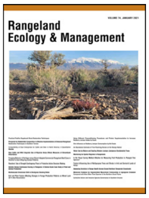
Rangeland Ecology & Management xxx (xxxx) xxx
1134

Contents lists available at ScienceDirect

Rangeland Ecology & Management

journal homepage: www.elsevier.com/locate/rama



Modeling Riparian Use by Cattle – Influence of Management, Season, and Weather ☆

Mary M. Rowland [1],*, Ryan M. Nielson [2], David W. Bohnert [3], Bryan A. Endress [3], Michael J. Wisdom [1], Joshua P. Averett [4]

[1] U.S. Forest Service, Pacific Northwest Research Station, La Grande, OR 97850, USA
[2] Eagle Environmental, Inc., Santa Fe, NM 87508, USA
[3] Eastern Oregon Agricultural Research Center, Oregon State University, Burns, OR 97720, USA
[4] Eastern Oregon Agricultural Research Center, Oregon State University, Union, OR 97883, USA

ARTICLE INFO

Article history:
Received 29 February 2024
Revised 5 August 2024
Accepted 18 August 2024
Available online xxx

Key Words:
Beef cattle
Beta regression
Decision support
Grazing management
Herding
Riparian use model

ABSTRACT

Because riparian ecosystems are highly valued for their diverse ecological services, past and ongoing disturbances in riparian zones have led to extensive restoration efforts, litigation, and compliance monitoring of the effects of livestock grazing. Better understanding of the factors that influence cattle riparian use, especially in landscapes supporting threatened or endangered fish, could lead to improved predictions of management outcomes and riparian recovery for sustainable grazing systems. Although published models predict habitat selection by cattle, there is a gap in our understanding of cattle use, or occupancy, in riparian zones. As part of a long-term, multi-disciplinary project in a semi-arid riparian system in Oregon, USA, we collected 4 yr (2017-2020) of cattle telemetry data to identify factors affecting riparian use by cattle. We used beta regression in a Bayesian hierarchical framework to model the daily proportion of cattle locations in the riparian zone. We hypothesized that riparian use would 1) increase with increasing Julian date, temperature, solar radiation, days in pasture, and days since herding, and 2) decrease with higher humidity and precipitation. The best model predicted that use was greater with increasing days since herding, number of days grazing in a pasture, and Julian date, and lower as relative humidity increased. Daily riparian use by cattle averaged 0.167 (SD = 0.180) across years and pastures. The final model performed well, based on k-fold cross validation (Pearson's correlation = 0.72; 90% CI from 0.66 to 0.77). Our findings demonstrate the importance of considering management strategies (herding, grazing seasons) that affect riparian use by cattle, in tandem with weather, pasture characteristics, and other factors, and can be used in decision support systems to guide riparian grazing management.

Introduction

Riparian ecosystems worldwide provide multiple ecological services and support high biodiversity in relation to the relatively small proportion of the landscape they occupy (Obedzinski et al. 2001; National Resource Council 2002; Bestelmeyer and Briske 2012; Swanson et al. 2015). Riparian systems face numerous threats, including dams and water diversion, vegetation removal, exotic species, and recreation (Obedzinski et al. 2001; Poff et al. 2012). Improper livestock use has also altered some riparian systems, especially in the western U.S. (Kauffman and Krueger 1984; Armour et al. 1994; Erhart and Hansen 1997; National Resource Council 2002; Poff et al. 2012), leading to controversy, litigation, and changes in grazing management (Wyman et al. 2006; Charnley et al. 2018).

Disturbance by cattle (*Bos taurus*) in riparian zones can negatively impact streamside vegetation, bank stability, and water quality (Kauffman and Krueger 1984; Harris et al. 2002; DelCurto et al. 2005; Roper and Saunders 2021; Kauffman et al. 2022). In a review of monitoring data collected on Bureau of Land Management grazing allotments, failures of riparian condition standards (e.g., watershed health) were more associated with livestock grazing than

---

☆ This work was supported by the U.S. Forest Service Pacific Northwest Research Station, Wallowa-Whitman National Forest, Oregon State University, Oregon Department of Fish and Wildlife, Oregon Watershed Enhancement Board, Grande Ronde Model Watershed, and Bonneville Power Administration.

* Correspondence: Rowland, Mary M., U.S. Forest Service, Pacific Northwest Research Station, 1401 Gekeler Lane, La Grande, OR 97850, USA.
E-mail address: mary.rowland@usda.gov (M.M. Rowland).

https://doi.org/10.1016/j.rama.2024.08.023
1550-7424/

were failures of upland standards (Veblen et al. 2014). Thus, sustainable grazing in riparian areas, especially those supporting special status species such as fish listed under the U.S. Endangered Species Act (ESA), requires strategic management to limit disturbance by cattle in the riparian zone (Platts and Wagstaff 1984; Charnley et al. 2018).

In response to these challenges, management agencies have developed several standards and associated thresholds for grazing compliance indicators (e.g., stubble height, streambank alteration) to monitor riparian health (Clary and Leininger 2000; Heitke et al. 2008; Burton et al. 2011; Roper 2020). Measurements are made along the "greenline," described by Swanson et al. (2015) as "the vegetated streambank closest to the active channel" and more formally defined by Burton et al. (2011) as "a linear grouping of perennial plants at or near the water's edge along a stream channel." If measurement thresholds are exceeded during the grazing season, or over successive years, range managers may alter permit conditions by lowering stocking densities, excluding riparian areas with fencing, or reducing grazing season length. All these conservation efforts come with the possibility of economic losses for permittees (Charnley et al. 2018; Roper 2020).

A variety of factors affect cattle distributions, including topography and forage condition. Many studies have documented the consistent influence of slope on habitat use by cattle, a product of the energetic costs of grazing on and traversing steep terrain (Mueggler 1965; Cook 1966; Bryant 1982; Roath and Kruger 1982; Roever et al. 2015; Rivero et al. 2021). Grazing behaviors are strongly shaped by the interactions of terrain and forage quantity and quality, a pattern found in grazing systems worldwide (Rivero et a. 2021). Flatter and greener streamside environments are commonly selected in late summer when riparian areas provide more succulent vegetation and a reliable source for daily watering needs (Parsons et al. 2003; Roper and Saunders 2021).

Climate and weather patterns also affect how cattle distribute across landscapes. Thermal stress as temperatures peak during summer months can exacerbate cattle requirements for water (National Academies of Sciences, Engineering, and Medicine 2016), which can increase heat loads and concomitant cattle behavior (Sprinkle et al. 2021), including use of riparian areas (Harris et al. 2002; Franklin et al. 2009; Malan et al. 2018). With increasing solar radiation in semi-arid environments, cattle often seek the more shaded environments of riparian areas compared to uplands (National Resource Council 2002; Parsons et al. 2003; Tucker et al. 2008; Lees et al. 2019; Cheleuitte-Nieves et al. 2020). Cattle may also select sites within an optimal range of relative humidity (Bryant 1982; Roath and Krueger 1982) or combinations of temperature and humidity (Roath and Krueger 1982; Loza et al. 1992; Franklin et al. 2009). Periods of drought can likewise influence cattle distributions (Roever et al. 2015), leading to more riparian use when upland forage senesces (Marlow and Pogacnik 1986) or, conversely, increased upland use if greenup follows rainfall events (Bork et al. 2001). We define riparian use in this paper as synonymous with riparian occupancy, not utilization of riparian forage.

Temporal factors, for example, seasonality or day of year, can drive cattle riparian use by serving as proxies for increasing temperatures and the typical decline in forage quality and abundance, especially in uplands, from peak conditions early in the grazing season to senescence later (Parsons et al. 2003; DelCurto et al. 2005; Malan et al. 2018; Raynor et al. 2021). This pattern is especially true when cattle graze in semi-arid systems; for example, cattle in eastern Oregon, USA were on average 62 m farther from streams in early (mid-June to mid-July) versus late (mid-August to mid-September) summer (Parsons et al. 2003).

Past grazing experience can also alter cattle behavior on multiple timescales (e.g., seasonal, annual). Large herbivores like cattle have "spatial memories" and behavioral types that may influence their distributions (Bryant 1982; Bailey et al. 1996; Creamer and Horback 2024). For example, Walburger et al. (2009) found that older cows placed in the same pastures in consecutive years grazed at higher elevations and farther from water than younger cows with less experience. Similarly, Howery et al. (1998) reported that cows returned to locations where they were reared as calves.

Herding is a well-established management tool for achieving optimal cattle distributions (Skovlin 1957; Cook 1966; Bailey 2004, 2005; Bailey et al. 2008), but studies that quantified the efficacy of herding are uncommon. Among those that did, most revealed positive effects of range riding. In a Montana study, herding reduced the time cattle spent near perennial streams and resulted in increased stubble heights near waterways compared to controls (Bailey et al. 2008). On public lands in Idaho, herding led to less time spent by cattle in the riparian area but was effective only with daily riding (Butler 2000). In eastern California, Derose et al. (2020) reported that herding effort was positively (but not significantly; $P > 0.2$) associated with riparian richness metrics (e.g., invertebrate taxa). These studies did not, however, report on the effects of weather or seasonality.

As described above, research on factors that influence cattle space use is well-established, including habitat selection models to predict static spatial distributions of cattle in pastures with riparian areas (Clark et al. 2016; Kaufmann et al. 2013; Roever et al. 2015). Some studies have estimated riparian use by cattle (Bailey et al. 2008; Franklin et al. 2009; Johnson et al. 2016; Roper and Saunders 2021), while others have documented effects of livestock grazing on key stream and riparian monitoring metrics (Carter et al. 2017; Goss and Roper 2018; Roper and Saunders 2021). None, however, have developed predictive models that identify the dynamic temporal factors that influence riparian use by cattle.

Better quantification of the interactions of range riding, season, and weather in a multivariate framework can both inform livestock management and benefit special resource needs such as salmonid habitat. Increases in global warming on North American rangelands (Polley et al. 2013), ongoing declines in stocks of endangered salmonids (Wilson et al. 2022), recent publications describing negative effects of riparian grazing (Jones et al. 2022; Krall and Roni 2023), and calls for livestock removal from public lands (Beschta et al. 2013; Swette and Lambin 2021; Kauffman et al. 2022; Ripple et al. 2022) all point to the importance of such models.

We initiated a long-term study in eastern Oregon, USA with the overarching goal of better understanding how wild and domestic ungulate grazing affects stream and riparian restoration for salmonids. To support this goal, we sought to investigate the compatibility of a suite of cattle grazing practices with stream restoration, including frequent range riding and pasture moves (Averett et al. 2017; Wisdom et al. 2021). This paper focuses on cattle use of the riparian zone. Our objective was to predict riparian use by cattle during summer by modeling temporal factors, weather, cattle behavior, and herding, using 4 yr (2017-2020) of telemetry location data. In predicting riparian use, we sought to complement existing spatial models of habitat use by cattle. We predicted that riparian use would 1) increase with increasing Julian date, temperature, solar radiation, days in pasture, and days since herding, and 2) decrease with higher humidity and daily and prior (e.g., weekly) precipitation. Understanding how these specific components influence cattle use of riparian zones, combined with existing knowledge about factors that affect use, such as pasture characteristics, offsite water, and stocking rates, can help managers develop sustainable grazing practices and predict outcomes of management decisions in these essential systems (Figure 1).

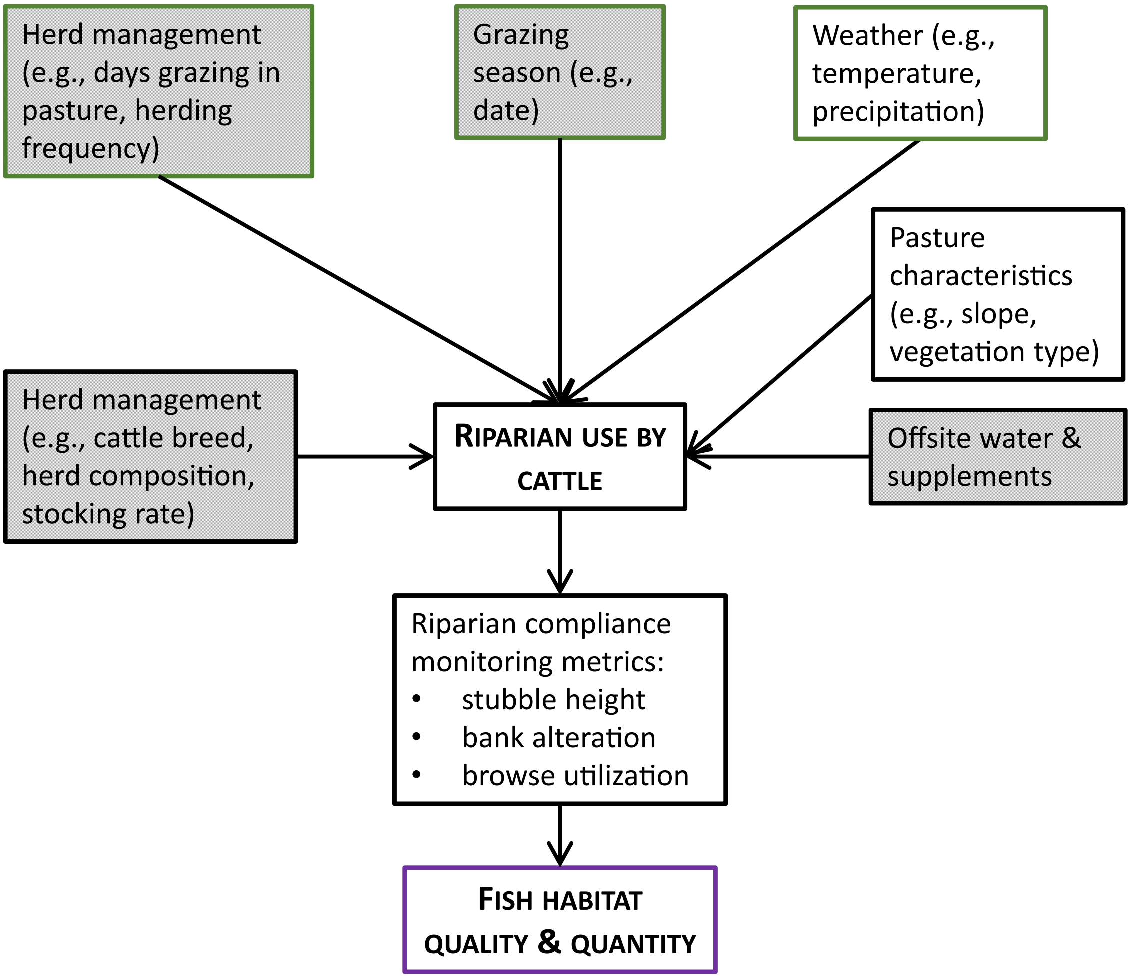


Figure 1. Schematic depicting potential influences on riparian grazing by cattle, which is linked to metrics often used in compliance monitoring to evaluate fish habitat. Gray stippled boxes indicate factors that management can influence, and boxes outlined in green depict those addressed in the cattle riparian use model. Other known factors that may affect riparian monitoring metrics and fish habitat, such as wild ungulates and inherent stream and greenline characteristics, are not shown.

Materials and Methods

Study area

The Meadow Creek study area encompasses 2 218 ha within the Starkey Experimental Forest and Range (Starkey) in northeastern Oregon, USA. Starkey is a long-term research site established by the U.S. Forest Service (USFS) to investigate grazing and rangeland management practices in semi-arid lands common to the Intermountain West (Figure 2; Rowland et al. 1997). Climate and vegetation communities at Starkey are typical of forested and upland riparian systems in the Blue Mountains ecoregion. Average annual precipitation at Starkey is 51 cm, most of which falls between November and June (Rowland et al. 1997).

Cattle have grazed the Starkey landscape since the mid-1800s, with grazing managed under standard USFS allotment operating plans since the early 1900s (Skovlin 1991). For research in the Meadow Creek drainage, grazing is managed in cooperation with Oregon State University (Bryant 1982; Walburger et al. 2009). The Meadow Creek Riparian Restoration Project within Starkey was implemented by the USFS in 2012–2013 to improve habitat conditions for endangered salmonids (Averett et al. 2017). As part of the experimental design, the study area was divided into 5 pastures (Fig. 2, Appendix A). Cattle were initially excluded from Meadow Creek (Pastures 1, 2, and 5 from 2013 to 2016; Figure 2) following establishment of the new pasture fencing to implement the initial phase of herbivory experiments evaluating effects of wild ungulates on riparian restoration in the absence of cattle (Averett et al. 2017). Cattle had previously been excluded from Pastures 3 and 4 since 1991 (Case and Kauffman 1997).

The riparian corridor defined for our analysis encompassed 13 km of Meadow Creek, a perennial stream supporting federally threatened steelhead (*Oncorhynchus mykiss*) and Chinook (*O. tshawytscha*) salmon. The corridor included 58 ha (2.6%) of the study area and was mapped as the combination of lowland and riverine potential vegetation types as described by Wells et al. (2015). Uplands (2 160 ha; 97.4%) composed the remainder, with percentages similar to those reported in other riparian grazing studies (Johnson et al. 2016). Elevation in the riparian zone ranged from 1 122 to 1 240 m, and up to 1 448 m in the uplands and the corridor width varied from 71 to 125 m across pastures.

Dominant vegetation types along Meadow Creek were dry meadow, wet meadow, and open forest (Averett et al. 2017). Common meadow species included meadow foxtail (*Alopecurus pratensis* L.), Idaho fescue (*Festuca idahoensis* Elmer), Northwest Territory sedge (*Carex utriculata* Boott), and panicled bulrush (*Scirpus microcarpus* J. Presl & C. Presl). Black hawthorn (*Crataegus douglasii* Lindl.) and gray alder (*Alnus incana* L. (Moench)) were common deciduous woody species, with forests dominated by ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) and Douglas-fir

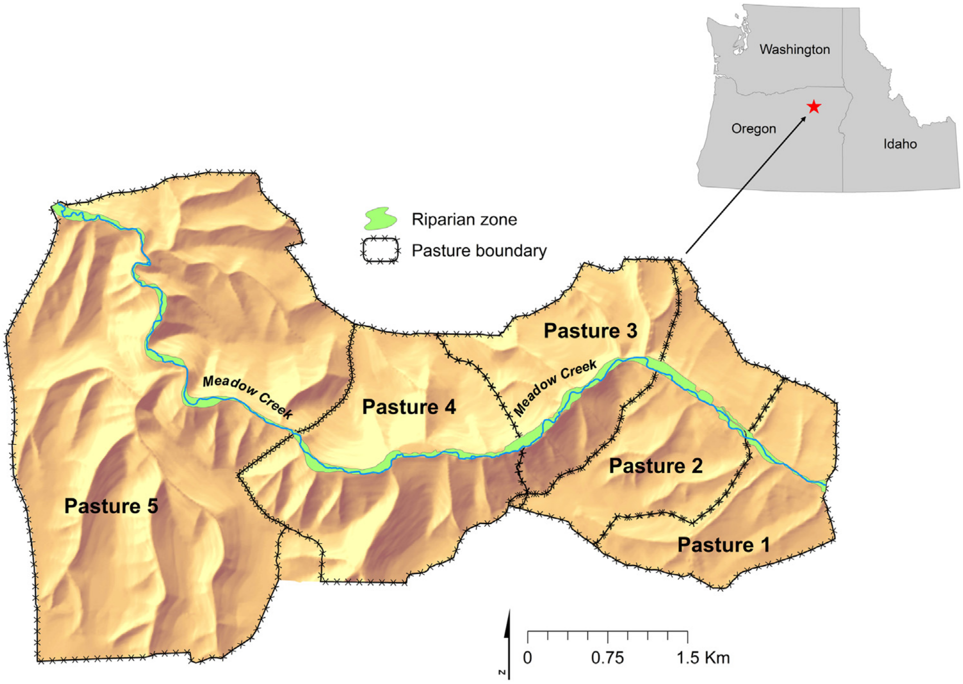


Figure 2. Meadow Creek Study Area in the Starkey Experimental Forest and Range, northeastern Oregon, USA, depicting five pastures and the riparian zone used to model riparian use by cattle. The riparian corridor included 58 ha (2.6%) of the study area and was mapped as the combination of lowland and riverine potential vegetation types as described by Wells et al. (2015). See Appendix A for more information about pasture characteristics.

(*Pseudotsuga menziesii* (Mirb.) Franco) (see Averett al. al. 2017 for details). Upland grasslands were dominated by bunchgrasses including Sandberg bluegrass (*Poa secunda* J. Presl) and bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Á. Löve) on droughty soils and Idaho fescue and prairie Junegrass (*Koeleria macrantha* (Ledeb.) Schult.) in mesic grassland sites, with increasing abundance of North Africa grass (*Ventenata dubia* (Leers) Coss.) (Averett and Endress 2022). Other common grassland species included slender cinquefoil (*Potentilla gracilis* Douglas ex. Hook.), scabland sagebrush (*Artemisia rigida* (Nutt.) A. Gray) and common yarrow (*Achillea millefolium* L.), with understory species in forests including Geyer's sedge (*C. geyeri* Boott), pinegrass (*Calamagrostis rubescens* Buckley), and heartleaf arnica (*Arnica cordifolia* Hook.).

Cattle grazing system, stocking rate, and location data

Implementation of an intensive grazing management system (Society for Range Management, 1998) for the Meadow Creek experiment began in 2017 using a deferred rotation system across the five pastures, with grazing beginning in Pasture 1 in 2017 and 2018 and in Pasture 5 in 2019 and 2020 (Fig. 2). Turnout dates ranged from 4 June – 23 June, with end-of-season dates from 5 September to 3 October (Table S1). The grazing management plan authorized by the USFS prescribes 15 d of grazing annually in Pastures 1–4 and 62 d in Pasture 5, to account for differences in pastures sizes (Appendix A). Sixty cow-calf pairs (Red Angus × Angus) were stocked in 2017, increasing to 80 cow-calf pairs the remaining 3 yr. Herd age distribution was established as approximately equal numbers of 3- through 10-yr-old cows and was held consistent by rotating out the same number of older cows (~10 yr) as new 3-yr-olds added each year. Stocking rates (i.e., ha/animal unit month) in 2018-2020 ranged from 5.1 to 10.1 across pastures, comparable to current stocking rates on adjacent USFS allotments in the Blue Mountains ecoregion. Nutritional supplements were provided, and several upland water sites, including troughs, springs, and ponds, developed on both sides of the stream in each pasture to better distribute cattle (Appendix A).

Each year ~30% of the cows, distributed equally across cow age (excluding calves, which were not collared), were fitted with Global Positioning System (GPS) telemetry collars that recorded locations every 30 min. Cows that had worn a GPS collar the prior year were collared again if possible, and data were downloaded at the end of each grazing season. To finalize the telemetry data set for modeling, we first omitted data from collars with <100 locations and fix success rates $<80\%$ within a pasture each year (Table 1; Nielson et al. 2009). Next, we assigned "move dates" as the days on which $>50\%$ of the collared cattle had been moved from one pasture to the next. We then censored the following dates from the data set to reduce the chance of disturbance from cattle management activities not of interest influencing cattle distributions: 1) days of first turnout into Meadow Creek and removal at the end of the grazing season each year; and 2) move dates between pastures (Table S1). A multitude of activities occurred on those dates, for example, cattle being driven to Starkey, unloaded into holding pens, and released into the pasture. With our response variable of proportion of locations in the riparian area, we assumed that telemetry data from these dates would not represent the primary management activity of interest, i.e., herding to keep cattle in the uplands. Last, we created the response variable for modeling as the proportion of cattle locations each day that occurred in the riparian area, that is, we tallied telemetry locations across all collars each day and divided those occurring in the riparian corridor, as defined for our analyses, by the total locations for that day to obtain the daily proportion. We refer to this proportion as "riparian use," a measure of occupancy by cattle in the riparian zone (Marlow and Pogacnik 1986; Franklin et al. 2009; Carter et al. 2017), in contrast to other definitions of use applied to cattle grazing (e.g., percent use, defined as "grazing use of current growth;" Society for Range Management, 1998).

Covariate development

We developed a set of *a priori* covariates hypothesized to affect riparian use by cattle based on extensive literature review

Table 1
Telemetry data used to model riparian use by cattle, Meadow Creek Study Area, eastern Oregon, USA.

Year	No. cow/calf pairs[1]	No. collars[2]	No. locations (range)	Mean fix success rate
2017	60	20	60 765 (171 to 1 684)	93.0
2018	80	17	40 360 (102 to 1 093)[3]	94.1
2019	80	14	51 782 (173 to 4 036)	90.5
2020	80	18	63 750 (113 to 2 922)	96.3

[1] Three bulls were also grazed for a portion of each grazing season to accommodate a 60-day breeding season.
[2] Numbers indicate collars used for analyses based on fix success rates exceeding 80% and ≥100 locations for each collar for all pasture/year combinations (see text for details).
[3] Telemetry collar programming error in 2018 resulted in fewer total locations that year.

Table 2
Covariates considered in beta regression models to predict riparian use by cattle, Meadow Creek Study Area, eastern Oregon, USA. All covariates except *Days since herding* and *Season* were standardized before modeling; see text for details.

Covariate category	Covariate	Description	Rationale	Example references
Herding	Days since herding, Days since herding (categorical)	Days elapsed since range rider present (categories = 0, 1, 2, or ≥3)	Herding reduces time in riparian area	Butler (2000), Derose et al. (2020)
Precipitation	Precip, Precip1, Precip2	Total precipitation (mm) on sampling date and during prior 1 or 2 weeks	Increased forage quantity and quality in uplands	Bryant (1982), Harris et al. (2002)
Relative humidity	Max RH, Mean RH, Min RH	Maximum, average, and minimum relative humidity (RH; proportion) recorded during the 24-h day	Humidity can increase thermal stress	Franklin et al. (2009), Shaw and Dodd (1979)
Solar radiation	Max solar, Mean solar	Maximum and average solar radiation (W/m^2) recorded during the 24-h day	Increasing use of shade as solar radiation increases	Lees et al. (2019), Tucker et al. (2008)
Temperature	Max temp, Mean temp, Min temp	Maximum, average, and minimum temperature (°C) recorded during the 24-h day	Higher temperatures can decrease time spent foraging and increase time near water	Bryant (1982), Parsons et al. (2003)
Other	JDate, JDate^2	Days since 1 Jan each (Julian) calendar year (1 Jan = 0), including quadratic form	Proxy for increasing forage senescence and thermal stress.	Brown et al. (2022), Parsons et al. (2003)
Other	Pasture days	Integer reflecting number of days cattle have been in each pasture each year	Learned behavior influences animal distributions	Butler (2000), Harris et al. (2002)
Other	PropHeat	Daily proportion of values (categories 0, 1; $n = 48$ per day) when Max temp >25°C	Index of heat stress	DelCurto et al. (2005)
Other	Season	Season categories: early (<1 August; value = 0), late (≥1 August; value = 1)	Proxy for differences in forage senescence and thermal stress	Brown et al. (2022), Marlow and Pogacnik (1986)
Other	THI	Temperature-Humidity Index (THI) combining daily Max temp and Min RH (Franklin et al. 2009:2155)	THI influences shade-seeking behavior	Franklin et al. (2009), Loza et al. (1992), Malan et al. (2018), Sprinkle et al. (2021)

(Table 2). To evaluate the role of range riding, we created a herding covariate using daily journals maintained by range riders. We recorded any day with active range riding directed at moving cattle (versus other activities such as mending fences) as a herding day. The covariate developed for modeling—*Days since herding*—had a value of 0 for active herding days (Table 2).

We next created a set of temporal and weather-centric covariates for modeling (Table 2). For temporal covariates we hypothesized that duration of grazing in a pasture could affect time spent in the riparian area, given that cattle learn over time about prevailing conditions in uplands versus the riparian corridor (Butler 2000; Harris et al. 2002). This covariate, *Days in pasture*, documented the total days cattle were grazed in each pasture annually (Table 2). Other temporal covariates included Julian date (*Jdate*, in linear and quadratic form), a proxy for increasing heat load and seasonal declines in forage quantity and quality, and a categorical variable representing season (early, late; Table 2).

Precipitation data came from the NRCS Snowpack Telemetry (SNOTEL) weather station located within Starkey (https://wcc.sc.egov.usda.gov/reportGenerator/; County Line Station) to create daily, weekly, and biweekly accumulated precipitation for the 4 yr of our study (Table 2). For the remaining weather covariates, we acquired data every 30 min from a weather station (Em50 Data Collection System, Decagon Devices, Inc.) located along Meadow Creek, including temperature, relative humidity, and solar radiation. We also derived new covariates based on these data, such as the Temperature-Humidity Index (*THI*; Franklin et al. 2009; Malan et al. 2018; Sprinkle et al. 2021) (Table 2). Values of THI >72 are considered a mild heat load for cattle, with those reaching 79 or more classified as severe (Sprinkle et al. 2021).

Data analysis

Statistical model

We used a Bayesian hierarchical approach (Kéry and Royle 2020) and beta regression (Ferrari and Cribari-Neto 2004; Douma and Weedon 2019) to model daily proportions of locations within the riparian area (Appendix B). We chose beta regression over other models (e.g., log-normal, glm with logit-link) due to it restricting estimates to the [0,1] interval and flexibility in handling overdispersion observed in the data. Douma and Weeden (2019) suggest caution in using beta regression over binomial regression with maximum likelihood when the sample sizes are low. However, we used Markov chain Monte Carlo (MCMC) methods in a Bayesian hierarchical model with count-based proportions based on large sample sizes (i.e., 47 locations/collar/day x number of collars). We incorporated a random pasture effect to account for the lack of independence in the repeated measures of the average daily proportions within a pasture over time. We used the beta regression formulation in Smithson and Verkuilen (2006) and provide code for the Bayesian hierarchical model using Rjags (Kellner 2021) in Supplemental Material (S2).

Beta regression assumes independence between observations and that observations are continuous between 0 and 1 but do not include 0 or 1. Any zeros in our data were either the result of no actual use of the riparian area, sample size (number of cattle collared), or the fix schedule and missing shorter intervals of riparian use (e.g., when crossing Meadow Creek). To fit beta-regression models, we transformed the response by adding 0.001 to the zero proportions prior to modeling (Douma and Weedon 2019).

Model development

After deriving 18 model covariates for each grazing season (2017-2020; Table 2), we checked for collinearity among covariates using Pearson's correlation coefficient; if two covariates were highly correlated ($|r| > 0.6$), we did not include them in the same model. We then created six covariate groups: herding, precipitation, relative humidity, solar radiation, temperature, and "other," which represented a set of temporal and derived covariates (Table 2). We chose to retain all covariates in the "other" group for modeling, given the diversity of potential contributions from this set (e.g., seasonality and derived indices based on temperature). For the remaining groups, we applied a two-stage information-theoretic approach (Rowland et al. 2018) whereby we first compared covariates in each category using univariate models with beta regression. We chose the best covariate from each group for the next modeling step based on the Watanabe-Akaike information criterion (WAIC; Hobbs and Hooten 2015; Watanabe 2010) values resulting from beta regression. The use of WAIC is like other information criteria such as Akaike's (AIC; Burnham and Anderson 2002), the Bayesian information criterion (BIC; Burnham and Anderson 2002), and the Deviance information criterion (DIC; Hobbs and Hooten 2015) in that the model with the lower value is determined to be better. However, compared to the others, WAIC is fully Bayesian (unlike AIC or BIC), based on the actual predictive procedure (not DIC), and is valid for hierarchical models (unlike AIC, BIC, or DIC; Hobbs and Hooten 2015).

We could not find any description of potential models of riparian use in the literature to evaluate, so we then developed a list of all possible models by combining the 10 remaining covariates, limiting the number of covariates in a model to six. We used this subjective limit to avoid overly complicated models. We identified strong multicollinearity between all temporal and weather covariates (e.g., relative humidity, *Pasture days*) and the combination of a linear and quadratic form of Julian date (e.g., weather $\sim Jdate + Jdate^2$; Fig. S3). Thus, we only considered the linear and quadratic forms for Julian date in models that did not contain evidence of multicollinearity. We also initially considered interactions between *Season* and four covariates (three precipitation covariates and *MinTemp*). Because our preliminary investigations revealed no significant interactions, however, we excluded these interactions from our final model set. We standardized all covariates prior to modeling by subtracting the mean and dividing by the standard deviation.

We fitted all models in a Bayesian hierarchical framework using MCMC methods and the R package jagsUI (Kellner 2021) and ranked models by WAIC values. We calculated 90% Bayesian credible intervals (CIs; percentile method) for all coefficients. If the 90% CI included 0, we concluded that the estimate was not statistically significant (equivalent to an alpha level of 0.10). We used Normal(0, 10) priors for coefficients in the model for the proportion of use and a Gamma(0.1, 0.1) prior for the precision parameter φ. The Gamma distribution assumed for φ is a common choice of a prior for a distribution of non-negative continuous values. We selected the shape and scale values of 0.1 for the Gamma because they provided vague priors. Comparisons of MCMC results using other values for the Gamma shape and scale parameters did not show signs of sensitivity to the values selected. We ran three chains of 20 000 iterations following a burn-in of 5 000 iterations. We did not thin or reduce the number of iterations in the MCMC process. Although thinning is often seen in the literature, it is only advantageous in storage costs and data handling (Gilks et al. 1995) and posterior distributions are better approximated without thinning (Hobbs and Hooten 2015).

Model evaluation

We used common methods for evaluating convergence and goodness-of-fit for Bayesian hierarchical models including the Gelman-Rubin diagnostic (Rhat: Gelman and Rubin 1992), trace plots, residual plots, and plots of posterior distributions to evaluate model convergence (Sinharay 2003). We assumed that we obtained sufficient convergence when all Rhat values were <1.05 and there appeared to be adequate mixing among chains (Hobbs and Hooten 2015). In addition, we conducted several posterior predictive checks (P_B; Hobbs and Hooten 2015; Conn et al. 2018) using the Freeman-Tukey measure of model fit (Conn et al. 2018) and other discrepancy statistics based on the mean, 10%, and 90% quantiles of the simulated data based on the model. Bayesian *p*-values and other discrepancy checks based on posterior distributions provide insight into the difference between the observed and simulated data based on the posterior distributions of the model coefficients. A large or small Bayesian *p*-value (>0.95 or <0.05) based on simulated data strongly suggest lack of model fit, potentially due to model choice or prior distributions, whereas a *p*-value close to 0.5 indicates there is insufficient evidence of poor fit.

By combining locations across animals and calculating the total proportion of the cattle locations in the riparian corridor for the day, we removed any potential effect of temporal autocorrelation in individual cattle locations. The daily response of all collared cows also negates concerns about the independence between collared cows, provided they represent the average cow in the pasture. The autocorrelation we were concerned about and address in our approach is that of the residuals of our model for use within a day (not every 30 min). We evaluated the assumption of lack of independence in standardized model residuals between days by calculating residual temporal correlation using Moran's I (Moran 1948) in a single dimension (time). As described above, we recognized the lack of independence across years within a pasture, and thus used pasture as a random effect in our model.

To evaluate the ability of the best model to predict daily riparian use within a particular year, we used k-fold cross-validation (Fielding and Bell 1997), defining the individual yr 2017–2020 for *k*. We dropped one year and refit the final model using the remaining 3 yr, and calculated Pearson's correlation coefficients between the predicted values of riparian use and the new estimates of observed use. We then repeated this process, using individual pastures (1–5) for *k*, dropping one pasture and refitting the model with the remaining four pastures. Last, we created marginal plots for each covariate in the best model to reveal the change in predicted use as each single covariate changes, holding all others constant at their median values.

Results

After censoring the dataset to meet our criteria for appropriate dates, we had 338 days available for modeling across the 4 yr. Start-of-season grazing for data used in modeling ranged from 5 June (2018) to 24 June (2020), with end dates from 14 August (2018) to 2 October (2019; Table S1). Telemetry data, filtered for number of locations and fix success, yielded annual cattle locations from 14 to 20 GPS collars (18% to 33% of cows) ranging from >63 000 (2020) to ~ 40 000 (2018), with mean fix success rate exceeding 90% in all years (Table 1). A collar programming error midseason in 2018 accounted for the compressed season and lower

Table 3
Mean proportion of daily cattle locations in the riparian area, Meadow Creek Study Area, eastern Oregon, USA, by pasture and year.

Pasture	Year				Mean
	2017	2018	2019	2020	
1	0.040	0.041	0.041	0.062	0.046
2	0.185	0.181	0.178	0.159	0.175
3	0.645	0.423	0.431	0.670	0.542
4	0.327	0.216	0.169	0.282	0.248
5	0.202	–[1]	0.099	0.106	0.136
Mean	0.280	0.215	0.183	0.256	0.167

[1] Telemetry collar programming error in 2018 resulted in no locations in Pasture 5 that year.

location count in that year, with no locations recorded within Pasture 5.

Cattle use of riparian area

Use of the riparian zone by cattle varied by season, year, and pasture (Table 3). Cattle frequented the riparian area often, with riparian use recorded on 88% ($n = 300$) of sampling dates and mean daily proportional use of 0.167 (SD = 0.180) across years and pastures. Of the 39 days with no riparian use, 85% were in Pasture 5, and 74% occurred before 1 August (i.e., early season). Cattle spent ∼40% more time in the riparian corridor in late summer ($\bar{x} = 0.199$, SD = 0.186) versus early ($\bar{x} = 0.142$, SD = 0.172). Mean proportions were highest in the initial year of grazing (2017; $\bar{x} = 0.228$, SD = 0.209) and in Pasture 3 ($\bar{x} = 0.530$, SD = 0.203) (Table 3).

Model covariates

We brought 10 covariates forward for modeling, including all from the “other” category and the best from each of the five remaining groups, based on their WAIC values: *Days since herding* (herding), *Precip1* (precipitation), *Mean RH* (relative humidity), *Max solar* (solar radiation), and *Max temp* (temperature; see Table 2 for descriptions). Cattle were herded frequently, with range riding occurring on 50% of days modeled ($n = 169$; Fig. 3) and *Days since herding* rarely exceeding four ($n = 10$). *Mean RH* was consistent across years, with average values ranging from 0.58 to 0.70 (Appendix C) and lowest in late July. Weekly precipitation (*Precip1*) was more variable, with 62% of modeled dates having no rainfall the preceding week. The maximum weekly sum recorded (45.72 mm) occurred in 2018, the wettest grazing season, and was 9-fold greater than the maximum in 2020 (Appendix C). Number of days cattle had grazed in a pasture averaged 18.5 across all years and pastures but was $\le$10 for nearly half ($n = 158$) of our sampling dates. Among daily *THI* values, 146 (43%) indicated a mild heat load, but only 11 (3%) were $\ge$79 (severe heat load; Sprinkle et al. 2021). The maximum value recorded was 81.

Best models of cattle riparian use

We evaluated 241 models to predict cattle use of the riparian area. The best model contained four covariates: *Mean RH, Days since herding, Pasture days*, and *JDate* (Tables 4, 5; Fig. 4). Predicted use was greater with increasing *Days since herding*, number of days cattle had grazed in a pasture (*Pasture days*), and *JDate*, but lower as *Mean RH* increased (Fig. 4). Bayesian CIs did not span 0 for these four parameters in any of the best 10 models, and signs of coefficients remained consistent across this model subset (Table 4). Notably, the 60 best models all contained the covariate pair *Days since herding* and *Pasture days*. Other covariates represented in the top 10 models included *Max solar* (5 models), *Precip1* (4), and *THI* (2; Table 4). Predicted riparian use was greater with increasing precipitation the preceding week and as *THI* increased; coefficients were significant *THI* but not *Precip1* (Table 4). By contrast, signs for the *Max solar* parameter flipped among models and this covariate was not significant in any of the top 10 models (Table 4).

Model evaluation and performance

The best model converged, based on the suite of MCMC diagnostics we explored. Gelman-Rubin (Rhat) values were 1 for all parameters in the model, and trace plots and marginal posterior distributions revealed good mixing and consistent results among the three chains (Fig. S4). The Bayesian *p*-value for the posterior predictive check for the Freeman-Tukey discrepancy was 0.55. Mean simulated use was 0.1730 (90% CI from 0.1565 to 0.1907), similar to the average observed use of 0.1673. Based on the final model, the mean 10th quantile of the simulated data was 0.0931 (90% CI from 0.0006 to 0.3290), with an observed value of 0.0017, whereas the mean 90th quantile was 0.2790 (90% CI from 0.0467 to 0.6000), with an observed value of 0.4241. These posterior predictive checks did not indicate significant lack of fit, but the discrepancy measures based on lower tail (10$^{\text{th}}$ quantile) of the simulated data suggest that the final model may slightly over-predict when riparian use is low.

Predicted versus observed values of riparian use were positively correlated, based on k-fold validation, with Pearson’s correlations of predicted values of riparian use and estimates of observed use across years ranging from 0.69 (2020) to 0.74 (2017). Using pastures as folds, the lowest correlation was in Pasture 3 (0.56) but was similar across the remaining pastures (0.69–0.79). The overall correlation of predicted versus observed values was 0.72 (90% CI from 0.67 to 0.78; Fig. 5). Again, evidence suggested that the model tended to over-predict somewhat when riparian use was low. The largest temporal correlation among residuals 1 d apart was 0.38 (90% CI from 0.03 to 0.74) in Pasture 5 in 2019, but correlation beyond one day was <0.2 and all CIs covered 0.0. Ninety-percent CIs for Moran’s I in all other years in Pasture 5 (2017 and 2020) and other Pastures (1–4) included 0.0.

Discussion

Our experimental study at Meadow Creek helped illustrate the role of management-based and selected weather-related abiotic covariates in predicting riparian use by cattle. The top-performing model included two key herd management strategies, revealing a positive relationship between *Days since herding* and *Pasture days* with predicted use. The co-occurrence of these covariates in the 60 top models corroborated their strong contribution in our model set and is consistent with other studies (e.g., Butler 2000; Walburger et al. 2009; Derose et al. 2020). We focused our model on the riparian zone, rather than the pasture scale, to direct attention to the specific sites monitored for compliance in most riparian grazing allotments.

Range riding clearly affected riparian use—daily proportions in the riparian area nearly doubled by the 5th day since herding (Fig. 4). Not all cattle responded similarly, however, as seen by the rapid return of some collared cows to the riparian zone soon after herding while others remained in the uplands for days (Fig. 3). Butler (2000) reported that with daily herding <4% of the herd returned to the riparian area the following day, but that percentage increased to 16%–24% with one day’s riding missed. Benefits of range riding include greater residual riparian forage (Bailey 2004), increased stubble heights and lower cattle fecal abundance (Bailey et al. 2008), less bank trampling (Butler 2000), and greater biodiversity (Derose et al. 2020). Although published data are unavailable, several permittees grazing cattle allotments on the national

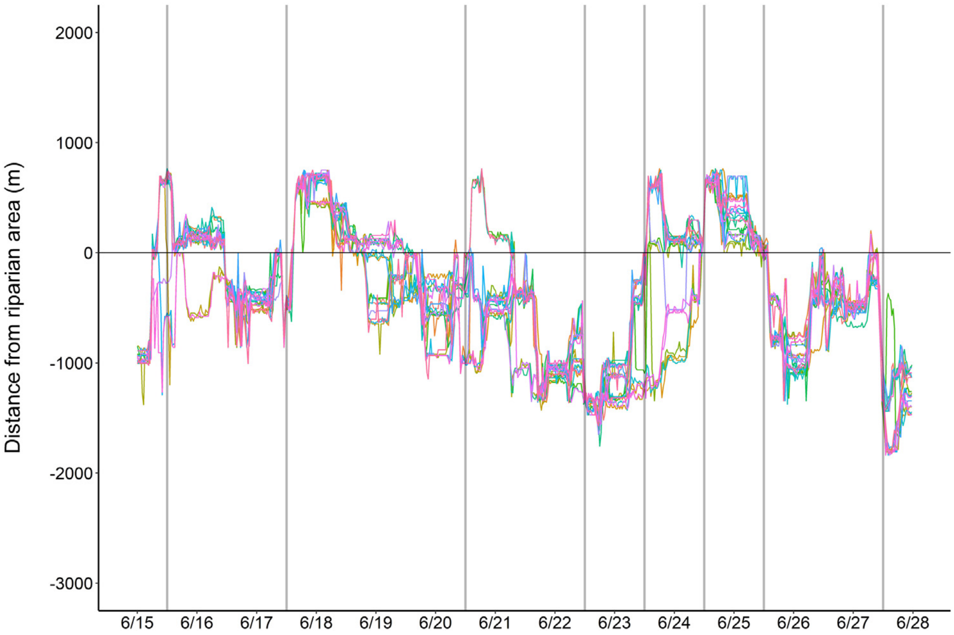


Figure 3. Example depiction of cattle locations in relation to the riparian zone in the Meadow Creek Study Area, northeastern Oregon, USA. The graph displays distances of telemetered cattle from the riparian zone used in our analyses (0 horizontal line) in Pasture 1 during June 2017. Colors represent individual collared cows, and gray vertical lines depict dates of range rider "pushes" to move cattle to the uplands. Locations above the horizontal line are on the north side of the creek, and below this line the south side.

Table 4
Model ranks based on the Watanabe-Akaike information criterion (WAIC) for the top 10 models predicting riparian use by cattle. Delta (Δ)WAIC is the difference in WAIC compared to the top model. A positive coefficient is represented by a '+' before the covariate name, and a negative coefficient by '–'. Covariates with significant coefficients ($\alpha = 0.10$) based on 90% Bayesian credible intervals excluding 0 are denoted by '*'.

Model rank	Probability of riparian use model[1]	ΔWAIC
1	Intercept – Mean RH*[2] + Days since herding* + Pasture days* + JDate*	0.0000
2	Intercept + Precip1 – Mean RH * + Days since herding* + Pasture days* + JDate*	0.1311
3	Intercept + Max solar – Mean RH * + Days since herding* + Pasture days* + JDate*	1.1900
4	Intercept + Precip1 + Max solar – Mean RH * + Days since herding* + Pasture days* + JDate*	1.4964
5	Intercept – Mean RH* + Days since herding* + Pasture days*	1.6401
6	Intercept + Days since herding* + THI* + Pasture days* + JDate*	1.9224
7	Intercept + Precip1 – Mean RH* + Days since herding* + Pasture days*	2.3162
8	Intercept – Max solar – Mean RH* + Days since herding* + Pasture days*	2.4947
9	Intercept + Precip1 – Max solar – Mean RH* + Days since herding* + Pasture days*	2.6824
10	Intercept + Max solar + Days since herding* + THI* + Pasture days* + JDate*	2.8944

[1] See Table 2 for complete descriptions of covariates.
[2] All covariates in the 10 models except *Days since herding* were standardized prior to modeling; see text for details.

Table 5
Estimates of parameters in the best model predicting riparian use by cattle in the Meadow Creek Study Area, eastern Oregon, USA. The mean (estimate), standard deviation (SD), and 90% Bayesian credible intervals (CI) were obtained from their posterior distributions.

Parameter	Mean	SD	Lower CI	Upper CI
Intercept	-1.2477	0.1427	–	–
Mean RH[1,2]	-0.2007	0.0524	-0.2870	-0.1152
Days since herding	0.1576	0.0356	0.0985	0.2157
Pasture days[2]	0.2901	0.0591	0.1923	0.3869
JDate[2]	0.1206	0.0496	0.0388	0.2019
Phi[3]	6.0334	0.5143	5.2096	6.8985

[1] See Table 2 for complete descriptions of covariates.
[2] These parameters were standardized prior to modeling; see text for details.
[3] Scalar used in beta regression. See Appendix B and S2 for more information.

forest adjacent to Starkey employ range riders daily or every few days, especially in pastures with ESA-listed fish (A. Johnson, USFS, personal communication). The Meadow Creek study intentionally implemented an intensive grazing system (Society for Range Management, 1998) in which relative increases in labor and capital, i.e., herding, were employed to test the efficacy of this system in a riparian area with fisheries concerns. Follow-on analyses will further elucidate the effectiveness of range riding to meet ecological and economic objectives for riparian management.

We concur with Bailey (2004) and Swanson et al. (2015) that herding, integrated with complementary strategies such as upland supplements and water, is fundamental for riparian recovery and sustainable grazing and is likely most effective when pasture sizes are relatively small (National Resource Council 2002). Past studies also documented the influence of grazing experience on cattle distributions (Bryant 1982; Bailey 2005; Walburger et al. 2009); presumably cattle use uplands less as they gain spatial knowledge of the comparatively superior riparian forage and water resources as the grazing season progresses (National Resource Council 2002; Parsons et al. 2003).

The remaining covariates in our top model, *JDate* and *Mean RH*, are also supported in published literature. Parsons et al. (2003) reported that cattle use of riparian areas was significantly greater in late summer pastures versus early; similarly, Marlow and Pogacnik (1986) found that cattle spent more time feeding in the riparian zone late August–September compared to June–July. The inclusion of *JDate* rather than *Season* in our best models (Table 4) likely

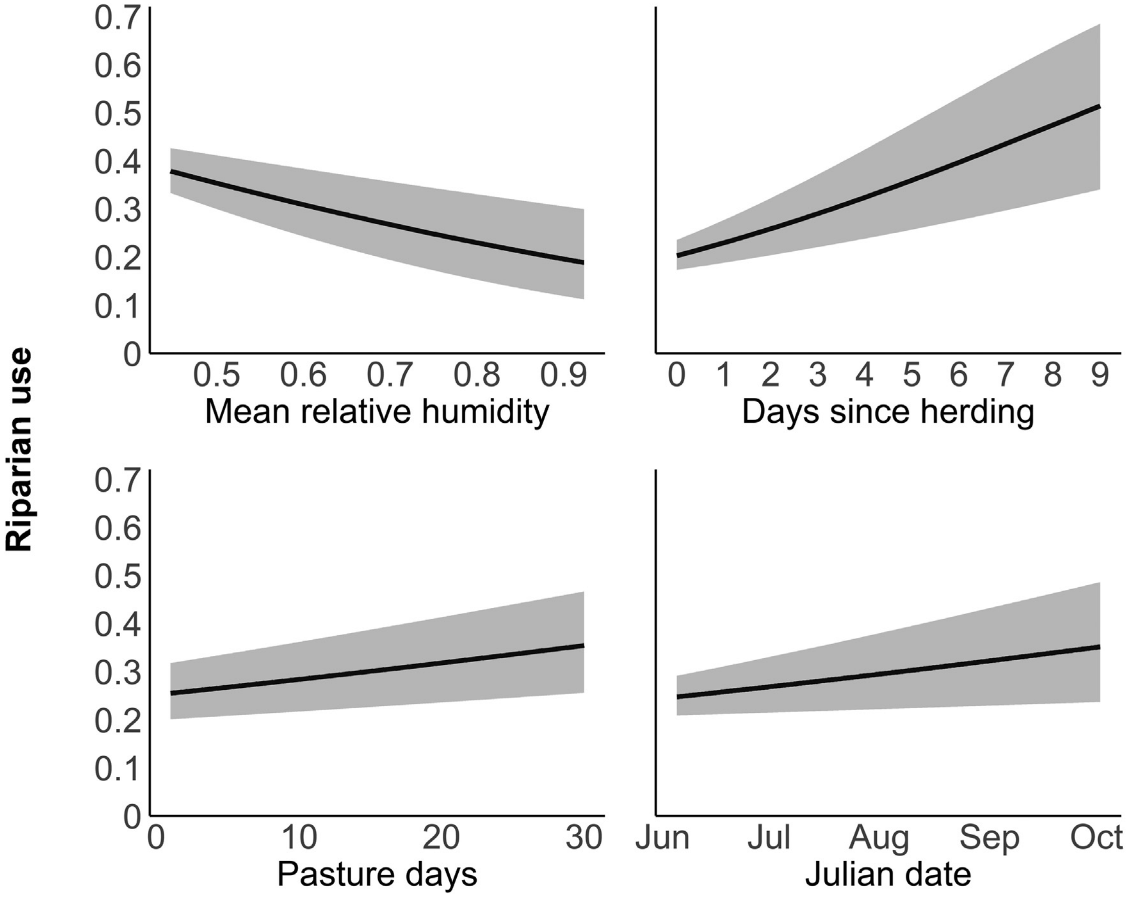


Figure 4. Marginal plots of predicted riparian use by cattle (i.e., daily proportion of cattle locations in the riparian area) in relation to covariates in the best model predicting daily riparian use, Meadow Creek Study Area, northeastern Oregon, USA. Each plot demonstrates the change in predicted use as the single covariate changes, holding all others constant at their median values. Shaded areas represent 90% credible intervals.

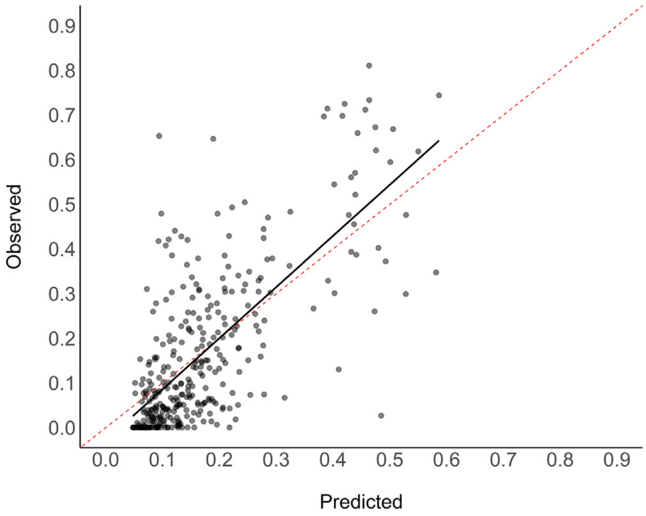


Figure 5. Observed versus modeled predictions of proportions of daily riparian use by cattle in the Meadow Creek Study Area, northeastern Oregon, USA. The red dashed line represents a correlation of 1 (i.e., y = x); the black line represents the linear regression of observed vs predicted values for illustration purposes only.

reflected the more precise measure offered by a continuous versus categorical covariate.

Our finding of a negative relationship between predicted riparian use and relative humidity mirrors results of a previous study along Meadow Creek in which both yearling and adult cows moved upslope as relative humidity increased (Fig. 4; Bryant 1982). Although not in the best model, *THI* occurred in 2 of the top 10 models, with a positive, significant coefficient in both (Table 4), consistent with other studies evaluating this index in relation to riparian use by cattle (Franklin et al. 2009; Malan et al. 2018). Daily *THI* values indicative of mild or severe heat load occurred on 46% of our sampling dates.

Variability in cattle use

Cattle use of the riparian area of Meadow Creek differed among years and pastures (Table 3) but differed little between daytime versus nighttime (Fig. S5). Moreover, mean proportional riparian use (0.167, or 16.7%) was markedly higher than many values reported in the literature, despite intensive range riding. In a study comparable to ours in terms of quantifying telemetry locations in the riparian zone, Johnson et al. (2016) used GPS data from a 5-yr study on USFS grazing allotments in eastern Oregon to evaluate cattle presence in two buffer zones (30, 60 m) around perennial streams, areas comparable to our riparian zone. The highest percentage of cattle locations in the 60-m buffer for any site/month combination was 17.2%, but average use across sites and years was only 2.5% — more than five-fold smaller than the Meadow Creek average.

Other studies also reported relatively low riparian occupancy; however, disparities between our findings and theirs may be attributed in part to differences in methodologies, including our use of 24-h telemetry versus daytime-only data. For example, Roper and Saunders (2021) used cameras to document daytime cattle presence on 39 stream reaches in the Pacific Northwest, finding that even in reaches with the greatest livestock presence ($n = 17$), no cattle were documented in the riparian area on 28–89% of sampled days and riparian occurrence averaged 1.7%. However, cameras in this study were focused on short (~110-m) reaches along the greenline, where monitoring data were collected. Rates of riparian occupancy similar to ours, however, were reported in a grazing experiment in Montana. There, Bailey et al. (2008) found that telemetered cattle in the control group (no herding) spent 33 ± 2% of their time within 100 m of a perennial stream, in contrast to herded cattle (22 ± 2%).

Differences in riparian use across pastures in Meadow Creek likely reflect a combination of diverse environmental conditions and our deferred rotation system. For example, Pastures 3 and 4 had the greatest riparian use ($\bar{x} = 0.54$ and 0.25, respectively; Table 3), despite Pasture 4 having the lowest stocking rate (Appendix A). These pastures are characterized by higher percentages of steep terrain (Appendix A), a well-documented influence on cattle distribution (Cook 1966; Ganskopp and Vavra 1987; Ganskopp and Bohnert 2009) that can impede the efficacy of range riding. However, Pasture 5 also had relatively low riparian use (less than Pasture 2; Table 3), despite having a relatively large percentage of the pasture in steep slopes, comparable to that in Pastures 3 and 4 (Appendix A). This finding indicates that pasture-level slope conditions are not the sole landscape characteristic driving riparian use.

Importantly, given the deferred rotation grazing system in Meadow Creek, Pastures 3 and 4 were never grazed early in the year (Table S1) when forage quality and quantity were greatest. Last, Pastures 3 and 4 also had the largest percentage area in the riparian zone, though this percentage was small (<5.0%) for all pastures (Appendix A).

Contrasts in use across years may be explained in part by weather patterns and herder experience. Riparian use was lowest in 2019, the study year of the most favorable weather (e.g., lowest values of *Max solar, Max temp, THI,* and *Proportion Heat*; Appendix C), and the highest (1.22) August self-calibrating Palmer Drought Severity Index (scPDSI; Wells et al. 2004), indicating slightly wet conditions. By contrast, the first year of our experiment (2017) had the highest riparian use, likely a cumulative effect of range riders lacking experience in the study system and relatively warm, dry conditions (e.g., highest *Max temp* and *Proportion Heat* values; Appendix C). Herding occurred on only 34 (44%) sampling days in 2017. Despite cattle being herded almost daily in Pasture 3 that year, mean riparian use was 0.645 and the grazing season in that pasture was the most restricted of all years (Table S1), reflecting the inability of range riders to maintain cattle in the uplands.

Model performance and utility

Our model relied on a robust data set (>200,000 GPS locations over 4 yr) to meet our objective to quantify the influence of a suite of covariates in predicting riparian use by cattle. Prior model fitting on the location data using logistic regression with a random effect for pasture failed to converge, likely due to overdispersion in the data in combination with the small sample sizes at the pasture level (3–4 yr). Failing to account for overdispersion in the data can result in CIs that are too narrow and incorrect inference. The model performed reasonably well, given the challenges inherent in developing accurate predictive models of cattle distributions (Anthony and Germino 2022; Senft et al. 1987). Using a longer data stream under a wider range of environmental conditions and applying the model in traditional federal grazing allotments could strengthen model relevance. Continued use of GPS-collared cattle in research will help refine knowledge of cattle behavior and distribution in riparian and other rangeland systems (Cheleuitte-Nieves et al. 2020).

The Meadow Creek study revealed higher proportions of riparian use than commonly reported. Concomitantly, the targeted grazing season within each pasture was achieved or exceeded only 7 times (37%) in the 4 yr of the experiment (Table S1). Pasture moves in the study were based primarily on results of periodic "trigger monitoring" of the greenline by range staff, an ocular assessment of the three riparian indicators used for grazing compliance: stubble height, bank alteration, and woody browse use. Lost grazing days due to one or more trigger thresholds being reached before the planned move date translate directly into shortened grazing seasons, with economic costs to producers. For example, Pasture 4 was grazed for the planned length (15 days) only two of 4 yr, and Pasture 3 never reached its full allocation of days (Table S1).

Our model could help managers anticipate when conditions that precipitate earlier-than-desired pasture moves might occur. For example, model predictions could be analyzed in relation to riparian Multiple Indicator Monitoring (MIM; Burton et al. 2011) metrics (e.g., stubble height, browse utilization) that have been widely adopted as standards for livestock grazing. MIM data have been collected yearly along Meadow Creek immediately after cattle are moved from a pasture and at the end of the grazing season in all pastures. In our study, streambank alteration was the most common trigger leading to a pasture move (unpublished data), which could be related to cumulative daily riparian occurrence by cattle to determine what levels of use are associated with reaching or exceeding monitoring thresholds. Over the duration of our study MIM indicated that grazing compliance standards, developed to facilitate recovery of riparian zone conditions and benefit listed salmonid species, were met in each year (USDA Forest Service Pacific Northwest and Southwest Regions 2018).

Model utility was demonstrated by the inclusion of three covariates that can be manipulated by range managers: frequency of range riding (*Days since herding*), number of grazing days in a pasture (*Pasture days*), and grazing dates (*JDate*). Values of the fourth, relative humidity, cannot be managed but can be accounted for when developing grazing plans by accessing readily available current and historic weather data. Our model can thus be used to predict levels of riparian use as a function of range management decisions under a variety of plausible scenarios (e.g., range riding schedules, days grazing per pasture) and potential grazing outcomes. Outputs from the model will also be incorporated into decision support systems for range allotments with riparian pastures, linking to additional components that influence grazing systems (e.g., wild ungulate use; Averett et al. 2017; Roper and Saunders 2021) and stream conditions critical for fish and other riparian resources (Platts et al. 1987; Roper and Saunders 2021; Fig. 1). Our model has heuristic value in that its structure and components can aid future studies exploring riparian use by cattle or investigating alternative herding and grazing strategies in more depth.

Using model predictions to inform changes in grazing strategies may be hindered by economic and regulatory constraints, especially in public lands grazing allotments supporting ESA-listed fish (Charnley et al. 2018). First, paying for more intensive range riding may be infeasible for some permittees. Second, grazing season lengths, turnout and end-of-season dates, and allotted days per pasture are all prescribed by federal land management agencies in allotment management plans, with sometimes little flexibility (Charnley et al. 2018). For example, an earlier onset of grazing would likely decrease cattle use of the riparian area, but such changes are challenged by the need to protect salmonid redds (Ballard and Krueger 2005) and potential soil damage (Marlow and Pogacnik 1986) early in the season.

Whatever management strategies are adopted to promote sustainable riparian grazing, effects of a warming climate should be explicitly considered and incorporated. Although cumulative precipitation at Starkey has not changed during the last 30 yr, monthly average rainfall for May through August during 2015–2019 was lower than the corresponding 30-yr averages (1981–2010), ranging from 2.1 mm (May) to 11.4 mm (June) less (Brown et al. 2022). Mean summer (June-August) temperatures also have increased by 2°C ($P = 0.04$) and senescence of graminoids is three weeks longer compared to the early 1990s (Brown et al. 2022), results likely applicable to much of the interior Northwest. Late season grazing is expected to become more compressed given climate projections across rangelands in much of North America (Joyce et al. 2013; Polley et al. 2013), potentially forcing ranchers to purchase additional feed or graze private property longer. Thus, predictions of riparian use from our model should be made in the context of shifting climate regimes, using the best available and site-specific climate model outputs.

Implications

Limits on livestock use within many allotments on western public lands are determined by the effects of cattle grazing in riparian areas, regardless of upland conditions or forage utilization. By focusing our model on cattle use in the riparian zone rather than the pasture scale, we targeted the specific area monitored for grazing compliance in federal allotments supporting ESA-listed fish, i.e., the greenline (USDA Forest Service Pacific Northwest and Southwest Regions 2018). Thus, our model has potential to influence grazing decisions across thousands of hectares of federal grazing allotments where ESA-listed fish are present; for example, more than half of the allotments on national forests in the Blue Mountains Ecoregion contain critical habitat for listed fish (Charnley et al. 2018). Early pasture moves resulting from greenline trigger monitoring can lead to unused forage in the uplands and the need for producers to offset this loss (Bailey 2004; Swanson et al. 2015). Although many prior studies link cattle occurrence in riparian zones to grazing compliance indicators (e.g., DelCurto et al. 2005; Harris et al. 2002; Roper and Saunders 2021), our model provides an additional link by serving as a tool to predict that occurrence. As such, it can help guide management to strategically minimize riparian use, promote riparian recovery, and maximize grazing days as part of a comprehensive decision support system.

Our findings demonstrate the importance of management strategies (e.g., herding, grazing season) that affect riparian use by cattle and highlight the need for their explicit consideration in developing grazing plans, in tandem with weather, pasture characteristics, and other factors (Fig. 1). Although our study did not address all factors related to riparian grazing (Fig. 1), our model complements other readily available data on features such as pasture characteristics and offsite water that collectively influence riparian use by cattle. Creating pastures with specific riparian objectives, in contrast to managing riparian areas within much larger pastures, may offer a solution in some cases (Ehrhart and Hansen 1997; Wyman et al. 2006; Swanson et al. 2015). Other management strategies to consider when grazing in pastures with streams supporting endangered fish are 1) using cattle breeds with better feed efficiency, which may use steeper terrain and distribute more evenly than other cattle (Sprinkle et al. 2021); and 2) using virtual or other fencing systems to exclude cattle (Campbell et al. 2018; Boyd et al. 2022). Regardless, regulatory flexibility, cooperative monitoring, and adaptive experimentation are needed to promote fish recovery while sustaining grazing operations (Charnley et al. 2018). Viewing rangeland science as a complex socio-ecological system that embraces adaptive management and explicitly considers animal distribution, as done in our study, will benefit future grazing management in riparian systems and beyond (Jablonski et al. 2023).

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mary M. Rowland: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Ryan M. Nielson:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **David W. Bohnert:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization. **Bryan A. Endress:** Writing – review & editing, Methodology, Conceptualization. **Michael J. Wisdom:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Joshua P. Averett:** Writing – review & editing, Investigation, Conceptualization.

Acknowledgments

We appreciate the inputs of Aric Johnson, Jim Capurso, Brett Roper, and Robert Garcia in the design of the Meadow Creek grazing study, and Martin Vavra for his many insights early in the development of the manuscript. Jennifer Hafer and Bridgett Naylor derived key spatial data and summarized herding records. Hans Hayden, Ryan Kennedy, Dennis Rea, Brian Dick, Cheryl Borum, and Eric DeWitt provided trigger monitoring data and assisted with implementation of the grazing system in Meadow Creek. Range riders and management staff were invaluable in this work, including Belle Blair, Kenny Fite, Mark Fite, Jake Ricker, and others. We appreciate the thoughtful review of an earlier version of this manuscript by Bryan Stevens.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2024.08.023.

References

Anthony, C.R., Germino, M.J., 2022. Predictive models of selective cattle use of large, burned landscapes in semiarid sagebrush-steppe. Rangeland Ecology & Management 85, 1–8. doi:10.1016/j.rama.2022.07.007.

Armour, C., Duff, D., Elmore, W., 1994. The effects of livestock grazing on western riparian and stream ecosystem. Fisheries 19 (9), 9–12. doi:10.1577/1548-8446(1994)019%3C0009:TEOLGO%3E2.0.CO;2.

Averett, J.P., Endress, B.A., 2022. Forb composition gradients and intra-annual variation in a threatened Pacific Northwest Bunchgrass Prairie. Ecology and Evolution 12, e902. doi:10.1002/ece3.9021.

Averett, J.P., Endress, B.A., Rowland, M.M., Naylor, B.J., Wisdom, M.J., 2017. Wild ungulate herbivory suppresses deciduous woody plant establishment following salmonid stream restoration. Forest Ecology and Management 391, 135–144. doi:10.1016/j.foreco.2017.02.017.

Bailey, D.W., 2004. Management strategies for optimal grazing distribution and use of arid rangelands. Journal of Animal Science 82 (suppl_13), E147–E153. doi:10.2527/2004.8213_supplE147x.

Bailey, D.W., 2005. Identification and creation of optimum habitat conditions for livestock. Rangeland Ecology & Management 58 (2), 109–118. doi:10.2111/03-147.1.

Bailey, D.W., Gross, J.E., Laca, E.A., Rittenhouse, L.R., Coughenour, M.B., Swift, D.M., Sims, P.L., 1996. Mechanisms that result in large herbivore grazing distribution patterns. Journal of Range Management 49 (5), 386–400. doi:10.2307/4002919.

Bailey, D.W., Van Wagoner, H.C., Weinmeister, R., Jensen, D., 2008. Evaluation of low-stress herding and supplement placement for managing cattle grazing in riparian and upland areas. Rangeland Ecology & Management 61 (1), 26–37. doi:10.2111/06-130.1.

Ballard, T.M., Krueger, W.C., 2005. Cattle and salmon I: Cattle distribution and behavior in a northeastern Oregon riparian ecosystem. Rangeland Ecology & Management 58 (3), 267–273. doi:10.2111/1551-5028(2005)58[267:CASICD]2.0.CO;2.

Beschta, R.L., Donahue, D.L., DellaSala, D.A., Rhodes, J.J., Karr, J.R., O'Brien, M.H., Fleischner, T.L., Deacon Williams, C., 2013. Adapting to climate change on western public lands: addressing the ecological effects of domestic, wild, and feral ungulates. Environmental Management 51 (2), 474–491. doi:10.1007/s00267-012-9964-9.

Bestelmeyer, B.T., Briske, D.D., 2012. Grand challenges for resilience-based management of rangelands. Rangeland Ecology & Management 65 (6), 654–663.

Bork, E.W., Thomas, T., McDougall, B., 2001. Herbage response to precipitation in central Alberta boreal grasslands. Journal of Range Management 54 (3), 243–248.

Boyd, C.S., O'Connor, R., Ranches, J., Bohnert, D.W., Bates, J.D., Johnson, D.D., Davies, K.W., Parker, T., Doherty, K.E., 2022. Virtual fencing effectively excludes cattle from burned sagebrush steppe. Rangeland Ecology & Management 81, 55–62. doi:10.1016/j.rama.2022.01.001.

Brown, C.L., Coe, P.K., Clark, D.A., Wisdom, M.J., Rowland, M.M., Averett, J.P., Johnson, B.K., 2022. Climate change effects on understory plant phenology: implications for large herbivore forage availability. Environmental Research: Ecology 1, 011002. doi:10.1088/2752-664X/ac7fb0.

Bryant, L.D., 1982. Response of livestock to riparian zone exclusion. Journal of Range Management 35 (6), 780–785.

Burnham, K.P., Anderson, D.R., 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer, New York, NY, USA, p. 488. doi:10.1007/978-0-387-22456-5_6.

Burton, T.A., Smith, S.J., Cowley, E.R. 2011. Multiple indicator monitoring (MIM) of stream channels and streamside vegetation. Technical Reference 1737-23 (Revised). BLM/OC/ST-10/003+1737+REV. USDI Bureau of Land Management, National Operations Center, Denver, CO, USA, p. 155.

Butler, P.J., 2000. Cattle distribution under intensive herded management. Rangelands 22 (2), 21–23.

Campbell, D.L., Haynes, S.J., Lea, J.M., Farrer, W.J., Lee, C., 2018. Temporary exclusion of cattle from a riparian zone using virtual fencing technology. Animals 9 (1), 5.

Carter, J., Catlin, J.C., Hurwitz, N., Jones, A.L., Ratner, J., 2017. Upland water and deferred rotation effects on cattle use in riparian and upland areas. Rangelands 39 (3), 112–118. doi:10.1016/j.rala.2017.06.003.

Case, R.L., Kauffman, J.B., 1997. Wild ungulate influences on the recovery of willows, black cottonwood and thin-leaf alder following cessation of cattle grazing in northeastern Oregon. Northwest Science 71 (2), 115–126.

Charnley, S., Gosnell, H., Wendel, K.L., Rowland, M.M., Wisdom, M.J., 2018. Cattle grazing and fish recovery on US federal lands: can social–ecological systems science help? Frontiers in Ecology and the Environment 16 (S1), S11–S22. doi:10.1002/fee.1751.

Cheleuitte-Nieves, C., Perotto-Baldivieso, H.L., Wu, X.B., Cooper, S.M., 2020. Environmental and landscape influences on the spatial and temporal distribution of a cattle herd in a South Texas rangeland. Ecological Processes 9 (1), 39. doi:10.1186/s13717-020-00245-6.

Clark, P.E., Lee, J., Ko, K., Nielson, R.M., Johnson, D.E., Ganskopp, D.C., Pierson, F.B., Hardegree, S.P., 2016. Prescribed fire effects on resource selection by cattle in mesic sagebrush steppe. Part 2: mid-summer grazing. Journal of Arid Environments 124, 398–412. doi:10.1016/j.jaridenv.2015.03.005.

Clary, W.P., Leininger, W.C., 2000. Stubble height as a tool for management of riparian areas. Journal of Range Management 53 (6), 562–573.

Conn, P.B., Johnson, D.S., Williams, P.J., Melin, S.R., Hooten, M.B., 2018. A guide to Bayesian model checking for ecologists. Ecological Monographs 88, 526–542.

Cook, C.W., 1966. Factors affecting utilization of mountain slopes by cattle. Journal of Range Management 19 (4), 200–204.

Creamer, M., Horback, K., 2024. Consistent individual differences in cattle grazing patterns. Applied Animal Behaviour Science 271, 106176. doi:10.1016/j.applanim.2024.106176.

DelCurto, T., Porath, M., Parsons, C.T., Morrison, J.A., 2005. Management strategies for sustainable beef cattle grazing on forested rangelands in the Pacific Northwest. Rangeland Ecology & Management 58 (2), 119–127.

Derose, K.L., Battaglia, C.F., Eastburn, D.J., Roche, L.M., Becchetti, T.A., George, H.A., Lile, D.F., Lancaster, D.L., McDougald, N.K., Tate, K.W., 2020. Riparian health improves with managerial effort to implement livestock distribution practices. The Rangeland Journal 42 (3), 153–160. doi:10.1071/RJ20024.

Douma, J.C., Weedon, J.T., 2019. Analysing continuous proportions in ecology and evolution: a practical introduction to beta and Dirichlet regression. Methods in Ecology and Evolution 10 (9), 1412–1430. doi:10.1111/2041-210X.13234.

Ehrhart, R.C., Hansen, P.L., 1997. Effective cattle management in riparian zones: a field survey and literature review. Montana BLM Riparian Technical Bulletin No. 3. USDI Bureau of Land Management, Montana State Office, Missoula, MT, USA, p. 51. Accessed 11 June 2024.

Ferrari, S., Cribari-Neto, F., 2004. Beta regression for modelling rates and proportions. Journal of Applied Statistics 31 (7), 799–815.

Fielding, A.H., Bell, J.F., 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Environmental Conservation 24 (1), 38–49. doi:10.1017/S0376892997000088.

Franklin, D.H., Cabrera, M.L., Byers, H.L., Matthews, M.K., Andrae, J.G., Radcliffe, D.E., McCann, M.A., Kuykendall, H.A., Hoveland, C.S., Calvert II, V.H., 2009. Impact of water troughs on cattle use of riparian zones in the Georgia Piedmont in the United States. Journal of Animal Science 87 (6), 2151–2159. doi:10.2527/jas.2008-1522.

Ganskopp, D., Vavra, M., 1987. Slope use by cattle, feral horses, deer, and bighorn sheep. Northwest Science 61 (2), 74–81.

Ganskopp, D.C., Bohnert, D.W., 2009. Landscape nutritional patterns and cattle distribution in rangeland pastures. Applied Animal Behaviour Science 116 (2), 110–119. doi:10.1016/j.applanim.2008.10.006.

Gelman, A., Rubin, D.B., 1992. Inference from iterative simulation using multiple sequences. Statistical Science 7, 457–472.

Gilks, W.R., Richardson, S., Spiegelhalter, D.J., 1995. Markov Chain Monte Carlo in practice. Chapman & Hall/CRC, Boca Raton, FL, USA, p. 504.

Goss, L.M., Roper, B.B., 2018. The relationship between measures of annual livestock disturbance in western riparian areas and stream conditions important to trout, salmon, and char. Western North American Naturalist 78 (1), 76–91. doi:10.3398/064.078.0108.

Harris, N.R., Johnson, D.E., George, M.R., McDougald, N.K., 2002. The effect of topography, vegetation, and weather on cattle distribution at the San Joaquin Experimental Range, California. In: Standiford, R.B., et al. (tech. editor), Proceedings of the Fifth Symposium on oak woodlands: Oaks in California's challenging landscape. Gen. Tech. Rep. PSW-GTR-184. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, USA, pp. 53–63.

Heitke, J.D., Henderson, R.C., Roper, B.B., Archer, E.K., 2008. Evaluating livestock grazing use with streambank alteration protocols: challenges and solutions. Rangeland Ecology & Management 61 (6), 647–655.

Hobbs, N.T., Hooten, M.B., 2015. Bayesian models: a statistical primer for ecologists. Princeton University Press, Princeton, NJ, USA, p. 320.

Howery, L.D., Provenza, F.D., Banner, R.E., Scott, C.B., 1998. Social and environmental factors influence cattle distribution on rangeland. Applied Animal Behaviour Science 55 (3-4), 231–244.

Jablonski, K.E., Derner, J.D., Bailey, D.W., Davies, K.W., Meiman, P.J., Roche, L.M., Thacker, E.T., Vermeire, L.T., Stackhouse-Lawson, K.R., 2023. Principles for successful livestock grazing management on western US rangelands. Rangelands 46 (2), 35–41. doi:10.1016/j.rala.2023.11.001.

Johnson, D.E., Larson, L.L., Wilson, K.D., Clark, P.E., Williams, J., Louhaichi, M., 2016. Cattle use of perennial streams and associated riparian areas on a northeastern Oregon landscape. Journal of Soil and Water Conservation 71, 484–493.

Jones, C.S., Duncan, D.H., Rumpff, L., Robinson, D., Vesk, P.A., 2022. Permanent removal of livestock grazing in riparian systems benefits native vegetation. Global Ecology and Conservation 33, e01959. doi:10.1016/j.gecco.2021.e01959.

Joyce, L.A., Briske, D.D., Brown, J.R., Polley, H.W., McCarl, B.A., Bailey, D.W., 2013. Climate change and North American rangelands: assessment of mitigation and adaptation strategies. Rangeland Ecology & Management 66 (5), 512–528.

Kauffman, J.B., Beschta, R.L., Lacy, P.M., Liverman, M., 2022. Livestock use on public lands in the western USA exacerbates climate change: implications for climate change mitigation and adaptation. Environmental Management 69, 1137–1152. doi:10.1007/s00267-022-01633-8.

Kauffman, J.B., Krueger, W.C., 1984. Livestock impacts on riparian ecosystems and streamside management implications: a review. Journal of Range Management 37 (5), 430–438. http://www.jstor.org/stable/3899631. Accessed 21 August 2021.

Kaufmann, J., Bork, E.W., Blenis, P.V., Alexander, M.J., 2013. Cattle habitat selection and associated habitat characteristics under free-range grazing within heterogeneous Montane rangelands of Alberta. Applied Animal Behaviour Science 146 (1), 1–10. doi:10.1016/j.applanim.2013.03.014.

Kellner, K. 2021. jagsUI: a wrapper around "rjags" to streamline "JAGS" analyses. R package version 1.5.2. https://CRAN.R-project.org/package=jagsUI. Accessed 25 January 2022.

Kéry, M., Royle, J.A., 2020. Applied hierarchical modeling in ecology: Analysis of distribution, abundance and species richness in R and BUGS: Volume 2. Dynamic and advanced models. Academic Press, Cambridge, MA, USA, p. 820. doi:10.1016/C2015-0-04070-9.

Krall, M., Roni, P., 2023. Effects of livestock exclusion on stream habitat and aquatic biota: a review and recommendations for implementation and monitoring. North American Journal of Fisheries Management 43 (2), 476–504. doi:10.1002/nafm.10863.

Lees, A.M., Sejian, V., Wallage, A.L., Steel, C.C., Mader, T.L., Lees, J.C., Gaughan, J.B., 2019. The impact of heat load on cattle. Animals 9 (6), 322. https://www.mdpi.com/2076-2615/9/6/322. Accessed 14 July 2023.

Loza, H.J., Grant, W.E., Stuth, J.W., Forbes, T.D.A., 1992. Physiologically based landscape use model for large herbivores. Ecological Modelling 61 (3), 227–252. doi:10.1016/0304-3800(92)90020-F.

Malan, J.-A.C., Flint, N., Jackson, E.L., Irving, A.D., Swain, D.L., 2018. Offstream watering points for cattle: Protecting riparian ecosystems and improving water quality? Agriculture, Ecosystems & Environment 256, 144–152. doi:10.1016/j.agee.2018.01.013.

Marlow, C.B., Pogacnik, T.M., 1986. Cattle feeding and resting patterns in a foothills riparian zone. Journal of Range Management 39 (3), 212–217. doi:10.2307/3899051.

Moran, P.A., 1948. The interpretation of statistical maps. Journal of the Royal Statistical Society. Series B (Methodological) 10 (2), 243–251.

Mueggler, M.F., 1965. Cattle distribution on steep slopes. Journal of Range Management 18, 255–257.

National Academies of Sciences, Engineering, and Medicine, 2016. Nutrient requirements of beef cattle. Eighth revised edition. The National Academies Press, Washington, DC, USA, p. 494.

National Resource Council, 2002. Riparian areas: functions and strategies for management. The National Academies Press, Washington, DC, USA, p. 448.

Nielson, R.M., Manly, B.F.J., McDonald, L.L., Sawyer, H., McDonald, T.L., 2009. Estimating habitat selection when GPS fix success is less than 100%. Ecology 90 (10), 2956–2962. doi:10.1890/08-1562.1.

Obedzinski, R.A., Shaw III, C.G., Neary, D.G., 2001. Declining woody vegetation in riparian ecosystems of the western United States. Western Journal of Applied Forestry 16 (4), 169–181.

Parsons, C.T., Momont, P., Delcurto, A, McInnis, T., Porath, M.L., 2003. Cattle distribution patterns and vegetation use in mountain riparian areas. Journal of Range Management 56 (4), 334–341. http://www.jstor.org/stable/4004036. Accessed 10 August 2023.

Platts, W.S., Armour, C., Booth, G.D., Bryant, M., Bufford, J.L., Cuplin, P., Jensen, S., Lienkaemper, G.W., Minshall, G.W., Monsen, S.B., Nelson, R.L., Sedell, J.R., Tuhy, J.S., 1987. Methods for evaluating riparian habitats with applications to management. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT, USA, p. 177 Gen. Tech. Rep. INT-GTR-221.

Platts, W.S., Wagstaff, F.J., 1984. Fencing to control livestock grazing on riparian habitats along streams: Is it a viable alternative? North American Journal of Fisheries Management 4 (3), 266–272. doi:10.1577/1548-8659(1984)4%3C266:FTCLGO%3E2.0.CO;2.

Poff, B., Koestner, K.A., Neary, D.G., Merritt, D., 2012. Threats to western United States riparian ecosystems: A bibliography. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA, p. 78 Gen. Tech. Rep. RMRS-GTR-269.

Polley, H.W., Briske, D.D., Morgan, J.A., Wolter, K., Bailey, D.W., Brown, J.R., 2013. Climate change and North American rangelands: trends, projections, and implications. Rangeland Ecology & Management 66 (5), 493–511.

Raynor, E.J., Gersie, S.P., Stephenson, M.B., Clark, P.E., Spiegal, S.A., Boughton, R.K., Bailey, D.W., Cibils, A., Smith, B.W., Derner, J.D., Estell, R.E., Nielson, R.M., Augustine, D.J., 2021. Cattle grazing distribution patterns related to topography across diverse rangeland ecosystems of North America. Rangeland Ecology & Management 75 (1), 91–103. doi:10.1016/j.rama.2020.12.002.

Ripple, W.J., Wolf, C., Phillips, M.K., Beschta, R.L., Vucetich, J.A., Kauffman, J.B., Law, B.E., Wirsing, A.J., Lambert, J.E., Leslie, E., 2022. Rewilding the American West. BioScience 72 (10), 931–935. doi:10.1093/biosci/biac069.

Rivero, M.J., Grau-Campanario, P., Mullan, S., Held, S.D.E., Stokes, J.E., Lee, M.R.F., Cardenas, L.M., 2021. Factors affecting site use preference of grazing cattle studied from 2000-2020 through GPS tracking: a review. Sensors 21, 2696. doi:10.3390/s21082696.

Roath, L.R., Krueger, W.C., 1982. Cattle grazing and behavior on a forested range. Journal of Range Management 35 (3), 332–338. doi:10.2307/3898312.

Roever, C.L., DelCurto, T., Rowland, M., Vavra, M., Wisdom, M., 2015. Cattle grazing in semiarid forestlands: Habitat selection during periods of drought. Journal of Animal Science 93 (6), 3212–3225. doi:10.2527/jas.2014-8794.

Roper, B.B., 2020. Using stubble height to monitor livestock disturbance near streams: How a recent critique is relevant to the protection of cold-water salmonids. Rangelands 42 (3), 72–76. doi:10.1016/j.rala.2020.04.003.

Roper, B.B., Saunders, W.C., 2021. How cattle and wild ungulate use of riparian areas effects measures of streambank disturbance. Rangeland Ecology & Management 74 (1), 32–42. doi:10.1016/j.rama.2020.08.009.

Rowland, M.M., Bryant, L.D., Johnson, B.K., Noyes, J.H., Wisdom, M.J., Thomas, J.W., 1997. The Starkey Project: History, facilities, and data collection methods for ungulate research. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA, p. 62 Gen. Tech. Rep. PNW-GTR-396.

Rowland, M.M., Nielson, R.M., Wisdom, M.J., Coe, P.K., Cook, J.G., Hafer, J.M., Johnson, B.K., Naylor, B.J., Cook, R.C., Vavra, M., 2018. Linking nutrition with landscape features in a regional habitat-use model for elk in western Oregon and Washington. Wildlife Monographs 199 (1), 31–49. doi:10.1002/wmon.1033.

Senft, R., Coughenour, M., Bailey, D., Rittenhouse, L., Sala, O., Swift, D., 1987. Large herbivore foraging and ecological hierarchies: Landscape ecology can enhance traditional foraging theory. BioScience 37 (11), 789–795.

Shaw, R.B., Dodd, J.D., 1979. Cattle activities and preferences following strip application of herbicide. Journal of Range Management 32 (6), 449–452.

Sinharay, S., 2003. Assessing convergence of the Markov Chain Monte Carlo algorithms: a review. ETS Research Report Series 52. doi:10.1002/j.2333-8504.2003.tb01899.x, 2003i–.

Skovlin, J.M., 1957. Range riding - the key to range management. Journal of Range Management 10 (6), 269–271.

Skovlin, J.M., 1991. Fifty years of research progress: A historical document on the Starkey Experimental Forest and Range. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA, p. 58 Gen. Tech. Rep. PNW-GTR-266.

Smithson, M., Verkuilen, J., 2006. A better lemon squeezer? Maximum-likelihood regression with beta-distributed dependent variables. Psychological Methods 11 (1), 54–71.

Society for Range Management (SRM), 1998. In: Bedell, T.E. (Ed.), A glossary of terms used in range management, Fourth edition editor. https://rangelandsgateway.org/glossary accessed 1 June 2024.

Sprinkle, J.E., Ellison, M.J., Hall, J.B., Yelich, J.V., Willmore, C.M., Brennan, J.R., 2021. Grazing behavior and production for lactating cows differing in residual feed intake while grazing spring and summer rangeland. Translational Animal Science 5 (2), txab063. doi:10.1093/tas/txab063.

Swanson, S.R., Wyman, S., Evans, C., 2015. Practical grazing management to meet riparian objectives. Journal of Rangeland Applications 2, 1–28.

Swette, B., Lambin, E.F., 2021. Institutional changes drive land use transitions on rangelands: the case of grazing on public lands in the American West. Global Environmental Change 66, 102220. doi:10.1016/j.gloenvcha.2020.102220.

Tucker, C.B., Rogers, A.R., Schütz, K.E., 2008. Effect of solar radiation on dairy cattle behaviour, use of shade and body temperature in a pasture-based system. Applied Animal Behaviour Science 109 (2), 141–154. doi:10.1016/j.applanim.2007.03.015.

USDA Forest Service Pacific Northwest and Southwest Regions. 2018. Aquatic and riparian conservation strategy, p. 135. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd644753.pdf.

Veblen, K.E., Pyke, D.A., Aldridge, C.L., Casazza, M.L., Assal, T.J., Farinha, M.A., 2014. Monitoring of livestock grazing effects on Bureau of Land Management land. Rangeland Ecology & Management 67 (1), 68–77. doi:10.2111/REM-D-12-00178.1.

Walburger, K.J., Wells, M., Vavra, M., DelCurto, T., Johnson, B., Coe, P., 2009. Influence of cow age on grazing distribution in a mixed-conifer forest. Rangeland Ecology & Management 62 (3), 290–296. doi:10.2111/08-163R1.1.

Watanabe, S., 2010. Asymptotic equivalence of Bayes cross validation and widely applicable information criterion in singular learning theory. Journal of Machine Learning Research 11 (12), 3571–3594.

Wells, A., Crow, E., Blaha, R., 2015. Riparian vegetation mapping in the Grande Ronde Watershed, Oregon: Monitoring and validation of spring Chinook habitat recovery and population viability. ABR, Inc. - Environmental Research & Services, Anchorage, AK, USA, p. 183.

Wells, N., Goddard, S., Hayes, M.J., 2004. A self-calibrating Palmer drought severity index. Journal of Climate 17 (12), 2335–2351.

Wilson, K.L., Bailey, C.J., Davies, T.D., Moore, J.W., 2022. Marine and freshwater regime changes impact a community of migratory Pacific salmonids in decline. Global Change Biology 28 (1), 72–85. doi:10.1111/gcb.15895.

Wisdom, M., Rowland, M., Averett, J., Bohnert, D., DeBano, S., Endress, B., 2021. Ungulate grazing relationships with riparian restoration: Meadow Creek experiment. Stream Notes. U.S. Forest Service National Stream and Aquatic Ecology Center, Washington, DC, USA, p. 8. https://agsci.oregonstate.edu/sites/agscid7/files/eoarc/attachments/ungulate_grazing_relationships_with_riparian_restoration.pdf

Wyman, S., Bailey, D., Borman, M., Cote, S., Eisner, J., Elmore, W., Leinard, B., Leonard, S., Reed, F., Swanson, S., Van Riper, L., Westfall, T., Wiley, R., Winward, A., 2006. Riparian area management: Grazing management processes and strategies for riparian-wetland areas. U.S. Department of the Interior, Bureau of Land Management, National Science and Technology Center, Denver, CO, USA, p. 105 Technical Reference No. 1730-20.