{-1} at the end of the growing season. These values represent an estimate of 125 and 100 mg crude protein g^{-1} dry matter, respectively, which would represent Grade 4 hay with 85 to 100% relative feed value (van Soest, 1982). At similar N rates applied as in our study, crude protein from several bermudagrass hay harvests throughout the year was 100 ± 25 mg g^{-1} in Alabama (Wood et al., 1993) and 124 ± 19 mg g^{-1} in Texas (Evers, 1998).

Although forage C/N ratio was affected by fertilization regime (Table 2), differences of 1 to 2 g g^{-1} were much less than seasonal changes (6 to 8 g g^{-1}). Among fertilization means, there was a tendency for lower forage C/N ratio to be associated with higher forage mass and N content (Table 2).

Differences in surface residue components among fertilization regimes were mostly consistent with the trends that occurred in forage components but more significant (Table 2). Inorganic fertilization appeared to be a more effective nutrient source for sequestration of N into forage mass and subsequent surface residue components than either clover + inorganic or broiler litter fertilization.

The effect of defoliation regime on forage mass was large, but also an intentional consequence of the treatments employed (Fig. 2), which led to major changes in forage C/N ratio. Forage N content and C/N ratio were affected by defoliation regime at the beginning and end of the growing season (Table 2). At the end of the growing season, forage C/N ratio was lowest under grazing to maintain low forage mass (22 g g^{-1}) and highest under unharvested management (35 g g^{-1}). Forage C/N ratio was not different between grazing to maintain high forage mass (29 g g^{-1}) and hayed management (30 g g^{-1}) averaged across years but was lower under grazing to maintain high forage mass (28 ± 5 g g^{-1}) than under hayed management (33 ± 5 g g^{-1}) at the end of 1995, 1996, and 1997. The difference in forage C/N ratio between high and low forage mass with grazing probably reflected the change in growth form of

Table 2. Forage and surface residue mass, N content, and C/N ratio at the beginning and ending of each grazing season averaged across 5 yr as affected by fertilization and defoliation regimes.

	Forage						Surface residue					
	Mass		N content		C/N		Mass		N content		C/N	
Fertilization and defoliation regime	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
	— Mg ha^{-1} —		— kg ha^{-1} —		— g g^{-1} —		— Mg ha^{-1} —		— kg ha^{-1} —		— g g^{-1} —	
Inorganic												
Unharvested	3.28	6.15	64	94	23	34	14.79	12.90	208	214	27	23
High forage mass with grazing	3.33	4.77	71	81	21	27	8.99	10.51	133	146	22	20
Low forage mass with grazing	3.50	2.03	78	40	20	22	4.54	6.65	65	91	20	18
Hayed	3.06	2.28	58	36	25	31	3.59	3.50	44	43	22	22
Mean	3.29	3.81	68	63	22	28	7.98	8.39	113	124	23	21
Clover + inorganic												
Unharvested	2.70	5.97	49	81	24	37	12.33	11.96	169	170	28	25
High forage mass with grazing	2.51	4.74	49	77	23	29	8.50	8.12	122	107	24	21
Low forage mass with grazing	3.25	1.83	78	35	19	22	5.12	5.70	83	80	20	18
Hayed	3.53	1.84	74	29	21	31	4.75	3.71	61	41	22	21
Mean	3.00	3.59	63	56	22	30	7.68	7.37	109	100	23	21
Broiler litter												
Unharvested	2.71	5.71	52	78	22	35	12.22	11.32	142	149	26	24
High forage mass with grazing	3.09	5.09	58	81	24	30	8.27	10.50	99	110	23	21
Low forage mass with grazing	2.87	2.06	58	35	22	24	4.13	8.30	53	85	21	20
Hayed	2.85	2.04	56	36	25	29	3.14	3.29	38	38	22	21
Mean	2.88	3.73	56	57	23	29	6.94	8.35	83	95	23	21
Mean												
Unharvested	2.90	5.94	55	84	23	35	13.11	12.06	173	177	27	24
High forage mass with grazing	2.98	4.86	59	80	22	29	8.59	9.71	118	121	23	21
Low forage mass with grazing	3.20	1.98	72	37	20	22	4.60	6.88	67	85	20	19
Hayed	3.14	2.05	63	34	24	30	3.83	3.50	48	41	22	21
$LSD_{(p = 0.1)}$ among fertilization means	0.51	0.41	14	7	1*	1*	1.09	0.96*	18*	17*	1	1
$LSD_{(p = 0.1)}$ among defoliation regime means	0.46	0.58*	9*	8*	1*	2*	1.33*	1.11*	20*	18*	1*	1*
$LSD_{(p = 0.1)}$ among interactions	0.80*	1.00*	19*	15*	2*	3*	2.30*	1.92*	34*	32*	2*	2*

* Denotes significance among treatment means.

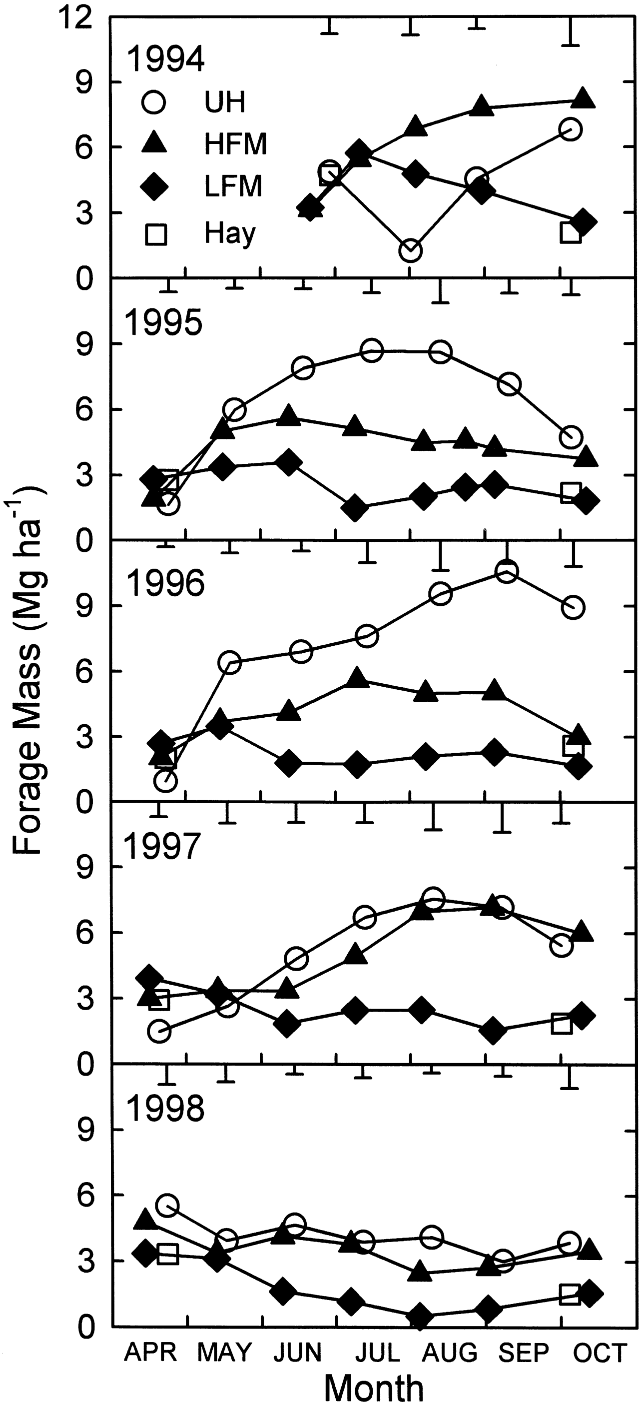


Fig. 2. Forage mass throughout the summer as affected by defoliation regime (UH is unharvested, HFM is grazing to maintain high forage mass, LFM is grazing to maintain low forage mass, and Hay is hayed) when averaged across fertilization regimes from 1994 to 1998. Vertical bars at the top of each panel indicate the least significant difference ($P = 0.1$) among defoliation regimes within each month of sampling.

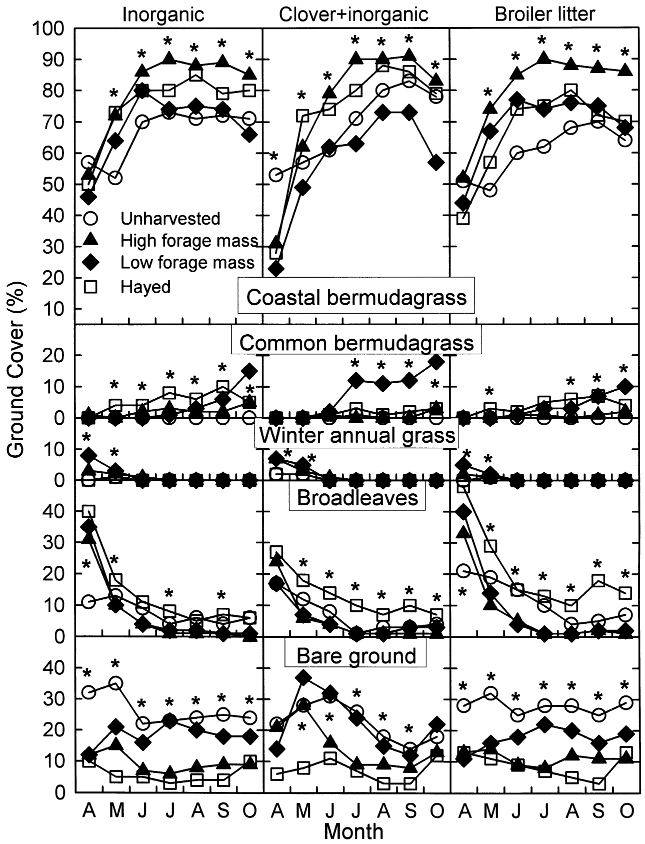


Fig. 3. Ground cover as affected by defoliation regime within each fertilization regime throughout the summer. An asterisk above a set of values within a botanical category, fertilization regime, and month of sampling indicates a significant difference ($P = 0.01$) between at least two defoliation regime means.

Coastal bermudagrass in response to grazing, whereby lower forage mass resulted in more prostrate growth with predominantly young shoots compared with upright growth with a combination of mature stems and young shoots primarily at the top of the canopy under high forage mass (Roth et al., 1990). With increasing maturity, forage C/N ratio increases (Holt and Conrad, 1986; Hoveland, 1992). Nutritive value of consumed forage by grazing cattle, however, may not have been different between forage mass treatments (Roth et al., 1990), since cattle would have likely selected the top layers of forage with higher N concentration (Wilkinson et al., 1970), which could have been more similar to that of the low-growing young shoots available under grazing to maintain low forage mass. In contrast to the inverse relationship between forage mass and forage C/N ratio among fertilization regimes due to fertility, there was a positive relationship between forage mass and forage C/N ratio among defoliation regimes due to differences in maturation of forage.

The intentional effects of defoliation regime on forage mass also led to changes in surface residue N content and C/N ratio (Table 2). Surface residue N content was inversely related to the degree of forage utilization, indicating that unutilized forage at the end of the growing season became a long-term cumulative input to the surface residue component of the pasture ecosystem. Surface residue C/N ratio reflected the same relative changes that occurred in forage C/N ratio among defoliation regimes. Surface residues with lower C/N ratio would likely be more rapidly mineralized and contribute to an overall improvement in soil fertility and nutrient cycling (Vigil and Kissel, 1991). The higher N concentration of surface residues under grazing to maintain low forage mass compared with unharvested management was consistent with higher total, particulate, microbial biomass, and mineralizable C and N in the surface 2 cm of soil under grazing to maintain low forage mass during the same time period (Franzluebbers et al., 2001; Franzluebbers and Stuedemann, 2001, 2003a).

Ground Cover of Pastures

As intended, Coastal bermudagrass was the dominant ground cover in all management systems, except in April with clover + inorganic fertilization (Fig. 3), at which time crimson clover was a large component (Table 3). Cutting of the winter-annual crimson clover following the April evaluation reduced this component to a sporadic species thereafter. Ground cover of crimson clover in pastures, although variable among years, was positively related to forage utilization (Table 3). Under haying and grazing to maintain low forage mass, where forage mass was reduced to a minimum before the winter planting time, crimson clover established the best. Large quantities of either standing forage mass (grazing to maintain high forage mass) or surface residue mass (unharvested management) led to poor development of crimson clover, most likely due to poor surface conditions that inhibited light penetration to the developing seedlings. Springer (1997) found a negative linear relationship between bermudagrass height at the end of the growing season and establishment of either crimson clover or white clover (*Trifolium repens* L.), possibly due to poorer soil–seed contact caused by the inability of seeding equipment to cut through residue, increased shading of seedlings, and better habitat for insects to feed on legume seedlings with taller bermudagrass.

Although Coastal bermudagrass was intended to be the sole forage in all treatments except with clover + inorganic fertilization, ground cover of Coastal bermudagrass in July and August at the peak of its development varied from 62 to 90% (Fig. 3). The highest percentage ground cover as Coastal bermudagrass was always under grazing to maintain high forage mass, irrespective of fertilization regime, except early in the growing season (April–May) when Coastal bermudagrass composition was low under all management systems (53 ± 14%).

Annual changes in ground cover as Coastal bermudagrass were most striking under unharvested management, irrespective of fertilization regime (Table 4). The rates of change resulted in a decline from 81% at the beginning of the experiment to 60% with clover + inorganic fertilization and to 46% with broiler litter fertilization at the end of 5 yr. The decline in ground cover as Coastal bermudagrass under unharvested management resulted in an increase as bare ground (Fig. 3; Table 4), which indicated a thinning of the stand by mature forage that created shade at the soil surface and prevented new basal shoot development.

Decline in ground cover as Coastal bermudagrass was also high under grazing to maintain low forage mass, especially with clover + inorganic fertilization (Table 4). This decline was greater early in the growing season than later. The decline in ground cover as Coastal bermudagrass with grazing to maintain low forage mass resulted in increased bare ground, especially early in the growing season with clover + inorganic fertilization, followed by encroachment with common bermudagrass later in the growing season under all fertilization regimes (Fig. 3; Table 4). This result was consistent with observation of a strong reduction in Coastal bermudagrass shoot density in mid-April and first-harvest hay yield in early June due to increasing vigor of overseeded rye (*Secale cereale* L.) in response to increasing N fertilizer application (Welch et al., 1967). These changes were attributed to lower light intensity, soil temperature, and soil water content with overseeded rye during the early bermudagrass development period in April. Despite these early-season effects, no difference was observed in cumulative annual Coastal bermudagrass production between bermudagrass only or bermudagrass overseeded with rye. Overseeding of crimson clover in our study appeared to result in similar biophysical limitations to the early development of Coastal bermudagrass.

Table 3. Percentage ground cover of crimson clover in pastures with clover + inorganic fertilization in April as affected by defoliation regime.

Year	Defoliation regime†				$LSD_{(P = 0.1)}$
	UH	HFM	LFM	H	
	%				
1994	ND‡	45	47	ND	9
1995	0	2	25	48	15
1996	0	11	42	24	10
1997	0	20	36	42	10
1998	1	6	44	11	13
Mean	5	17	39	36	8

† UH, unharvested; HFM, grazing to maintain high forage mass; LFM, grazing to maintain low forage mass; H, hayed.

‡ ND, not determined.

Decline in ground cover as Coastal bermudagrass was moderate under hayed management, varying from 2 to 4% per year (Table 4). Ground cover as common bermudagrass with inorganic fertilization and as broadleaves with clover + inorganic and broiler litter fertilization increased with time under hayed management (Fig. 3; Table 4). It is unclear why changes in ground cover differed among fertilization regimes, but it may have been due to differences in soil surface nutrient availability that altered competitive advantages of various species.

Ground cover as Coastal bermudagrass with grazing to maintain high forage mass did not change on an annual basis although there were declines early in the growing season with clover + inorganic fertilization (Table 4). The early-season declines were likely due to similar competitive effects that were observed under grazing to maintain low forage mass by the crimson clover cover crop.

Encroachment of common bermudagrass occurred under grazing to maintain low forage mass in all fertilization regimes from August to October (Table 4). The low forage mass may have reduced energy reserves of Coastal bermudagrass below a sustainable threshold, thereby allowing invasion with common bermudagrass

Table 4. Basal ground cover of pastures as Coastal bermudagrass and as undesired species (common bermudagrass, winter annual grass, winter annual broadleaves, and bare ground) as affected by fertilization and defoliation regimes during the first 5 yr of management. Ground cover changes (% yr^{-1}) for each treatment are based on linear regression with a common intercept (%) of the form: $y = \beta_0 + \beta_1 \cdot \mathrm{yr}$.

		Inorganic				Clover + inorganic				Broiler litter				
Period	Intercept	UH†	HFM‡	LFM§	H¶	UH	HFM	LFM	H	UH	HFM	LFM	H	LSD$_{(P = 0.1)}$
	%	% yr^{-1}												
							Coastal bermudagrass							
April	55.0	0.6	−0.7	−3.8#	−2.7	−0.2	−5.7**	−9.0***	−6.3***	−2.0	−1.1	−4.1#	−4.9**	4.6
May	76.6	−8.2***	−1.6	−3.9#	−0.8	−6.4***	−3.3#	−7.5***	−1.7	−8.7***	−0.6	−2.4	−4.9**	3.8
June	87.2	−7.4***	−0.5	−2.5#	−2.9#	−9.3***	−1.5	−7.3***	−4.6***	−10.1***	−0.3	−2.7#	−4.2**	3.1
July††	99.9	−8.6***	−2.5#	−7.2***	−5.0***	−8.9***	−2.6#	−10.2***	−5.2***	−11.5***	−2.6#	−7.4***	−6.8***	3.5
August	92.1	−8.7***	−1.3	−5.3***	−2.2#	−4.0**	−0.4	−6.7***	−0.9	−8.4***	−1.6	−5.6***	−3.4**	2.9
September	87.3	−6.2***	0.1	−3.9***	−2.4#	−2.2#	1.1	−4.4***	−0.6	−6.0***	−0.1	−3.7***	−4.6***	2.6
October	76.1	−3.1#	3.3#	−2.5#	0.9	−0.4	2.4#	−4.8***	0.3	−4.6***	2.8#	−1.3	−2.0	3.3
Mean	81.1	−5.7***	−0.3	−4.0***	−1.9#	−4.2***	−1.3	−7.0***	−2.5#	−7.0***	−0.3	−3.7***	−4.1***	2.5
							Common bermudagrass							
April	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
May	0.5	−0.1	−0.1	−0.1	0.8***	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	−0.1	0.6#	0.6
June	2.3	−0.6#	−0.2	−0.6#	0.7**	−0.6#	−0.5#	−0.3	−0.5#	−0.5#	−0.4	−0.6#	0.0	0.7
July††	4.0	−1.0#	−0.5	−0.6	0.8	−0.7	−1.0#	2.2***	−0.5	−1.0#	−0.9#	−0.0	0.2	1.3
August	0.4	−0.1	0.7#	1.1**	1.8***	−0.1	−0.1	3.5***	0.2	−0.1	−0.1	1.0#	1.4***	1.0
September	2.4	−0.7	−0.2	1.7**	1.9***	−0.7	−0.7	3.6***	−0.4	−0.6	−0.3	1.5**	1.2#	1.3
October	4.4	−1.2	−0.2	3.4***	−0.6	−1.2	−0.3	5.0***	−0.6	−1.2	−0.2	1.6#	−0.4	1.9
Mean	1.8	−0.5	−0.0	0.7**	0.8**	−0.4	−0.4	2.0***	−0.2	−0.5	−0.2	0.5#	0.4	0.7
							Winter annual grass							
April	3.8	−1.0#	−0.3	1.6***	−1.0#	−1.0#	0.8#	0.8#	−1.0#	−1.0#	−0.3	0.6	−1.0#	1.1
							Winter annual broadleaves							
April	4.2	2.2#	8.4***	9.7***	10.9***	4.9***	6.9***	4.3***	7.8***	5.3***	8.7***	11.1***	12.6***	3.0
							Bare ground							
April	25.2	1.2	−4.3**	−4.2**	−4.1**	−0.7	−2.2	−3.7#	−4.6**	0.7	−4.0**	−4.4**	−3.6#	3.7
May	16.0	6.2***	0.0	1.7	−3.2#	4.5**	2.8#	5.7***	−1.9	5.0***	−0.6	−0.4	−2.0	3.4
June	12.4	3.9***	−1.3	1.5	−2.3#	6.2***	0.3	6.0***	−0.7	4.6***	−1.2	1.5	−1.3	2.4
July††	−2.3	7.9***	2.4#	7.0***	1.4	8.7***	3.1**	7.2***	2.2#	9.2***	2.8#	6.8***	2.5#	2.7
August	4.3	7.7***	1.2	4.6***	−0.3	4.4***	1.3	3.5***	−0.4	8.6***	2.5#	5.1***	0.0	2.4
September	6.8	6.6***	0.9	2.8***	−0.6	2.9***	0.3	1.3	−1.1	6.4***	1.1	2.7**	−1.2	2.0
October	17.5	2.6**	−2.6**	−0.8	−1.7#	0.9	−1.9#	−0.3	−1.1	4.0***	−2.3#	−0.5	−0.7	2.3
Mean	12.3	5.0***	−0.7	1.6#	−1.8#	3.6***	0.3	2.6***	−1.3#	5.2***	−0.5	1.3#	−1.2	1.7

** Indicates significantly different values from zero at $P = 0.01$.
*** Indicates significantly different values from zero at $P = 0.001$.
† UH, unharvested.
‡ HFM, grazing to maintain high forage mass.
§ LFM, grazing to maintain low forage mass.
¶ H, hayed.
# Indicates significantly different values from zero at $P = 0.1$.
†† Estimates were not available in July 1994; therefore, regressions were from 1995 to 1998 only.

following occasionally favorable precipitation events later in the summer. A similar, but lesser invasion of common bermudagrass occurred later in the summer under hayed management with inorganic and broiler litter fertilization. Common bermudagrass encroachment into pastures grazed to a low forage mass is typical in the southeastern USA (Bates et al., 1996; Gates et al., 1999), partly because its prostrate growth habit makes it more tolerant to conditions of low forage mass.

Encroachment of annual grasses during the winter dormant period of bermudagrass was greatest under grazing to maintain low forage mass with inorganic fertilization (Table 4). Annual broadleaves were even more encroaching during the winter period under all management systems. The encroachment of broadleaves was positively related to the extent of forage utilization, indicating that less forage or surface residue mass created opportunities for broadleaves to proliferate. These low-growing broadleaves did not appear to greatly inhibit the development of overseeded crimson clover, nor did they pose a serious threat to the persistence of Coastal bermudagrass. However, the development of winter annual grasses and broadleaves in this study highlights a period of opportunity to increase forage production and potential animal grazing days by overseeding of bermudagrass pastures with cool-season grasses or legumes, which has been demonstrated in several other studies (Welch et al., 1967; Carreker et al., 1977; Wilkinson and Stuedemann, 1983). Our results from overseeding crimson clover into bermudagrass with grazing to maintain low forage mass highlight the need to carefully manage the cool-season forage in the spring to avoid loss of Coastal bermudagrass stand. We allowed crimson clover to reach full bloom before cutting to maximize biological N fixation, but this likely reduced the early-season development of Coastal bermudagrass.

Forage Productivity

Differences in hay yield due to fertilization regime occurred primarily early in the growing season from April to June each year (Table 5). Clover + inorganic

Table 5. Hay yield on a monthly basis from April to October and as an annual total during 1994 to 1998 as affected by fertilization regime.

Year and fertilization	April	May	June	July	August	September	October	Annual total
	Mg ha^{-1}							
1994								
Inorganic	ND†	ND	ND	5.95	1.88	2.10	1.18	10.69
Clover + inorganic	ND	ND	ND	3.76	2.07	2.30	1.10	9.19
Broiler litter	ND	ND	ND	4.79	2.35	1.53	1.18	9.57
LSD$_{(P = 0.1)}$	ND	ND	ND	0.82*	1.87	0.95	0.48	3.97
1995								
Inorganic	0.88	0.62	3.28	0.66	1.87	2.26	0.46	10.03
Clover + inorganic	2.62	0.24	1.55	0.69	1.70	2.61	0.50	9.91
Broiler litter	0.98	0.45	2.05	0.68	1.07	2.44	0.56	8.24
LSD$_{(P = 0.1)}$	0.97*	0.22*	0.70*	0.41	1.09	0.75	0.08*	3.02
1996								
Inorganic	0.54	0.43	2.13	1.12	3.00	0.45	0.24	7.92
Clover + inorganic	0.95	0.39	0.68	0.84	2.78	0.37	0.20	6.20
Broiler litter	0.78	0.66	1.07	0.88	2.31	0.43	0.24	6.37
LSD$_{(P = 0.1)}$	0.18*	0.30	0.95*	0.48	0.92	0.17	0.14	2.44
1997								
Inorganic	0.58	0.18	1.19	2.86	1.54	0.58	0.45	7.37
Clover + inorganic	2.81	0.08	0.45	2.15	1.32	0.48	0.32	7.62
Broiler litter	0.90	0.16	0.61	2.37	1.31	0.55	0.37	6.27
LSD$_{(P = 0.1)}$	0.25*	0.08*	0.42*	0.94	0.61	0.14	0.26	1.82
1998								
Inorganic	0.61	0.67	1.53	0.40	0.40	1.35	0.45	5.40
Clover + inorganic	0.60	0.33	0.66	0.23	0.30	1.35	0.40	3.86
Broiler litter	0.56	0.47	0.85	0.29	0.33	1.20	0.46	4.15
LSD$_{(P = 0.1)}$	0.53	0.31*	0.85*	0.28	0.26	0.85	0.17	2.46
5-yr mean								
Inorganic	0.65	0.47	2.03	2.20	1.74	1.35	0.56	8.28
Clover + inorganic	1.74	0.26	0.83	1.53	1.63	1.42	0.50	7.36
Broiler litter	0.80	0.44	1.14	1.80	1.47	1.23	0.56	6.92
LSD$_{(P = 0.1)}$	0.42*	0.11*	0.30*	0.32*	0.37	0.23	0.08	0.91*

* Denotes significance among treatment means.

† ND, not determined.

fertilization produced greater quantity of hay in April than inorganic or broiler litter fertilization during 1995, 1996, and 1997. This result was an intentional consequence of overseeding the warm-season pastures with the winter-annual crimson clover, which produced peak forage mass in April. An opposite effect occurred for hay production in May where hay yield under inorganic and broiler litter fertilization was greater than under clover + inorganic fertilization in 1995, 1997, and 1998. Hay yield in June was greatest with inorganic fertilization during most years. The higher hay yields during May and June in most years and from the first cutting in July in 1994 with inorganic fertilization compared with the organic fertilization regimes occurred most likely because of the immediate availability of applied inorganic N to bermudagrass forage. Since clover forage was harvested as hay, crimson clover root and stubble were the only sources of organic N supplied, which would have likely required more time for release of biologically fixed N than that of leaves and stems (Franzluebbers et al., 1994a, 1994b). Availability of N from broiler litter can be highly variable, but analyses from 15 different broiler houses in northern Georgia revealed 34 ± 12% of total N in an immediately available pool, 31 ± 7% of total N in an intermediately available pool with a half-life of 15-29 d under ideal conditions, and 35 ± 12% of total N in a resistant pool not considered available during the first growing season (Gordillo and Cabrera, 1997).

When the second application of N occurred in July, the source of N fertilization had relatively little impact on hay yield during August, September, and October. The high temperature and frequent drying and rewetting of soil during summer months allowed more ideal conditions for rapid mineralization of N from organically applied sources as well as from soil organic matter. In a controlled incubation, mineralization of C from cowpea green manure [*Vigna unguiculata* (L.) Walp.] was equivalent during 68 d under alternating dried and rewetted conditions as under continuously moist conditions (Franzluebbers et al., 1994b).

Averaged across years, hay yield with clover + inorganic fertilization was more than double that with inorganic or broiler litter fertilization during April (Table 5). During May, June, and July, hay yield was greater with inorganic fertilization than with clover + inorganic fertilization. Hay yield was greater with broiler litter fertilization than with clover + inorganic fertilization in May and June and greater with inorganic fertilization than with broiler litter fertilization in June and July.

Total annual hay yield was not different among fertilization regimes during any single year (Table 5). However, when averaged across years, inorganic fertilization produced hay yield 12% greater than with clover + inorganic fertilization and 20% greater than with broiler litter fertilization. It appears that the immediate availability of N with the inorganic source was efficiently utilized throughout the year, considering also little evidence of leaching loss from any of the fertilization regimes (Franzluebbers and Stuedemann, 2003b). However, it can also be stated that the organic fertilization sources produced equal quantities of hay in any single year while at the same time utilizing very important resources available to producers in the southeastern USA, i.e., biological N fixation with the overseeding of crimson clover and animal manure readily available within the region that must be effectively utilized to avoid environmental degradation.

Lower hay yield with clover + inorganic fertilization than with inorganic fertilization in our study was consistent with observations of slightly lower hay yield but improved forage N concentration when various legumes were overseeded into bermudagrass compared with bermudagrass alone in Oklahoma (Mullen et al., 2000). We based supplemental inorganic N fertilization in the clover + inorganic treatment on the assumption that carryover of N from clover would be 110 kg N ha^{-1} (Carreker et al., 1977). Overman et al. (1992) estimated that when overseeded crimson clover forage mass was removed as hay, actual N carryover from clover to bermudagrass would be 33 kg ha^{-1} yr^{-1}. It is therefore possible that the reduced 5-yr-mean hay yield we observed with clover + inorganic compared with inorganic fertilization was due to lower availability of N.

Similar to our results, hay yield of bermudagrass fertilized with broiler litter (300 kg N ha^{-1} yr^{-1}) was lower (14.9 vs. 16.4 Mg dry matter ha^{-1} yr^{-1}) than with inorganic fertilization (220 kg N ha^{-1} yr^{-1}) during a 2-yr evaluation in northern Alabama but statistically significant in only two of six hay cuttings (one positive and one negative) (Wood et al., 1993). In eastern Texas, hay yield of Coastal bermudagrass fertilized with broiler litter to supply the same quantity of N as with inorganic fertilizer (220 kg N ha^{-1} yr^{-1}) was reduced (8.1 vs. 9.5 Mg dry matter ha^{-1} yr^{-1}) during a 2-yr evaluation (Evers, 1998).

Forage mass of the unharvested treatment was typically greater with inorganic fertilization than with either clover + inorganic or broiler litter fertilization early in the summer but became more similar among fertilization regimes by the end of the growing season (Table 6). This early-season fertilization effect was evident during the first 3 yr but not during the last 2 yr of the experiment. Both the reduced early-season growth during the early years and the lack of differences at any time during the later years with organic compared with the inorganic sources of fertilization suggest that additional time was needed for mineralization of organically bound nutrients. Once that time became available, there were no major differences in forage mass among inorganic and organic sources when fertilized with equivalent rates of N.

Peak forage mass of the unharvested treatment was not different among fertilization regimes during any single year (Table 6). However, averaged across years, peak forage mass with inorganic fertilization was 18% greater than with clover + inorganic fertilization and 20% greater than with broiler litter fertilization. These relative differences among fertilization regimes were similar to those observed for total annual hay yield (Table 5) although peak forage mass of the unharvested treatment was 1.09 ± 0.27 Mg ha^{-1} greater than total annual hay yield.

Forage productivity was greater with inorganic fertilization (8.89 Mg ha^{-1} yr^{-1}) than with clover + inorganic fertilization (7.83 Mg ha^{-1} yr^{-1}) and broiler litter fertil-

Table 6. Unharvested forage mass during April to October and estimate of peak forage mass during 1994 to 1998 as affected by fertilization regime.

Year and fertilization	April	May	June	July†	August	September	October	Peak‡
	Mg ha^{-1}							
1994								
Inorganic	ND§	ND	6.64	6.37	7.58	11.48	13.97	14.04
Clover + inorganic	ND	ND	2.76	3.79	5.16	9.01	11.17	11.21
Broiler litter	ND	ND	5.21	5.06	6.25	8.38	10.45	10.43
LSD$_{(P = 0.1)}$	ND	ND	2.60*	0.66*	1.57*	3.96	3.58	4.63
1995								
Inorganic	1.53	6.75	9.13	9.56	9.87	6.85	4.53	10.10
Clover + inorganic	1.88	6.12	7.55	8.17	7.39	7.81	5.03	8.46
Broiler litter	1.57	5.05	6.97	8.31	8.59	6.76	4.57	8.46
LSD$_{(P = 0.1)}$	1.29	1.20*	1.25*	2.33	4.00	2.48	2.49	2.49
1996								
Inorganic	0.72	8.12	7.79	8.37	9.64	10.77	8.45	10.27
Clover + inorganic	1.03	5.40	5.07	5.81	8.76	9.91	8.93	9.79
Broiler litter	1.11	5.64	7.84	8.63	10.19	11.01	9.36	10.52
LSD$_{(P = 0.1)}$	0.61	1.32*	1.54*	4.18	5.14	3.04	5.60	4.61
1997								
Inorganic	1.16	3.27	4.41	7.67	7.51	8.08	6.59	7.98
Clover + inorganic	1.88	2.16	5.17	6.89	8.56	7.49	4.91	7.44
Broiler litter	1.44	2.51	4.85	5.61	6.61	5.91	4.81	6.47
LSD$_{(P = 0.1)}$	2.15	2.52	3.89	3.38	4.66	4.31	3.60	2.93
1998								
Inorganic	6.33	4.96	5.24	4.92	4.64	3.01	3.56	5.78
Clover + inorganic	5.97	3.80	3.99	3.21	4.24	3.24	3.59	3.96
Broiler litter	4.23	3.03	4.69	3.47	3.43	2.79	4.40	4.32
LSD$_{(P = 0.1)}$	2.96	2.57	1.90	2.03	0.94*	1.82	4.93	2.64
5-yr mean								
Inorganic	2.44	5.77	6.64	7.38	7.85	8.04	7.42	9.63
Clover + inorganic	2.69	4.37	4.91	5.58	6.82	7.49	6.73	8.17
Broiler litter	2.09	4.06	5.91	6.22	7.01	6.97	6.72	8.04
LSD$_{(P = 0.1)}$	0.78	0.78*	0.95*	0.95*	1.24	1.18	1.44	1.17*

* Denotes significance among treatment means.

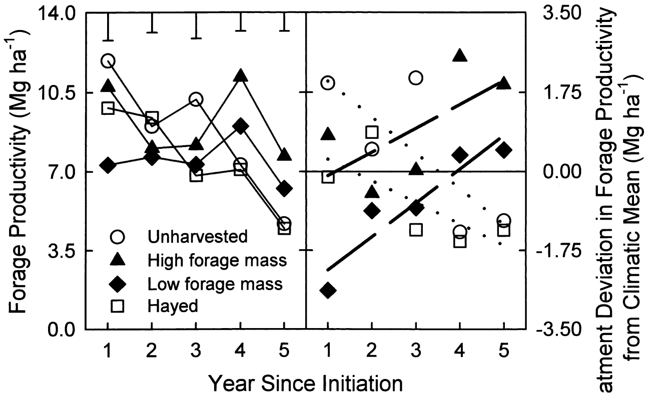
† Values in July 1994 represent forage cut for hay, which were added to the standing stock of forage in subsequent months during 1994.

‡ Peak forage mass was calculated using linear + quadratic regression of seasonal forage mass against day of year for each replication.

§ ND, not determined.

ization (7.88 Mg ha^{-1} yr^{-1}) when averaged across defoliation regimes and years (Table 7). Although an interaction between fertilization and defoliation regimes was not significant when averaged across years, differences in forage productivity were significant in two of three fertilization comparisons with unharvested management, in none of the three comparisons under grazing to maintain high forage mass, in one of three comparisons under grazing to maintain low forage mass, and in one of three comparisons under haying (Table 7).

Forage productivity was affected by defoliation regime each year (Table 7) although the order of treatment rank changed with time when averaged across fertilization regimes (Fig. 4). During the first 2 yr, grazed strategies (i.e., high and low forage mass) were lower in productivity than ungrazed strategies (i.e., unharvested and hayed). There was no difference between grazed and ungrazed strategies in the third year. In the fourth and fifth year, forage productivity of the grazed strategies was greater than that of ungrazed strategies. Conceptually, we expected little difference in forage productivity among defoliation regimes during the first year or two, since feedback mechanisms would have required some time to develop. It is possible that forage productivity under grazed strategies may have been underestimated because we did not account for trampling and spoilage of forage by grazing cattle. Although surface residue mass contains feces and soil contamination, accumulation of this pool during the growing season (Table 2) under grazed strategies may give an indication of the extent of unaccounted forage produced during the year. The difference in surface residue mass between final and initial samplings averaged across years and fertilization regimes was 1.13 and 2.29 Mg ha^{-1} yr^{-1} for high- and low-forage-mass treatments, respectively. We could not separate dung and soil contamination from this estimate, nor account for decomposition changes in this pool during the course of the growing season, which could have been as high as 0.33 to 1.05 Mg ha^{-1} yr^{-1} based on the average difference in surface residue mass during the growing season of hayed and unharvested strategies, respectively.



	Intercept	Slope	Intercept	Slope
Unharvested	13.45	-1.61	2.79	-0.79
High forage mass	10.05	-0.30	-0.62	0.53
Low forage mass	7.73	-0.07	-2.94	0.75
Hayed	11.42	-1.30	0.76	-0.48
LSD$_{(P = 0.1)}$		1.04		0.74

Fig. 4. Annual forage productivity as affected by defoliation regime averaged across fertilization regimes during 1994 to 1998 and treatment deviations from annual means (to account for differences in climatic conditions) as a function of years since initiation of the study among defoliation regimes.

Despite the uncertainty in absolute forage productivity with grazed strategies due to the indirect method employed, we believe the temporal divergence between ungrazed and grazed strategies remains valid. Data in Fig. 4 suggest that defoliating forage continuously with grazing resulted in a positive shift in pasture productivity, perhaps by (i) avoiding the "boom and bust" growth pattern of haying management, (ii) avoiding the inhibitory effects of maturation on regrowth with unharvested management, or (iii) improving soil nutrient status with recycling of nutrients through manure deposition (Franzluebbers and Stuedemann, 2001; Franzluebbers et al., 2004). In addition, enhancement of forage regrowth has been attributed to thiamine in animal saliva (Reardon et al., 1972; McNaughton, 1985) although this enhancement has not always been found and has been demonstrated only under highly controlled laboratory conditions (Matches, 1992). Differences in defoliation intensity, traffic, and nutrient cycling between mechanical defoliation and animal grazing have been suggested to affect plant responses (Matches, 1992), and our results support this contention. In addition, although we did not determine insect occurrence, damage to less frequently defoliated bermudagrass has been found to decrease forage dry matter accumulation (Hawkins et al., 1979).

Forage productivity was greater when unharvested

Table 7. Forage productivity as affected by fertilization and defoliation regimes during the first 5 yr of management.†

	Inorganic				Clover + inorganic				Broiler litter				
Year	UH‡	HFM§	LFM¶	H#	UH	HFM	LFM	H	UH	HFM	LFM	H	LSD$_{(p = 0.1)}$
	Mg ha^{-1}												
1994	14.04	11.10	7.74	10.69	11.21	9.59	7.09	9.19	10.43	11.54	7.07	9.57	2.09*
1995	10.10	7.64	8.10	10.03	8.46	8.53	6.74	9.91	8.46	7.96	8.09	8.24	1.50*
1996	10.27	8.47	7.60	7.92	9.79	8.10	7.14	6.20	10.52	7.92	7.22	6.37	1.96*
1997	7.98	12.24	10.38	7.37	7.44	10.41	8.23	7.62	6.47	10.85	8.42	6.27	1.40*
1998	5.78	8.17	6.84	5.40	3.96	7.46	5.61	3.86	4.32	7.44	6.31	4.15	1.41*
Mean	9.63	9.52	8.13	8.28	8.17	8.82	6.96	7.36	8.04	9.14	7.42	6.92	1.06*

* Denotes significance among treatment means.
† Forage productivity was determined by different procedures for each defoliation regime (see Materials and Methods section for details).
‡ UH, unharvested.
§ HFM, grazing to maintain high forage mass.
¶ LFM, grazing to maintain low forage mass.
# H, hayed.

than when hayed in 1994 and 1996 (Fig. 4; Table 7) and when averaged across years (8.62 vs. 7.52 Mg ha^{-1} yr^{-1}). This result is in accordance with several previous studies where forage yield of less frequently harvested Coastal bermudagrass has been greater than that of more frequently harvested (Holt and Lancaster, 1968; Monson and Burton, 1982; Holt and Conrad, 1986). The difference in productivity between unharvested and hayed forage in our study could have also been related to cumulative changes in soil properties with time due to the continuous removal of forage mass with haying, which lowered the recycling of nutrients from plant residues into (i) soil organic and surface residue C and N pools (Franzluebbers et al., 2001), (ii) N-supplying capacity of surface soil (Franzluebbers and Stuedemann, 2001), and (iii) exchangeable soil K (Franzluebbers et al., 2004). The change in ground cover with time may have also contributed to the difference in productivity, in which the more productive Coastal bermudagrass component declined and the less productive common bermudagrass and broadleaf components increased with time under haying compared with unharvested management (Table 4).

Estimated forage productivity was greater under high than under low forage mass with grazing in 1994, 1997, and 1998 (Fig. 4; Table 7) and when averaged across years (9.2 vs. 7.5 Mg ha^{-1} yr^{-1}). Maintenance of greater ground cover as Coastal bermudagrass, lower encroachment of common bermudagrass, and lower development of bare ground (Table 4) under high than low forage mass with grazing could partly explain the greater estimated productivity under grazing to maintain high forage mass. Soil organic matter components and surface soil compaction were not greatly affected between high and low forage mass with grazing (Franzluebbers et al., 2001; Franzluebbers and Stuedemann, 2003a), suggesting soil nutrient supply and soil surface conditions affecting rooting and water dynamics would have been similar.

The difference in estimated forage productivity between high and low forage mass with grazing was 1.7 ± 1.2 Mg ha^{-1} yr^{-1} among years, nearly equivalent to the difference in forage mass at the end of the growing season, which averaged 4.53 ± 1.59 Mg ha^{-1} under grazing to maintain high forage mass and 2.54 ± 1.11 Mg ha^{-1} yr^{-1} under grazing to maintain low forage mass (Fig. 2). Despite the higher estimated forage productivity with grazing to maintain high forage mass, cattle stocking density was lower with high forage mass (5.9 ± 2.1 head ha^{-1}) than with low forage mass (8.4 ± 2.8 head ha^{-1}) (mean ± standard deviation among fertilization regimes, years, and stocking periods). Stocking density gives no indication of cattle performance or production, which will be reported elsewhere (J.A. Stuedemann, unpublished data,1998). Forage allowance (calculated from forage mass before a 28-d period divided by total cattle weight stocked during that period) was 2.64 ± 1.18 kg forage kg^{-1} body weight (mean ± standard deviation among fertilization regimes, years, and periods; $n = 23$) under high forage mass and 0.92 ± 0.40 kg forage kg^{-1} body weight under low forage mass. Coastal bermudagrass is known to alter its morphology toward a less prehensible, prostrate growth habit with grazing to maintain low forage mass, allowing it to achieve a similar growth rate to that under grazing to maintain high forage mass (Roth et al., 1990). More prostrate morphology with grazing to maintain low forage mass was associated with greater rhizome mass of ‘Florakirk’ bermudagrass compared with grazing to maintain high forage mass at the end of 2 yr (Pedreira et al., 2000), suggesting that energy reserve of closely grazed bermudagrass might be maintained without sacrificing productivity. Our results, however, indicate that grazing to maintain low forage mass reduced forage productivity of Coastal bermudagrass pastures across several years and that a long-term optimum forage mass target might be between the two forage masses maintained in our study.

From an environmental quality perspective, forage production under either grazing to maintain high forage mass or unharvested management would be more desirable than under grazing to maintain low forage mass because the greater forage and surface residue coverage would reduce water runoff and particulate-borne nutrient transport across the landscape (Phillips, 1998). From an agronomic perspective, higher forage productivity under grazing to maintain high rather than low forage mass effectively contributed to a surface buffer of forage mass that suppressed winter annual growth (Table 2) and allowed greater persistence of Coastal bermudagrass by limiting encroachment of undesirable forage components (Table 4). From an animal production perspective, the 46 ± 47% greater cattle stocking density under low than under high forage mass could lead to greater short-term economic gain although at the risk of reducing medium-term forage productivity and economic outcome.

CONCLUSIONS

Pastures grazed to maintain high forage mass, whether fertilized inorganically or organically, had the highest productivity with the highest persistence of Coastal bermudagrass. Cattle producers in the Piedmont region could use information from this experiment to (i) sustain medium-term forage productivity and preserve Coastal bermudagrass stands by stocking cattle to moderately utilize forage (high forage mass) or (ii) maximize short-term economic gain and risk losing long-term forage productivity by stocking cattle to fully utilize forage (low forage mass). Although we acquired revealing ecosystem responses from the first 5 yr of this study, more time is needed to appropriately relate short- and long-term economics with pasture productivity and environmental consequences.

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