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# Drought and grazing patch dynamics under different grazing management

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**Abstract**

Land deterioration does not occur uniformly over time or over a landscape. The differential use of preferred areas in the landscape results in uneven distribution of animal impact, and periods of below average precipitation compound the effects of herbivory, providing periods of accelerated deterioration. This study investigates whether rotational grazing during a drought cycle allows reduction of deterioration caused by patch-selective grazing in large (1800–2100 ha) paddocks by providing adequate rest between grazing events. From 1995 through 2000, herbaceous and bare ground changes were measured on adjacent heavily grazed and lightly grazed patches in rotationally and continuously grazed paddocks.

The weather interacted with grazing treatment ($p<0.0001$), species ($p<0.0001$) and the combined effects of the other factors ($p<0.0014$), indicating the dominant effect of weather, particularly precipitation, on changes in herbaceous basal area. When summer growing conditions were favorable, the rotational grazing treatment resulted in greater increases of perennial herbaceous basal areas ($p<0.05$) and lower proportions of bare ground ($p<0.10$) than the continuously grazed treatment. Although rotational grazing did not prevent deterioration in basal area and bare ground with the series of four drought years, it did decrease the rate of deterioration. The changes in basal area were primarily due to changes in summer growing perennial $C_4$ midgrasses and $C_4$ shortgrasses. Grazing treatment did not influence species aerial biomass composition ($p > 0.1$). When monitoring to effect sustainable use, the commonly used parameter of species composition appears to be a much less sensitive indicator of change than bare ground and basal area. This study provides evidence that, in

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large paddocks in this environment, rotational grazing can reduce the deterioration and allow improvement of both shortgrass and midgrass patches.
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*Keywords:* Basal area; Continuous grazing; Patch overgrazing; Patch selection; Rotational grazing; Spatial heterogeneity; Species composition

## 1. Introduction

High interannual rainfall variability characterizes semi-arid range environments, and droughts of different intensity and frequency are a normal and recurring phenomenon (Stafford Smith, 1996). Although the effects of climate substantially outweigh the effects of grazing in determining primary production and regulating the rate and direction of plant composition changes, different management can significantly alter the impact of livestock on range plants (Archer and Smeins, 1991). The tall-, mixed- and shortgrass prairies of North America evolved with grazing and are well adapted to defoliation but the introduction of livestock has changed the frequency, intensity, extent and magnitude of grazing. This has resulted in general deterioration of the range resource, including changes in species composition, decreased production and increased interannual variability of primary production (Weaver, 1950; Pieper and Heitschmidt, 1988; Archer and Smeins, 1991; Thurow, 1991, pp. 141–159; Frank and McNaughton, 2002). The co-occurrence of periodic droughts compounds these effects (Herbel, 1986), resulting in periods of accelerated deterioration.

Grazing ungulates entering an area for the first time establish a pattern of use that becomes reinforced over time (Bailey et al., 1996; Turner, 1999). They concentrate on short, leafy areas that contain relatively high nutrient concentrations (McNaughton, 1984) and neglect previously ungrazed plants and patches. In subsequent years, animals are attracted to previously grazed areas, enlarging them and creating new ones nearby (Bakker et al., 1983; Fuls, 1992). The stocking rate on these semi-permanent heavily grazed patches is much higher than the intended stocking rate of the paddock as a whole (Kellner and Bosch, 1992). This leads to progressive deterioration characterized by replacement of taller perennial grasses by shorter perennial grasses, then annual grasses and finally bare ground. These changes in the vegetation and soil generally result in decreased infiltration and increased runoff and erosion (Thurow et al., 1986). This reduces primary production and increases the variability of production, exacerbating the effects of drought (Kelly and Walker, 1976; MacDonald, 1978; Snyman and Fouche, 1991). This deterioration is not easily reversed (Fuls and Bosch, 1991). Large paddocks that are continuously grazed have been observed by both ranchers and scientists to deteriorate due to this patch selective grazing (Andrew, 1988; Kellner and Bosch, 1992; Pickup and Stafford Smith, 1993; Norton, 1998).

Rotational grazing has been proposed as a remedy for this deterioration (Booysen, 1975; Booysen and Tainton, 1978; Kirkman and Moore, 1995) but research

comparing rotational with continuous grazing has generally concluded that the effect of rotational grazing per se on defoliation patterns is weak or absent. However, research on rotational grazing systems has invariably been carried out using small paddocks, usually less than 25 ha and often less than 5 ha. In addition, research areas are specifically chosen to be as uniform as possible. Both these factors significantly reduce the variability that causes patch selection and the associated deterioration in large paddocks (Norton, 1998).

A large body of scientific evidence indicates that even in homogeneous circumstances, selectivity, i.e. patch grazing, should increase as the area under consideration increases in size (Senft et al., 1985; Stuth, 1991; Bailey et al., 1996). It appears that selection is affected a little by small-scale heterogeneity at the feeding station level but is profoundly affected by large-scale heterogeneity at the landscape level (WallisDeVries and Schippers, 1994). Both the spatial arrangement of grazing patches and the scale of patchiness are major determinants of selectivity during grazing (WallisDeVries et al., 1999). In addition, patterns of herbivory on the landscape are controlled by spatial distribution of topography, water, cover, minerals and inter- and intra-specific social interactions (Coughenour, 1991). Spatial and temporal variability in primary production localizes and intensifies herbivore impacts (Illius and O'Connor, 1999).

This study examines herbaceous vegetation and bare ground dynamics during a drought cycle on adjacent heavily grazed and lightly grazed patches under continuous and rotational grazing in large, heterogeneous paddocks. We hypothesize that in large paddocks under moderate levels of stocking, rotational grazing will result in higher perennial herbaceous basal area and less bare ground than continuous grazing. By providing periods with no livestock grazing, rotational grazing will allow recovery from herbivory, positively influencing basal area and bare ground, key factors influencing primary production and its variability.

## 2. Materials and methods

### 2.1. Study area

The investigation was conducted in the Rolling Plains of north-central Texas on the Waggoner Experimental Ranch (WER) (33°50′N, 99°5′W) near Vernon. The climate is continental with an average 220 frost-free, growing days. Mean annual precipitation is 648 mm varying from 490 to 1000 mm. It is bimodally distributed with peaks in May (95 mm) and September (76 mm)($n = 72$). Mean monthly temperature varies from −2.3°C in January to 36.4°C in July ($n = 72$). Elevation ranges from 335 to 396 m.

Honey mesquite (*Prosopis glandulosa*) trees dominated the vegetation at 9–31% crown cover. The herbaceous vegetation was dominated by Texas wintergrass (*Nassella leucotricha*), silver bluestem (*Bothriochloa laguroides*), sideoats grama (*Bouteloua curtipendula*), meadow dropseed (*Sporobolus compositus*), buffalograss (*Buchloe dactyloides*), the annual Japanese brome grass (*Bromus japonicus*), and the

forbs heath aster (*Aster ericoides*), plantain (*Plantago* spp), annual broomweed (*Gutierrezia texana*), and western ragweed (*Ambrosia psilostachya*). Nomenclature follows Diggs et al. (1999). The herbaceous vegetation is characterized by alternating shortgrass and midgrass patches 5–15 m in diameter with Texas wintergrass dominating under the canopies of mesquite trees.

The experimental area consisted of 3 range sites: silty-clay bottomland, clay-loam flats and shallow-clay slopes. The bottomland range sites are level to 1% slope and are silty clays of the Wheatwood series (fine-silty, mixed, active, thermic Fluventic Haplustept). The clay-loam range sites consist of moderately fertile, moderately deep clay-loams of the Tilman series (fine, mixed, thermic Typic Paleustoll) with 1–3% slopes. The shallow-clay range sites consist of moderately fertile, shallow-clays of the Vernon series (fine, mixed, active, thermic Typic Haplustepts) with 3–8% slopes.

### 2.2. Climatic conditions

The monthly rainfall deviations from the long-term monthly means are presented in Fig. 1. Potentially, 60% of annual primary production takes place in May and June. If growing conditions are poor in these 2 months, production for the year is significantly reduced. In 1995, the year treatment began, a relatively dry winter and spring was followed by a wet summer. Early autumn was normal but through late autumn and into winter it was again dry. Spring and summer of 1996 was exceptionally dry followed by a wet autumn. Winter and spring of 1997 were close to normal and followed by a slightly wet summer and dry autumn going into 1998. Late winter and spring were wet in 1998 and the rest of the year was very dry. Summer of 1999 was wetter than average but autumn and winter of 1999 into 2000 were drier than average. In 2000 both summer and autumn rains failed.

Temperatures were close to the long-term mean (17.3°C) in 1995 through 1997 (16.9–17.2°C) but above the long-term mean in 1998 through 2000 (18.7–18.8°C).

The climatic conditions during this period were sufficiently droughty to force even moderately stocked ranchers to destock by 30–50%. Ranchers in the region have also been eligible for drought relief assistance from 1996 through 2001(Farm Service Agency, United States Department of Agriculture, Wilbarger County, Texas).

### 2.3. Treatments

The two treatments were continuous grazing and rotational grazing using an 8-pasture, 1-herd rotation. The experiment began in April 1995 and continues. The two continuously grazed replicates are 1506 and 1295 ha, and the two rotationally grazed replicates are 1858 and 2131 ha in size. Prior to commencement of the experiment, the rotationally grazed treatment areas were continuously grazed at the same stocking rate as the continuously grazed treatment areas. A similar mix of soils was present on all treatment areas and both replicates of each treatment.

Each replicate was stocked with a herd of commercial Hereford cows bred to Hereford bulls to calve in January through March. Each herd started with equal proportions in each of the age groups 3–8 years old. Calves were weaned and

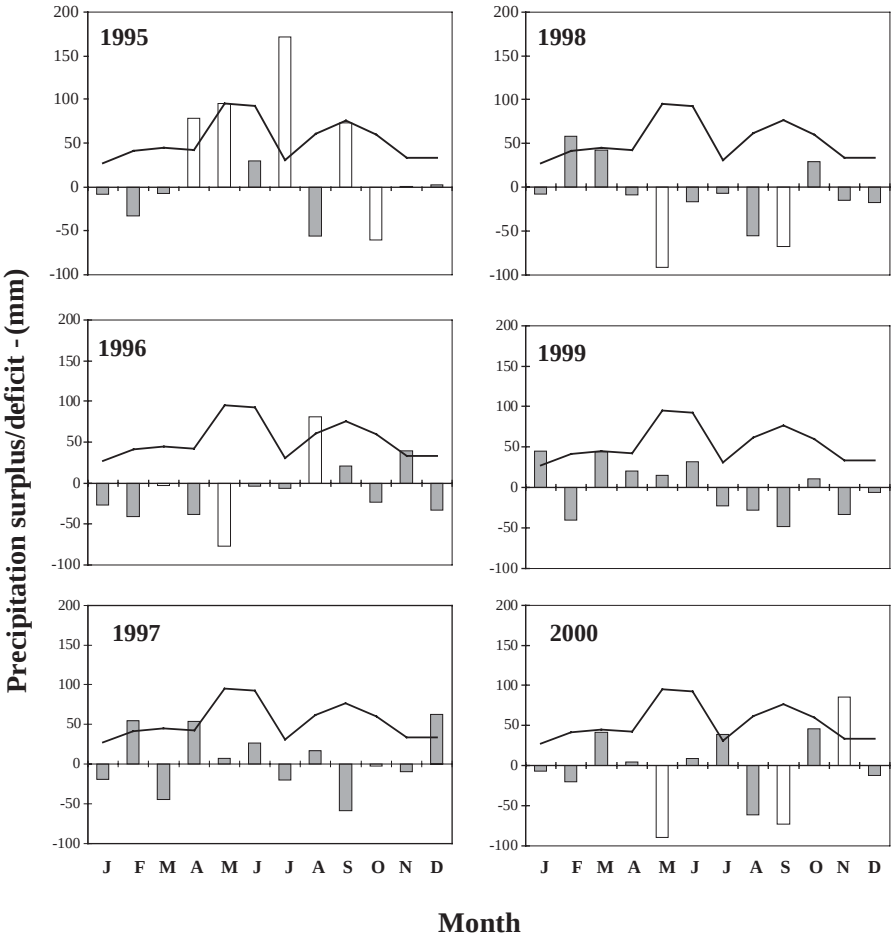


Fig. 1. Monthly precipitation surplus or deficit (▭) relative to the long-term mean monthly precipitation (▩)($n = 25$ years) for the Waggoner Experimental Ranch in north central Texas from 1995 to 1998.

removed from the project at the end of October each year. Non-pregnant cows were identified and removed from the project at weaning and replaced with 3-year-old pregnant cows. The same stocking rates were applied to all replicates. Initially, replicates were stocked at 7.5 ha $AUY^{-1}$. In autumn of 1997 stock numbers were decreased to 12 ha $AUY^{-1}$ for 1998–2000 because of extended drought conditions. Most commercial ranches in the area made similar adjustments over this time period.

The following management protocols were followed. In the rotational grazing treatment, cattle were moved when preferred plants were moderately defoliated. The aim was to leave, on average, no less than 30% of the canopy of preferred plants in any period of occupation. In practice, this resulted in periods of absence of approximately 45 and 90 days during fast and slow forage growth periods,

respectively. Animal management was otherwise the same between the treatments. Stream, river and earthen ponds were spatially situated so that all grazing was within a 1.2 km of water. The same mineral supplement was available year-round in both treatments. Supplements, as 39% protein cubes, were fed every third day in winter to achieve a body condition score of 5 at the end of winter. Mineral and protein supplements were placed to spread grazing pressure as much as possible. No fire management took place in the areas reported here.

### 2.4. Measurements

From 1995 to 2000, herbaceous vegetation change, bare ground and litter cover were monitored on 3 range sites at 4 separate locations per replicate (1 in each quarter) along 1000-m-long transects. Herbaceous plant composition by biomass was estimated at the landscape scale along these transects using the dry-weight-rank method of t'Mannetje and Haydock (1963) as modified by Jones and Hargraves (1979) and implemented as outlined by Dowhower et al. (2001) using $0.05\,m^2$ quadrats every 50 m along each transect. The dry-weight-rank method provides an estimate of biomass by species but we report biomass by functional group to simplify interpretation. Bare ground was estimated at each quadrat placement so that bare ground, litter cover and herbaceous foliage cover totaled 100%. These estimates were made in spring, mid-summer and autumn, and averaged for each year.

Density and basal area by species were measured from 1996 to 2000 using the *T*-square, nearest-neighbor distance method (Krebs, 1989) to account for non-random distribution of plants. These measurements were only done on the clay-loam and shallow-clay range sites. Paired $10\,m \times 10\,m$ permanent plots were established in both the clay-loam (3 plot pairs) and shallow-clay (3 plot pairs) soil–vegetation associations in each of the two replicates per treatment. Plot pairs were immediately adjacent to each other. One plot of each pair was dominated by shortgrass, the other by midgrass species. These are subsequently referred to as having a "short" or a "tall" patch condition. Apart from herbaceous species differences, the plots were chosen to be identical with regard to aspect, slope, soil series and the presence of woody and succulent plants.

Since it is hypothesized that the process of deterioration does not happen uniformly over the area but is concentrated on the shortgrass patches that are selected in preference to the tall patches, we stratified sampling on short and tall patches. Had we sampled across and through these different patches and recorded a mean value for the whole area under consideration, we would probably have incurred a type 2 error, namely not finding differences where there were differences.

We believe that the different species composition between paired short and tall plots was primarily due to the shorter patches having been subjected to heavier grazing pressure. However, it is possible that these differences were due to edaphic or other differences. To account for this possibility we used the starting conditions in each sample plot as a covariable so that all changes are expressed relative to the starting condition. Any changes from the initial condition were used to address the hypothesis by assessing whether the rotational grazing treatment resulted in different

species composition, herbaceous basal area, litter cover or bare ground relative to the continuous grazing treatment.

To simplify interpretation, we report biomass by functional group. Since the primary limiting factor in these ecosystems is soil moisture, the functional groups we chose are those influencing water infiltration the most. Vegetation type affects the amount and structure of associated cover, and consequently the infiltration rate differs among vegetation types. The amount of cover, and hence the rate of infiltration, is usually greatest with bunch midgrasses followed in decreasing order by sod-forming shortgrasses, annual grasses, forbs and bare ground (Thurow, 1991). The following five plant functional groups were measured; perennial $C_4$ midgrasses, perennial $C_4$ shortgrasses, perennial $C_3$ midgrasses, perennial and annual forbs, and annual grasses.

Plots were located at least 300 m from livestock watering or gathering points, and paths and animal gathering areas were avoided. Plot pairs within each replicate were located from 500 m to 3 km apart in different areas of each replicate. Twenty sample points were relocated randomly each year in each paired plot. At each of these points each of the above five functional groups were measured.

To determine density, two distances were measured to the nearest centimeter from each random point (after Krebs, 1989). The first distance $x_i$ is from the random point $O$ to the nearest plant $P$. The second distance $z_i$ is that from the plant $P$ to its nearest neighbor $Q$ with the restriction that the angle $OPQ$ must be more than 90° (the $T$-square distance). The population density ($\lambda$) was then calculated from $n$ distances (after Lamacraft et al., 1983) as

$$\lambda = \frac{n^2}{2\sum(x_i)\sqrt{2}\sum(z_i)}. \tag{1}$$

To determine basal area, the mean diameter of each tuft at points $P$ and $Q$ (above) was measured to the nearest centimeter for perennial grasses and to the nearest millimeter for annual grasses after Hardy and Tainton (1993). The determination of what constituted a discrete tuft was as follows. If the spaces between what once was a single tuft were separated at ground level by 1 cm, it was considered to be a different tuft and the tuft unit nearest to the point was recorded. If a portion of the tuft was dead, the diameter of the living portion was recorded. With stoloniferous species such as *Buchloe dactyloides*, the mean tuft diameter of the nearest node with roots was recorded as above. Basal area was determined for grasses only, since it is spurious to compare the basal area of tufted species such as grasses with single stemmed forbs.

### 2.5. Statistical analyses

GLM was used (SAS Institute, 1988) to test for differences in treatment and year by soil, vegetation (patch) condition and species functional group. Initial year data were used as a covariable to adjust for antecedent conditions. LS means were compared by calculating separate slopes by main effects except for grazing treatment that results in the same calculated LS means, regardless of the populations being

compared. Data were tested for normality (Shapiro–Wilk test) (Steel and Torrie, 1960) and homogeneity of variance. Statistical probabilities for basal area are based on square-root transformed data and means presented are raw data means. Replicates were used as the error term to test for grazing effects on species proportions of basal area, standing crop and percentage bare ground. Year was treated as a repeated measure. Significance is at $p<0.05$ unless otherwise noted.

## 3. Results

### 3.1. Basal area

Interpretation of main effects is suspect when there are significant interactions (Table 1). Consequently, discussion of results will concentrate on the interactions. Year effect interacted with grazing treatment ($p<0.0001$), species ($p<0.0001$) and the combined effects of the other factors ($p<0.0014$), indicating the dominant effect of weather, particularly precipitation, on changes in herbaceous basal area (Table 1). Treatment interacted significantly with species functional group ($p = 0.0962$), and also interacted with year to influence total basal area and $C_4$ midgrass ($p<0.001$), $C_4$ shortgrass, $C_3$ midgrass and annual grass ($p<0.05$) but not forbs ($p > 0.1$).

Table 1
GLM testing effect of covariant, grazing treatment (Trt), species functional group (Sp), range site/soil (S), patch condition (Pc), year (Yr), and sum of replicates on herbaceous basal area in 1996–2000 using 1996 basal area values as the covariable

| Source | Df. | Type I SS as % of total SS | Type III, $F$[a] | Type III, $p$ |
|---|---|---|---|---|
| Covariable | 100 | 75.10 | 72.89 | 0.0001 |
| Trt | 1 | 0.47 | 8.28 | 0.1025 |
| Trt × rep[b] | 2 | 0.09 | 1.73 | 0.2369 |
| Sp | 4 | 1.42 | 11.72 | 0.0001 |
| Trt × Sp | 4 | 0.26 | 2.13 | 0.0962 |
| S | 1 | 0.12 | 0.60 | 0.4442 |
| Pc | 1 | 0.12 | 4.55 | 0.0394 |
| Trt × Sp × S × Pc | 28 | 2.40 | 2.81 | 0.0016 |
| Trt × Sp × S × Pc × rep[c] | 38 | 1.06 | 0.99 | 0.4962 |
| Year | 4 | 1.63 | 48.55 | 0.0001 |
| Trt × Yr | 4 | 0.36 | 7.07 | 0.0001 |
| Sp × Yr | 16 | 1.53 | 7.10 | 0.0001 |
| Trt × Sp × Yr | 16 | 0.53 | 3.08 | 0.0002 |
| Trt × Sp × S × Pc × Yr | 120 | 2.42 | 1.66 | 0.0014 |
| Trt × Sp × S × Pc × Yr × rep[d] | 160 | 1.74 | 1.06 | 0.3227 |

[a] Based on residual error.
[b] Used as error term for treatment.
[c] Used as error term for non-year main effects and non-year interactions.
[d] Used as error term for year main effects and year interactions.

### 3.2. Total basal area

Total herbaceous basal areas for both range sites and patch conditions are presented in Fig. 2. In 1997, following close to average precipitation in the first half of the year, basal area increased a great deal on the clay-loam soils ($p<0.05$) and increased significantly more on the rotationally grazed areas than on the continuously grazed areas ($p<0.02$). For the following 3 years, basal areas declined on these soils, particularly in short-patches ($p<0.05$). This decline in basal area was probably due to the lower than average precipitation in the second half of 1997 and summers of 1998 and 2000, and autumn of 1999. On the shallow-clay soils under continuous grazing, basal area values increased in 1997 ($p<0.05$) and remained at this level in 1998 ($p<0.05$) then decreased in 1999 and 2000 ($p<0.05$). With rotational grazing, basal area values increased ($p<0.05$), but peaked in 1998 rather than 1997 on the short-patches before decreasing in 1999 and 2000 ($p<0.05$) (Fig 2). On the shallow-clay short-patches, basal area was higher in 2000 on the continuously grazed than on the rotation treatment in 1999 and 2000 ($p<0.05$). This was due to

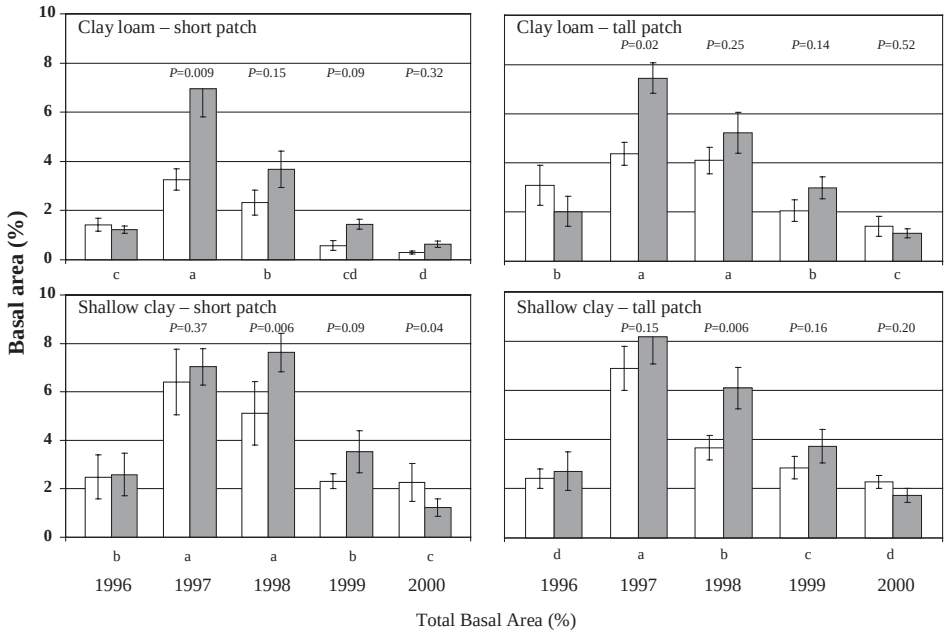


Fig. 2. Total herbaceous basal area (%) on paired, short and tall patches on clay-loam and shallow-clay range sites under continuous grazing (▭) and an 8-pasture rotational (▩) grazing treatment on the Waggoner Experimental Ranch in north central Texas from 1996 to 2000. Bars represent ∀ 1 S.E. Means between years with a different letter differed at $p<0.05$. Probabilities presented are for grazing treatment differences in each year. Statistical analyses and means separations were run on square-root transformed data adjusted to incorporate the effect of initial 1996 basal area values as a covariable and were calculated using Treatment × Year × replicate as the error term.

changes in the summer growing $C_4$ mid- and shortgrasses, probably in response to the summer drought conditions prevailing over this period (see below).

The plant functional groups responsible for increases in basal area due to grazing treatment were different on each soil and in tall- or short-patches. The response of each functional group is presented below.

### 3.3. $C_4$ midgrass basal area

The $C_4$ midgrass functional group was dominated by five grasses: *Aristida* spp., *B. laguroides*, *B. curtipendula*, *S. compositus* and *S. cryptandrus* (Table 2). Midgrasses were more prevalent on tall- than short-patches and *B. curtipendula* was the only preferred grass to be more abundant in short- than tall-patches. This functional group made up a major portion of the total basal area, except on the clay-loam short-patches (Fig. 3). On all soils, the basal area of these warm season midgrasses increased from 1996 to 1997 and decreased each following year.

Table 2
Basal cover composition of graminoid species functional groups in the short and tall patch paired plots (1996–2000)

| Composition of functional groups | Indicator value[a] | Clay-loam sites | | Shallow-clay sites | |
|---|---|---|---|---|---|
| | | Short patch% ($\times 10^{-2}$) | Tall patch% ($\times 10^{-2}$) | Short patch% ($\times 10^{-2}$) | Tall patch% ($\times 10^{-2}$) |
| $C_4$ Midgrass | | | | | |
| *Aristida* spp. | — | 18 | 61 | 35 | 66 |
| *Bothriochloa laguroides* | M | 2 | 20 | 97 | 144 |
| *Bouteloua curtipendula* | M | 1 | 5 | 86 | 78 |
| *Eriochloa sericea* | M | 1 | 6 | 5 | 18 |
| *Sporobolus compositus* | M | 2 | 42 | 9 | 26 |
| *Sporobolus cryptandrus* | H | 10 | 22 | 2 | 2 |
| *Tridens albescens* | M | 6 | 15 | 3 | 6 |
| *Tridens muticus* | M | 1 | 2 | 0 | 3 |
| $C_4$ Shortgrass | | | | | |
| *Bouteloua gracilis* | M | 0 | 0 | 0 | 0 |
| *Bouteloua hirsuta* | H | 0 | 0 | 65 | 5 |
| *Bouteloua rigidiseta* | H | 20 | 11 | 206 | 81 |
| *Buchloe dactyloides* | H | 215 | 20 | 20 | 24 |
| *Chloris verticillata* | M | 3 | 36 | 2 | 8 |
| *Schedonnardus paniculatus* | H | 2 | 0 | 0 | 1 |
| $C_3$ Midgrass | | | | | |
| *Nassella leucotricha* | M | 18 | 196 | 14 | 74 |
| Annual grass | | | | | |
| *Bromus japonicus* | M | 8 | 18 | 0 | 1 |
| *Hordeum pusillum* | H | 1 | 0 | 0 | 0 |

[a] Indicator values: M = moderate use; H = heavy use.

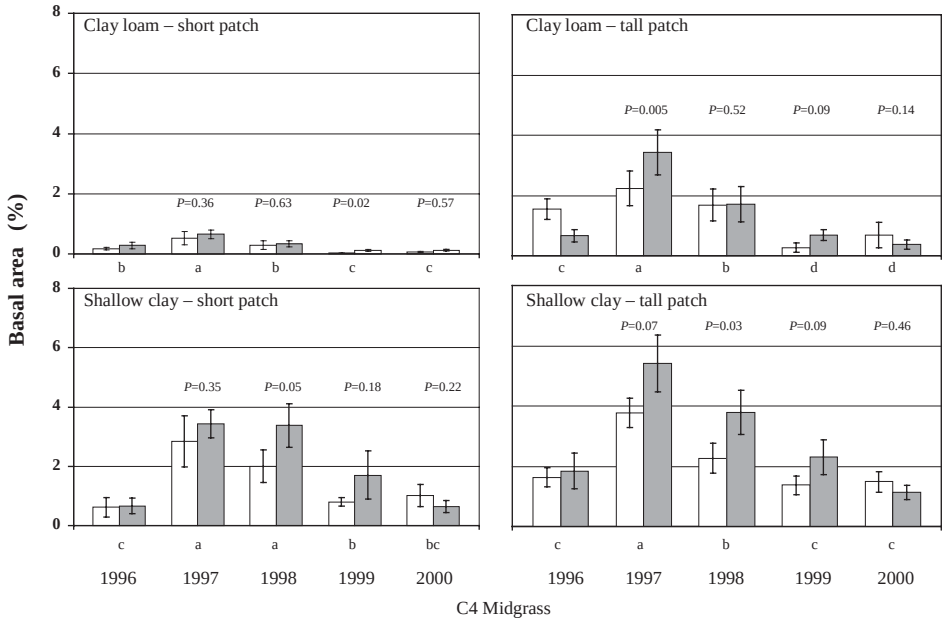


Fig. 3. $C_4$ midgrass basal area (%) on paired, short and tall patches on clay-loam and shallow-clay range sites under continuous grazing (▭) and an 8-pasture rotational grazing treatment (▩) on the Waggoner Experimental Ranch in north central Texas from 1996 to 2000. Bars represent ∀ 1 S.E. Means between years with a different letter differed at $p<0.05$. Probabilities presented are for grazing treatment differences in each year. Statistical analyses and means separations were run on square-root transformed data adjusted to incorporate the effect of initial 1996 basal area values as a covariable and were calculated using Treatment × Year × replicate as the error term.

Basal area was higher on the shallow-clay short-patches under rotational grazing only in 1998 ($p = 0.05$) but was higher in both treatments in 1997 through 1999 ($p<0.09$). On clay-loam short-patches, $C_4$ midgrasses made up only a small portion of the total basal area and, although it changed between years ($p<0.05$), it only changed in response to grazing treatment ($p = 0.02$) in 1999. On the clay-loam tall-patches, $C_4$ midgrasses made up a significant portion of total basal area and there was a significant increase in this functional group under rotational grazing in 1997 and 1999 ($p<0.09$) (Fig. 3).

### 3.4. $C_4$ shortgrass basal area

The $C_4$ shortgrasses consisted mainly of *B. dactyloides*, *B. rigidiseta* and *B. hirsuta* (Table 2). The $C_4$ shortgrasses were a relatively minor component in tall-patches on both clay-loam and shallow-clay soils but did change basal area between years ($p<0.05$) (Fig. 4). There were no differences between grazing treatments on the shallow-clay tall-patches ($p > 0.1$) but the rotational grazing treatment had higher basal areas on the clay-loam tall-patches in 1997 and 1999 ($p<0.03$).

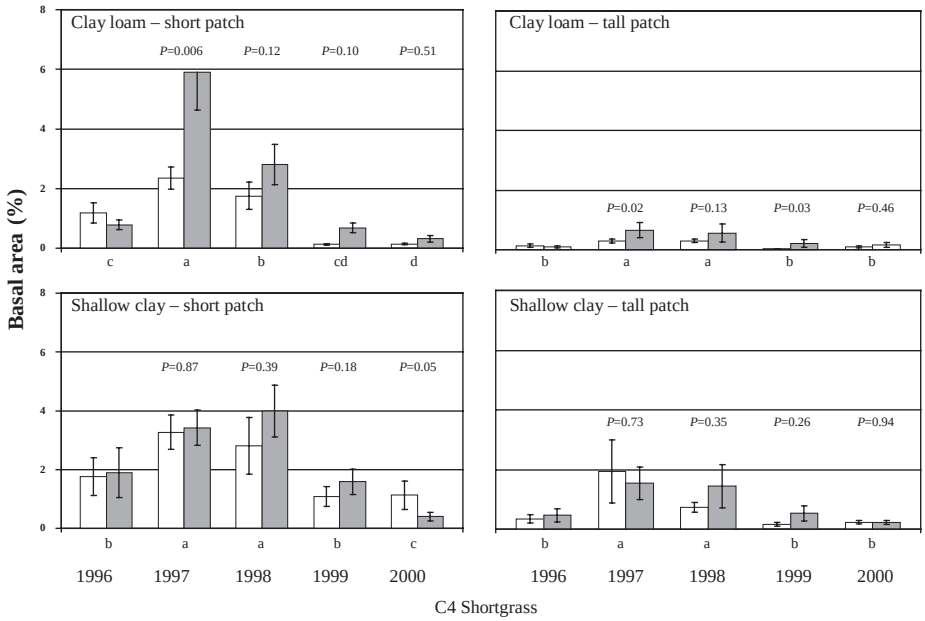


Fig. 4. $C_4$ shortgrass basal area (%) on paired, short and tall patches on clay-loam and shallow-clay range sites under continuous grazing (▭) and an 8-pasture rotational grazing treatment (▩) on the Waggoner Experimental Ranch in north central Texas from 1996 to 2000. Bars represent ∀ 1 S.E. Means between years with a different letter differed at $p<0.05$. Probabilities presented are for grazing treatment differences in each year. Statistical analyses and means separations were run on square-root transformed data adjusted to incorporate the effect of initial 1996 basal area values as a covariable and were calculated using Treatment × Year × replicate as the error term.

On the clay-loam short-patches, which were mostly *B. dactyloides*, the rotational grazing treatment had higher basal areas only in 1997 ($p = 0.006$) (Fig. 4). On the shallow-clay short-patches, which were predominantly *B. rigidiseta* (Table 2), this functional group increased basal area between 1996 and 1999 ($p<0.05$) but not due to grazing treatment ($p > 0.1$). In 2000 basal area was higher on the continuously grazed shallow-clay short-patches ($p = 0.05$).

### 3.5. $C_3$ midgrass basal area

The $C_3$ midgrass functional group is made up almost entirely of *N. leucotricha*. It is a minor component of short-patches on both soils (Table 2) and is more abundant on the clay-loam than on the shallow-clay soils ($p<0.05$) (Fig. 5). Except in tall-patches on the clay-loam soils, it changed little in basal area over the years or between grazing treatments ($p > 0.1$). On the clay-loam soil tall-patches, it increased markedly in response to the rotation treatment from 1996 to 1997 and 1998 ($p<0.05$) but changed little over this period under continuous grazing ($p > 0.1$). On the shallow-clay tall-patches it increased from 1996 to 1997 ($p<0.05$) before decreasing slowly to 2000 but there was no response to grazing treatment ($p > 0.1$).

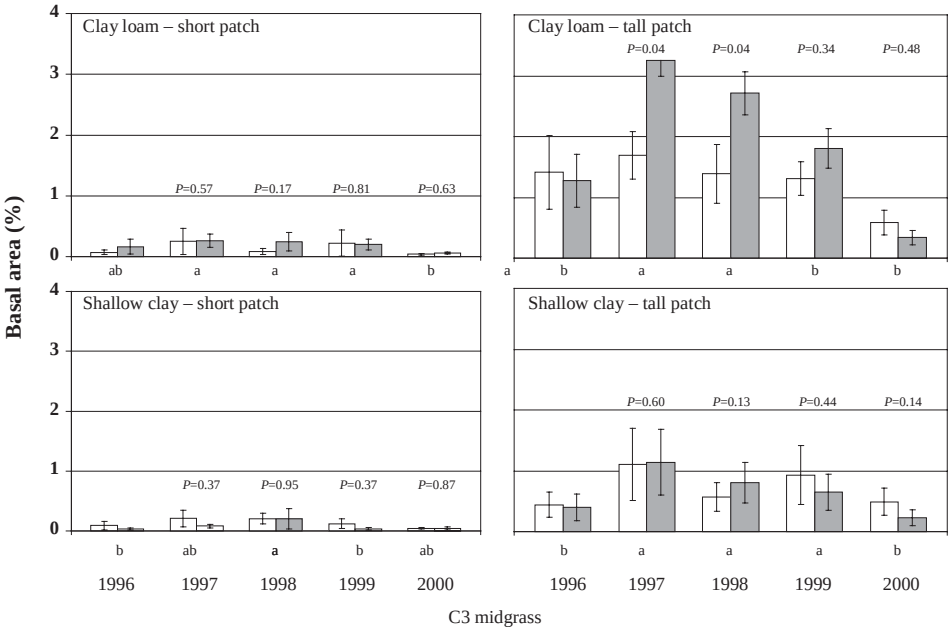


Fig. 5. $C_3$ midgrass basal area (%) on paired, short and tall patches on clay-loam and shallow-clay range sites under continuous grazing (▭) and an 8-pasture rotational grazing treatment (▩) on the Waggoner Experimental Ranch in north central Texas from 1996 to 2000. Bars represent ∀ 1 S.E. Means between years with a different letter differed at $p<0.05$. Probabilities presented are for grazing treatment differences in each year. Statistical analyses and means separations were run on square-root transformed data adjusted to incorporate the effect of initial 1996 basal area values as a covariable and were calculated using Treatment × Year × replicate as the error term.

### 3.6. Annual grass basal area

Annual grasses made up a very small portion of the total basal area and were almost absent from the shallow-clay soil areas (Fig 6). This component was made up almost entirely of *B. japonicus* (see Table 2). They were prominent in 1998, 1999 and 2000 except on the shallow-clay short-patches. This was due mainly to cool season climatic conditions that favor these species. Annual grass basal areas were greater on the rotations in clay-loam short-patches in 1999 ($p = 0.004$) and clay-loam tall-patches in 2000 ($p = 0.03$). In contrast, annual grass basal areas were higher in the continuous graze treatment in shallow-clay tall- and short-patches in 1999 ($p = 0.05$).

### 3.7. Bare ground

Bare ground was also significantly influenced by grazing treatment ($p = 0.10$) and treatment interacted significantly with year ($p = 0.057$) but not soil (range site) ($p = 0.18$), indicating the need to analyse grazing treatment effects by year, as

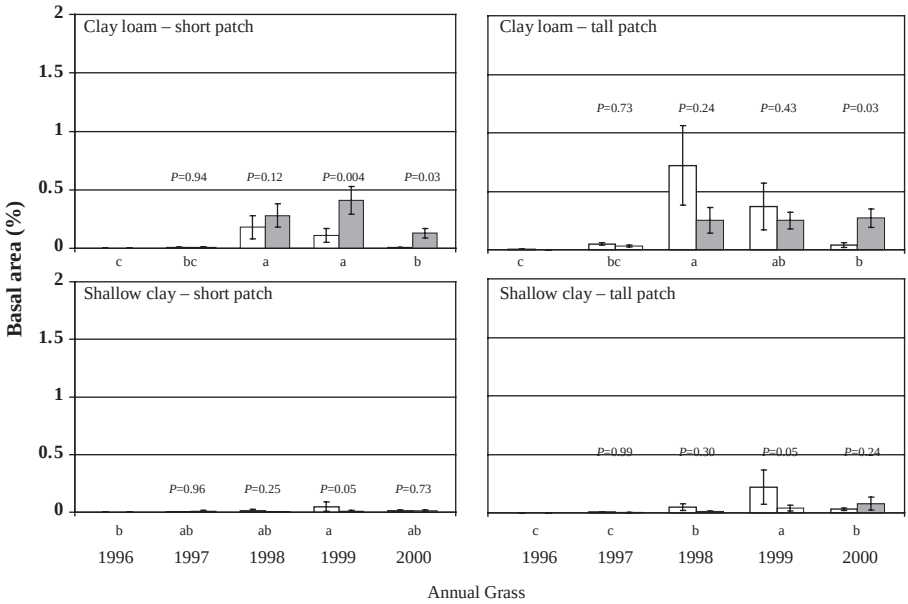


Fig. 6. Annual grass basal area (%) on paired, short and tall patches on clay-loam and shallow-clay range sites under continuous grazing (▭) and an 8-pasture rotation grazing treatment (▩) on the Waggoner Experimental Ranch in north central Texas from 1996 to 2000. Bars represent ∀ 1 S.E. Means between years with a different letter differed at $p<0.05$. Probabilities presented are for grazing treatment differences in each year. Statistical analyses and means separations were run on square-root transformed data adjusted to incorporate the effect of initial 1996 basal area values as a covariable and were calculated using Treatment × Year × replicate as the error term.

presented in Fig 7. The amount of bare ground generally increased at all three range sites with the passage of years in response to the continuing summer drought conditions. On the deeper, less droughty bottomland soils there were no differences in bare ground between treatments in any of the years. On the more droughty clay loam and shallow-clay range sites there were differences in percentage bare ground due to grazing treatment (Fig. 7). The higher bare ground values on the rotation treatment in 1998 was an anomaly which defies explanation.

### 3.8. Species biomass composition

$C_4$ tall grasses occur only in small quantities in specific microsites and were very stable between years. Up until 1997 these grasses made up only 3–4% total perennial biomass but this increased during 1998–2000 ($p<0.05$)(Table 3). These plants were confined to specific microsites of deeper soils, often in run-on positions, so this increase in biomass is probably due to production from these plants being less affected by the dry summers compared to the other functional groups.

The $C_4$ midgrasses were also relatively stable between years, increasing from 1995 to 1996 but declining in the drier summers of 1998 through 2000 with very low

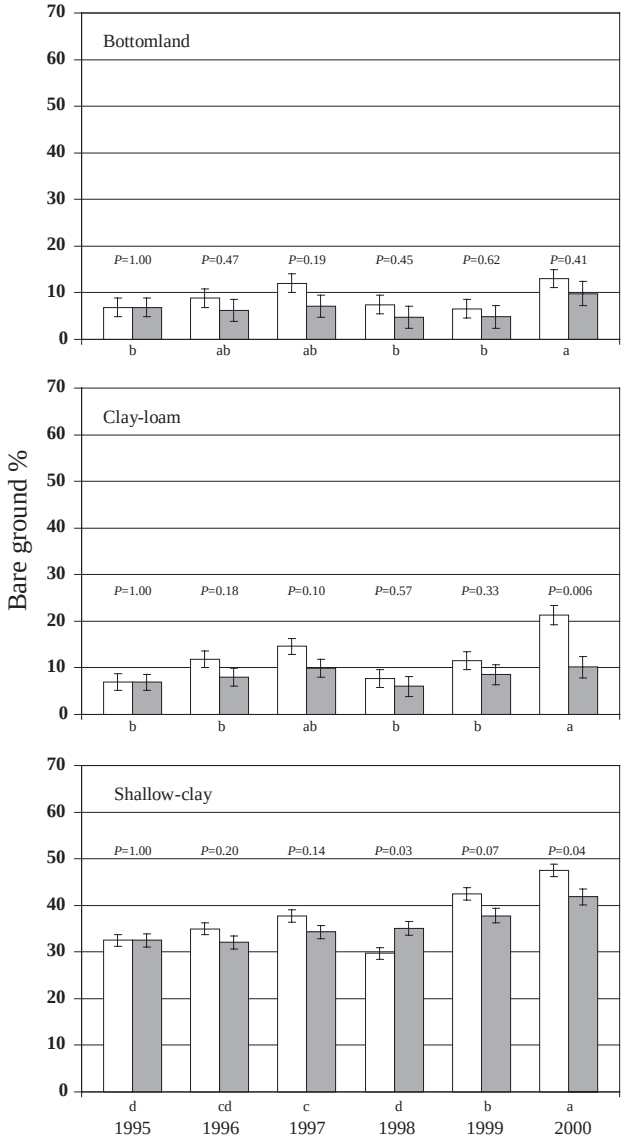


Fig. 7. Bare ground under continuous grazing (▭) and 8-pasture rotation (▢) grazing treatment measured along landscape transects. Bars represent ∀ 1 S.E. Means between years with a different letter differed at $p<0.05$. Probabilities presented are for grazing treatment differences in each year. Statistical analyses and means separations were untransformed data adjusted to incorporate the effect of initial 1995 bare ground values as a covariable using replicate as the error term.

production in 1999 ($p<0.05$) (Table 3). The principle midgrasses are the highly desirable *B. curtipendula*, and the moderately desirable *B. laguroides* and *S. compositus*. Over the entire experimental area and period, these species comprise

Table 3
Composition of herbaceous functional groups as a percentage of perennial forage biomass measured along landscape transects

| Plant category | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|
| $C_4$ Tall grass | $3^{c}$ | $4^{c}$ | $4^{b}$ | $5^{abc}$ | $6^{ab}$ | $6^{a}$ |
| $C_4$ Midgrass | $40^{c}$ | $53^{a}$ | $47^{b}$ | $47^{b}$ | $41^{c}$ | $47^{b}$ |
| $C_4$ Shortgrass | $13^{b}$ | $15^{a}$ | $16^{a}$ | $12^{b}$ | $9^{c}$ | $11^{b}$ |
| $C_3$ Midgrass | $25^{bc}$ | $24^{c}$ | $26^{abc}$ | $24^{c}$ | $28^{ab}$ | $30^{a}$ |
| Perennial forbs | $20^{a}$ | $4^{d}$ | $7^{d}$ | $11^{c}$ | $16^{b}$ | $6^{d}$ |
| Annual grass | $9^{c}$ | $1^{d}$ | $3^{d}$ | $13^{b}$ | $27^{a}$ | $11^{bc}$ |
| Annual forbs | $5^{c}$ | $0^{d}$ | $11^{b}$ | $1^{d}$ | $20^{a}$ | $4^{c}$ |

Means in the same row with the same letter are not significantly different ($p > 0.05$).
*Note*: perennial species total 100.

approximately 8%, 15% and 7% of the perennial herbaceous biomass, respectively (data not presented). These grasses are the most productive functional group even in dry summers (Table 3). The ratio of biomass to basal areas of these groups is 1.04 for $C_4$ midgrass and 1.5 for $C_3$ midgrass, compared to that of 0.32 for $C_4$ shortgrass.

The $C_4$ shortgrasses, principally *B. dactyloides* and *B. rigidiseta*, increased through 1997 but declined in the dry summers of 1998 through 2000 when summer conditions were drier and hotter than average (Table 3). *N. leucotricha*, the major $C_3$ midgrass, was stable between years in spite of the large climatic variability (Table 3).

Perennial forbs made a major contribution to biomass in 1995, 1998 and 1999 but were much less evident in 1996, 1997 and 2000 (Table 3). Since temperatures were mild during winter each year and spring moisture was adequate in all but 1996 there is no evident climatic correlation with these changes in abundance.

Annual grasses varied in biomass from year to year but were much more abundant in 1998–2000 (Table 3). This may be connected to the declining total basal area of perennial grasses that was measured after 1997. This would have provided increased establishment sites for these opportunistic, cool-season growing plants.

There was no apparent pattern with the annual forbs which were prominent only in 1997 and 1999 (Table 3). Our expectation was that as opportunistic, cool-season plants their abundance would have been similar to that of the annual grasses.

### 3.9. Biomass composition

Grazing treatment had almost no influence on the biomass composition of the different plant functional groups. In 1996, the $C_4$ shortgrasses were less abundant in the 8-pasture treatment and in 1998, $C_3$ midgrass was less abundant on the continuously grazed treatment. Since the experiment began in 1995 it is doubtful that the difference in abundance of shortgrasses in 1996 was due to treatment. In 1998 $C_3$ midgrasses were more abundant in the rotation treatment ($p < 0.10$). In 1999 the annual grasses were more abundant in the continuous relative to the rotation treatment ($p < 0.10$), but this was reversed in the following year ($p < 0.10$) and the

annual forbs were also more abundant in 1999 on the continuous treatment ($p<0.10$).

## 4. Discussion

The weather was a dominating influence, having a significant effect on basal area and biomass for all species functional groups and the amount of bare ground, and interacted significantly with grazing treatment. This reflects the strong influence of the different weather patterns recorded each year, especially precipitation. The dry summers and mild and wet winters experienced in 4 of the 5 experimental years were the major climatic factors associated with the changes in species biomass composition. The biomass of $C_4$ and $C_3$ midgrasses and the $C_4$ shortgrasses were relatively stable over the experimental period despite the weather fluctuations. In contrast, the biomass of annual grasses and the perennial and annual forbs varied considerably from year to year. Although weather conditions were favorable for winter-growing plants during most winter and spring periods during the experiment, the dry summer weather in 1996, 1998 and 2000 resulted in winter-growing perennials remaining static relative to the winter-growing annuals. The dry summers were also associated with an increase in bare ground during the experiment.

As hypothesized, grazing treatment also had a significant effect. The extended number of years with below average summer rain resulted in diminishing differences between treatments for basal area but increased the amount of bare ground measured. In the large paddocks of this experiment, the rotation treatment resulted in greater perennial herbaceous basal areas and lower proportions of bare ground than the continuously grazed treatment. However, grazing treatment did not influence species biomass composition. We believe that lack of response in species composition and reversal of the deterioration spiral referred to above, particularly on the short-patches, is a function of the dry summers experienced over the experimental period. Increases in taller and more palatable species composition are dependent on the availability of resources for recovery (Lee and Bazzaz, 1980; Wallace et al., 1984; Coughenour et al., 1985; Polley and Detling, 1989), and a positive response is possible only if sufficient resources are available (Louda et al., 1990). As a consequence, favorable climatic conditions for recovery will probably be necessary for an increase in taller, more productive and palatable grasses, in addition to the respite from grazing afforded by the rotational grazing.

The increases in basal area with rotational grazing were largely due to increases in $C_4$ mid- and shortgrasses. On the shallow-clay soils, the $C_4$ midgrasses increased from 1996 to 1997 and decreased each subsequent year. Basal area was higher on the shallow-clay short-patches under rotational grazing only in 1998 but was higher in both treatments in 1997 through 1999. On clay-loam short-patches, $C_4$ midgrasses made up only a small portion of the total basal area and although it changed between years it only changed in response to grazing treatment in 1999. On the clay-loam tall-patches, $C_4$ midgrasses made up a significant portion of total basal area and there was a significant increase in this functional group under rotational grazing

in 1997 and 1999. The higher basal areas of $C_4$ midgrasses on the shallow-clay soils are probably related to the low presence of mesquite trees on these soils. The presence of the summer growing, deciduous mesquite trees on clay-loam soils increases competition for water with summer growing, herbaceous plants relative to the shallow-clay soils with low levels of mesquite. Shorter grasses would be more competitive under more stressful moisture conditions.

The $C_4$ shortgrasses were a relatively minor component in tall-patches on both clay-loam and shallow-clay soils but did change basal area between years. With this functional group, there were no differences between grazing treatments on the shallow-clay tall-patches but the rotational grazing treatment had higher basal areas on the clay-loam tall-patches in 1997 and 1999. On the clay-loam short-patches the rotational grazing treatment had higher basal areas only in 1997. On the shallow-clay short-patches this functional group increased basal area between 1996 and 1999 but not due to grazing treatment. In 2000, basal area was higher under continuous grazing on the shallow-clay short-patches. As above, the absence of mesquite on the shallow-clay soils probably lessened the effect of summer drought.

The main $C_3$ midgrass, *N. leucotricha*, was a minor component of short-patches on both soils. This was expected since this species is known to decrease under heavy stocking (Heitschmidt et al., 1985, 1989). It was more abundant on the clay-loam than on the shallow-clay soils. The absence of *N. leucotricha* from shortgrass patches reinforces our belief that these shortgrass patches are caused by heavy grazing pressure. Except in tall-patches on the clay-loam soils, it changed little in basal area over years or between grazing treatments. On the clay-loam soil tall-patches, it increased markedly in response to the rotation treatment from 1996 to 1997 and 1998 but changed little over this period under continuous grazing. On the shallow-clay tall-patches it increased from 1996 to 1997 before decreasing slowly to 2000 but there was no response to grazing treatment. It was less affected by the drought than the summer growing grasses since it avoids competition with mesquite by growing in late autumn, winter and spring. No meaningful changes due to treatment were measured in perennial forbs or the annual grasses and forbs.

The fact that species biomass composition changed very little between years and treatments while basal area and bare ground, both important parameters influencing infiltration, runoff and erosion did change, calls into question the use of species composition as the primary measure of range ecosystem health. In the short-term at least, parameters indicating ecosystem health, such as bare ground, litter cover and basal area, appear to be much more sensitive and hence important parameters for monitoring to effect sustainable use.

## 5. Conclusions

The alternating patches of short and mid grasses are probably a natural feature of this ecosystem contributing to species, seral and landscape diversity. They almost certainly contribute to wider biodiversity, benefiting livestock and wildlife with an expanded feeding resource and habitat. However the shortgrass patches may also be

the focal points of land deterioration. With alternating drier and wetter periods, the vegetation responds with cycles of deterioration and recovery. This study was implemented to determine how much deterioration was occurring and whether recovery was complete through wet and dry cycles under continuous grazing, and to what extent rotational grazing management could prevent or mitigate deterioration.

The differential use of preferred areas in the landscape results in uneven distribution of animal impact, and periods of below average precipitation compound the effects of herbivory, providing periods of accelerated deterioration. By providing periodic rests from defoliation, rotational grazing management has the potential to minimize the effects of patch overgrazing. In this study, the greater increase in basal area with rotational grazing during the only average or above average precipitation year probably indicates that greater improvement in basal area is possible during favorable years with rotational than with continuous grazing.

Deterioration of herbaceous cover during this period of extended drought proceeded at a relatively slow rate. Although rotational grazing did not prevent deterioration in basal area and bare ground with the series of drought years, it did decrease the rate of deterioration. This is a material result. The percentage of incoming precipitation that infiltrates on bunch midgrass, sod-forming shortgrass and bare ground is 76%, 55% and 25%, respectively (Thurow, 1991). If average or above-average precipitation had occurred after 2 years of drought instead of 4 years of drought, the evidence from this experiment would predict an increased herbaceous basal area and decreased area of bare ground with rotational compared to continuous grazing. This has meaningful implications for sustaining and restoring the range resource and improving productivity.

This study provides evidence that, in large paddocks in this environment, rotational grazing can reduce the deterioration and allow improvement of both shortgrass and midgrass patches. It will be important to determine, during a cycle of average or above-average precipitation, whether the areas under continuous grazing will recover and whether rotational grazing will allow for more rapid and complete recovery.

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