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Estimating influence of stocking regimes on livestock grazing distributions

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ABSTRACT

Livestock often concentrate grazing in particular regions of landscapes while partly or wholly avoiding other regions. Dispersing livestock from the heavily grazed regions is a central challenge in grazing land management. Position data gathered from GPS-collared livestock hold potential for increasing knowledge of factors driving livestock aggregation patterns, but advances in gathering the data have outpaced advancements in analyzing and learning from it. We fit a hierarchical seemingly unrelated regression (SUR) model to explore how season of stocking and the location where cattle entered a pasture influenced grazing distributions. Stocking alternated between summer on one side of the pasture one year and fall on another side of the pasture the next year for 18 years. Waypoints were recorded on cattle for 50 d each year. We focused our analysis on the pasture's 10 most heavily grazed 4-ha units, because these units were the most prone to negative grazing impacts. Though grazing of the study units was always disproportionately heavy, it was much heavier with the summer than fall stocking regime: Bayesian confidence intervals indicate summer grazing of study units was approximately double the average fall grazing value. This is our core result, and it illustrates the strong effect stocking season or date or both can have on grazing distributions. We fit three additional models to explore the relative importance of stocking season versus location. According to this analysis, stocking season played a role, but stocking location was the main driver. Ostensibly minor factors (e.g. stocking location) can greatly influence livestock distributions.

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1. Introduction

Domestic livestock grazing has degraded expansive areas of rangeland on every continent (Fernandez et al., 2009; Hess and Holechek, 1995; Yayneshet et al., 2009). To curb the degradation, complete grazing exclusion is sometimes recommended (Lunt et al., 2007; Magner et al., 2008), though recommendations more typically call for reducing livestock numbers to more sustainable levels (Michalk et al., 2003) or seasonally adjusting numbers to reflect current forage availability (Campbell et al., 2000; O'Reagain et al., 2009). Other recommendations emphasize adjusting the timing of grazing to periods when biomass removal is least likely to compromise plant fitness (Halstead et al., 2002) or seed production (Conlan et al., 1994).

Still other efforts begin by recognizing that grazing is often highly uneven (Bailey et al., 1996; Coughenour, 1991), with some areas grazed to perhaps unsustainable levels and other areas in the same pasture grazed very little. This grazing unevenness is a central problem in range management, and it can lead to overgrazing even under low stocking rates (Fuls, 1992; Teague and Dowhower, 2003; Willms et al., 1988). Several methods, including herding, placing attractants (e.g. water, salt, minerals) in underutilized areas and subdividing pastures are routinely used with varying levels of success to increase the uniformity of grazing, encourage use of unused portions of pastures, and provide rest from grazing (Barnes et al., 2008; Hart et al., 1993; Muller et al., 2007; Vallentine, 1990).

Another potential way to prevent overgrazing of particular pasture regions may involve shifting the location entry where livestock enter pastures. Gillen et al. (1985) found 25% of cattle activity in a particular meadow in a large pasture (4500 ha) occurred the day of stocking, despite cattle being in the pasture for two months: a finding likely explained by the meadow being only 0.8 km from the entry point. Aside from this one observation, we know of no data suggesting entry point effects on grazing distributions.

As with entry location, entry date is another easily manipulated factor that can influence grazing distributions, with riparian areas providing the prime example. Cattle tend to concentrate less in riparian areas when stocked early summer, as opposed to late summer when upland water is scarce and upland forage senesced (e.g. Gillen et al., 1985; Parsons et al., 2003; Roath and Krueger, 1982). Aside from riparian zones, we know of no studies investigating stocking date effects on grazing distributions. Stocking date could have pronounced effects because livestock tend to seek out the highest quantity/quality forage (Ganskopp and Bohnert, 2009;

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Lamoot et al., 2005; Pinchak et al., 1991; Smith et al., 1992), and the locations of the best forage can shift throughout the year (Gusewell et al., 2007; Wallisdevries, 1996).

We analyzed 18 years of cattle position data from a large heterogeneous pasture. Stocking of the pasture alternated between summer along the pasture's east side one year and fall along the pasture's south side the next year. Our overall goal was to explore how this variation in season and location of stocking affected grazing of the most heavily grazed regions of the pasture. Our first specific objective was to identify the 10 regions that experienced the heaviest grazing over the 18-year study period. These 10 regions served as our study units. Our second objective was to quantify how grazing intensity within these study units differed between the two alternating stocking regimes. Our third objective was to infer whether differences in grazing pressure owed primarily to the shift in season versus location of stocking.

2. Materials and methods

2.1. Study area

We studied a 2373 ha pasture located within the Starkey Experimental Forest and Range 35 km southwest of La Grande, OR. The terrain is mountainous with large benches intersected by drainages. Elevation ranges between 1100 and 1500 m, and mean annual precipitation is 64 cm. The pasture is dominated by four general habitat types: (1) meadow, (2) grassland, (3) forest with grass understory, and (4) forest with shrub understory. Dominant grassland species are bluebunch wheatgrass (*Pseudoroegneria spicata*), Sandberg bluegrass (*Poa secunda*) and the introduced wiregrass (*Ventenata dubia*), and dominant understory grasses are pinegrass (*Calamagrostis rubescens*) and Idaho fescue (*Festuca idahoensis*). Dominant tree species are Douglas fir (*Pseudostuga menzesii*), grand fir (*Abies grandis*) and ponderosa pine (*Pinus ponderosa*), and the subshrubs/shrubs twinflower (*Linnaea borealis*), oceanspray (*Holodiscus discolor*), big huckleberry (*Vaccinium membranaceum*), and grouse huckleberry (*Vaccinium scoparium*) predominate the understory.

2.2. Grazing management

Throughout the study period (1990–2007), 500 cattle grazed the pasture for about 50 d each year. Stocking occurred around June 20 (hereafter "summer") and September 1 (hereafter "fall") in odd- and even-numbered years, respectively. In addition to the stocking date, the release point into the pasture also differed between odd- and even-numbered years (Fig. 1).

2.3. Animal location and vegetation data

Each year, between 26 and 52 cattle were fitted with radio or GPS collars, except for 1990 when only 16 cattle were fitted. We limited our analysis to the 'grazing day', when cattle were likely to be feeding as opposed to resting, drinking or traveling. In accordance with observations from Howery et al. (1996), we defined the grazing day as comprising two 4-h periods; one beginning 0.5 h before sunrise, the other ending 0.5 h after sunset. From 1990 to 2004, a LORAN-C based telemetry system was used to record between 0.2 and 2.3 waypoints per cow per grazing day (Kie et al., 2005). From 2005 to 2007, a GPS was used to record between 3.1 and 4.2 waypoints per cow per grazing day.

Photo-interpreted habitat type and forage production data are available over a grid of 30-m × 30-m cells for the entire pasture (Rowland et al., 1998). We used these data to calculate forage production and describe the habitat types of our study units.

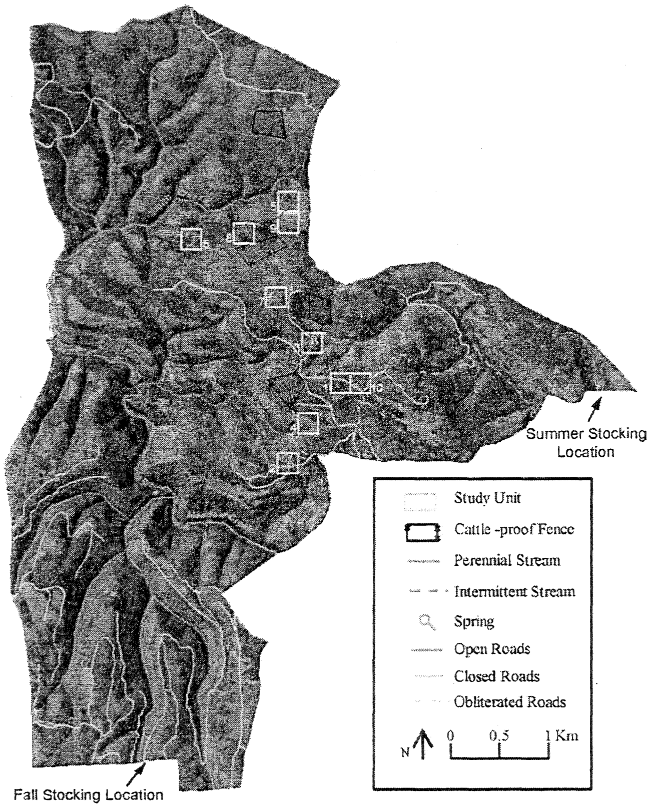

Fig. 1. Positions of study units, stocking locations and other select features in a pasture used to study effects of stocking location and date on cattle grazing distributions.

2.4. Analysis

Null hypothesis significance testing is the simplest and likely most widely used method for analyzing livestock position data (Franklin et al., 2009; Ganskopp and Bohnert, 2009). However, significance tests suffer a major limitation in that they cannot estimate the magnitude of differences between stocking regimes (Berger and Sellke, 1987; Rinella and James, 2010). Resource selection functions (RSF) are another widely used option for modeling animal position data (e.g. Johnson et al., 2004; Long et al., 2009) and they have been used for modeling livestock distributions (Walburger et al., 2009). The RSF approach involves dividing study areas into cells and using logistic regression to model the (proportional) probability animals enter given cells as a function of habitat variables and other predictors. RSF were inadequate for our purposes because they do not estimate the magnitudes of cell use we desired. Spatiotemporally autoregressive (STAR) models were another option, but STAR models are difficult to fit to large datasets, often forcing reliance on approximations instead of the desired likelihood function (e.g. Banerjee et al., 2004). Furthermore, STAR modeling would have involved devising a likelihood function for the number of waypoints in each cell. This would have resulted in a dataset comprised of many zeros and many large counts, and the appropriate likelihood function for such a dataset is unclear.

Given these complications, and our desire to focus attention on overgrazing-prone regions of the pasture, we chose to model only the 10 most heavily used 4-ha (200-m × 200-m) units. We decided on 10 units because smaller numbers would likely result in imprecise estimates of hierarchical model variances (Gelman and Hill, 2007), and larger numbers would shift our focus to less heavily grazed regions. The 4-ha size was used because the data demonstrated substantial spatial aggregation at this scale. To select our study units, we gridded the pasture into units, computed the proportion of waypoints (animal position coordinates) registering from each unit, averaged these percentages over years and selected the 10 units with the greatest averages. The unit positions were essentially identical whether selected using all data, exclusively data from the fall stocking regime or exclusively data from the summer stocking regime. Therefore, particularly heavy grazing under just one of the two stocking regimes did not determine study unit positions or predispose our analysis toward finding large differences between stocking regimes. This indicated, it would have remained logical to proceed as we did even if heavy grazing under only one stocking regime had determined positioning of the units.

The non-random selection of study units did not hinder our goal of investigating variation within and among study units. A large literature describes use of seemingly unrelated regressions (SUR) for modeling relationships within and among non-randomly selected entities, such as industrial firms (e.g. Boot and de Witt, 1960; Greenberg, 2008) or countries (e.g. Garcia-Ferrer et al., 1987). The likelihood for our SUR model was:

$$\ln y_{jk} \sim N(\alpha_k + \beta_k x_{jk} + \gamma_j + \delta_k t_{jk}, \sigma) \tag{1}$$

where y_{jk} is the proportion of waypoints registering from study unit k, year j and N(mu, sigma) is the normal distribution with mean mu, standard deviation sigma. Three of the 180 y_{jk} equaled zero and so were set equal to the smallest value in the dataset. The α_k are the $k = 1,2, \ldots, 10$ study unit means. Elements of x equal 1 for observations from the summer stocking regime and 0 for observations from the fall stocking regime, so β_k is the mean difference between these two regimes for study unit k. The γ_j are the $j = 1,2, \ldots, 18$ year effects. These year effects allow for correlations among the study units. The t_{jk} are years standardized to mean 0, standard deviation 1; so the δ_k capture study unit-specific time trends.

Our hierarchical Bayesian approach to parameter estimation required assigning prior distributions to all model parameters (Gelman et al., 2004). The γ were assumed to follow a normal distribution with mean 0, standard deviation τ_γ. Similarly, the α, β and δ were assumed trivariate normally distributed:

$$\begin{pmatrix} \alpha_k \\ \beta_k \\ \delta_k \end{pmatrix} \sim N\left(\begin{pmatrix} \mu_\alpha \\ \mu_\beta \\ \mu_\delta \end{pmatrix}, \begin{pmatrix} \tau_\alpha^2 & \tau_{\alpha\beta} & \tau_{\alpha\delta} \\ \tau_{\alpha\beta} & \tau_\beta^2 & \tau_{\beta\delta} \\ \tau_{\alpha\delta} & \tau_{\beta\delta} & \tau_\delta^2 \end{pmatrix} \right) \tag{2}$$

The μ and τ_γ were assigned uniform prior distributions, and the prior on the random error variance was $p(\sigma^2) \propto 1/\sigma^2$. The covariance matrix of Eq. (2) was given the inverse-Wishart distribution with degrees of freedom equal to the dimension of the covariance matrix plus 1 and scale parameter equal to the identity matrix. These are oft-used, non-informative priors (Gelman et al., 2004). All conditional distributions were of standard form, so we used Gibbs sampling to simulate the posterior distribution. We wrote a program in FORTRAN (Intel Corporation, 2003) that constructed three parallel chains of length 20,000, discarded the first half of each chain as burnin and assessed convergence via the procedure of Gelman and Rubin (1992).

The Bayesian approach allowed us to use posterior predictive checks to evaluate Eq. (1) (e.g. Rubin, 1981, 1984). The most critical check evaluated the assumption of no residual correlation among study units. We simulated 1000 replicate datasets and used the simulations to place 95% confidence intervals on each of the 45 correlations (unit 1 with unit 2, unit 1 with unit 3, ..., unit 9 with unit 10). The number of raw data-based correlations falling outside their corresponding confidence intervals was 1, which is close to the value expected by chance ($2.25 = 0.05 \times 45$) so we concluded the residuals were not highly correlated.

We fit three simpler models to gain insight into which factor(s) (i.e. season or location of stocking or both) caused differences between the summer and fall stocking regimes. One model estimated the proportion of cattle registering one or more waypoints in one or more study units in year $j(y_j)$:

$$\ln y_j \sim N(\alpha + \beta x_j, \sigma) \tag{3}$$

where α and β are scalars, and x is as described for Eq. (1). Another model estimated the number of days required for cow l to register her first waypoint in a study unit in year j (y_{lj}), omitting cattle that never registered waypoints in study units. The model was:

$$\ln y_{lj} \sim N(\alpha + \beta x_j + \gamma_j, \sigma) \tag{4}$$

where α and β are as described for Eq. (3), and the γ_j are as described for Eq. (1). Another model estimated the proportion of cow l's waypoints registering from study units following her first registry from a study unit (y_{lj}):

$$\ln y_{lj} \sim N(\alpha + \beta x_{lj} + \gamma_j + \delta t_{lj}, \sigma) \tag{5}$$

This model is the same as Eq. (4), except for δ, which is a scalar, and the t_{lj} which are as defined for Eq. (1). Except for the inverse-Wishart prior, fitting procedures and prior distributions for Eq. (3)–(5) were as described for Eq. (1).

3. Results and discussion

Our interpretation of results assumes grazing pressure (i.e. forage utilization) was a fixed proportion of time spent in an area (i.e. waypoint density). This assumption is likely well-met because we restricted our dataset to times of day when cattle normally graze and because the stocking date effects were quite dramatic, so modest deviations from the assumption would not greatly alter our conclusions. Also, our principal goal was to evaluate differences in grazing pressure between the stocking regimes. To achieve this goal, the assumption that forage utilization was a stable proportion of waypoint density needed hold only for the study units, not the entire pasture. This assumption seems particularly safe when applied exclusively to the study units because it is unlikely cattle would congregate in the study units to graze in fall but for other purposes in summer.

Our method for selecting heavily grazed study units selected a cluster of units near the center of the pasture (Fig. 1). The average distance to the study units was shorter from the summer (3.6 km) than fall (5.1 km) stocking location, and roads connected several of the study units to the summer stocking location (Fig. 1). Each study unit contained meadow and/or grassland interspersed with timbered patches (Table 1, Fig. 1).

In fall, waypoint density in the study units exceeded the pasture mean by 510% ± 260 SD, suggesting grazing was highly aggregated in the study units in fall. As aggregated as this estimate makes fall

Table 1

Hectares of tree/shrub, tree/grass, grassland, and meadow habitat in 4-ha study units used to quantify effect of stocking date on cattle grazing intensity.

Study	Tree/grass	Tree/shrub	Grassland	Meadow
1	2.84	0.96	0.20	0.00
2	0.86	1.57	0.00	1.57
3	1.63	1.80	0.57	0.00
4	0.33	0.59	0.00	3.07
5	0.45	0.45	0.00	3.11
6	0.57	3.05	0.38	0.00
7	0.00	0.04	0.00	3.96
8	0.00	2.99	0.00	1.01
9	0.00	0.77	0.00	3.23
10	0.00	2.75	0.00	1.25
Total	6.69	14.96	1.15	17.21

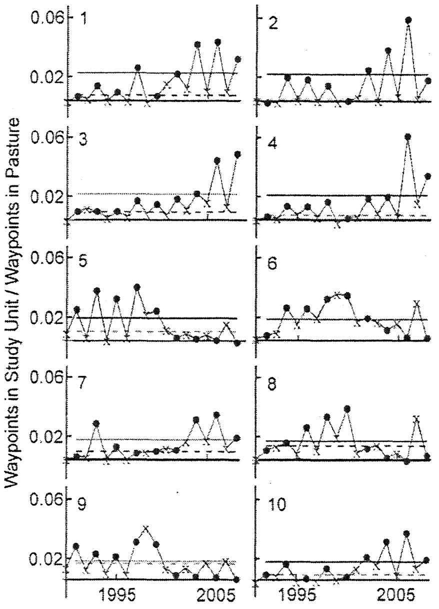

Fig. 2. Cattle position data from the ten most heavily grazed 4-ha sections of a 2373-ha pasture. The x-axis is positioned at the waypoint ratio expected under even grazing (i.e. 0.0017). The dot symbols represent years when stocking occurred along the east side of the pasture in summer and the x symbols represent years when stocking occurred along the south side of the pasture in fall. Lines represent averages over summer (solid) and fall (dashed) stocking years.

grazing appear, the raw data suggest (Figs. 2 and 3) and our statistical estimates confirm (Fig. 4) that grazing was appreciably more aggregated in summer. For example, point estimates for study units one and two were approximately 1.2 (Fig. 4A), suggesting these units were grazed over three times ($3.3 = e^{1.2}$) more heavily in summer than fall. Ninety-five percent Bayesian confidence intervals (CI) that exclude zero provide strong evidence that, averaged over years, six of the 10 study units were grazed more heavily in summer than fall (Fig. 4A). Positive point estimates suggest the remaining four units were also grazed more heavily in summer, but here the CI overlap zero so the evidence is weaker (Fig. 4A).

Fig. 4B estimates the difference between individual summer grazing years and the average of fall grazing years, thereby indicating the year-to-year consistency of the differences between summer and fall stocking. The CI provide strong evidence that study unit grazing was consistently heaviest in years with summer stocking, with the possible exception of 1991 (Fig. 4B). Most point estimates are 0.75 or greater, suggesting study units were grazed more than twice as heavily ($2.1 = e^{0.75}$) when stocking occurred summer as compared to fall (Fig. 4B).

To investigate the relative importance of stocking season versus location, we explored the amount of time cattle spent in study units after first entering them. If cattle spent greater percentages of time in study units after locating them in summer compared to fall, this would suggest cattle preferred grazing the study units in summer over fall because of differences in forage quality/quantity. Alternatively, if after first locating study units cattle spent similar amounts of time in them regardless of stocking date, this would suggest the study units were similarly desirable for grazing regardless of stocking date. The specific parameter we estimated was ln(% of time in summer − % of time in fall). The CI on this parameter barely overlaps zero (0.11 ± 0.12), and the most likely value suggests cattle spent $12\% = 100 \times e^{0.11} - 100$ more time in study units after locating them in summer compared to fall.

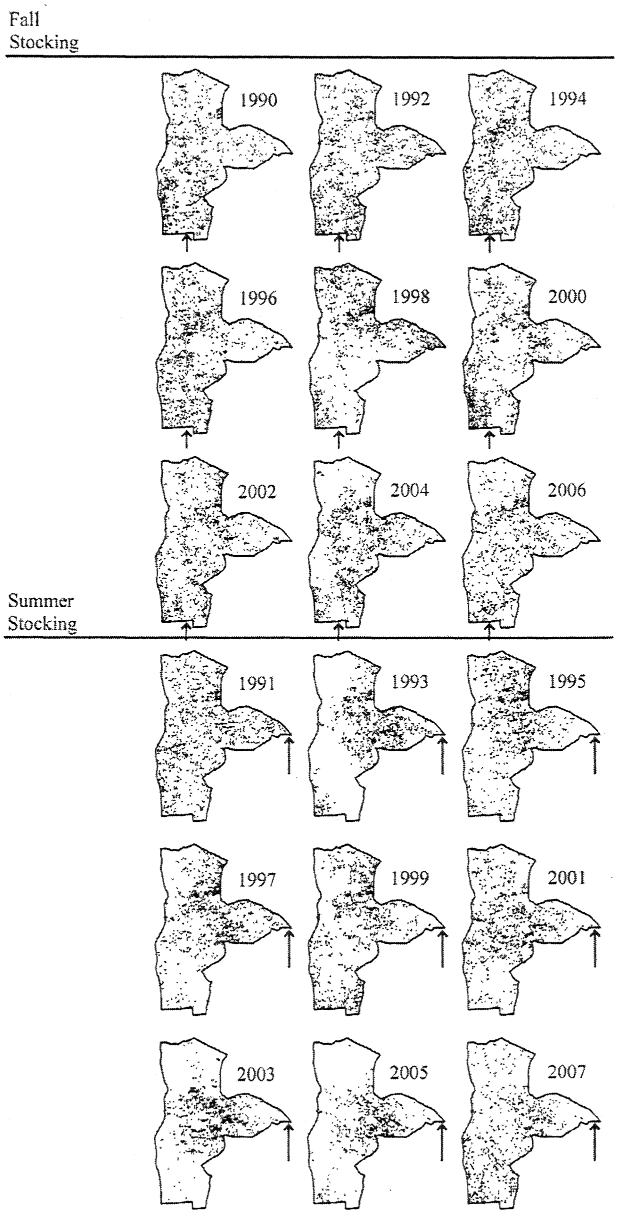

Fig. 3. 1200 Randomly sampled cattle positions per year from a study that evaluated effects of stocking location and date on cattle grazing distributions. Cattle were stocked summer in odd-numbered years and fall in even-numbered years, and arrows denote the stocking locations.

Next we evaluated the difference in the percentage of cattle that located study units: ln(% of cattle in summer − % of cattle in fall). Here, the CI is strictly positive (0.33 ± 0.18) and the most likely value implies an average of $39\% = 100 \times e^{0.33} - 100$ more cattle located study units in summer. Finally, we estimated the difference in time needed for cattle to locate study units: ln(day in summer − day in fall). The CI on this variable is strictly negative (-2.3 ± 0.17), and the most likely value suggests cattle located the study units in an average of $90\% = 100 - 100 \times e^{-2.3}$ fewer days under summer compared to fall stocking. Based on point estimates, cattle located the study units in an average of 2.2 d in summer and 22 d in fall.

The optimal approach for analyzing livestock position data depends on the goal. Our goal was to determine if stocking regime characteristics greatly influenced grazing pressure within the most overgrazing-prone regions of the pasture. Our modeling approach was well suited for achieving this goal: it focused attention in the

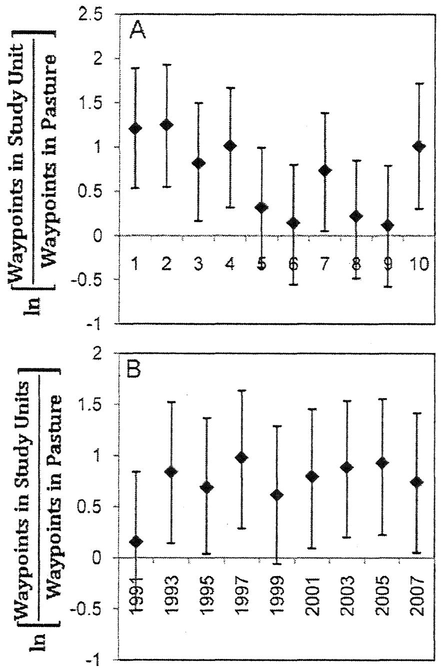

Fig. 4. Most likely values (dots) and 95% Bayesian confidence intervals (bars) estimating grazing intensity within the ten most heavily grazed 4-ha study units of a 2373-ha pasture. Cattle were stocked along the east side of the pasture in summer in odd-numbered years and along the south side of the pasture in fall in even-numbered years. (A) Intervals for individual study units estimate differences between summer and fall stocking (i.e. summer – fall), with the zero line representing no difference and positive values indicating greater use under summer stocking. (B) Intervals estimate differences between summer stocking years and the average of fall stocking years (i.e. summer – average of fall), with the zero line representing no difference and positive values indicating greater use under summer stocking.

relevant pasture regions and yielded easily interpretable quantitative estimates. Furthermore, posterior predictive checks, which are a key feature of Bayesian statistical modeling, allowed us to check modeling assumptions. Model checking is particularly important with spatially explicit observations that are repeated through time because of the potential for auto- and spatial correlation. According to predictive checks of our model, including study unit-specific terms sufficiently accounted for auto-correlation, and the year parameters sufficiently accounted for correlation among the study units. Our model could be easily expanded to handle data exhibiting residual correlation.

The most likely parameter estimates suggest grazing of study units tended to exceed the pasture mean by a factor of 10 in summer stocking years. This indicates that, unless the study units were atypically productive, the forage consumption to production ratio in study units greatly exceeded the pasture mean. Data from Rowland et al. (1998) indicate study unit forage production (348 $\mathrm{kg\,ha^{-1}} \pm 23\mathrm{SE}$) resembled the pasture mean (335 $\mathrm{k\,ha^{-1}} \pm 5\mathrm{SE}$). However, the photo-interpreted forage estimates of Rowland et al. (1998) could be somewhat unreliable. Nevertheless, we scouted the study units near the end of the summer stocking year of 2009, and portions of the study units were clearly overgrazed, with some exhibiting heavy trampling and rather large (~20-m × 20-m) patches of nearly bare ground. Given these considerations, management dispersing cattle away from the study units seems advisable. To an extent, such management was in place throughout the study period: by alternating the stocking location, the grazing managers tended to reduce grazing of study units every other year. This seems a good precautionary approach, because annually repeated heavy defoliation during the summer growth period can cause weed invasions and otherwise degrade plant communities (e.g. Manseau et al., 1996; Rinella and Hileman, 2009; Wang et al., 2009).

The striking differences between stocking regimes depicted in Fig. 4 were likely driven more by location than season of stocking. Whereas our estimates suggest cattle were less apt to concentrate on the study units after locating them in fall compared to summer, the effect is far too small to account for the large differences of Fig. 4. Therefore, the dominant mechanism likely involves the substantially greater numbers of cattle that located study units under the summer stocking regime and the dramatically shorter times they took to find the study units with this regime. In turn, these shorter search times and greater cattle numbers are likely explained by shorter travel distances and roads associated with the summer stocking location (Fig. 1).

It is not readily apparent why cattle would remain in and around the study units after consuming large portions of the available forage, especially when many areas possessed largely untapped forage supplies in some years (Fig. 3). Superficially, it seems water availability could explain this finding (Gillen et al., 1985; Parsons et al., 2003) because three of the study units overlapped permanent springs and all the study units were in fairly close proximity to reliable water sources. However, if reliable water sources determined livestock grazing patterns in the study pasture, we would expect heavier grazing of the study units in fall compared to summer because seasonal ponds and streams provide water throughout the pasture in summer.

A more likely explanation involves homing behavior. Livestock commonly establish home ranges that comprise only portions of large pastures (Hernandez et al., 1999; Hunt et al., 2007; Lawrence and Wood-Gush, 1988). When cattle were stocked into our large study pasture in summer, they tended to quickly establish home ranges that were roughly centered on the study units (Fig. 3). The locations of these home ranges may have reflected relatively high forage availability and gentle terrain, which provided easy access to feed, water and resting camps (Fig. 1) (Holechek et al., 1998; Mueggler, 1965). Once established, cattle home ranges have proven quite persistent, even in the presence of drought and herding (Howery et al., 1996). As forage availability declined in the vicinity of the heavily grazed study units, foraging efficiency (i.e. intake rates) would have also declined (Gregorini et al., 2009; Searle et al., 2005b). But livestock can compensate for low intake rates by increasing the time they spend foraging (Garcia et al., 2003; Popp et al., 1997; Roguet et al., 1998), so cattle may have avoided migration by increasing their foraging times (Searle et al., 2005a).

4. Conclusions

This study showed certain regions of a large mountainous pasture were grazed much more heavily than others and that altering the stocking location greatly reduced grazing of the overused regions. This supports Laca's (2009) assertion that the focus should shift from grazing theory to practical, data-based approaches to grazing management. After all, what theory (e.g. optimal foraging theory, hierarchy theory) would have predicted the patchy grazing pattern we observed, let alone the high sensitivity of the pattern to the studied stocking regimes? Grazing distributions are determined by complex interactions among topography, forage availability, water sources, and other land features, and these features vary dramatically from pasture to pasture (Hunt et al., 2007). Moreover, behavioral differences between herds and individuals within herds further complicate the picture (Searle et al., 2010). Given the potential shortcomings of theory and the complicated relationships that determine grazing distributions, animal position data coupled with adaptive management likely provide the best avenue for quantifying, predicting and improving grazing distributions. It is becoming increasingly feasible to gather animal position data with GPS (Laca, 2009; Trotter et al., 2010), and GPS could aid grazing management much as it currently aids grazing research (e.g. Franklin et al., 2009; Pandey et al., 2009). Grazing managers could use GPS data to identify livestock distribution problems and experiment with strategies to remedy the problems. Our data shows that the remedy need not necessarily be expensive: it can be as simple as changing the location of stocking.

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