MANAGEMENT OF IMPROVED PASTURES

IN OKLAHOMA

I. TALL FESCUE SEED PRODUCTION

II. PASTURE VARIABILITY

By

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CHAPTER 1

1. Effect of Fall Grazing on Tall Fescue Seed Production in Oklahoma

1.1. Abstract

Tall fescue [*Festuca arundinacea* Schreb. = *Lolium arundinaceum* (Schreb.) S.J. Darbyshire] is currently used to extend the grazing season in cow-calf operations in eastern Oklahoma and north central Texas. Tall fescue could be managed as a multiple use crop: for forage and for seed production. There is little information available about the effects of fall-grazing on seed production in regions where the species approaches the geographical limits of adaptation. The objective of this study was to determine the effects of fall-grazing on tall fescue seed yield, seed yield components, and seed germination. Tall fescue entries Dovey (E^-), Georgia 5 (E^+), Georgia 5 (E^-), and Kentucky 31 (E^+) were subjected to fall-grazing and fall no-grazing treatments during two years (2002-2003 and 2003-2004) at the Noble Foundation Red River Demonstration and Research Farm, located near Burneyville, OK. Seed yield in 2003 was reduced by drought. However, fall-grazing generally favored seed production through increasing the number of seedheads. In 2004, with average weather conditions, seed yield substantially increased and grazing did not affect seed production. Although seedhead number was favored by fall-grazing, number of seeds per seedhead and seed weight remained constant in the fall-grazed tall fescue. Germination was unaffected or increased slightly by grazing in 2003 and 2004. Based on the

results of this study, fall-grazing can be a viable component of multiple use tall fescue systems of Oklahoma and north central Texas.

1.2. Introduction

It is estimated that there are one half million hectares of tall fescue [*Festuca arundinacea* Schreb. = *Lolium arundinaceum* (Schreb.) S.J. Darbyshire] grown for pastures in Oklahoma. Tall fescue has an important role in reducing winter feed costs by extending the grazing season of warm-season bermudagrass [*Cynodon dactylon* (L.) Pers.] in caw-calf operations of the southern USA. In Missouri, wintering cost per cow was reduced $117 by grazing stockpiled tall fescue (Lacefield et al., 2003).

Forage production in the transition area that includes Missouri, Kansas, Arkansas, and Kentucky has used both forage and seed production to increase the profitability of tall fescue. This form of multiple use management allowed the region to become the supplier of the bulk of tall fescue seed in the USA since its introduction to the country. However, due to high variability of the seed price from year to year, seed production declined. For example, in Kentucky in the early 1950's an area of nearly 30,000 ha was harvested for seed production. Today, only about 300 ha are harvested for seed (Lacefield et al., 2003).

According to Young (1997), favorable weather, good soils, standard seed production practices, infrastructure, and developed markets, have consolidated the Pacific Northwest coast of the USA as the region that supplies forage and turf seed to much of the domestic USA and export markets. Nevertheless, tall fescue seed production for forage purposes could face pressures in the future from other grasses and legumes for forage and for aesthetic uses due to differences in profitability among these products (Hopkins et al., 2003). This possibility could represent the opportunity for current tall fescue farmers in the central and southern USA to renew interest in implementing (or re-implementing) a multiple use management system.

Limited research has been conducted on the advantages or disadvantages of grazing (or defoliation) on seed production of cool-season grasses (Hopkins et al., 2003; Anderson and Frank, 2003). Furthermore, research about the effects of fall-grazing on seed production is in general scarce to inexistent (according to our present knowledge) for the wet regions of Texas and Oklahoma. This region is located in the “upper South region”, close to both the western and southern limits of tall fescue adaptation in the USA (Burns and Chamblee, 1979).

In an experiment to assess the potential of tall fescue and other cool-season grass species as a forage and seed system, Green and Evans (1957) reported that grazing in December tended to increase tall fescue seed production in a research conducted in England. Treatments grazed in October only, October and December, December and February, and non-grazed treatments yielded similarly and were intermediate; but grazing in March, and particularly April, seriously decreased seed yields. Evans (1975) in Washington state clipped bluegrass (*Poa pratensis* L.) under several developmental stages and reported that the non-grazed treatment yielded the least, while one clipping in late fall, before inflorescence initiation, yielded the most. In contrast to these reports, Lambert (1956) found deleterious effect on seed yields of orchardgrass (*Dactylis glomerata* L.) when grazed either during the fall or fall and winter in New Zealand. In England, Roberts (1958) observed, in general, none or positive effects of winter grazing on seed yield of timothy (*Phleum pratense* L.) and perennial ryegrass (*Lolium perenne* L.), but a sharp decrease when grazing occurred during spring or winter and spring. Later, Roberts (1965) reported a decrease in seed yields of perennial ryegrass, orchardgrass, meadow fescue (*Festuca pratensis* Huds.), and timothy, only when grazing occurred after the beginning of inflorescence formation. Worrell et al. (1992) grazed winter wheat (*Triticum aestivum* L.) at three developmental stages in South Carolina and reported different effects of grazing on grain production, depending on the year. Finally, a research conducted in New Zealand by Brown (1980) concluded that grazing perennial and annual ryegrass (*Lolium multiflorum* Lam.) during the fall decreased seed yield compared with a non-grazed control.

Anderson and Frank (2003) proposed that the source of conflicting results regarding the effect of grazing (or defoliation in general) over reproductive parameters in grasses might be due to differences in the scale level at which measurements were done (individual plant or at plot level), or in the developmental stage at which defoliation occurred. Developmental stages in grass plants are associated with morphological changes, and morphology of plants at the time of defoliation can be critical in determining seed production. Defoliation prior to internode elongation results in removal of leaf material only, but defoliation after stem elongation will damage the reproductive meristem, hurting seed yields (Rolston et al., 1997).

Tall fescue as with many perennial cool-season grasses, generally produce two main generations of tillers: One during the spring and one during the fall (Wolf et al., 1979). However, only the fall generation can be induced and initiated to switch from vegetative to reproductive tillers because conducive environmental conditions occur only during the fall and spring each year (Aamlid et al., 1997). For many cool-season grass species, induction proceeds in two steps. The first is a short day requirement and/or low temperatures followed by increased daylength (Aamlid et al., 1997; Evans, 1964). These two steps normally occur during transition from fall-winter to spring and induction does not imply any morphological changes in the shoot apex (Evans, 1964). Photoperiod and temperature can interact with low light intensity and its associated influence on photosynthesis and resulting carbohydrate status to affect flowering.

It has been proposed that a positive carbohydrate status in plants is a prerequisite for normal flowering induction, but unlike photoperiod and temperature, light intensity doesn’t directly control the transition (Aamlid et al., 1997). The morphology of the shoot apex changes at inflorescence initiation (the double ridge stage), and internode elongation and ear emergence of the young inflorescence occur at floral differentiation. During internode elongation the young reproductive structures are pushed above the soil surface exposing them to grazing. Hill (1971) reported that in ryegrass, grazing would not affect seed production if allowed until before seedhead development; but once a seedhead starts to form at the base of a tiller and is pushed up through the leaf sheath, the seedhead becomes susceptible to removal by livestock.

In order to avoid grazing off seedheads, Brotemarkle and Kilgore (1989) recommend removing cattle from forage and seed production tall fescue pastures by mid March in southern Kansas. Since this is at higher latitude than southern Oklahoma, the elevation of the apical meristem above the soil surface for tall fescue in southern Oklahoma and northern Texas should occur well before March 15.

Grazing management to achieve a multiple use system implies grazing forage during mid to late fall through early winter, which is compatible with stockpiled forage systems. By grazing the pasture at this time, a double benefit is achieved. First, tall fescue serves its main purpose, i.e., functions as a source of forage after warm-season grasses have stopped growing. Second, in preparation to seed harvest the following spring, young, newly developed tillers at the base of plants benefit from increased light interception. Light intensity has been reported to be the most critical factor affecting tiller survival (Aamlid et al., 1997). Seedhead number per unit area has been found to be one of the most important components for seed production of cool-season grasses (Nordestgaard and Andersen, 1991). With abundant number of seedheads, seed yield potential can be exploited, provided favorable environmental conditions occur the following spring. If the number of seedheads is reduced, the capacity to compensate by greater seed size or seeds per tiller is limited (Watson and Watson, 1982).

Integrating forage and livestock into grass seed production systems may provide an alternative enterprise for farmers and ranchers in the Southern Plains. Previous research found that, for some cool-season grasses, opportunities for spring grazing and seed production were limited in this region (Hopkins et al., 2003); but effects of fall-grazing on tall fescue seed production have not been explored. The objectives of this research were to determine the effect of fall-grazing on seed yield and seed yield components, as well as germination of tall fescue grown for forage and seed production in Oklahoma.

1.3. Materials and Methods

1.3.1. Experimental site

This research was conducted as part of a beef cattle grazing trial near Burneyville, OK from 1999 to 2004 involving various tall fescue entries and grazing combinations. Details regarding stand establishment, grazing management, etc. were provided by Hopkins and Alison (2006). Nitrogen (N) fertilizer was applied at 84 kg ha^{-1} in October 2000, 2001, and 2002 and 25 kg ha^{-1} in March 2001, 2002, and 2003. No pesticides were used for either weed or insect control. Paddocks were grazed by two steers (*Bos taurus* L.) beginning at approximately 300 kg each from 21 Nov. 2002 to 5 Feb. 2003 (76 days) and from 3 Dec. 2003 to 25 Feb. 2004 (85 days). It should be noted that spring-grazing proceeded as part of a different research project (Hopkins and Alison, 2006) and was not evaluated in this study. Maximum and minimum annual temperatures averaged 24° C and 11° C, respectively, from 1994 to 2004. Information about mean and actual precipitation during the study is presented (Table 1-1).

1.3.2. Treatment and design structures

Four tall fescue entries were used in this research. Dovey and Georgia 5, were endophyte-free, whereas Georgia 5 and Kentucky 31 were endophyte-infected. From now on throughout this paper, we identify Georgia 5 endophyte free as "Georgia 5 (E^{-})"; the other entries are referred just by the name of the entry, without reference to endophyte status. The grazing treatments were fall-grazed and fall non-grazed (although fall-grazing extended until some part of the winters). The treatment structure was a 2 × 4 factorial and treatments were assigned by using a randomized complete block in a split-plot design structure, with three replications and two subsamples per subplot. Main plots were entries and subplots were grazing treatments.

1.3.3. Treatments and data collection procedures

Twelve grazing paddocks (70 × 70 m) were arranged into three blocks with four paddocks per block. Each cultivar was established in one of the four paddocks at random in each replication. Two exclosures (3 × 5 m) were employed to prohibit grazing in parts of each paddock during the fall. An area adjacent to each exclosure was designated as a "fall-grazed area" for seed yield sampling, resulting in six grazed/non-grazed pairs of exclosures for each entry. New exclosures were constructed around fall-grazed areas prior to spring grazing, so that none of the areas used to measure seed yield and seed yield components were grazed in spring.

Seed yield was determined by harvesting the 3 × 5 m exclosures with a Hege 140 combine (Wintersteiger, Inc.; Salt Lake City, UT), minus two areas consisting of frames of 0.09 m^2 each. From these frames all seedheads were hand-clipped to determine seed yield components. The harvested seed was cleaned using a South Dakota blower with an opening set at 45° angle (Watson and Watson, 1982). The cleaned seed was weighed to calculate seed yield.

Seed yield components consisted of seedheads per area, number of seed per area, number of seeds per seedhead, and individual seed weight. Seedheads per area was calculated by counting the seedheads in a frame with a known area (0.09 m^2). Seed number per area was calculated by dividing total seed yield by individual seed weight (Young et al. 1998). Number of seeds per seedhead was obtained by dividing the number of seeds per area by the number of seedheads per area. Seed weight was determined by weighing and counting all seeds in an approximately 1 g sample of seed, and dividing seed weight by the number of seeds. Seed yields are reported from the mechanical harvest and seed yield components from the manual process.

Seed harvested in the spring of 2003 was stored at 4°C with 30% humidity from harvest until mid December of 2003. After that, the seed was handled and stored at room conditions. Seed harvested in the spring of 2004 was always handled and stored at room temperature and humidity conditions. Germination tests were initiated on 24 Sept. 2006, in accordance with the Association of Official Seed Analysis (AOSA, 1998). Seed was prechilled during 7 days at 5 to 10° C, under light and imbibed with a 0.2% solution of potassium nitrate (KNO_3). After prechilling, seed was germinated at alternating temperatures from 15° to

25° C for 16 and 8 hours, respectively. Seedlings were counted at 16 and 23 days after the beginning of the incubation treatment.

1.3.4. Statistical analysis

For both seed yield and seed yield components, years were analyzed separately. Mixed models analyses of the data were performed where entry and grazing treatments were fixed effects with blocks as random effects. Correlation analyses of seed yield components and seed yield were also performed. All analyses were conducted using SAS, version 9.1 (SAS Institute, 2003). All tests were conducted with a nominal significance level of $P = 0.05$.

1.4. Results and Discussion

1.4.1. Seed yield

Precipitation varied greatly during the course of this study. Mean total annual precipitation from 1994 to 2002 was 857 mm, but only 481 mm during 2003. Furthermore, from January to April, during the time when the young, induced tillers would grow and develop seedheads, precipitation totaled only 87 mm in 2003, compared with 262 mm in 2004 and a mean of 251 mm from 1994 to 2004 (Table 1-1).

Seed yield in 2003 was poor because of severe drought conditions from the fall of 2002 to the beginning of the spring of 2003 (Table 1-1). A model for dealing with heterogeneity of variances was necessary to adequately fit the data. Mean seed yield across all treatments averaged only 26 kg ha^{-1} (Table 1-2).

Grazing treatment did not affect seed yield of Kentucky 31 or Dovey in 2003. Dovey performed poorly throughout the study, as a result, Dovey did not respond to grazing treatment, whereas the other three entries averaged almost 70% greater production in response to fall-grazing. Subsequently, this resulted in a significant (P = 0.002) entry × grazing treatment interaction. Dovey clearly produced less seed than the other entries, otherwise, seed yield did not differ among entries. Fall-grazing resulted in seed yields in some cases almost five times greater than the fall non-grazing treatment.

An early deficit of soil moisture prior to stem elongation has been shown to reduce the number of seedheads produced, which drastically reduced seed yield (Rolston et al., 1997). Similarly, Evers and Nelson (2000) concluded that variability of precipitation was responsible for lower and variable seed production of annual ryegrass in northeastern Texas. Another possibility contributing to accentuate the observed low seed yields could have been related with seed shatter. It has been observed that tall fescue seed shatters easily when ripe and can decrease seed yields by 50% or more (Jennings, 2005). In the present research, the mechanical harvest process appears to have lead to similar seed losses.

In 2004 seed yield responded favorably to improved distribution and amounts of rainfall. Mean yield was 231 kg ha^{-1}across all entries (Table 1-2). Entries were significantly different in seed yield in 2004 (P < 0.001). Dovey, averaged 60 kg ha^{-1} and, again, produced significantly less seed than each of the other three entries. Georgia 5 had greater seed yield than Kentucky 31 (P =

0.016). No significant differences in seed yield due to grazing treatments were observed (*P* = 0.111). By eliminating Dovey from the analysis, seed yield mean in 2004 was 288 kg ha^{-1}, and this favorably compared with a mean of 252 kg ha^{-1} reported for tall fescue seed production in nine states during the late 1970's (Youngberg and Wheaton, 1979). More recently, Jennings (2005) indicated that fescue seed yields in Arkansas yielded approximately 200 kg ha^{-1}, but added that experienced farmers have consistently produced 400 to 600 kg ha^{-1}.

1.4.2. Seed yield components

1.4.2.1. Seedheads per area

In 2003, a significant entry × grazing treatment interaction (*P* = 0.044) occurred for number of seedheads per area (Table 1-3). Fall-grazing had no effect on the number of seedheads per area for Dovey or Kentucky 31. Dovey produced 30 vs. 23 and Kentucky 31 had 129 vs. 123 seedheads m^{-2} for fall-grazing and fall non-grazing, respectively (Table 1-4). Conversely, Georgia 5 and Georgia 5 (E^{-}) produced a significantly greater number of seedheads in response to fall-grazing. Georgia 5 produced 238 vs. 93, and Georgia 5 (E^{-}) 206 vs. 92 seedheads m^{-2} under fall-grazing and non fall-grazing, respectively. In 2004, fall-grazing resulted in more (*P* = 0.032) seedheads m^{-2} than the fall non-grazing treatment (Table 1-3). The fall-grazing produced 522 seedheads m^{-2}, while the fall non-grazing produced 427 seedheads m^{-2} (Table 1-4).

An increased number of seedheads in response to defoliation seems to be logical. The effect of defoliation during periods of heavy forage accumulation and tiller initiation is generally beneficial due to increased light interception by the developing tillers at the base of the grass plants. Young et al. (1996) indicated that the primary effect of grazing in annual ryegrass seed production systems was to increase the number of vegetative tillers, initially, and of seedheads, latter. Thus, although in our study number of vegetative tillers in response to grazing was not determined, it is likely that an increased number of seedheads was the result of an increment of vegetative tillers in response to fall-grazing.

The low level of precipitation from November 2002 until April 2003, likely reduced the productivity of seedheads in the fall-grazing treatments of Georgia 5 and Georgia 5 (E^{-}). Fall-grazing led to greater seed yield potential of entries Georgia 5 and Georgia 5 (E^{-}) by stimulating a larger number of seedheads, but did not result in greater seed yield because apparently drought adversely affected young tillers after grazing.

Another possible negative effect of the winter-spring drought of 2002-2003 was that the N fertilizer application in March, intended to help maintain tiller and spikelet fertility, was ineffective because of a shortage of water needed to transport N into the plants. Hampton and Fairey (1997) indicate that management practices that avoid N stress prolong photosynthetic tissue duration, thus, producing assimilates and consequently increasing the number of viable seed heads and number of seeds per spikelet. In 2003, the number of seedheads and seeds per seedhead were reduced, indicating that N shortage likely decreased both seed yield potential and utilization of the seed yield potential. In 2004, with a normal precipitation level, seed yield was comparable to yield levels harvested by multiple use tall fescue growers of the Midwest (200 to

300 kg ha^{-1}). Seed yields were supported by a minimum critical number of seedheads (around 400 to 500 seedheads meter $^{-1}$), a reasonable number of seeds per seedhead, and seed size (Tables 1-4 to 1-7), suggesting that N was not critically limiting seedhead number or seedhead productivity.

Average seedhead numbers for tall fescue reported here of 117 and 475 seedheads m^{-2} for 2003 and 2004, respectively (Table 1-4), compare to a range of 300 to 600 (Lafarge, 2006), 388 for variety Fawn grown in Oregon (Young et al., 1998), and 278 to 404 tillers m^{-2} grown in Mississippi for an unclipped treatment in two years (Watson and Watson, 1982).

1.4.2.2. Seeds per area and seeds per seedhead

Dovey produced significantly fewer seeds per area and fewer seeds per seedhead than any other entry in 2003 and 2004 (Tables 1-5 and 1-6). The fewer number of seeds per seedhead may indicate that seed had already been shattered from the mature seedheads of Dovey at harvest. Dovey is defined as a “very early entry”, according to the Forage Information System of Oregon State University, (Forage Information System, 2007, visited on 4 Feb. 2007). Lewis (1969), cited by Watson and Watson (1982), indicated that the level of reduction in seed yield varied with cultivar due to maturity differences. Jennings (2005) reported that tall fescue seed shatters easily when ripe and that this can decrease seed yields drastically.

Other than Dovey, seeds per area or seeds per seedhead did not differ between entries or grazing treatments (Tables 1-5 and 1-6). We collected 1,050 and 22,700 seeds m^{-2} for 2003 and 2004, respectively, an average number of 9 seed per seedhead in 2003, and 46 in 2004. This compares to an average of 46,500 seeds m^{-2} and 130 seeds per seedhead in Oregon reported by Young et al. (1998). It is worthwhile to note that the number of seeds per seedhead is an average; thus, it is not possible to determine differences in productivity among individual seedheads. In reality, it was entirely possible that only some seedheads produced all the viable seed while other apparently fit seedheads produced few seeds, if any.

1.4.2.3. Seed weight

Seed weight was not affected by entry or grazing treatments in 2003, although there was a trend (P = 0.094) for lighter seed from Kentucky 31 compared to entries Georgia 5 and Georgia 5 (E^-) (Table 1-7). In 2004 fall-grazing resulted in statistically heavier seed than fall non-grazing (P = 0.043) with Kentucky 31 producing lighter seed than the other entries in the study (P = 0.013) (Table 1-7). The number of tall fescue seeds kg^{-1} ranges from 387,000 to 574,000 (Hannaway et al., 1999), equivalent to a range of 2.6 to 1.7 mg $seed^{-1}$, respectively. Seed weight in this research, ranging from 2.1 to 1.8 mg $seed^{-1}$ fell within the range of normal seed size for tall fescue.

1.4.3. Correlations between seed yield and seed yield components

Seed number was strongly correlated with seed yield, whereas seed weight was not correlated with seed yield (Table 1-8). These results agree with those of Young et al. (1998) who reported that seed yields correlated closely with number of seeds produced per area, but weakly and negatively correlated with weight per seed. Hebblethwaite and Hampton (1982) (cited by Hampton and Fairey, 1997), found that seed number per unit area explained 63 and 98 % of the total variance of seed yield of two perennial ryegrass cultivars over a 10 year period in one location. Our results, supported by other studies (Young et al., 1998; Elgersma, 1990), further illustrate that tall fescue and perennial ryegrass are not able to compensate for low seed numbers by producing larger seeds. Tall fescue seed production seems to be dependent primarily on the production of seedheads per area, given that these were strongly correlated with seed yield, regardless of grazing treatment. Seed weight remained constant and seeds per seedhead changed little across entries or grazing treatments within each year.

Based on our results, we agree that the initial importance of the number of seedheads per area is recognized as one of the most important conditions defining final seed production. However, environmental conditions and level of carbohydrate reserves in the plants after defoliation seem to set limits to the degree in which seedheads number actually impact seed production. Evidently, compensation mechanisms start to operate among seed yield components that neutralize the potential advantage of an increased number of seedheads after a minimum critical number is reached. Anderson and Frank (2003) reported a greater number of seedheads in grazed plots compared to non-grazed plots, but with a greater number of seeds per tiller in the non-grazed plots. They concluded that because of these offsetting responses, seed production was not affected by grazing at plot level.

In 2004, although fall-grazing resulted in a significantly greater number of seedheads and slightly heavier seeds but the same number of seeds per seedhead, these differences were not sufficient to produce greater seed yield as compared to the fall non-grazing treatment. Although not specifically measured, our findings suggest that a low efficiency of the use of the yield potential might have occurred in the fall-grazing treatment, as compared with fall non-grazing treatments. This in agreement with the onset of compensation mechanisms operating among seed yield components, in agreement with Anderson and Frank (2003). A low efficiency of the use of the yield potential has been identified as one of the most limiting factors for high seed yield of diverse grass species (Elgersma, 1985). The degree of importance of the efficiency of use of the yield potential depends, to a large extent, on the efficacy with which abortion of seedheads is avoided. Hampton and Fairey (1997) considered that a major cause for poor floret site utilization was abortion of developing seeds because insufficient assimilates were available to fulfill the demand of all the potential seeds. Thus, our findings point out that tall fescue, once reaching a minimum critical number of seedheads, is able to produce comparable seed yields within a range of seedheads per area, regardless of grazing management during the fall.

In addition to the effect of environment (weather, soil fertility), an additional limiting factor for seed production in multiple use tall fescue management systems is the effect of grazing and the expenditure of resources for regrowth.

Chastain and Young (1998) indicated that the number and size of vegetative tillers before floral induction (during the fall) was highly correlated with seed yield in young fields of orchardgrass (r = 0.93) and tall fescue (r = 0.95). Although a sufficient number of tillers may be ready to undertake regrowth from the base of the canopy after grazing in the fall-winter, the size of these tillers may be critical. Fall grazing intensities may need to be moderate to light so as to allow increased number of seedheads while minimizing investment in regrowth, and thus maximizing size of such tillers.

Leaf area index represents the size of the photosynthetic apparatus responsible for carbohydrate acquisition for maintenance and growth of the plant. After fall-grazing, leaf area index is obviously reduced and should limit the capacity of the plants to save reserves needed for seed production. Redmon et al. (1995, 1996) suggested that one of the causes of reducing winter wheat grain yields in dual-purpose systems (grazing and grain), was due to the plant's inability to regain a minimum photosynthetic capacity after defoliation but prior to floral initiation.

1.4.4. Germination

In 2003, seed germination averaged approximately 81% and did not differ between entries or grazing treatments. In 2004, germination was slightly higher, compared with the previous year, ranging from over 83 to 91%. Dovey had lower germination than the other entries, and fall-grazing resulted in greater germination (89%) than fall non-grazing (86%). It should be noted that germination tests were conducted in late 2006 with seed harvested in the springs of 2003 and 2004 (more than three and two years old, respectively). The overall germination percentage of both seed lots is unlikely to have changed substantially over time. Preliminary germination tests conducted only on the seed harvested in 2004, on July 2004, yielded exactly the same germination (87%) as two years latter. Cardwell (1984) indicated, however, that aging of seeds is reflected in seedling vigor (instead of germination). Thus, it is possible that seedling vigor, not germination, might have been different after two to three years of storage.

1.5. Conclusions

All entries generally performed similarly, except for Dovey which doesn't appear to be adapted for seed production to the conditions that prevailed during this study. Fall defoliation led to a greater number of seedheads, which is often the first condition limiting final seed yield. However, a greater number of seedheads per area did not always result in greater seed yield apparently due to environmental constraints leading to low efficiency of the use of the yield potential. Neither seed size nor germination percentage was affected by fall-grazing. Thus, fall-grazing in Oklahoma appears not to have negative effects on tall fescue seed yield and seed quality. When managed appropriately, tall fescue seed production can be a viable component for multiple use systems in the Southern Great Plains, where tall fescue is adapted.

1.6. References

Aamlid, T.S., O.M. Heide, B.R. Christie, and R. L. McGraw. 1997. Reproductive development and the establishment of potential seed yield in grasses and legumes. p. 9-44. *In* Fairey, D.T., and J.G. Hampton (ed.) Forage seed production. CAB International, New York, NY.

Anderson, M.T., and D.A. Frank. 2003. Defoliation effects on reproductive biomass: Importance of scale and timing. J. Range Manage. 56:501-516.

Association of Official Seed Analysts. 1998. Rules for testing seeds. AOSA, Lincoln, NE.

Brotemarkle, J., and G. Kilgore. 1989. Seed production management for bromegrass and tall fescue. Publication MF-924. Cooperative Extension Service, Kansas State University. Manhattan, KS.

Brown, K.R. 1980. Seed production in New Zealand ryegrasses. N. Z. J. Exp. Agric. 8:27-32.

Burns, J.S., D.S. Chamblee. 1979. Adaptation. p. 9–30. *In* R. C. Buckner and L. P. Bush (eds.). Tall Fescue. American Society of Agronomy, Crop Science Society of America. Madison, WI..

Cardwell, V. B. 1984. Seed germination and crop production. p. 62. *In* M. B. Tesar (ed.) Physiological basis of crop growth and development. American Society of Agronomy, Crop Science Society of America. Wisconsin, Madison

Chastain, T.G., and W.C. Young. 1998. Vegetative plant development and seed production in cool-season perennial grasses. Seed Sci. Res. 8:295-301.

Elgersma, A. 1985. Floret site utilization in grasses: definitions, breeding perspectives and methodology. J. Appl. Seed Prod. 3:50-54.

Elgersma, A. 1990. Seed yield related to crop development and to yield components in nine cultivars of perennial ryegrass (*Lolium perenne* L.). Euphytica 49:141–154.

Evans, L. T. 1964. Reproduction. p. 126-153. *In* Barnard C. Grasses & grasslands. Macmillan and Co. Toronto, Canada.

Evans, D.W. 1975. Cougar Kentucky bluegrass seed production as affected by clipping to simulate grazing. Crop Sci. 15:601-602.

Evers, G.W., and L.R. Nelson. 2000. Grazing termination date influence on annual ryegrass seed production and reseeding in the Southeastern USA. Crop Sci. 40:1724-1728.

Green, J.O., and T.A. Evans. 1957. Grazing management for seed production in leafy strains of grasses. J. Br. Grassl. Soc. 12:4–9.

Forage Information System. 2007. Dovey tall fescue [Online]. Available at http://forages.oregonstate.edu/main.cfm?PageID=364&SpecID=8&use=Forage (verified on 4 Feb. 2007). Oregon State Univ., Corvallis.

Hampton, J.G., and D.T. Fairey. 1997. Components of seed yield in grasses and legumes. p. 52. *In* Fairey, D.T., and J.G. Hampton (ed.) Forage seed production. CAB International, New York, NY.

Hannaway, D., S. Fransen, J. Cooper, M. Teel, M. Chaney, T. Griggs, R. Halse, J. Hart, P. Cheeke, D. Hansen, R. Klinger, and W. Lane. 1999. Tall fescue

(*Festuca arundinacea* Schreb.). PNW Ext. Ser. Circ. 504. Oregon State Univ., Corvallis, OR.

Hill, M.J. 1971. Closing ryegrass crops for seed production. N. Z. J. Agric. 123:43.

Hopkins, A.A., and M.W. Alison. 2006. Stand persistence and animal performance for tall fescue endophyte combinations in the south central USA. Agron. J. 98:1221-1226.

Hopkins, A.A., E.G. Krenzer, G.W. Horn, C.L. Goad, L.A. Redmon, D.D. Redfearn, and R.R. Reuter. 2003. Spring grazing reduces seed yield of cool-season grasses grown in the southern Great Plains. Agron. J. 95:855-862.

Jennings, J. 2005. Seed production of tall fescue. Cooperative extension service, University of Arkansas, Little Rock, AR.

Lacefield, G.D., J.C. Henning, and T.D. Phillips. 2003. Tall fescue. Kentucky Agric. Exp. Stn., Univ. of Kentucky, Lexington, KY.

Lafarge, M. 2006. Reproductive tillers in cut tall fescue swards: differences according to sward age and fertilizer nitrogen application, and relationships with the local dynamics of the sward. Grass Forage Sci. 61:182-191.

Lambert, J.P. 1956. The effects of grazing on seed production in cocksfoot (*Dactylis glomerata* L.) N.Z. J. Sci. Technol. 37:432–442.

Nordestgaard, A., and S. Andersen. 1991. Stability of high production efficiency in perennial herbage seed crops. J. Appl. Seed Prod. 9:27 32.

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

Redmon, L.A., E.G. Krenzer, D.J. Bernardo, and G.W. Horn. 1996. Effect of wheat morphological stage at grazing termination on economic return. Agron. J. 88:94-97.

Roberts, H.M. 1958. The effect of defoliation on the seed-producing capacity of bred strains of grasses. I. Timothy and perennial ryegrass. J. Br. Grassl. Soc. 13, 255–261

Roberts, H.M. 1965. The effect of defoliation on the seed- producing capacity of bred strains of grasses. III. Varieties of perennial ryegrass, cocksfoot, meadow fescue and timothy. J. Br. Grassl. Soc. 20, 283–289.

Rolston, M.P., J.S. Rowarth, W.C. Young III, and G.W. Mueller-Warrant. 1997. Grass seed crop management. p. 105-126. *In* Fairey, D.T., and J.G. Hampton (ed.) Forage seed production. CAB International, New York, NY.

SAS Institute, Inc. 2003. SAS version 9.1. Cary, NC.

Watson, C.E., and V.H. Watson. 1982. Nitrogen and date of defoliation effects on seed yield and seed quality of tall fescue. Agron. J. 74:891-893.

Wolf, D.D., R.H. Brown, and R.E. Blaser. 1979. Physiology of growth and development. p. 75–92. *In* R.D. Buckner and L.P. Bush (ed.) Tall fescue. ASA, CSSA, and SSSA, Madison, WI.

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

Young, W.C. III. 1997. *Festuca arundinacea* Scheb. (tall fescue) in the USA. p. 287-310. *In* Fairey, D.T., and J.G. Hampton (ed.) Forage seed production. CAB International, New York, NY.

Young, W.C. III, D.O. Chilcote, and H.W. Youngberg. 1996. Annual ryegrass seed yield response to grazing during early stem elongation. Agron. J. 88:211-215.

Young, W.C., III, H.W. Youngberg, and T.B. Silverstein. 1998. Management studies on seed production of turf-type tall fescue: II. Seed yield components. Agron. J. 90:478-483.

Youngberg, H., and H.N. Wheaton. 1979. Seed production. p. 141-153. *In* R.C. Buckner, and L.P. Bush (ed.) Tall Fescue. Agron. Monogr. 20. ASA, CSSA, SSSA, Madison, WI.

Table 1-1. Precipitation at the Noble Foundation Red River Demonstration and Research Farm, near Burneyville, OK, during 2002, 2003, partial 2004, and average of 1994-2004.

Month	2002	2003	2004†	Mean 1994-2004
		mm		
Jan.	23	0	35	42
Feb.	29	52	62	62
Mar.	56	25	30	59
Apr.	119	10	135	88
May	45	158	22	97
June	113	76	-	98
July	35	5	-	37
Aug.	48	63	-	70
Sept.	47	49	-	88
Oct.	151	2	-	90
Nov.	24	28	-	61
Dec.	96	13	-	65
TOTAL	786	481	284	857

† The experiment was completed prior to 1 June 2004.

Table 1-2. Seed yield of four tall fescue entries subjected to fall-grazing and fall non-grazing in pastures, near Burneyville, OK, during 2003 and 2004.

Entry	Fall-grazing	Fall non-grazing	SE†
	kg ha^{-1}		
		2003	
Dovey	2 bA‡	2 bA	0.6
Georgia 5	55 aA	14 abB	12.6
Georgia 5 (E^-)	48 aA	10 abB	6.2
Kentucky 31	52 aA	26 aA	10.4
		2004	
Dovey	78 bA	42 cA	15.8
Georgia 5	340 aA	311 aA	25.6
Georgia 5 (E^-)	332 aA	278 bA	62.7
Kentucky 31	266 aA	198 bA	42.8

†SE, standard error for treatment combination means.

‡ For a given year within columns, means followed by the same lower case letter are not significantly different at the *P* = 0.05 level. For a given year within rows, means followed by the same upper case letter are not significantly different at the *P* = 0.05 level.

Table 1-3. Seedheads per area, seed number, seeds per seedhead, and seed weight of four tall fescue entries subjected to fall-grazing and fall non-grazing in pastures, near Burneyville, OK, during 2003 and 2004.

Source of variation	Seedheads	Seed number	Seeds per seedhead	Seed weight
		2003		
Entry (E)	***	*	*	NS
Grazing treatment (G)	**	NS	NS	NS
E × G	*	NS	NS	NS
		2004		
Entry (E)	NS	**	**	*
Grazing treatment (G)	*	NS	NS	*
E × G	NS	NS	NS	NS

*, **, and ***, significantly different at P = 0.05, 0.01, and 0.001, respectively. NS, no significant difference at P = 0.05.

Table 1-4. Mean seedheads per area of four tall fescue entries subjected to fall-grazing and fall non-grazing in pastures, near Burneyville, OK, during 2003 and 2004.

Entry	Fall-grazing	Fall non-grazing	Mean	SE†
	No. m^{-2}			
		2003		
Dovey	30	23	27	8.6
Georgia 5	238	93	166	23.0
Georgia 5 (E-)	206	92	149	32.4
Kentucky 31	129	123	126	46.9
Mean	151	83		
		2004		
Dovey	386	320	353	51.6
Georgia 5	586	519	553	37.6
Georgia 5 (E-)	559	448	504	74.9
Kentucky 31	558	421	490	29.2
Mean	522	427		

†SE, standard error for treatment combination means.

Table 1-5. Mean seed number of four tall fescue entries subjected to fall-grazing and fall non-grazing in pastures, near Burneyville, OK, during 2003 and 2004.

Entry	Fall-grazing	Fall non-grazing	Mean	SE†
	No. $m^{-2} \times 10^{3}$‡			
		2003		
Dovey	0.05	0.06	0.06	0.00
Georgia 5	1.58	1.22	1.40	0.08
Georgia 5 (E-)	1.50	1.24	1.37	0.21
Kentucky 31	1.41	1.32	1.37	0.13
Mean	1.14	0.96		
		2004		
Dovey	9.70	7.33	8.52	0.88
Georgia 5	28.90	23.97	26.43	3.50
Georgia 5 (E-)	31.03	22.63	26.83	7.32
Kentucky 31	31.33	26.70	29.02	10.26
Mean	25.24	20.16		

‡ The actual numbers were multiplied by this to obtain the reported numbers.

†SE, standard error for treatment combination means.

Table 1-6. Mean seeds per seedhead of four tall fescue entries subjected to fall-grazing and fall non-grazing in pastures, near Burneyville, OK, during 2003 and 2004.

Entry	Fall-grazing	Fall non-grazing	Mean	SE†
		2003		
Dovey	2	3	3	0.1
Georgia 5	7	13	10	0.8
Georgia 5 (E-)	7	13	10	2.0
Kentucky 31	11	9	10	2.4
Mean	7	10		
		2004		
Dovey	26	23	25	1.6
Georgia 5	50	47	48	3.7
Georgia 5 (E-)	54	46	50	5.0
Kentucky 31	59	64	62	3.8
Mean	47	45		

†SE, standard error for treatment combination means.

Table 1-7. Mean seed weight of four tall fescue entries subjected to fall-grazing and fall non-grazing in pastures, near Burneyville, OK, during 2003 and 2004.

Entry	Fall-grazing	Fall non-grazing	Mean	SE†
		mg $seed^{-1}$		
		2003		
Dovey	1.9	2.0	1.9	0.10
Georgia 5	2.0	1.9	2.0	0.08
Georgia 5 (E-)	2.1	2.0	2.1	0.10
Kentucky 31	1.9	1.8	1.8	0.07
Mean	2.0	1.9		
		2004		
Dovey	2.1	2.0	2.1	0.05
Georgia 5	2.1	2.0	2.1	0.02
Georgia 5 (E-)	2.2	2.1	2.2	0.04
Kentucky 31	1.9	1.8	1.9	0.06
Mean	2.1	2.0		

†SE, standard error for treatment combination means.

Table 1-8. Pearson's correlation coefficients (*r*) between seed yield with seedheads, seed number, seeds per seedhead, and seed weight of four tall fescue entries subjected to fall-grazing and fall non-grazing in pastures, near Burneyville, OK, during 2003 and 2004.

	Seedheads	Seed number	Seeds per seedhead	Seed weight
		2003		
Fall-grazing	0.88 ***	0.99 ***	0.54	0.50
Fall non-grazing	0.84 ***	0.99 ***	0.70 *	- 0.11
		2004		
Fall-grazing	0.86 ***	0.99 ***	0.85 ***	0.16
Fall non-grazing	0.87 ***	0.99 ***	0.90 ***	0.12

*, **, and ***, significant at P = 0.05, 0.01, and 0.001, respectively.

CHAPTER 2

2. Spatial and Temporal Variability of Soil Fertility in Terraced Pastures

2.1. Abstract

Soil testing is a tool to determine fertilizer and lime needs, but spatial and temporal variability along with inappropriate soil sampling methodologies may result in unreliable test results. A study was conducted to quantify the contribution of several temporal and spatial variables to soil test variability and to propose practices for improving soil sampling in terraced pastures. Two methods of sampling were employed. Sampling along a strip crossed multiple microreliefs (by-strips) and sampling along a microrelief crossed multiple fertilizer treatments (by-microreliefs). The by-strips sampling method was tested for three years, two seasons per year, four pastures, and five fertilizer treatments. The by-microreliefs method was tested for two years, two seasons per year, four pastures, and five microrelief points. Soil samples were analyzed for pH and plant available N, P, and K. Temporal variability was consistently greater than spatial variability across the soil fertility parameters tested. Variation from pasture to pasture was negligible; however, the effect of terrace channels had a large impact on soil fertility variability, particularly for soil test P and K. The two sampling methodologies complemented each other to provide a clear picture about the spatio-temporal dynamics of nutrients in these sloped, terraced pastures. Some recommendations that could help increase soil sampling precision in terraced

pastures include allowing some substantial precipitation to occur between grazing and sampling to minimize the effects of animal excreta and collect soil cores representing all microrelief areas except terrace channels to form a composite sample. Terrace channels are comparable to “hot spots” in proximities to areas where livestock gather, where a separate sample may be needed, and managed differently from the rest of the pasture.

2.2. Introduction

Agronomic decisions about introduced pasture management depend largely on soil test results to determine how to maintain adequate soil fertility levels for sustainable forage production. Soil test results for pastures tend to be highly variable in space (Anderson et al., 1992; Bogaert et al., 2000) as well as time (Conyers et al., 1997; Fisher et al., 1998), and thus, are difficult to interpret. Soil sampling methods and test results may not work as well for pastures as for cropped soils because they differ in many aspects. In general, fields used for crop production tend to be flatter than pastures, have generally a higher yield potential, and are less variable. Giltrap and Hewitt (2004) reported that cropland had lower coefficients of variation for soil fertility parameters than pastures in New Zealand. Pastures are frequently located on irregular topography and grazing animals can cause large variation of soil fertility at various scales (Barrow, 1967) through irregular fecal and urine deposition patterns over the pastures (Fisher et al., 1998; Franzluebbers et al., 2000). West et al. (1989) concluded that distinctive zones of nutrient enrichment occurred in the proximities of water sources and that these “hot spots” should be avoided or sampled separately at the time of collecting soil samples in pastures. Soil sampling methods should distinguish between flat and sloped pastures (Morton et al., 2000). Minimal emphasis has been placed on adopting soil sampling strategies specific for soils in pastures.

Besides the effect of patterns of deposition of animal excreta on pastures, other sources of variability that have been identified and studied include grazing methods and stocking rates (Mathews et al., 1994a; Mathews et al., 1994b; Sauer and Meek, 2003), site topography (López et al., 2003), organic or chemical fertilizer management practices (Daniels et al., 2001; Saggar et al., 1990; Sigua et al., 2004), and seasonal changes (Pote et al., 1999; Walter et al., 2003).

During 1930’s an ecological disaster consisting in the loss of millions of tons of top soil through wind and water erosion occurred. This was caused by a combination of drought and unsound agricultural practices (cultivated and overgrazed soil left unprotected). In response to the problem, an extensive federal program was put in place to conserve and reclaim the soil. States that were most damaged were those of the region collectively known as the “Dust bowl”, namely, Kansas, Oklahoma, Texas, New Mexico, and Colorado (Lauber, 1958). The strategy of the Soil Conservation Service (SCS) to protect and restore the soil focused in breaking the force of the wind and save soil moisture. Among the most popular practices promoted by the SCS were contour plowing, terracing and listing, and strip farming (Lauber, 1958). As part of this national conservation effort, much of the formerly cropped land across the USA reverted to pastures, keeping as part of their new landscape the terraces that were built to conserve soil and water.

Estimating the variability of soil fertility in pastures has relied on different soil sampling techniques that have been reported to have various degrees of reliability. While reliability is a measure of reproducibility of measurements, accuracy is the correctness of the measurement, and correctness, according to Mason (1992), will always be unknown. Therefore, in soil sampling the target is to achieve the highest precision possible.

Coefficients of variation (CV) are frequently used to express variability of various soil properties in a given area (Friesen and Blair, 1984). Unpublished data from four pastures at the Eastern Research Station (Oklahoma Agricultural Experiment Station), near Haskell, Oklahoma, sampled yearly from 1989-2004 (0-15 cm depth), had a CV of 55% for available phosphorus (P) and 47% for available potassium (K). In an early assessment of the variability within fields of soil chemical properties, Hemingway (1955) reported CV's for available P and K of 51 and 71%, respectively. Beckett and Webster (1971) concluded in a comprehensive literature review that within field CV's for nitrogen (N) and available P, and K, were 25-30, 45, and 70%, respectively. Brown (1993) reviewed a series of 24 research publications about soil variability in pastures and reported mean CV's of 232, 48, and 42% for N, P, and K, respectively.

We reviewed 16 papers from mid 1980's to date related to soil variability in pastures and found that the mean CV's were 4, 48, 43, and 36 %, for pH, N, and available P and K, respectively (Anderson et al., 1992; Bogaert et al., 2000; Chen et al., 2001; Conyers et al., 1997; Daniels et al., 2001; Fisher et al., 1998; Friesen and Blair, 1984; López et al., 2003; Mathews et al., 1999; Mathews et al., 1994a; Mathews et al., 1994b; Morton et al., 2000; Sauer and Meek, 2003; Sigua et al., 2004; Tarr et al., 2003; West et al., 1989). Consolidating all of these reviews and unpublished data, we suggest that the historic CV's around the world for pasture systems and uncultivated fields have been in general, small for soil pH, difficult to predict for mineral N, approximately 40-55% for P, and 35-70% for K. Morton et al. (2000) tested a sampling method specific for sloped pastures and reduced CV's of soil P and K from as much as 55% down to slightly over 20% by sampling 100 m transects at 10 m intervals from within a 0.3 m radius of each original sampling position during up to five years.

The effect of terraces in pastures is unknown and might deserve more attention in relation with soil sampling and fertilizer management practices. We hypothesize that terraces play an important role in nutrient distribution across the pastures and that soil sampling methods and fertilizer management practices can be improved through the implementation of procedures specifically designed for these systems. The objectives of this study were to quantify the relative contribution of several factors to soil test variability and to propose practices for improving soil sampling in terraced pastures.

2.3. Materials and Methods

2.3.1. Experimental site

This research was conducted at the Eastern Research Station located near Haskell, OK, with coordinates of 35° 44' north latitude and 95° 38' west longitude. The station consists of 120 ha and is located in the Cherokee Prairie Resource Area, which represents approximately 2.6 million hectares of eastern Oklahoma pasture land. Elevation of the station is about 180 m with a mean historic annual precipitation averaging 1040 mm with about 60% of this precipitation usually occurring from April through September. In the winter, the mean minimum temperature is 0° C, and in the summer the mean maximum temperature is 33° C (Townsend et al., 1987).

An area of 53 ha of the research station was designated for cattle grazing that had been managed as four pastures from 1978 to 1988. In 1989 a grazing demonstration was initiated using several pastures and some of the cow herd at the Eastern Research Station. For other activities, three of the four pastures were divided into two smaller pastures resulting in a total of seven pastures. Within these seven pastures, four were used to conduct the present study. Although many species of forage grasses have been planted through the years in the different pastures on the station, the predominant forage grasses were tall fescue [*Festuca arundinacea* Schreb. = *Lolium arundinaceum* (Schreb.) S.J. Darbyshire] and bermudagrass (*Cynodon dactylon* L.). Forage legumes (*Trifolium repens* L., *T. pratense* L., *T. vesiculosum* Savi, and *Medicago sativa* L., etc.), annual cool-season grasses (*Bromus* spp.) and warm-season grasses (*Digitaria* spp.) were also present in small quantity. More detailed descriptions of these pastures was provided by Caddel et al. (2005) and Redfearn et al. (2006).

One site (block) of 30 × 122 m was identified within each of the four different pastures. The sites were sloped (ranging from 1.5 to 3.7 %) and were located at a similar elevation gradient. Each site was relatively long and parallel with the natural slope of the land and perpendicular to water retention terraces. Records at the station indicate that these terraces were present at least 60 years ago. The four sites consisted of different soil series. Site 1 included Choteau (Fine, mixed, active, thermic Aquic Paleudolls) and Parsons (Fine, mixed, active, thermic Mollic Albaqualfs), sites 2 and 3 included only Choteau, and site 4 consisted of Dennis (Fine, mixed, active, thermic Aquic Argiudolls) and Choteau (Gray and Nance, 1978). These soils although were somewhat different from each other, shared some common characteristics (low permeability, for example) because they are geographically associated (or competing) soils (National Cooperative Soil Survey. 2006).

2.3.2. Treatments and data collection procedures

Within each site five 3.5 m wide fertilizer strips were randomly assigned to each of the four sampling sites during three years. Years were counted from August 1 to July 31 of the next year; therefore, years crossed parts of two calendar years: 2003-2004, 2004-2005, and 2005-2006. Fertilizer treatments consisted of the application of N (150 kg ha^{-1} N), P (150 kg ha^{-1} P_2O_5), K (200 kg ha^{-1} K_2O), NPK (150, 150, and 200 kg ha^{-1} N, P_2O_5, and K_2O, respectively), and a control; lime was applied to the NPK treatment only in the first year at a rate of 670 kg ha^{-1} ECCE. Every strip crossed three terraces and each terrace consisted of five microrelief points: a) top of terraces opposing the channels, b) top of terraces on channel side, c) the backslope of terraces, d) the terrace channels, and e) the nearly flat area between terraces of presumably undisturbed soil (Figures 2-1 top and bottom). Fertilizer treatments were randomly assigned to the strips prior to first application and repeated during the next two years.

Two soil sampling methods were used in this study: “by-strips” and “by-microreliefs”. The sampling depth was 0-15 cm for both methods. Microreliefs were fixed along the strips and the five microrelief points perpendicularly crossed all five fertilizer treatments. A microrelief was sampled by mixing single cores from each fertility strip along a microrelief on each of three terraces, resulting in 15 cores for each soil sample (Figure 2-1 bottom). Every year, the pastures were sampled on two sampling dates, one right after the grazing season finished, “the fall-winter” season, and the other right before the initiation of a new grazing season, “the spring season”. From now on in this manuscript, we refer to factor “sampling dates” as seasons, although soil samples were not always collected during the period of duration of the seasons as conventionally known. Also, we refer to factor “sampling sites” as pastures, although this term refers only to the sampled area within the different pastures. The total number of soil samples was 80 (two years × two seasons per year × four pastures × five microrelief points).

The by-strips samples were collected along the fertility strips, which crossed three terraces, by mixing single cores from each microrelief point, resulting in 15 cores for each soil sample (Figure 2-1 bottom). The total number of soil samples was 120 (three years × two seasons × four pastures × five fertilizer strips). Time of soil sampling, fertilizer applications, and monthly precipitation distribution are shown in Figure 2-2.

2.3.3. Laboratory analysis

Soil samples were dried at 60ºC over night in a forced air oven, ground to pass a 2-mm sieve, and analyzed for pH, NO_3 - N, plant available P, and K. Soil pH was measured by a glass electrode in a 1:1 soil:water suspension (Sims, 1996). Soil NO_3 - N was extracted with 0.01 M $Ca_3(PO_4)_2$ solution and quantified by the cadmium reduction method on a Lachat QuikChem 8000 (LACHAT, 1994). Soil available P and K were extracted using Mehlich–3 solution (Mehlich, 1984). Phosphorus in the extract was quantified colorimetrically using a Lachat, while K was analyzed by a Spectro CirOs ICP.

2.3.4. Treatment and design structures and statistical analysis

In the by strips-sampling method factors included three years, two seasons, four pastures, and five fertilizer treatments. Factors years, seasons, and pastures were random, and factor fertilizers was the only fixed effect. The fixed factor fertilizers was analyzed in a randomized complete block design repeated over two seasons per year across four pastures. A mixed model was used to obtain variance component estimates through the restricted maximum likelihood (REML) method for the random effects and to test the fixed effect (fertilizers) using PROC MIXED (SAS Institute, 2003). Proportions of each random component to the total variance were obtained. The Fisher's protected LSD procedure ($P < 0.05$) was used to compare treatment means when appropriate. CV's associated with the means of fixed effects were calculated by getting the square roots of the estimate of error variance divided by each least square mean (× 100). For the by-microreliefs sampling method, analyses proceeded identically as the by-strips sampling method, except that in this case the random factors were two years, two seasons per year, and four pastures. The fixed factor consisted of five microrelief points.

2.4. Results and Discussion

2.4.1. Variance components

The by-strips sampling method revealed a total variance of 0.040 for soil pH across random factors, equivalent to a standard deviation of only ± 0.2 of a pH unit (Table 2-1). The most variable random factor for soil pH was years, which accounted for 42% of the total variance. NO_3 -N variance was primarily affected by pastures, accounting for 61% of the total variance. However total NO_3 -N variance was 214, that is, a standard deviation of only ± 15 kg ha^{-1}. Agronomically speaking, unlike soil pH and NO_3 -N, total variance of P was large, 1072, a standard deviation of ± 33 kg ha^{-1}. From the total variance observed for P, temporal variables years and seasons accounted for 11 and 32%, respectively. Soil K behaved similarly to soil P, showing a relative large variance and having years (21%) and seasons (30%) as the most influential variables. Total variation for K was 7789, that is a standard deviation of ± 88 kg ha^{-1}.

Sampling by-microrelief, soil pH had a variance of 0.059, a standard deviation of ± 0.2 of a unit. Years, once again, explained a large proportion of the variation (41%) (Table 2-1). Nitrogen had a total variance of 208, which represents a standard deviation of ± 14 kg ha^{-1}. Seasons accounted for 70% of the total variance. Phosphorus had a total variance of 674, a standard deviation of ± 26 kg ha^{-1}; seasons explained 37% of the total. Finally, K had a variation of

7069, or a standard deviation of 84 kg ha^{-1}. Seasons accounted for one third of the total variance for K. Note that the 60% observed for the unexplained variance of K occurred due to variability within a microrelief.

For soil pH, the factor years had the largest influence among all random factors (Table 2-1). The effect of seasons was the highest for soil nutrients P and K. It was noted that P and K had a prominent increase in concentration during the season of fall-winter of 2005-2006, which coincided with a dry period prior to sampling (Figure 2-2), while cattle kept grazing. It should be noted that the fall-winter samples for 2005 were actually collected on 2 Feb. 2006 because excessive dry soil that impeded collecting accurate soil samples. After this clear increment in soil fertility levels, in February 2006, soil fertility returned to levels observed prior to this sampling event, as observed in the spring soil samples (collected on 4 Apr. 2006) (data not shown).

Distribution of precipitation is believed to have caused this effect. Precipitation during September through January of 2005-2006 was only 87 mm, compared to 330 and 530 mm during the same period in 2003-2004 and 2004-2005, respectively (Figure 2-2). However, precipitation occurring between early February (fall-winter season) and early April 2006 (spring season), was nearly 100 mm, with single rain events of 23 mm on 18 Mar. 2006, and combined total of 26 mm between 1 and 2 Apr. 2006.

As shown by a low fraction to the total of the variance, large scale spatial variability, i.e., variability from pasture to pasture, was not of great importance in this study except for the NO_3 –N in the by-strips sampling method (Table 2-1).

Beckett and Webster (1971) found that up to a half of the total variability at a field level was manifested within any square meter; other researchers also shared this same conviction (Friesen and Blair, 1984). Difference in soil orders did not significantly affect soil variability (Giltrap and Hewitt, 2004). On the other hand, Ball and Williams (1968) concluded that any seasonal variation within the main growing season at their sites was small and subordinate to spatial variation.

The apparent conflict between our results and those of Ball and William (1968) may be resolved by taking into account the precipitation levels and distribution. Their conclusions were based on two locations where yearly precipitation was normally large (1800 and 3800 mm), in which case the variability caused by either animal excreta or topography should be removed by precipitation. But in more variable and lower precipitation environments, similar to that in which our research was conducted, soil variability could be highly accentuated by lower total precipitation and erratic distribution. Precipitation occurring prior to the time of soil sampling, after the pastures have been grazed, seems to be critical. Significant precipitation would dilute highly concentrated spots left by urine and fecal animal depositions.

2.4.2. Fixed effects and CV's

Using sampling by-strips method, soil pH was different among fertilizer treatments (P = 0.022). This sampling method was precise enough to detect a slight decrease of pH in the N-fertilizer treatment, compared with any other fertilizer treatment (Table 2-2). Liebig et al. (2006) reported a decrease of 0.1 pH units for each 122 kg N ha^{-1} in grazed pastures after yearly applications of 45 kg N ha^{-1} during 30 years. Nitrogen in the NPK fertilizer treatment did not present a lower pH possibly due to the effect of the lime applied during the first year to this treatment. Mean CV's for pH by fertilizers was 2% which is similar to CV's of 4% reported by Gupta et al. (1999).

Soil N was not significantly different among fertilizer treatments (P = 0.082), with a mean CV of 33%. Phosphorus was significantly different (P = 0.005), with a mean CV of 25%. Soil P in P-fertilized treatments was nearly 2 times as high as in non P-fertilizer treatments. Potassium was significantly different among fertilizers (P = 0.007), and a CV of 14%, however, soil available K in K-fertilized treatments was only 1.4 times higher than in non K-fertilizer treatments. This is indicative of a lower stability of K-fertilizers than of P-fertilizers within the strips where fertilizers were originally placed and/or possible luxuriant consumption by the forages.

With the by-microreliefs sampling method, all fertility parameters were significantly different among microreliefs. Means and CV's for soil pH, NO_3-N, P and K are reported (Table 2-2). Soil pH was lower in terrace channels than in any other microrelief point. Leaching of base cations due to rainfall over time can decrease soil pH (Johnson and Zhang, 2002), and terrace channels have historically caught more water than other microreliefs in the pasture. Soil moisture calculations were conducted during the two sampling dates of 2005-2006 and terrace channels were slightly but significantly wetter than any other point of the microrelief (data not shown). These results are consistent with those of Bragg and Stephens (1979) who found terrace channels to contain the highest soil moisture in comparison with tops of terraces and intervals between terraces. Thus, if any potential for leaching existed in these pastures, that potential would be accentuated in terrace channels.

In contrast, NO_3-N in terrace channels was the same as tops of terraces but slightly higher than backslopes and flats. Soil available P and K were the greatest in terrace channels among all microreliefs. The effect of microrelief on K was practically the same as for P. Potassium in terrace channels was 1.8 times higher than the other four microreliefs, while P was 1.5 times greater in channels than in the rest of the microreliefs (from Table 2-2).

When combining the results about the patterns of lateral (regardless of slope) and by slope movement (regardless of fertilizers), these indicated that K had more lateral mobility than P, but both were approximately equally susceptible to be transported downwards to the drainage areas of the pastures (terrace channels). It might be possible that lateral movement of P and K is controlled by random deposition of animal excretions and by lateral movement during rain events causing runoff water. Even low intensity rains can cause runoff when the soil is already water saturated, as observed by Hegg at al. (1982).

The hypothesis about lateral movement is supported by Chen et al. (2001) who found extractable K to have greater redistribution than extractable P in a generally level to gentle rolling terrain. They attributed this difference to a greater content of K than of P in plant tissue and consequent animal intake and excretions. Findings by López et al. (2003) and Aarons et al. (2004) underlined the influence of slope over the distribution of several soil nutrients.

As proposed earlier, during rain events causing runoff, water may dilute and spread highly concentrated spots of urine, feces, chemical fertilizers, etc. Water runoff, while draining off through the natural slope of pastures and through terrace channels, probably decreases soil fertility levels (means) and variability (CV's) and accumulates an increased amount of water and nutrients in channels than in any other microrelief point of the pastures. Zhang et al. (2006) reported that P losses in runoff water after simulated rain of 75 mm h^{-1} were correlated with soil test P levels. Findings by Edwards et al. (2000) indicate that P runoff was highest with precipitation following a dry period, a similar scenario we observed in the present research.

2.5. Conclusions

Our results indicated that seasonal variation (and associated variation in precipitation) and microrelief exerted large influence on soil test parameters. Therefore, they deserve to be taken into account when designing a sampling methodology for terraced pastures. Based on these findings, we propose that following some basic recommendations could help improve the precision of soil samples in terraced pastures: 1) Allow substantial precipitation between grazing and soil sampling to stabilize soil test levels and reduce variability. 2) Collect soil cores representing all microrelief areas except terrace channels to form a composite sample. If desired, sample terrace channels separately but do not mix these with cores from the rest of the pasture. Terrace channels are comparable to “hot spots” in proximities to areas where livestock gather (watering, loafing, feeding, etc). As for fertilizer management strategies, especially for P and K fertilizers (but not for N), at least two approaches can be used. Given that terrace channels represent a small area of the total (approximately only 9-10 % in our pastures), a practical approach would be to avoid sampling channels and fertilize according to the needs of the rest of the pasture, acknowledging that terrace channels would likely be over-fertilized. An alternative option would be to collect separate soil samples from the channels and from the rest of the pasture and apply two different fertilizer rates: One for channels (in which case may require lower rates or less frequent fertilizer applications), and another rate for the rest of the pastures.

2.6. References

Aarons, S.R., A.R. Melland, and C.J.P. Gourley. 2004. Nutrient distribution within a dairy farm. Supersoil 2004: Proceedings of the 3rd Australian New Zealand Soils Conference, University of Sydney, Australia, 5 – 9 December 2004.

Anderson, D.L., E.A. Hanlon, O.P. Miller, V.R. Hoge, and O.A. Diaz. 1992. Soil sampling and nutrient variability in dairy animal holding areas. Soil Sci. 153:314-321.

Ball, D.F., and W.M. Williams. 1968. Variability of soil chemical properties in two uncultivated brown earths. J. Soil Sci. 19:379-391.

Barrow, N.J. 1967. Some aspects of the effects of grazing on the nutrition of pastures. J. Aust. Inst. Agric. Sci. 33:254-262.

Beckett, P.H.T., and R. Webster. 1971. Soil variability: A review. Soils Fert. 34(1):1-15.

Bogaert, N., J. Salomez, A. Vermoesen, G. Hofman, O. Van Cleemput, and M. Van Meirvenne. 2000. Within-field variability of mineral nitrogen in grassland. Biol. Fertil. Soils 32:186-193.

Bragg, T.B., and L.J. Stephens. 1979. Effects of agricultural terraces on the reestablishment of bluestem grasslands. J. Range Manage. 32:437-441.

Brown, A.J. 1993. A Review of Soil Sampling for Chemical-Analysis. Aust. J. Exp. Agr. 33:983-1006.

Caddel, J.L., D.D. Redfearn, and R.L. Woods. 2005. Sustainable grass-legume pastures for cow-calf herds: a case study. XX International Grassland Congress -- offered papers. p. 788.

Chen, W., W.P. McCaughey, C.A. Grant, and L.D. Bailey. 2001. Pasture type and fertilization effects on soil chemical properties and nutrient redistribution. Can. J. Soil Sci. 81:395-404.

Conyers, M.K., N.C. Uren, K.R. Helyar, G.J. Poile, and B.R. Cullis. 1997. Temporal variation in soil acidity. Aust. J. Soil Res. 35:1115-1129.

Daniels, M.B., P. Delaune, P.A. Moore, A. Mauromoustakos, S.L. Chapman, and J.M. Langston. 2001. Soil phosphorus variability in pastures: Implications for sampling and environmental management strategies. J. Environ. Qual. 30:2157-2165.

Edwards, D.R., T.K. Hutchens, R.W. Rhodes, B.T. Larson, and L. Dunn. 2000. Quality of runoff from plots with simulated grazing. J. Am. Water Res. Assoc. 36:1063-1073.

Fisher, E., B. Thornton, G. Hudson, and A.C. Edwards. 1998. The variability in total and extractable soil phosphorus under a grazed pasture. Plant and Soil 203:249-255.

Franzluebbers, A.J., J.A. Stuedemann, and H.H. Schomberg. 2000. Spatial distribution of soil carbon and nitrogen pools under grazed tall fescue. Soil Sci. Soc. Am. J. 64:635-639.

Friesen, D.K., and G.J. Blair. 1984. A Comparison of soil sampling procedures used to monitor soil fertility in permanent pastures. Aust. J. Soil Res. 22:81-90.

Giltrap, D.J., and A.E. Hewitt. 2004. Spatial variability of soil quality indicators in New Zealand soils and land uses. N. Z. J. Agric. Res. 47:167-177.

Gray, F., and E. Nance. 1978. Modern detailed soil survey: Eastern research station, Haskell. Research report (Oklahoma Agricultural Experiment Station) P-769. Stillwater, OK.

Gupta, R.K., S. Mostaghimi, P.W. McClellan, J.B. Birch, and D.E. Brann. 1999. Modeling spatial variability of soil chemical parameters for site-specific farming using stochastic methods. Water Air Soil Pollut. 110:17-34.

Hegg, R.O., C.L. Barth, V.L. Quisenberry, and W.H. Livingston. 1982. Terraced pasture for disposal of dairy yard runoff. Technical completion report A-

045-SC. Water resources research institute. Clemson University, Clemson, South Carolina.

Hemingway, R.G. 1955. Soil-sampling errors and advisory analyses. J. Agric. Sci. (Cambridge) 46:1-7.

Johnson, G.V., and H. Zhang. 2002. Cause and effects of soil acidity. Cooperative Extension Service F-2239. Oklahoma State University, Stillwater, OK.

LACHAT. 1994. QuickChem method 12-107-04-1-B. LACHAT Instrument, Milwaukee, WI.

Lauber, P. 1958. Dust Bowl: The Story of Man on the Great Plains. East Rutherford, N.J.: Coward, McCann and Geoghegan, Inc., New York, NY.

Liebig, M.A., J. Gross, S.L. Kronberg, J.D. Hanson, A.B. Frank, and R.L. Phillips. 2006. Soil response to long-term grazing in the northern Great Plains of North America. Agric. Ecosyst. Environ. 115:270-276.

López, I.F., M.G. Lambert, A.D. Mackay, and I. Valentine. 2003. The influence of topography and pasture management on soil characteristics and herbage accumulation in hill pasture in the North Island of New Zealand. Plant Soil 255:421-434.

Mason, B.J. 1992. Preparation of soil sampling protocols: Sampling techniques and strategies. USEPA, Office of research and development, Washington, DC.

Mathews, B.W., J.P. Tritschler, J.R. Carpenter, and L.E. Sollenberger. 1999. Soil macronutrient distribution in rotationally stocked kikuyugrass paddocks with short and long grazing periods. Commun. Soil. Sci. Plant Anal. 30:557-571.

Mathews, B.W., L.E. Sollenberger, V.D. Nair, and C.R. Staples. 1994a. Impact of grazing management on soil-nitrogen, phosphorus, potassium, and sulfur distribution. J. Environ. Qual. 23:1006-1013.

Mathews, B.W., L.E. Sollenberger, P. Nkedikizza, L.A. Gaston, and H.D. Hornsby. 1994b. Soil sampling procedures for monitoring potassium distribution in grazed pastures. Agron. J. 86:121-126.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Morton, J.D., D.B. Baird, and M.J. Manning. 2000. A soil sampling protocol to minimize the spatial variability in soil test values in New Zealand hill country. N. Z. J. Agric. Res. 43:367-375.

National Cooperative Soil Survey. 2006. Choteau series. Available on-line at: http://www2.ftw.nrcs.usda.gov/osd/dat/C/CHOTEAU.html.

Pote, D.H., T.C. Daniel, D.J. Nichols, P.A. Moore, D.M. Miller, and D.R. Edwards. 1999. Seasonal and soil-drying effects on runoff phosphorus relationships to soil phosphorus. Soil Sci. Soc. Am. J. 63:1006-1012.

Redfearn, D.D., J.L. Caddel, and R.L. Woods, Jr. 2006. Sustainable grass-legume pastures for cow-calf herds. American Forage & Grassland Council Abstracts.

Saggar, S., A.D. Mackay, M.J. Hedley, M.G. Lambert, and D.A. Clark. 1990. A nutrient-transfer model to explain the fate of phosphorus and sulfur in a grazed hill-country pasture. Agric. Ecosyst. Environ. 30:295-315.

Sauer, T.J., and D.W. Meek. 2003. Spatial variation of plant-available phosphorus in pastures with contrasting management. Soil Sci. Soc. Am. J. 67:826-836.

SAS Institute, Inc. 2003. SAS version 9.1. Cary, NC.

Sigua, G.C., M.J. Williams, and S.W. Coleman. 2004. Levels and changes of soil phosphorus in subtropical beef cattle pastures. Commun. Soil. Sci. Plant Anal. 35:975-990.

Sims, J.T. 1996. Lime requirement, pp. 491-515. In D.L. Sparks, ed. Methods of Soil Analysis, Part 3. Chemical Methods. SSSA and ASA, Madison, WI.

Tarr, A. B., K. J. Moore, P. M. Dickson, C. L. Burras, and M. H. Wiedenhoeft. 2003. Use of soil electroconductivity in a multistage soil-sampling scheme [Online]. Available at http://www.plantmanagementnetwork.org/cm/. Crop Manage. doi:10.1094/cm-2003-1029-01-RS.

Townsend, M., R. Long, G.F. Scott, and R. R. Gilbertson. 1987. Soil survey of Muskogee County Oklahoma. USDA Soil Conservation Service and Forest Service in cooperation with Oklahoma Agricultural Experiment Station and Oklahoma Conservation Commission.

Walter, C., R.A.V. Rossel, and A.B. McBratney. 2003. Spatio-temporal simulation of the field-scale evolution of organic carbon over the landscape. Soil Sci. Soc. Am. J. 67:1477-1486.

West, C.P., A.P. Mallarino, W.F. Wedin, and D.B. Marx. 1989. Spatial variability of soil chemical-properties in grazed pastures. Soil Sci. Soc. Am. J. 53:784-789.

Zhang, H., J.L. Schroder, R.L. Davis, J.J. Wang, M.E. Payton, W.E. Thomason, Y. Tang, and W.R. Raun. 2006. Phosphorus loss in runoff from long-term continuous wheat fertility trials. Soil Sci. Soc. Am. J. 70:163-171.

Table 2-1. Variance components affecting soil fertility parameters in terraced pastures of the Eastern Research Station, near Haskell, OK.

Sources of variation	pH $\hat{\sigma}^2$	pH %†	N $\hat{\sigma}^2$	N %	P $\hat{\sigma}^2$	P %	K $\hat{\sigma}^2$	K %
				By-strips sampling method				
Year (Y)	0.017	42	12	6	120	11	1657	21
Season within year (S)	0.004	9	0	0	340	32	2344	30
Pasture (P)	0.000	0	131	61	72	7	119	2
Y × P	0.006	14	29	13	6	1	129	2
Y × Fertilizer (F)	0.001	2	10	5	188	18	1453	19
S × F	0.000	0	3	1	109	10	0	0
Residual	0.013	33	29	14	237	21	2087	26
Total	0.040	100	214	100	1072	100	7789	100
				By-microrelief sampling method				
Year (Y)	0.024	41	0	0	0	0	0	0
Season within year (S)	0.007	12	146	70	252	37	2518	36
Pasture (P)	0.007	12	3	2	121	18	0	0
Y × P	0.000	0	23	11	0	0	0	0
Y × Microrelief (M)	0.000	0	0	0	51	8	284	4
S × M	0.000	0	0	0	0	0	0	0
Residual	0.021	35	35	17	251	37	4267	60
Total	0.059	100	208	100	674	100	7069	100

† Percent of the total variance.

Table 2-2. Means comparisons and coefficients of variation (CV) among fertilizers using the by-strips sampling method and among microreliefs using the by-microrelief sampling method in terraced pastures of the Eastern Research Station, near Haskell, OK.

	Mean†				CV			
Treatment	pH	N	P	K	pH	N	P	K
		kg ha^{-1}			%			
			By-strips					
Fertilizers								
Control	5.8 a	14	50 b	314 bc	2	39	31	15
P_2O_5	5.8 a	15	104 a	282 c	2	37	15	16
K_2O	5.8 a	14	53 b	445 a	2	38	29	10
N	5.6 b	22	47 b	286 c	2	24	33	16
NPK	5.8 a	21	98 a	364 b	2	26	16	13
Mean	5.8	17	70	338	2	33	25	14
LSD	0.1	7.4	31.1	77.9				
			By-microrelief					
Microreliefs								
Top terrace (a)	5.7 b	20 ab	67 b	264 c	3	29	24	25
Top terrace (b)	5.8 a	21 ab	72 b	282 bc	3	28	22	23
Backslope (c)	5.7 b	19 b	73 b	312 bc	3	32	22	21
Channel (d)	5.6 c	24 a	107 a	552 a	3	25	15	12
Flat slope (e)	5.8 a	18 b	67 b	352 b	3	34	24	19
Mean	5.7	20	77	352	3	30	21	20
LSD	0.1	4.2	25.2	79.5				

† Means followed by the same letter within a column are not significantly different at P = 0.05.

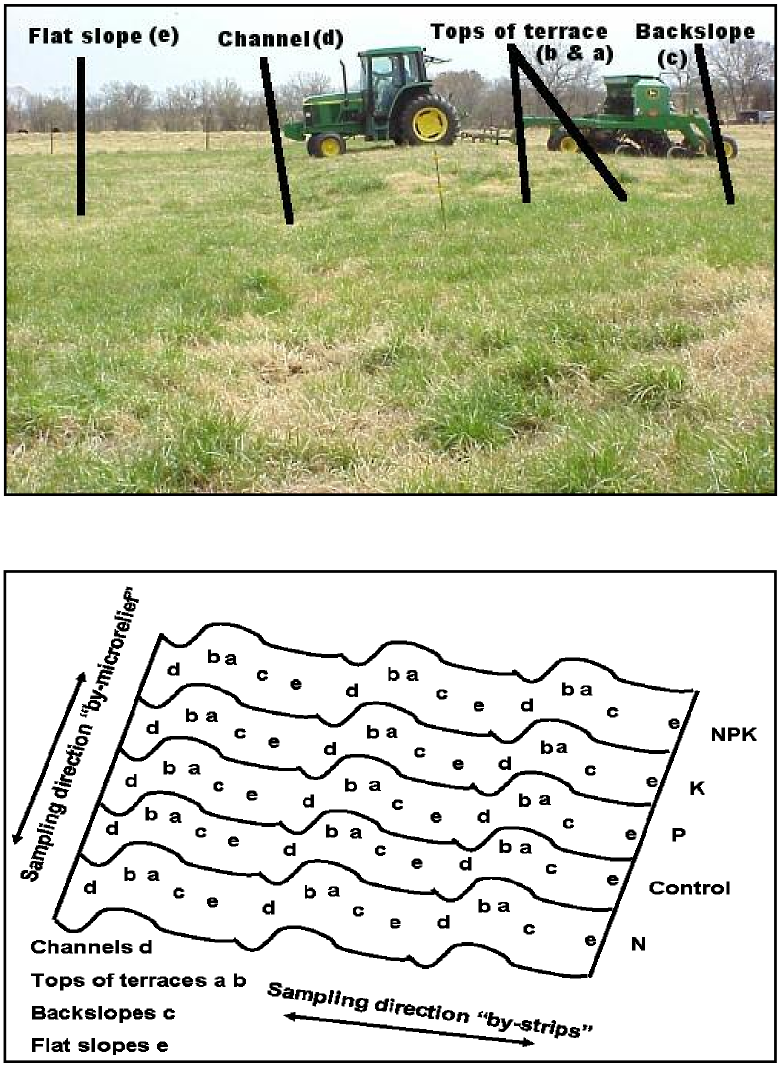

Figure 2-1. Microrelief points of a typical pasture (top), and patterns of soil cores collection with two methods (bottom) in terraced pastures of the Eastern Research Station, near Haskell, OK. Employed sampling methods were by-strips and by-microreliefs.

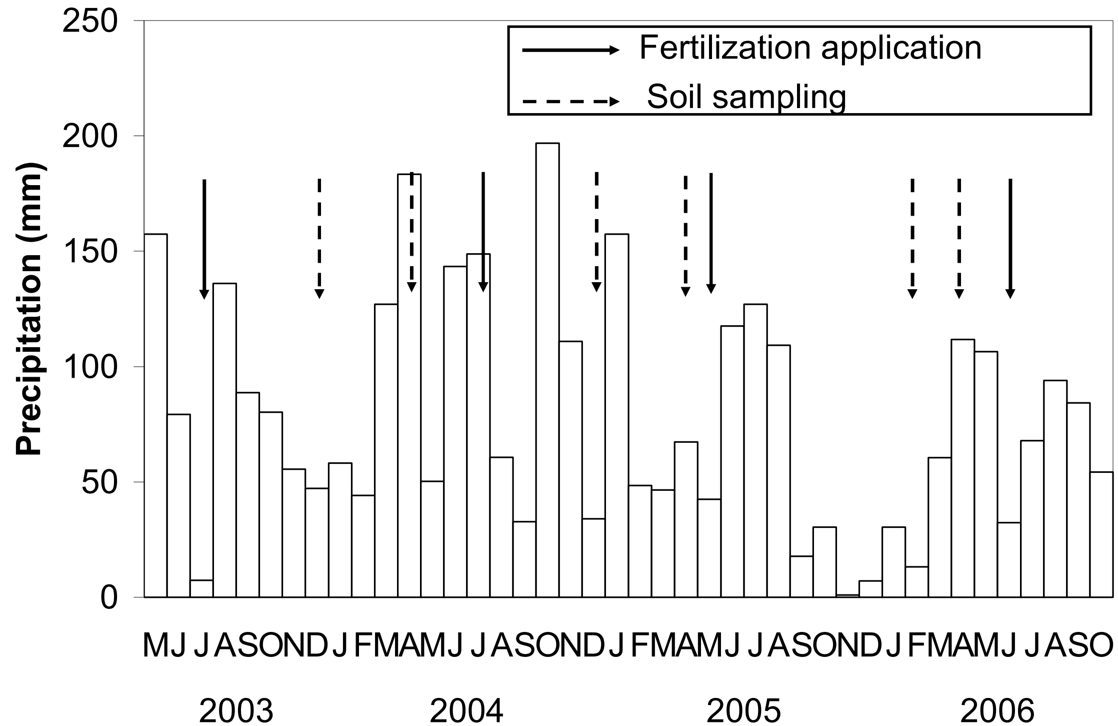

Figure 2-2. Monthly precipitation distribution, time of soil sampling and fertilizer applications during study on terraced pastures of the Eastern Research Station, near Haskell, OK.

CHAPTER 3

3. Forage Production and Variability in Terraced Pastures

3.1. Abstract

Sound knowledge about forage production on pastures is important for making decisions that positively impact the forage-livestock enterprise. In highly variable pastures, development of this information is difficult because forage yields are typically highly variable in space and time. This study was conducted to a) identify the factors that most influence forage variability and the role of seasons, fertilizers and microrelief on forage production and b) to describe the differences and to determine the effects of variable top soil depth caused by terraces on sloped, terraced pastures of eastern Oklahoma. Forage yield means and associated coefficients of variation (CV) were used to examine the effects of seasons, fertilizers, and microrelief points (created by terraces) during three years replicated over four pastures. Because of inequality of variances from year to year and within years, years were analyzed independently and individual error terms by season were used to test seasons, fertilizers, and microreliefs. These temporal differences were closely associated with precipitation and largely determined forage productivity. In general, as forage yield increased, variability decreased, but remained low and relatively constant when forage yields were about 3.0 Mg ha^{-1} per season or greater. Nitrogen fertilizer increased forage production and decreased CV's, but it depended on precipitation to be effective.

Relatively flat areas between terraces produced lower forage yields than terraces. This was likely due to differences in water holding capacities among microreliefs. Variability of precipitation over time along with microrelief (terraces and flats) appeared to be responsible for high temporal and spatial variability of forage production. Based on our results, other than nitrogen application, little or nothing can practically be done to reduce forage variability and increase forage yields in these pastures.

3.2. Introduction

In depth knowledge of factors that affect forage production and the variability associated with it, is essential for an effective pasture management. Acquiring this type of knowledge, however, is complicated because pastures are complex systems that can vary over time and space. For instance, an accurate estimation of annual and seasonal forage budget are important to adjust animal numbers to be maintained in a pasture. Fertilizer needs are often based on yield goals, but neither of these two problems can be resolved if forage yields are unknown because of high variability. A mean calculated from highly variable data is of little or no use and can lead pasture managers to make decisions that may have a negative impact on the sustainability of the enterprise (Belesky et al., 2002).

Among factors that have been documented to influence forage variability have been weather, soil fertility, topography, stocking rate, and grazing management. Often, two or more of these factors have been found to interact in determining production levels and variability. Woodward et al. (2001) and Durand et al. (1997) indicated that soil water content was the most limiting factor in pastures of New Zealand and France, respectively. Wallach (1975) analyzed the effects of soil moisture and temperature on growth of pastures and reported that only soil moisture was a reliable predictor of forage production in pastures of Israel. Smith and Stephens (1976) reported a range of forage production between extremes of 5,000 and 14,000 kg ha^{-1} in different years in Australia. They found soil moisture responsible for limiting production during the cool season, but temperature was responsible during the warm season. Birrell and Tompson (2006) reported that daylength, soil temperature, and soil moisture, explained three quarters of the variation of growth rate of forage in Australia.

Nitrogen (N) and available soil moisture were reported to affect production and botanical composition of forage of several cool-season grass monocultures and in mixtures with legumes in Australia (Lazenby and Lovett, 1975). Gonzalez-Dugo et al. (2005) found N nutrition and soil moisture to affect growth of tall fescue [*Festuca arundinacea* Schreb. = *Lolium arundinaceum* (Schreb.) S.J. Darbyshire] and annual ryegrass (*L. multiflorum* Lam.) in research conducted in France.

López et al. (2003) evaluated the effects of long term pasture management (N fertilizer applications and stocking rates) and topography over forage production in hill pastures in New Zealand. They found that position within slope had a greater influence on forage production than management practices. Belesky et al. (2002) studied the effects of site and defoliation management on forage production and composition in hill pastures in West Virginia. They found that aspect influenced forage production while clipping had a mixed influence. In Iowa, USA, Harmoney et al. (2001) and Guretzky et al. (2004) studied the influence of landscape position and stocking methods on forage distribution. They found that the interaction of landscape position × stocking method was significant in pasture management.

Easton et al. (1994) indicated that tall fescue yield in New Zealand depended on interactions among site, season, and management, while persistence depended on soil fertility and grazing management. In Australia, however, soil moisture was the most determinant factor. Johnston (1996), recognizing differences among and within species, identified environmental conditions and management practices favoring cool-season and warm-season forage grasses in New Zealand. He concluded that cool-season species required well-watered and cool conditions, while warm-season species were more competitive under high temperatures and solar radiation. Furthermore, within the warm-season category, certain groups responded differently to soil moisture status, N-fertilization, and grazing pressures.

During 1930's, in response to an ecological disaster consisting in the loss of millions of tons of top soil through wind and water erosion, an extensive federal program was put in place to conserve and reclaim soil. This disaster was caused by a combination of drought and unsound agricultural practices (cultivated and overgrazed soil left unprotected). Among the states that were most damaged were those of the region collectively known as the "Dust bowl", namely, Kansas, Oklahoma, Texas, New Mexico, and Colorado (Lauber, 1958).

The strategy of the Soil Conservation Service (SCS) to protect and restore soil focused on breaking the force of wind and saving soil moisture. Among the most popular practices promoted by the SCS were contour plowing, terracing and listing, and strip farming (Lauber, 1958). As part of this national conservation effort, much of the formerly cropped land across the USA was reverted to pastures. The terraces that were built to conserve soil and water remain until the present as part of the landscape of many pasture lands.

Despite the existence of terraced pastures in several regions within the "Dust bowl" region and the rest of the USA, little research has been conducted on terraced pastures and the variables that may be important in understanding forage production. Carberry (1934) reported a decrease of wheat yield on ridges of terraces under low precipitation conditions, compared to undisturbed soil, but yield increased when adequate precipitation occurred. This early study (Carberry, 1934) had the merit of noticing variable agronomic responses caused by terraces and associated water holding capacity. This study was conducted to a) identify the factors that most influence forge variability and the role of seasons, fertilizers and microrelief on forage production and b) to describe the differences and to determine the effects of variable top soil depth caused by terraces on sloped and terraced pastures of eastern Oklahoma.

3.3. Materials and Methods

3.3.1. Experimental site

This research was conducted at the Eastern Research Station located near Haskell, OK., with coordinates of 35° 44' north latitude and 95° 38' west longitude. The station consists of 120 ha and is located in the Cherokee Prairie Resource Area, which represents approximately 2.6 million hectares of eastern Oklahoma pasture land. Elevation of the station is about 180 m with a mean historic annual precipitation averaging 1040 mm with about 60% of this precipitation usually occurring from April through September. In the winter, the mean minimum temperature is 0° C, and in the summer the mean maximum temperature is 33° C (Townsend et al., 1987). Precipitation that occurred during this study is illustrated (Figure 3-1).

An area of 53 ha of the research station was designated for cattle grazing that had been managed as four pastures from 1978 to 1988. In 1989 a grazing demonstration was initiated using several pastures and some of the cow herd at the Eastern Research Station. For other activities, three of the four pastures were divided into two smaller pastures resulting in a total of seven pastures. From these seven pastures, four were used to conduct the present study. Although many species of forage grasses have been planted through the years in the different pastures on the station, the predominant forage grasses included tall fescue and bermudagrass (*Cynodon dactylon* L.). Forage legumes (*Trifolium repens* L., *T. pratense* L., *T. vesiculosum* Savi, and *Medicago sativa* L., etc.), annual cool-season grasses (*Bromus* spp.) and warm-season grasses (*Digitaria* spp.) were also present in small quantity. More detailed descriptions of these pastures were provided by Caddel et al. (2005) and Redfearn et al. (2006).

One site (block) of 30 × 122 m was identified within each of the four different pastures. The sites were sloped (ranging from 1.5 to 3.7%) and were located at a similar elevation gradient. Each site was relatively long and parallel with the natural slope of the land and perpendicular to water retention terraces. Records at the station indicate that these terraces were present at least 60 years ago. The four sites consisted of different soil series. Site 1 included Choteau (Fine, mixed, active, thermic Aquic Paleudolls) and Parsons (Fine, mixed, active, thermic Mollic Albaqualfs), sites 2 and 3 included only Choteau, and site 4 consisted of Dennis (Fine, mixed, active, thermic Aquic Argiudolls) and Choteau (Gray and Nance, 1978). These soils although were somewhat different from each other, shared some common characteristics (low permeability, for example) because they are geographically associated (or competing) soils (National Cooperative Soil Survey. 2006).

3.3.2. Treatments and data collection procedures

During three consecutive summers, five fertilizer treatments were applied in strips of 3.5 m wide across five microreliefs in each of the four sites, one site per pasture. From now on in this manuscript, we refer to “sampling sites” as “pastures”. Years were counted from August 1 to July 31 of the next year; therefore, years crossed parts of two calendar years: 2003-2004, 2004-2005, and 2005-2006. Seasons were defined according to the season when the forage grew, independently of the date of harvest. All seasons included four harvests (one for each pasture) and were somewhat variable in their calendar dates of initiation and termination, depending on changing growing conditions from year to year and when the pasture was scheduled to be utilized. The “fall season” included the forage grown after September 1 and before the termination of the growing season, during late fall to early winter. The “spring season” included the first forage grown after winter, and the “summer season” included the forage that grew after the first grazing rotation and before August 31 each year.

Fertilizer treatments consisted of the application of N (150 kg ha^{-1} N), P (150 kg ha^{-1} P_2O_5), K (200 kg ha^{-1} K_2O), NPK (150, 150, and 200 kg ha^{-1} N, P_2O_5, and K_2O, respectively), and a control; lime was applied to the NPK treatment only in the first year at a rate of 670 kg ha^{-1} ECCE. Every fertilizer strip crossed three terraces and each terrace consisted of five microrelief points. Five plots (1 × 5 m) in each strip were harvested to estimate forage yield. The five plots were fixed and included the following microreliefs: a) top of terraces opposing the channels, b) top of terraces on channel side, c) the backslope of terraces, d) the terrace channels, and e) the nearly flat area between terraces of presumably undisturbed soil. The five microrelief points crossed all five fertilizer strips perpendicularly and resulted in 25 plots per pasture.

Each pasture was grazed three times per year: spring, summer, and fall (as previously defined). The length of the grazing period was variable, depending on forage availability. Forage samples were obtained with a flail harvester just before cattle had access to the pastures. Although at the beginning of the research, during the fall of 2003-2004, the targeted stubble height was of 5 cm, it was changed to 10 cm beginning in the spring of 2003-2004 for the duration of the study. Fresh forage was weighed in the field and, except for a subsample of approximately 0.5 kg, forage was dropped back and scattered over the plots from where it had been harvested to avoid creating differences in nutrient removal in plots. The 0.5 kg samples were dried until reaching constant weight and dry weight recorded for dry matter calculations.

Soil cores of 4.5 cm of diameter by 120 cm of length were collected from two terraces at each pasture from the channels (d); the ridges of the terraces (representing top of terrace “a” and top of terrace “b”); the backslopes of terraces (c); and from the relatively flat areas between two terraces (e). Samples were collected from just outside the fertilized areas in each of the four pastures. The depth of top soil (A horizon), an intermediate layer between top soil and subsoil (Bt horizon), and subsoil (B horizon) was measured. Also, a subsample from the midpoint of both A and the Bt horizons was collected for soil texture analisis. The criteria used to separate these horizons were based on color and tactile and visual soil structure.

3.3.3. Treatment and design structures and statistical analysis

For forage yield, years were analyzed independently because inequality of variances. Treatment structure was a five × five × three factorial, fertilizers, microreliefs, and seasons, respectively (as formerly described). The design structure was a split block design replicated four times (pastures) per year. Repeated measures (three seasons per year) were used because fertilizer treatment applications were applied only in early summer. Homogeneity of variances among seasons was achieved by using the square root of original values of forage yield analyses. A mixed model analysis was performed (PROC

MIXED, SAS Institute, 2003). Fisher's protected LSD procedure ($P < 0.05$) was used to compare treatment means when appropriate.

Coefficients of variation (CV's) were used to measure variability of forage yields. Coefficients of variation were calculated by dividing the standard deviation (× 100) by the least square means of each level of fertilizer treatments. Standard deviations were calculated by obtaining the square root of the REML residual variance component estimates associated with the pasture × fertilizer × microrelief interaction for each of the three seasons and years. Similar calculations were done for each season and microrelief. Top soil depth was analyzed as a randomized complete block design with four replications (pastures) and two subsamples per microrelief (one soil core from each of two terraces). Factor microreliefs was the only fixed factor.

3.4. Results and Discussion

3.4.1. Forage yield

Cumulative forage yields of fertilizer and microrelief treatments summed across years and seasons provide a general indication of the forage yields produced during this research and of the effect of fertilizers and microreliefs (Table 3-1). The fertilizer × microrelief interaction was not significant ($P = 0.998$), but both the main effect of fertilizers and microrelief affected yield ($P < 0.001$). Nitrogen fertilizers (N and NPK) increased yield approximately 1.7 times more than fertilizers without N (K_2O, P_2O_5, and the control). The group of non N fertilizers, including the control, performed similarly, indicating no yield response from these fertilizers. This lack of response occurred because soil test P and K on those sites were at or above 100% sufficiency (Zhang et al. 1998), Tops of terraces on channel side (b) yielded approximately 20% more than tops of terraces opposing channels (a) and backslopes (c). Terrace channels (d) yielded intermediate between these two groups. The lowest yielding microrelief was the relatively flat intervals between terraces (e) with about 40% less than the mean of the microrelief points located on terraces (Table 3-1).

An overall ANOVA (the three years together) indicated that variance within years was unequal, leading to analyses of each year separately. Analyses of individual years revealed the highly significant effect of seasons (Table 3-2) and ratified the role of fertilizers and microreliefs observed on the cumulative analysis. Seasons interacted with microreliefs in 2003-2004, with fertilizers in 2004-2005, and during the last year, with both fertilizers and microreliefs. The three-way interaction was not significant in any case ($P > 0.05$).

The effectiveness of N fertilizers to promote forage yield, compared with non N fertilizers changed with seasons (Table 3-3). This was expected because fertilizer applications occurred every year during early summer and N was apparently used by the forage soon after fertilizer applications if moisture was available. Significant interactions occurred between seasons and microreliefs (Table 3-3) because flats (e) produced less than the rest of the microreliefs in the summer of 2003-2004, despite high precipitation and high available N. However, in the summer of 2005-2006 with dry conditions, flats (e) produced similarly low to the rest of the microreliefs. This may indicate that terraces cannot use their advantage to capture and retain water when precipitation is missing, thus, the disadvantage of flats (e) is not as important under water-limiting circumstances. Terraced areas in these pastures comprised about 40% of the total area of the pastures, while flat areas represented the remaining 60%.

3.4.2. Forage yield variability

The random variance from season to season within individual years was generally large. Random variances by season differed by more than seven times between the largest and the smallest in 2003-2004, less than two (fairly homogeneous) in 2004-2005, and as much as 277 times in 2005-2006, respectively (data not shown). Pastures were used as replications and the error term (residual) included variance due to pastures and interactions with pastures. Cumulative forage yield in the four pastures were 23.8, 25.7, 18.0, and 19.7 Mg ha^{-1} and variance due to pastures was relatively small compared to the fixed factors (fertilizers, microreliefs, seasons, and their interactions) as evidenced by the large F values in Table 3-2.

Since the groups of N fertilizers and non N fertilizers performed distinctively from each other, and that individual treatments performed similarly within each of these groups, a mean of the two N fertilizers (N and NPK) and a mean of the three non N fertilizers (Control, P_2O_5, and K_2O) were represented (Figure 3-2). Similarly, a comparable performance was observed on yields from microreliefs tops of terraces on channel sides (b) and terrace channels (d), and from microreliefs tops of terraces opposing terrace channels (a) and backslopes (c). Thus, only the means of both tops of terraces on channel sides (b) and channels (d), of both tops of terraces opposing channels (a) and backslopes (c), and of flats (e) were represented (Figure 3-3).

In 2003-2004 although CV's remained relatively constant within seasons, variability tended to decrease slightly as yields increased (Figures 3-2 and 3-3). Fall season had larger variability even though yields were apparently similar to those of the summer. This might be explained since the targeted stubble height was increased from 5 to 10 cm at the end of the fall, thus yields would have been lower in the fall than in the summer if clipped to the same height. Spring had lower yields and slightly smaller variability compared to the fall and summer. Nitrogen fertilizers (N or NPK) increased yields and decreased variability in all three seasons. Tops of terraces on channel sides (b) and channels (d) had the highest yields and lowest variability, but the seasonal trends remained similar as observed with fertilizers.

In 2004-2005 the highest yields and lowest variability was observed in the summer. In this season, N fertilizers had clearly greater yield levels but variability was similar to that of non N fertilizer treatments. Across seasons, although flat intervals (e) yielded statistically less than any microrelief, the variability of this microrelief in the summer was similar to the rest of the microreliefs. In 2005-2006 only the fall season produced enough forage to observe some effect of treatments due to drought. In this season, yields were low and CV's never dropped below 20%. In the summer little forage was produced, and variability was uniformly low.

In general, as yields increased, variability (CV's) decreased with the exception of the summer of 2005-2006, in which no effect of fertilizers or microrelief was apparent. It was observed that variability decreased and started stabilizing as yields reached about 3.0 Mg ha^{-1} season^{-1} (Figures 3-2 and 3-3). In this research, variability tended to be lower in the summer in the first two years likely due to the simultaneous occurrence of both N and precipitation. Both precipitation and N contributed to decrease variability while increasing yields.

Forage yields were primarily determined by precipitation and secondarily by N supply. The lack of response of forage yields to non N fertilizer treatments (K_2O, P_2O_5, and the control) is explained by the fact that P and K levels in the pastures were already at or above 100% sufficiency levels, as reported by Santillano-Cázares et al. (in review). Relatively flat areas (e) produced lower yields than microreliefs in terraces (a, b, c, or d). Tops of terraces on channel side (b) and channels (d) were likely the highest because channels received water and water dissolved nutrients from higher elevation points. Santillano-Cázares et al. (in review) proposed that this mechanism was responsible for high concentrations of P and K in terrace channels (d). Tops of terraces on channel sides (b) and terrace channels (d) often overlapped because of the relatively large size of the plots in relation to the size of the terraces. Flat intervals (e) produced the lowest yields because of their disadvantaged position influencing water-holding capacity.

3.4.3. Top soil depth

Depths of top soil (horizon A) by pasture and by microrelief (Table 3-4) were significant different among microreliefs ($P < 0.001$). Flat intervals (e), terrace channels (d), and backslopes (c) had similar top soil depths, about 43 cm (27 to 65 cm). Terrace tops (“a” and “b”) had the deepest top soil of all microreliefs with a mean of 86 cm (64 to 111 cm). These findings indicate that terraces were built with fertile top soil, coinciding with findings by Carberry (1934). The top soil comprised a relatively dark soil that crumbled easily into small aggregates from the soil surface down to the top of the Bt horizon. The Bt layer included a distinctively lighter color horizon than the top soil and was clearly plastic when humid and virtually unbreakable once dry.

The existence of this distinctive horizon (called “natric horizon” by Gray and Nance, 1978) in Choteau soils is accountable for the saturation of the top 60-90 cm (perched water table) during the winter and spring seasons (Townsend et al., 1987; National Cooperative Soil Survey, 2006). The subsoil included the remainder of the core which was slightly lighter than Bt and included various colors mottles. This section of the core crumbled into blocks relatively easy when dry and intermediately plastic when wet. Soil cores provided valuable information in that they confirmed the existence of a low permeable horizon approximately 40 cm underneath the top soil (Bt horizon).

Horizon Bt developed over time as downwards translocation of clay from the top soil in percolating water (Foth, 1990). The most dominant textural class in the top soil was silt loam, while in the Bt horizon (impermeable layer) was clay loam. Silt loam soil can hold approximately 30-45 mm of water per 30 cm of soil depth and clay loam 30-50 mm (California Fertilizer Association, 1995). With this water holding capacity, it would take roughly 100 mm of precipitation to saturate 60 cm of the soil profile. That soil depth would include all top soil (except in tops of terraces) plus 20 cm of this impermeable layer. Under these circumstances, any additional precipitation would likely move across the surface toward lower elevation points as runoff. This mechanism might be accountable for making slope of pastures a sizable difference in water holing capacity and forage productivity, even when dealing with 2% differences in slope that were encountered in this study.

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3.5. Conclusions

Our findings point out that variability of precipitation is responsible for highly variable forage production levels. Microreliefs (terraces and flat areas) represent an additional source for differences on soil water holding capacity and forage production variability. As forage yields increase above a minimum level of production, variability tended to stabilize. Nitrogen fertilizers can reduce variability though increasing forage production but it requires precipitation to be effective. Terraces demonstrated to have greater yield potential than relatively flat intervals because of higher water holding capacity due to a greater amount of soil that was used to build these terraces. Flat areas comprising 60% of the total area of the pastures did not seem to respond to the application of N fertilizers and further research is required to investigate the best way to manage flat areas efficiently. Maybe, slow release, more stable fertilizers, like poultry, could increase the productivity and decrease total variability. However, other than nitrogen application, little or nothing can practically be done to reduce forage variability and increase forage yields in these pastures.

3.6. References

Belesky, D.P., C.M. Feldhake, and D.G. Boyer. 2002. Herbage productivity and botanical composition of hill pasture as a function of clipping and site features. Agron. J. 94:351-358.

Birrell, H.A., and R.L. Thompson. 2006. Effect of environmental factors on the growth of grazed pasture in south-western Victoria. Aust. J. Exp. Agric. 46:545-554.

Caddel, J.L., D.D. Redfearn, and R.L. Woods. 2005. Sustainable grass-legume pastures for cow-calf herds: a case study. XX International Grassland Congress -- offered papers. p. 788.

California Fertilizer Association. 1995. Western Fertilizer Handbook. 8th edition. Interstate Publishers, Inc., Danville, IL.

Carberry, C. R. 1934. The immediate effect of terraces on the yield and quality of winter wheat. Master Sci. thesis. Oklahoma State University, Stillwater OK.

Durand, J.L., F. Gastal, S. Etchebest, A.C. Bonnet, and M. Ghesquiere. 1997. Interspecific variability of plant water status and leaf morphogenesis in temperate forage grasses under summer water deficit. European J. Agron. 7:99-107.

Easton, H.S., C.K. Lee, and R.D. Fitzgerald. 1994. Tall fescue in Australia and New-Zealand. N. Z. J. Agric. Res. 37:405-417.

Foth, H.D. 1990. Soil physical properties. P. 22-41. *In* Fundamentals of soil science, 8th edition. John Wiley & Sons. New York, NY.

Gonzalez-Dugo, V., J.L. Durand, F. Gastal, and C. Picon-Cochard. 2005. Short-term response of the nitrogen nutrition status of tall fescue and Italian ryegrass swards under water deficit. Aust. J. Agric. Res. 56:1269-1276.

Gray, F., and E. Nance. 1978. Modern detailed soil survey: Eastern research station, Haskell. Research report (Oklahoma Agricultural Experiment Station) P-769. Stillwater, OK.

Guretzky, J.A., K.J. Moore, C.L. Burras, and E.C. Brummer. 2004. Distribution of legumes along gradients of slope and soil electrical conductivity in pastures. Agron. J. 96:547-555.

Harmoney, K.R., K.J. Moore, E.C. Brummer, C.L. Burras, and J.R. George. 2001. Spatial legume composition and diversity across seeded landscapes. Agron. J. 93:992-1000.

Johnston, W.H. 1996. The place of C-4 grasses in temperate pastures in Australia. N. Z. J. Agric. Res. 39:527-540.

Lauber, P. 1958. Dust Bowl: The Story of Man on the Great Plains. East Rutherford, N.J.: Coward, McCann and Geoghegan, Inc., New York, NY.

Lazenby, A., and J.V. Lovett. 1975. Growth of pasture species on northern tablelands of New-South-Wales. Aust. J. Agric. Res. 26:269-280.

López, I.F., M.G. Lambert, A.D. Mackay, and I. Valentine. 2003. The influence of topography and pasture management on soil characteristics and herbage accumulation in hill pasture in the North Island of New Zealand. Plant and Soil 255:421-434.

National Cooperative Soil Survey. 2006. Choteau series. Available on-line at: http://www2.ftw.nrcs.usda.gov/osd/dat/C/CHOTEAU.html.

Redfearn, D.D., J.L. Caddel, and R.L. Woods, Jr. 2006. Sustainable grass-legume pastures for cow-calf herds. American Forage & Grassland Council Abstracts.

Santillano-Cázares, J., H. Zhang, J.L. Caddel, D.D. Redfearn, and C.L. Goad. Spatial and temporal variability of soil fertility in terraced pastures. Soil Sci. Soc. Am. J. (in review).

SAS Institute, Inc. 2003. SAS version 9.1. Cary, NC.

Smith, R.C.G., and M.J. Stephens. 1976. Importance of soil-moisture and temperature on growth of improved pasture on northern tablelands of New-South-Wales. Aust. J. Agric. Res. 27:63-70.

Townsend, M., R. Long, G.F. Scott, and R. R. Gilbertson. 1987. Soil survey of Muskogee County Oklahoma. USDA Soil Conservation Service and Forest Service in cooperation with Oklahoma Agricultural Experiment Station and Oklahoma Conservation Commission.

Wallach, D. 1975. Effect of environmental factors on growth of a natural pasture. Agric. Meteorol. 15:231-244.

Woodward, S.J.R., D.J. Barker, and R.F. Zyskowski. 2001. A practical model for predicting soil water deficit in New Zealand pastures. N. Z. J. Agric. Res. 44:91-109.

Zhang H., B. Raun, J. Hattey, G. Johnson, and N. Basta. 1998. OSU Soil test interpretations. Fact sheet F-2225. Cooperative Extension Service, Oklahoma State University, Stillwater Oklahoma.

Table 3-1. Cumulative forage yield of fertilizer and microrelief treatments across three years and three seasons in pastures of the Eastern Research Station, near Haskell, OK.

Treatment	Top terrace (a)	Top terrace (b)	Backslope (c)	Channel (d)	Flat (e)	Mean†
			$Mg\ ha^{-1}$			
Control	19.2	20.9	16.0	19.4	10.7	17.2 b
P_2O_5	16.3	18.3	16.5	19.3	9.7	16.0 b
K_2O	17.9	23.2	17.7	20.0	9.0	17.6 b
N	28.1	32.8	28.0	31.5	21.0	28.3 a
NPK	29.1	36.9	28.9	32.8	21.5	29.9 a
Mean‡	22.1 b	26.4 a	21.5 b	24.6 ab	14.4 c	

LSD = 2.93.

† Means followed by the same letter within the column are not significantly different at *P* = 0.05.

‡ Means followed by the same letter within the row are not significantly different at *P* = 0.05.

Table 3-2. ANOVA's of three years of the effect of seasons, fertilizers and microreliefs on forage yields in pastures of the Eastern Research Station, near Haskell, OK.

	2003-2004		2004-2005		2005-2006	
Source of Variation	F. Value	*P*	F. Value	*P*	F. Value	*P*
Fertilizers (F)	21.2	***	22.4	***	7.0	***
Microrelief (M)	7.6	***	6.3	**	10.1	***
F × M	0.4	NS	0.6	NS	0.2	NS
Season (S)	39.8	***	1376.0	***	118.7	***
S × F	0.6	NS	14.7	***	2.7	**
S × M	5.7	***	1.7	NS	4.4	***
S × F × M	0.3	NS	0.7	NS	0.5	NS

** and ***, significantly different at *P* level = 0.01 and 0.001, respectively. NS, non significant at least at *P* = 0.05.

Table 3-3. Effect of seasons × microreliefs and season × fertilizers interactions on means of forage yields by year and season in pastures of the Eastern Research Station, near Haskell, OK.

	Yield								
	2003-2004			2004-2005			2005-2006		
Treatment	Fall	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer
	Mg ha^{-1}†								
Fertilizers									
Control	3.77	2.22	3.25	0.87 b	0.51 b	3.71 b	1.15 b	0.15 b	0.19 b
P_2O_5	3.44	2.27	2.88	0.63 b	0.50 b	3.54 b	1.19 b	0.15 b	0.18 b
K_2O	3.83	2.21	3.30	0.99 ab	0.45 b	4.04 b	1.13 b	0.15 b	0.20 ab
N	5.57	4.03	5.67	1.29 a	0.74 ab	7.22 a	2.14 a	0.19 ab	0.21 ab
NPK	5.43	4.00	5.86	1.32 a	0.79 a	7.67 a	2.66 a	0.27 a	0.23 a
Mean	4.41	2.94	4.19	1.02	0.60	5.24	1.65	0.18	0.20
Microreliefs									
Top terrace (a)	4.89 a	3.59 a	3.82 b	0.87	0.71	5.10	1.42 b	0.17 ab	0.19 ab
Top terrace (b)	5.09 a	2.84 b	5.74 a	1.52	0.69	6.09	2.64 a	0.27 a	0.21 ab
Backslope (c)	4.13 ab	2.90 ab	4.12 b	1.13	0.69	5.32	1.49 b	0.15 b	0.20 ab
Channel (d)	4.74 ab	2.97 ab	4.94 ab	1.24	0.72	5.84	2.08 ab	0.23 ab	0.23 a
Flat (e)	3.19 b	2.42 b	2.33 c	0.35	0.20	3.84	0.64 c	0.10 b	0.18 b
Mean	4.41	2.94	4.19	1.02	0.60	5.24	1.65	0.18	0.20

†Columns within each year followed by the same letter are not significantly different at *P* = 0.05.

Table 3-4. Top soil depth by pastures and microreliefs in pastures of the Eastern Research Station, near Haskell, OK.

Pasture	Microrelief	n	Mean Top soil
			—— cm ——
1	Top (a and b)	2	94
2	Top (a and b)	2	111
3	Top (a and b)	2	74
4	Top (a and b)	2	64
1	Backslope (c)	2	37
2	Backslope (c)	2	44
3	Backslope (c)	2	65
4	Backslope (c)	2	37
1	Channel (d)	2	30
2	Channel (d)	2	56
3	Channel (d)	2	52
4	Channel (d)	2	37
1	Flat (e)	2	37
2	Flat (e)	2	57
3	Flat (e)	2	27
4	Flat (e)	2	37

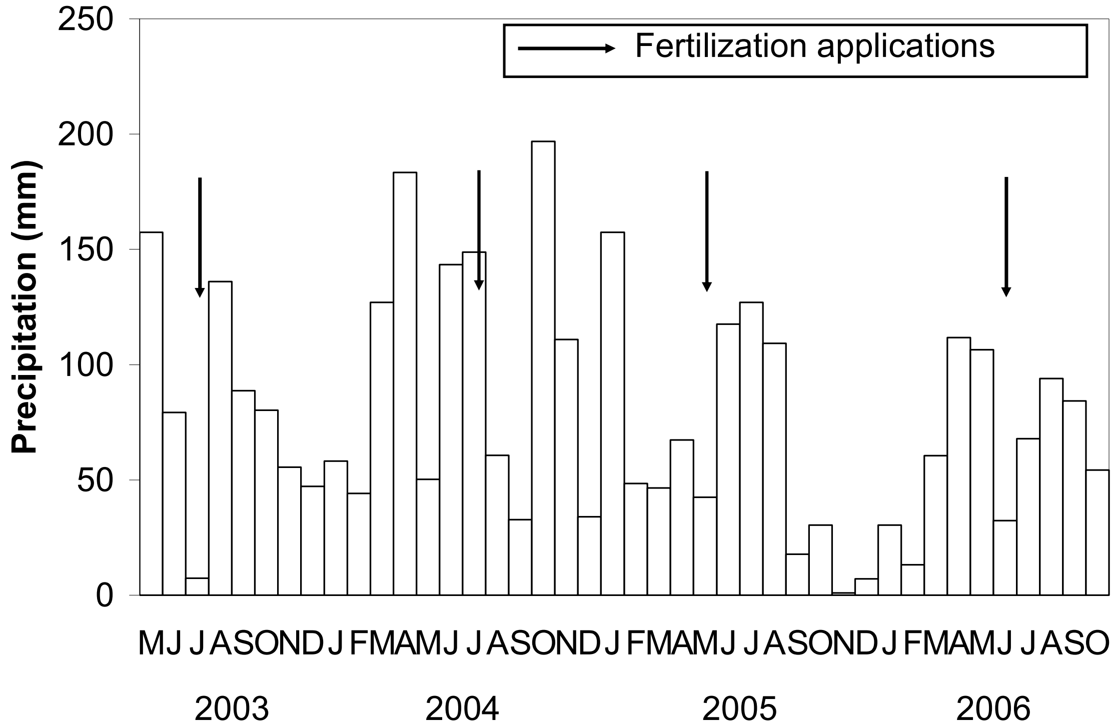

Figure 3-1. Precipitation and fertilizer applications in pastures of the Eastern Research Station, near Haskell, OK.

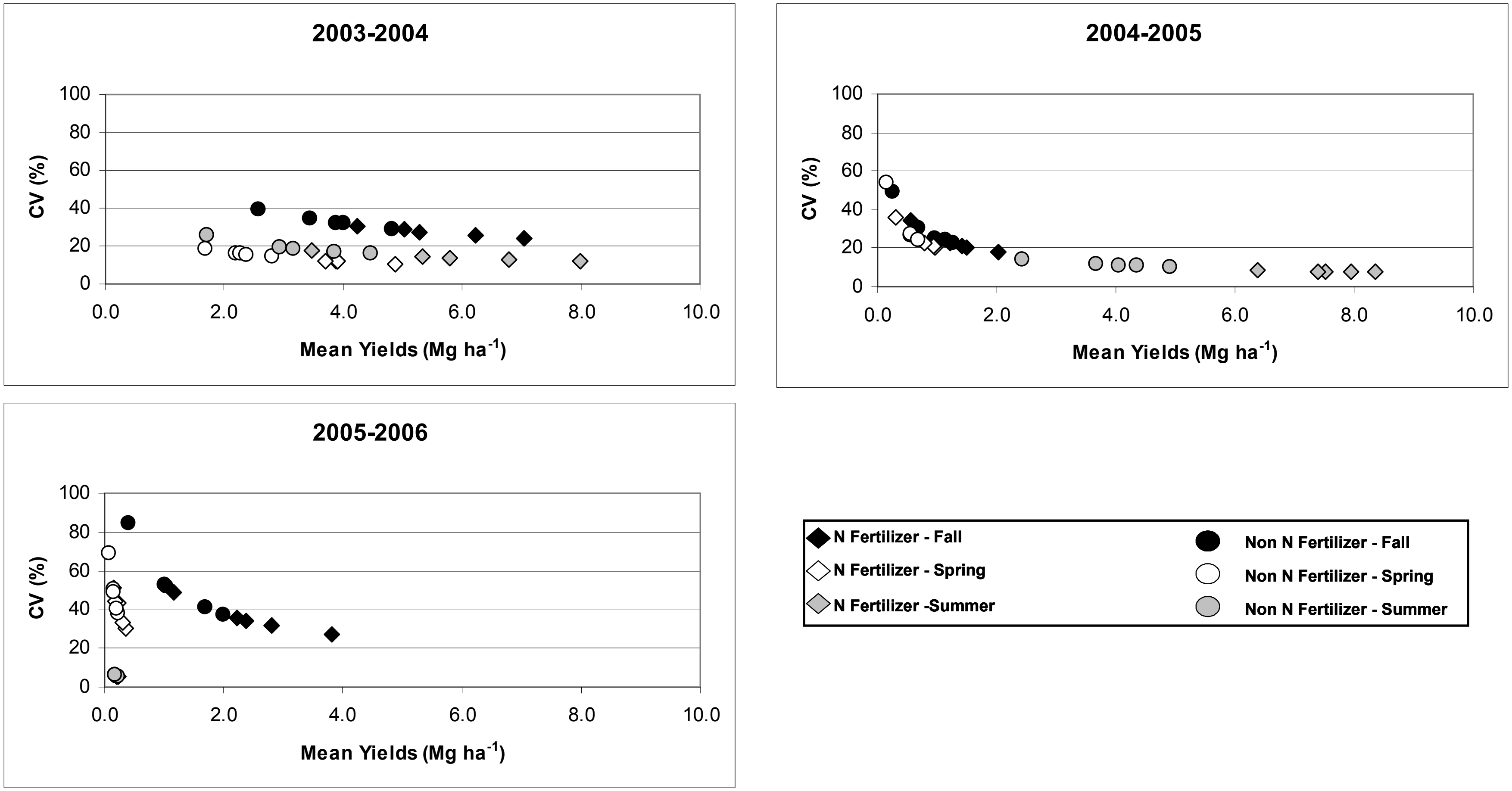

Figure 3-2. Variability of yields as function of the means of fertilizers and microreliefs treatment combinations by season during three years in pastures of the Eastern Research Station, near Haskell, OK. Each point is the mean of five microreliefs and four pastures.

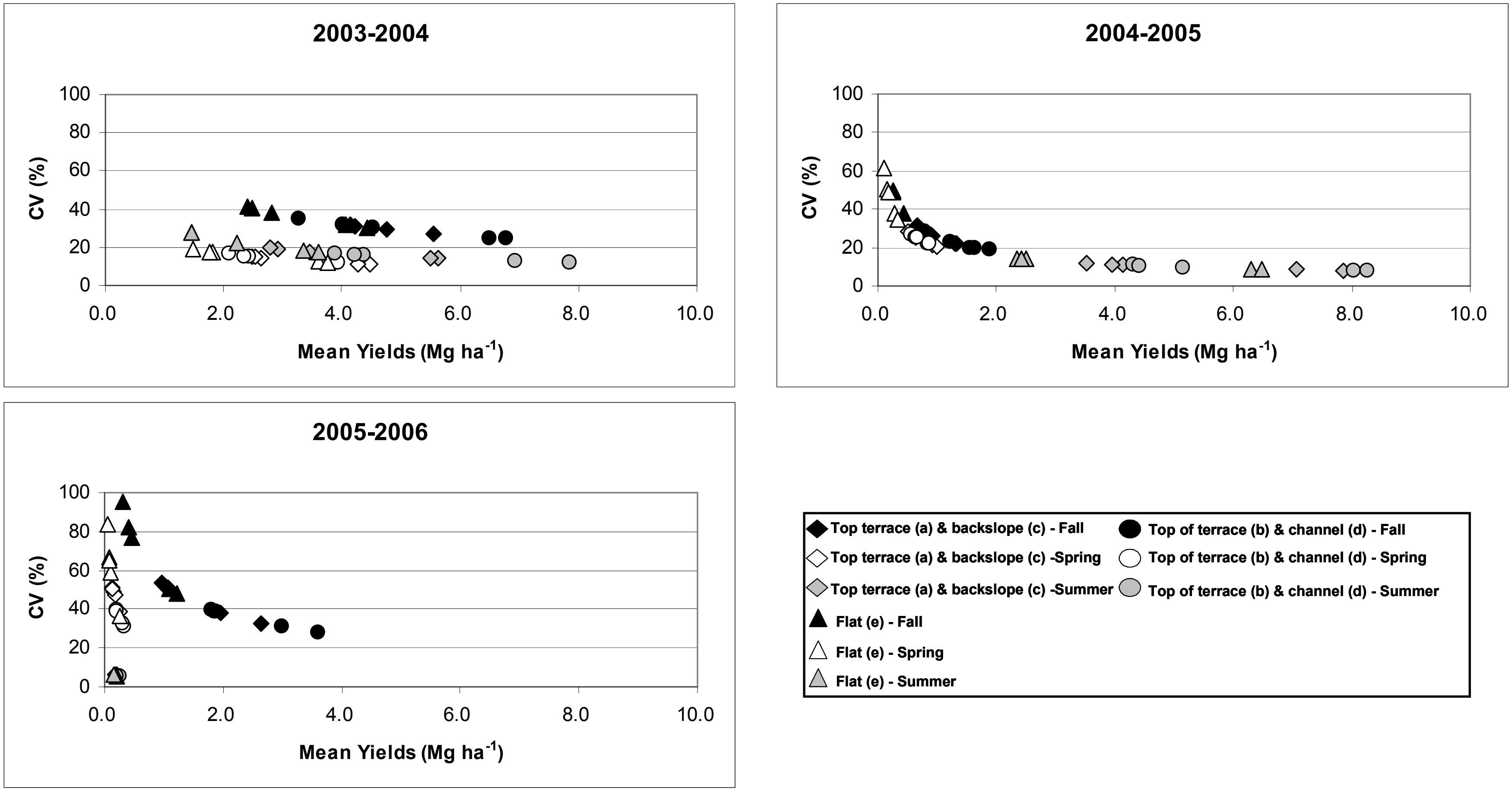

Figure 3-3. Variability of yields as function of the means of fertilizers and microreliefs treatment combinations by season during three years in pastures of the Eastern Research Station, near Haskell, OK. Each point is the mean of five fertilizers and four pastures.

CHAPTER 4

4. Relationship between Normalized Difference Vegetation Index (NDVI) and Forage Yields in Mixed Pastures

4.1. Abstract

Mixed pastures are typically highly variable in forage yields both in time and space. For pasture management and researching activities, obtaining quick, reliable, convenient, and non destructive estimates of forage yields in pastures would be useful to make informed decisions. Normalized difference vegetation index (NDVI) is a widely used index that has been used with encouraging results to estimate grain yields of annual crops like wheat (*Tritricum aestivum* L.) and corn (*Zea mays* L.). In mixed pastures, little information exists concerning the degree of association between NDVI and forage yield. The objective of this research was to test a hand-held sensor for estimating relative differences of forage yield in mixed grass-legume pastures. During five seasons, NDVI measurements were collected from five fertilizer treatment strips in four pastures. Forage yields were measured immediately after scanning. In four of five seasons, the correlation coefficients (r) were significant but inconsistent. The last two seasons, because of drought, yields were extremely low and the relations were of opposite sign, negative in the spring of 2004-2005 (r = - 0.75, P < 0.001) and positive during in the summer (r = 0.98, P < 0.001). We propose that the

relationship is simply random under such of low yields. Contrastingly, in the summer of 2004-2005, when high forage yields were recorded, an $r = 0.68$ ($P < 0.001$) was observed, but the correlation substantially increased in the fall of 2005-2006 ($r = 0.76$, $P < 0.001$), when forage yields decreased substantially. This evidencing that a probable loss of sensitivity of NDVI occurred as a result of high forage yields compared to when lower forage yields were recorded. It was concluded that NDVI is not a reliable estimator of forage yields in mixed pastures due to a loss of sensitivity under extremes of forage production levels and because a substantial fraction of the yield is often composed by non green forage, while NDVI was designed to detect green tissue.

4.2. Introduction

In mixed pastures, besides the complexity of including multiple species, these systems are typically highly variable in forage yields both in time and space. Obtaining quick, reliable, convenient, and non destructive estimates of forage yields in pastures would be beneficial to pasture management and research activities. Spectral reflectance is a tool that has been long used in the assessment of amount of several plant parameters like biomass and condition of the vegetation. The principles of the spectral reflectance technology rely on the amount and composition of light reflected from the vegetation. Vegetative indices result from combining two or more spectral bands and several indices have been developed to serve different purposes in the evaluation of different variables of interest of vegetation (Jackson and Huete, 1991).

Although with limitations, NDVI has been reported to correlate with certain physical properties of the vegetation canopy like leaf area index, vegetation cover, vegetation condition, and biomass (Carlson and Ripley, 1997). Encouraging results have been obtained using NDVI as a tool to predict grain yield in early stages of growth of corn (Teal et al., 2006) and winter wheat [Mullen et al. (2003); Raun et al. (2001)]. Most of these studies have gone through a series of tests to determine the latest developmental stage at which the crop's canopy reflectance can maintain a good relation with NDVI. For wheat it has been established between Feekes physiological growth stage 4-6 (Raun et al., 2001) and for corn at V8 (Teal at al., 2006). Another popular variable to which NDVI has been related has been the leaf area index (Curran, 1983).

Other researchers contend, or at least, restrict the value of NDVI as a predictive instrument to indirectly measure biomass and other vegetative parameters. Aparicio et al. (2000) and Aparicio et al. (2002) pointed out that one limitation of NDVI to estimate total dry matter was that when full canopy cover is achieved (at leaf area index of 3) in wheat, further increments in leaf area index didn't substantially change NDVI. Carlson and Ripley (1997) stated that, without doubt, NDVI was a deficient index to estimate total biomass because of an asymptotic performance of NDVI once full canopy closure was achieved. They explained that this occurred because nearly all the incident red light was absorbed by the upper leaf layer of a fully closed canopy. Near infrared radiation (NIR) is transmitted and reflected to lower levels of the canopy, that are unable to fully reflect back all the reflected light because of the blocking effect of higher layers of leaves in the canopy. Babar et al. (2006) found that indices based on only NIR were superior to NDVI or simple ratio (SR) in their power to estimate plant biomass of wheat genotypes.

Hill et al. (1999) identified eight general types of pastures using advanced very high resolution radiometer NDVI. However, it was not possible to distinguish within each pasture type the species composition due to difficulties in distinguishing between perennials, annuals, and native types where temporal conditions caused an accelerated senescence or where open woodlands confused profiles between improved and native pastures. Hill et al. (2004) reported that R^2 of around 0.70 were found between NDVI readings of pastures of Australia and pasture growth rates. They concluded that estimations of pasture growth rate based on NDVI are promising.

If NDVI was reliable in detecting relative differences in forage yields, calibration curves could be generated to estimate actual forage yields. Despite its potential value, NDVI has not been extensively tested to detect differences in forage production in mixed pastures. The objective of this research was to test a hand-held sensor for estimating relative differences of forage yield in mixed grass-legume pastures.

4.3. Materials and Methods

4.3.1. Experimental site

This research was conducted at the Eastern Research Station located near Haskell, OK., with coordinates of 35° 44’ north latitude and 95° 38’ west longitude. The station consists of 120 ha and is located in the Cherokee Prairie

Resource Area, which represents approximately 2.6 million hectares of eastern Oklahoma pasture land. Elevation of the station is about 180 m with a mean historic annual precipitation averaging 1040 mm with about 60% of this precipitation usually occurring from April through September. In the winter, the mean minimum temperature is 0° C, and in the summer the mean maximum temperature is 33° C (Townsend et al., 1987).

An area of 53 ha of the research station was designated for cattle grazing that had been managed as four pastures from 1978 to 1988. In 1989 a grazing demonstration was initiated using several pastures and some of the cow herd at the Eastern Research Station. For other activities, three of the four pastures were divided into two smaller pastures resulting in a total of seven pastures. Within these seven pastures, four were used to conduct the present study. Although many species of forage grasses have been planted through the years in the different pastures on the station, the predominant forage grasses were tall fescue [*Festuca arundinacea* Schreb. = *Lolium arundinaceum* (Schreb.) S.J. Darbyshire] and bermudagrass (*Cynodon dactylon* L.). Forage legumes (*Trifolium repens* L., *T. pratense* L., *T. vesiculosum* Savi, and *Medicago sativa* L., etc.), annual cool-season grasses (*Bromus* spp.) and warm-season grasses (*Digitaria* spp.) were also present in small quantity. More detailed descriptions of these pastures were provided by Caddel et al. (2005) and Redfearn et al. (2006).

One site (block) of 30 × 122 m was identified within each of the four different pastures. The sites were sloped (ranging from 1.5 to 3.7 %) and were located at a similar elevation gradient. Each site was relatively long and parallel with the natural slope of the land and perpendicular to water retention terraces. The four sites consisted of different soil series. Site 1 included Choteau (Fine, mixed, active, thermic Aquic Paleudolls) and Parsons (Fine, mixed, active, thermic Mollic Albaqualfs), sites 2 and 3 included only Choteau, and site 4 consisted of Dennis (Fine, mixed, active, thermic Aquic Argiudolls) and Choteau (Gray and Nance, 1978). These soils although were somewhat different from each other, shared some common characteristics (low permeability, for example) because they are geographically associated (or competing) soils (National Cooperative Soil Survey. 2006).

4.3.2. Treatments and data collection procedures

Five fertilizer treatments were applied in five 3.5 x 120 m strips, during the summer of each of three years. Fertilizer treatments consisted of the application of N (150 kg ha^{-1} N), P (150 kg ha^{-1} P_2O_5), K (200 kg ha^{-1} K_2O), NPK (150, 150, and 200 kg ha^{-1} N, P_2O_5, and K_2O, respectively), and a control; lime was applied to the NPK treatment only in the first year at a rate of 670 kg ha^{-1} ECCE. Years were counted from August 1 to July 31. Thus, each year included part of two calendar years: 2003-2004, 2004-2005, and 2005-2006. Seasons were defined according to the season when the forage grew, independently of the date of harvest. The "fall season" included the forage grown after the September 1 and before the termination of the growing season, during late fall to early winter. The "spring season" included the first forage grown after winter. And the "summer season" included the forage that grew after the first grazing rotation and before

August 31 each year. All seasons included four harvests (one for each pasture) and were somewhat variable in their calendar dates of initiation and termination, depending on changing growing conditions from year to year and when the pasture was scheduled to be utilized.

Beginning in the spring of 2005, until the end of the research in the summer of 2006 (five seasons), NDVI measurements were taken from the canopies just before clippings were made to measure forage yields, prior to grazing. Sensor readings were made from the center of each fertilizer strip for approximately 40 to 50 m to obtain a single mean NDVI value representative of the entire fertilizer strip. Seasons of canopy scanning and forage harvests are provided (Table 4-1). A hand held sensor (GreenSeeker® -Ntech Industries, Ukiah, CA) was used to measure NDVI. The formula used to calculate NDVI is: ρNIR – ρRed / ρNIR + ρRed, where ρNIR is the fraction of emitted near infrared radiation returned from the scanned area (reflectance) and ρRed is the fraction of emitted red radiation returned from the scanned area (reflectance) (Tucker, 1979). These calculations are automatically made by the sensor and NDVI values were directly obtained from PDA unit integrated to the sensor. Emitted and reflected light by the sensor was red (671 ± 6 nm) and near infrared (780 ± 6 nm). Technical details of the sensor are provided by Stone et al. (1996) and Raun et al. (2001).

Clippings were made with a flail harvester to a stubble height of 10 cm during the period of NDVI readings. Fresh forage was weighed in the field and subsamples of approximately 0.5 kg from each plot were weighed and dried to determine the percent dry matter. Dry matter yields per unit area were calculated. Forage yields reported are the average of five plots (microreliefs) per fertilizer strip.

4.3.3. Statistical analysis

Correlation coefficients (*r*) along with associated probability levels were obtained for all pairs of yield-NDVI measurements for each season from spring 2004-2005 until the summer 2005-2006 (PROC CORR, SAS Institute, 2003). Number of pairs of observations per season was not equal throughout this research because of measurements in the spring of 2004-2005 started after two of the pastures had been already grazed and in the summer of 2005-2006 ten observations were missing because of malfunction of the sensor.

4.4. Results and Discussion

The relationship between forage yield and NDVI was inconsistent (Table 4-2 and Figure 4-1). In four of five seasons NDVI was significantly related with forage yield but from the four significant, the last two had extremely low forage yield levels and had opposite sign relations, negative in the spring, and positive in the summer. From these two seasons it is suggested that the relationship of yield to NDVI under such of low yield levels, seems to be random. Taylor et al. (1998) reported that under low forage yields, correlation coefficients between various radiance light spectrums (including NDVI) with forage yields, decreased dramatically compared with those of high yields.

On the other hand, there is a documented weakness of NDVI to relate with vegetative biomass under full canopy coverage and/or with high forage yields (Carlson and Ripley, 1997; Serrano et al., 2000; Aparicio et al., 2000). In agreement with these reports, our results showed a loss of sensitivity of NDVI under high production levels, as observed during the summer of 2004-2005. In this season r was 0.68 (P < 0.001); however, a substantial increase in r was observed during the fall of 2005-2006 (r = 0.76, P < 0.001), when much lower forage yields were recorded.

Besides the inefficacy of NDVI to relate with forage yields when biomass is too low (Taylor et al., 1998) or too high (Curran, 1983; Carlson and Ripley, 1997), the inherent variability of pastures is high and seems to be playing a role as well. According to Curran (1983), one of the problems between leaf area index and NDVI result from variability in the substrate (senescent vegetation or bare soil underlying the green canopy). In mixed pastures containing both annual and perennial cool-season and warm-season grasses, we observed that the senescent fraction is almost always present at any given time and is often a substantial fraction of yield. This fraction, however, is highly variable to visualize from a vertical perspective. The visibility (or invisibility) of the substrate depend on the conditions provided for the green fraction of the vegetation and these can change over a short period of time or space.

Taylor et al. (1998) reported large spatial variability in a monoculture of bermudagrass. Variability of forage was suggested to have occurred due to differences in soil fertility. Smith and Stephens (1976) reported a range on forage yields in pastures of Australia from 5,000 to 14,000 kg ha^{-1}, and concluded that soil moisture was the major factor limiting pasture growth during part of the growing season. Therefore, it is suggested that temporal and spatial heterogeneity of the appearance of the herbage canopy in mixed pastures may represent an additional challenge for NDVI to accurately relate with forage biomass.

In mixed pastures, unlike in annual monoculture crops, all present species have seasonal growing patterns that are variable over time, depending on environmental conditions. Hill et al. (1999) argued that seasonal changes represented an obstacle to improve the reliability of NDVI to detect large scale differences among pasture species. Aparicio et al. (2002) concluded that NDVI lacked value as to estimate total biomass in wheat (*T. turgidum* L.) because low predictive ability for specific environment/growth stage conditions.

Varying environmental conditions, natural or man-dictated, affect differently the group of species in a mixed pasture. The dynamics of change within the pasture's canopy can be highly variable in space and time, causing the predictive value of the relationship of NDVI-forage biomass to be seriously compromised. Each time a pasture is scanned for NDVI measurements, there is a new set of conditions influencing the balance among growing and senescent material. Annual bromes, for instance, have been observed to vary in the time at which they start growing in the spring from year to year; these annual species along with tall fescue are the only bright green forage growing mixed at the canopy level or underneath the brown bermudagrass. Nevertheless, the appearance of the canopy in the pasture changes depending on how much bermudagrass grew after grazing the previous season and the condition for the cool-season annuals and for tall fescue to grow in the spring.

The presence of variable senescent vegetation in time and space was reported by Curran (1983), when he indicates *“As vegetation senesces, the near-infrared leaf reflectance does not significantly decreases. However, the breakdown of plant pigments causes a rise in red reflectance. Therefore if the amount of senescent vegetation in a canopy increases, the positive relation between near-infrared reflectance and green leaf area index will probably remain unchanged whereas the relation between red reflectance and green leaf area index will weaken and probably disappear (Curran, 1980c). This is a problem in semi-natural vegetation, particularly grasslands, where there is some senescent vegetation in the canopy throughout the year”.*

Longer duration experiments and the use of other vegetative indices may yield more promising results than NDVI on the stability of the relationship with forage yield in mixed pastures. Babar et al., (2006) found that near infrared based indices highly correlated with wheat biomass at late developmental stages (heading and grain filling), i.e., when canopy had already reached maximum biomass production. This may be indicative that near infrared based indices, instead of indices intended to measure canopy photosynthetic area could perform better than NDVI in estimating differences in biomass forage yields in mixed pastures.

Because of its short duration and because of restricted to only one location, we recognize the results of this study are not conclusive. However, we expect that at least it can serve as background information to plan more conclusive research about the potential of NDVI to relate to forage yield in mixed, terraced pastures. Given the large influence of the variation caused by terraces in soil fertility [Santillano-Cázares et al. (in review)] and forage yields [Santillano-Cázares et al. (unpublished data)], we would suggest to take into account microrelief points as part of the treatment structure and its interactions with fertilizers and seasons.

4.5. Conclusions

These results suggest that the utility of NDVI is severely limited as a tool to indirectly estimate forage yield in mixed pastures. Observations made in this study agree with previous reports that NDVI functions independently of forage biomass production at relatively low and relatively high levels. In addition, the species present in mixed pastures vary in the proportion to the total forage produced and in greenness over time due to changing environmental conditions. These two problems in mixed pastures minimize NDVI's ability to relate to forage biomass. Normalized difference vegetation index does not work accurately in relating with forage biomass on mixed pastures because frequently a substantial fraction of the yield is composed by non green forage and NDVI was designed to relate with green biomass and before full canopy closure.

4.6. References

Aparicio, N., D. Villegas, J. Casadesus, J.L. Araus, and C. Royo. 2000. Spectral vegetation indices as nondestructive tools for determining durum wheat yield. Agron. J. 92:83-91.

Aparicio, N., D. Villegas, J.L. Araus, J. Casadesus, and C. Royo. 2002. Relationship between growth traits and spectral vegetation indices in durum wheat. Crop Sci. 42:1547-1555.

Babar, M.A., M.P. Reynolds, M. Van Ginkel, A.R. Klatt, W.R. Raun, and M.L. Stone. 2006. Spectral reflectance to estimate genetic variation for in-season biomass, leaf chlorophyll, and canopy temperature in wheat. Crop Sci. 46:1046-1057.

Caddel, J.L., D.D. Redfearn, and R.L. Woods. 2005. Sustainable grass-legume pastures for cow-calf herds: a case study. XX International Grassland Congress -- offered papers. p. 788.

Carlson, T.N., and D.A. Ripley. 1997. On the relation between NDVI, fractional vegetation cover, and leaf area index. Remote Sens. Environ. 62:241-252.

Curran, P.J. 1983. Multispectral remote-sensing for the estimation of green leaf-area index. Philos. Trans. R. Soc. London Ser. Math. Phys. Engin. Sci. 309:257-270.

Gray, F., and E. Nance. 1978. Modern detailed soil survey: Eastern research station, Haskell. Research report (Oklahoma Agricultural Experiment Station) P-769. Stillwater, OK.

Hill, M.J., G.E. Donald, M.W. Hyder, and R.C.G. Smith. 2004. Estimation of pasture growth rate in the south west of Western Australia from AVHRR NDVI and climate data. Remote Sens. Environ. 93:528-545.

Hill, M.J., P.J. Vickery, E.P. Furnival, and G.E. Donald. 1999. Pasture land cover in eastern Australia from NOAA-AVHRR NDVI and classified Landsat TM. Remote Sens. Environ. 67:32-50.

Mullen, R.W., K.W. Freeman, W.R. Raun, G.V. Johnson, M.L. Stone, and J.B. Solie. 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95:347-351.

National Cooperative Soil Survey. 2006. Choteau series. Available on-line at: http://www2.ftw.nrcs.usda.gov/osd/dat/C/CHOTEAU.html.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, W.E. Thomason, and J.S. Schepers. 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93:131-138.

Redfearn, D.D., J.L. Caddel, and R.L. Woods, Jr. 2006. Sustainable grass-legume pastures for cow-calf herds. American Forage & Grassland Council Abstracts.

Serrano, L., I. Filella, and J. Peñuelas. 2000. Remote sensing of biomass and yield of winter wheat under different nitrogen supplies. Crop Sci. 40:723-731.

Santillano-Cázares, J., H. Zhang, J.L. Caddel, D.D. Redfearn, and C.L. Goad. Spatial and temporal variability of soil fertility in terraced pastures. Soil Sci. Soc. Am. J. (in review).

SAS Institute, Inc. 2003. SAS version 9.1. Cary, NC.

Smith, R.C.G., and M.J. Stephens. 1976. Importance of soil-moisture and temperature on growth of improved pasture on northern tablelands of New-South-Wales. Aust. J. Agric. Res. 27:63-70.

Stone, M.L., J.B. Solie, W.R. Raun, R.W. Whitney, S.L. Taylor, and J.D. Ringer. 1996. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Trans. ASAE 39:1623-1631.

Taylor, S.L., W.R. Raun, J.B. Solie, G.V. Johnson, M.L. Stone, and R.W. Whitney. 1998. Use of spectral radiance for correcting nitrogen deficiencies and estimating soil test variability in an established bermudagrass pasture. J. Plant Nutr. 21:2287-2302.

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98:1488-1494.

Townsend, M., R. Long, G.F. Scott, and R. R. Gilbertson. 1987. Soil survey of Muskogee County Oklahoma. USDA Soil Conservation Service and Forest Service in cooperation with Oklahoma Agricultural Experiment Station and Oklahoma Conservation Commission.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127-150.

Table 4-1. Seasons of NDVI measurements and forage harvest in pastures of the Eastern Research Station, near Haskell, OK.

Season/Year †	Pasture
Spring 2004-2005	1
Spring 2004-2005	2
Summer 2004-2005	1
Summer 2004-2005	2
Summer 2004-2005	3
Summer 2004-2005	4
Fall 2005-2006	1
Fall 2005-2006	2
Fall 2005-2006	3
Fall 2005-2006	4
Spring 2005-2006	1
Spring 2005-2006	2
Spring 2005-2006	3
Spring 2005-2006	4
Summer 2005-2006	1
Summer 2005-2006	2

† Two measurements in spring 2004-2005 and two in the summer of 2005-2006 are missing because scanning of pastures started after two pastures had been already grazed and because of malfunction of the sensor, respectively.

Table 4-2. Mean yields, NDVI values, coefficients of correlation, probability levels, and number of pairs of observations of five seasons during two years in pastures of the Eastern Research Station, near Haskell, OK.

Season/Year	Yield (Mg ha^{-1})	NDVI	*r*	*P*	*n*
Spring 2004-2005	1.19	0.73	0.49	0.214	8
Summer 2004-2005	5.23	0.67	0.68	<0.001	20
Fall 2005-2006	1.72	0.33	0.76	<0.001	20
Spring 2005-2006	0.20	0.51	-0.75	<0.001	20
Summer 2005-2006	0.26	0.60	0.98	<0.001	10

VITA

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Candidate for the Degree of

Doctor of Philosophy

Dissertation: MANAGEMENT OF IMPROVED PASTURES IN OKLAHOMA

I. TALL FESCUE SEED PRODUCTION II. PASTURE VARIABILITY

Major Field: Crop Science

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Title of Study: MANAGEMENT OF IMPROVED PASTURES IN OKLAHOMA

I. TALL FESCUE SEED PRODUCTION II. PASTURE VARIABILITY

Pages in Study: 102 Candidate for the Degree of Doctor of Philosophy

Major Field: Crop Science

Scope and Method of Study: This study consisted of four different research projects aiming to solve specific problems in pastures management. I. The objective was to determine the feasibility of using tall fescue as a multi use crop, for seed and for forage. Four entries and two grazing treatments, fall-grazing and fall non-grazing were tested. II. This study was intended to find the main sources of variability in soil sampling of terraced pastures and to propose recommendations to help improve soil testing in terraced pastures. Fertilizers and microreliefs were fixed; years, sampling dates, and sampling sites were random. Two soil sampling methods were employed. III. The objectives were to determine the factors that define forage production and variability in terraced pastures. The same factors as described for the second experiment were used. IV. This study was intended to determine the degree of association between normalized difference vegetation index (NDVI) and forage production. Yields and NDVI readings were collected on different fertilizer treatments repeated over four pastures during five seasons.

Findings and Conclusions: I. Fall-grazing did not negatively affected seed yields or germination. It was concluded that fall-grazing is a viable component of multiple use tall fescue systems of eastern Oklahoma and north central Texas. II. Both temporal variability (associated with variation of weather) and the effect of terraces are important in affecting fertility levels. We recommend to: 1) Allow substantial precipitation to occur between grazing and sampling to minimize the effects of feces and urine spots; and 2) For a composite sample, collect soil cores representing all microrelief areas except terrace channels. Terrace channels were highly concentrated with P and K. III. Nitrogen increased yields while decreased variability, however, it depended on precipitation to achieve these results. It was concluded that currently, no real viable options can substantially reduce variability in these pastures. IV. The NDVI-forage yield relationship was unstable. It was concluded that NDVI is not an accurate index to relate with forage biomass in mixed pastures.

ADVISER'S APPROVAL: Dr. Daren D. Redfearn