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Original Research

Virtual Fencing Effectively Excludes Cattle from Burned Sagebrush Steppe ☆

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ABSTRACT

On public lands grazing allotments in the western US sagebrush steppe, cattle are generally excluded from burned pastures for 2 yr post fire. If only a portion of a pasture burns, the burned area may be fenced, allowing for cattle grazing to resume in the unburned portion. However, traditional wire-based fencing is often not an option due to expense, conflicts with wildlife management objectives, and extensive procedural logistics. We evaluated the use of a "virtual fence" (VF) for excluding cattle from burned areas within small pastures in the sagebrush steppe of southeast Oregon. VF technology (Vence Corporation, San Francisco, CA) uses satellite-controlled collars that direct animal movement within user-defined polygons using auditory and electrical cues. We fall-burned a 0.6-ha area in each of six adjacent 2.1-ha pastures in a Wyoming big sagebrush plant community in 2019. In June 2020, each pasture was stocked with 3 mature dry cows for 14 d. All cows were fitted with VF collars; collars were programed to create a virtual fence around the burned area within three of the pastures (VF treatment), and remaining pastures had electrical and auditory cues turned off (control treatment). Collars recorded animal location every 5 min. Cows in the control treatment initially spent up to 40% of their time within the burned area, and forage utilization of the burned area was nearly 70%. Cows in the VF treatment spent approximately 4% of their time in the burned area on day 1 and were recorded in the burn only incidentally thereafter; forage utilization in the burn was $<$ 3%. Our trial suggests VF technology is effective in controlling rangeland cattle movements and can severely curtail use of burned areas. Additional work is needed to evaluate VF technology in larger rangeland settings.

Introduction

Grazing animal distribution within heterogeneous landscapes is a central challenge facing contemporary managers on western rangelands (Launchbaugh and Howery 2005). Livestock grazing, whether as a land use or as a land management tool, impacts rangelands globally and animal distribution is a primary determinant of its effects on both biotic and abiotic rangeland components (Bailey et al. 2004). Lack of control over livestock distribution is a critical component driving negative effects of livestock grazing such as expansion of nondesired plant species (Condon and Pyke 2018), undesired effects of grazing on soil properties (Daddy et al. 1988), and loss of habitat for wildlife species (Schieltz and Rubenstein 2016). Alternatively, sufficient control over animal distribution enables managers to use grazing as a tool for fine fuels management (Davies et al. 2015), reducing undesired plant species (Schmelzer et al., 2014, Davies et al., 2021), maintaining desired plant species (Davies et al. 2016), and managing structure in key wildlife habitats (Boyd et al. 2014).

The distribution of grazing animals within a land management unit is affected by a plethora of factors including water and supplement locations, spatial distribution of forage resources, topographic features, thermal regulation, behavioral characteristics of both grazing herds and individual animals within herds, as well as predator avoidance (Bailey et al. 2019). In large rangeland land-

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scapes, many, if not most, of these factors are often overlooked by managers or purposefully not considered in management planning due to difficulties in amelioration. Alternatively, managers may elect to use traditional wire or electric fencing to contain animals within a broad perimeter (Bailey 2004). Traditional fencing can be effective for breaking large landscapes into smaller pastures that conform to management goals and objectives. However, pasture perimeter fencing to define outer bounds of animal movement does little to control within-pasture distribution in complex rangeland environments (Bailey and Rittenhouse 1989). This can result in both undesired environmental effects, as well as lost management opportunities. One example of the latter is the missed opportunity costs associated with forage resources within partially burned pastures, particularly on publicly owned rangeland where policy generally precludes grazing burned pastures for a period of 2 yr following fire (Gates et al. 2017). In cases of partially burned pastures on public lands, agencies can construct traditional fencing to prevent animal use of burned areas (BLM 2007); however, such an alternative is costly, logistically intensive, and subject to a host of procedural clearances that may prohibit timely implementation, and it may have unintended negative impacts on other ecosystem services (Jakes et al. 2018).

An emerging alternative to traditional fencing is the use of virtual fencing technology. This technology relies on audible and/or tactile (e.g., electrical stimulus) cues from collars or other in situ devices to deter animals for crossing user-defined boundaries (Anderson 2007). Cues to the animal can be triggered from fixed devices (e.g., a buried wire; Umstatter et al. 2015) or through the use of remotely sensed positional data (e.g., from satellites; Umstatter 2011). In theory, such technologies could create a viable system for controlling rangeland animal distribution that does not incur the same financial, logistical, and procedural limitations inherent to traditional fencing (Anderson et al. 2014). Virtual fence (VF) systems have been under development and evaluation for more than a decade (Umstatter 2011; Marini 2018; Campbell et al. 2019; Lomax et al. 2019; Campbell et al. 2020). Recent advances in electronic communication and device (i.e., collar) design have the potential to greatly increase the efficacy of the technology while reducing costs but need further evaluation to determine their utility within precision agricultural systems (Campbell et al. 2019).

We tested the efficacy of a VF system for reducing cattle use of recently burned areas within small pastures in sagebrush (*Artemisia* L.) steppe vegetation in southeast Oregon. We hypothesized that animals within pastures that included a VF boundary between burned and unburned areas would spend less time in burned areas as compared with animals in "control" pastures without a virtual boundary (i.e., no auditory cues or electrical stimuli).

Materials and Methods

Study area

The study was conducted within a Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Welsch) plant community at the Northern Great Basin Experimental Range (NGBER), located approximately 55 km west of Burns, Oregon (43.48N, 119.72 W). The study site was flat, and elevation was approximately 1 400 m. Precipitation falls as rain or snow during the October–March period, and crop year inputs (September–June) average 25.7 cm (data file, Eastern Oregon Agricultural Research Center, Burns, Oregon). Before burning, the shrub component of study sites was dominated by Wyoming big sagebrush with lesser amounts of rabbitbrush (*Chrysothamnus nauseosus* [Pall.] and Britt.). Common perennial understory species included needlegrass (*Achnatherum* sp. P. Beauv.), bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] A. Love), bottlebrush squirreltail (*Elymus elymoides* [Raf.] Swezey), Sandberg's bluegrass (*Poa secunda* J. Presl), and the non-native crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.). The non-native annual cheatgrass (*Bromus tectorum* L.) was also present at the site. Sites have been historically grazed by cattle at moderate levels during the growing season and had not burned in the preceding 18 yr.

Experimental design

All animal care and management used in this study was evaluated and approved by the Oregon State University Institutional Animal Care and Use Committee (ACUP 2020-0074).

We used a systematic-randomized block design consisting of three blocks and two virtual fencing treatments. Each block contained two adjacent 2.1-ha pastures and the three blocks were adjacent to each other (Fig. 1). The two treatments were defined by the presence or absence of virtual fencing. In pastures with virtual fences, collars were used to track cattle locations and administer auditory and electrical cues to discourage use of burned areas. In control pastures, collars were only used to track cattle locations (i.e., no auditory cues or electrical stimuli). We used a systematic process for randomizing treatment assignment to pasture within block in which the first pasture (pasture 1 in Fig. 1) was randomly assigned as a control and the remaining pasture within that block was assigned to the VF treatment. We then repeated that order of treatment assignment across the remaining two blocks. The reason for this approach was that we anticipated social behavioral influences of animals between pastures and wanted to equalize the number of adjacent VF and control pastures between adjacent blocks. In September 2019, the fall before grazing, we burned approximately 30% of each pasture using a single prescribed burn with a strip headfire technique and drip torches containing a 40:60 mixture of unleaded gasoline and diesel, creating burned and unburned subplots within each pasture (see Fig. 1).

Data collection

We used a VF system designed and manufactured by Vence Corp (San Diego, CA). In this system, the end user communicates with a solar or AC-powered base station via cellular link using the HerdManager software platform. The base station in turn uses a VHF radio signal to communicate user-defined coordinates of virtual boundaries and other information to a GPS collar worn by the animal. The collar is powered by a lithium battery and monitors animal location at user-defined intervals. Each collar has a speaker for auditory cues and two metal electrical contacts spaced 5 cm apart. The collar is designed with a weight ballast that keeps the electrical contacts in contact with only one side of the animals' neck; thus, in theory, when the animal receives an electrical stimulus, it turns away from the that stimulus, causing the animal to alter its path of travel away from the virtual boundary. Collars are designed to first deliver an auditory cue to an animal as it approaches a virtual boundary (i.e., "auditory zone"), followed by a mild electrical stimulus animal if the animal continues its direction of travel (i.e., the animal crossed into the "electrical stimulus zone"). The spatial locations of both the auditory and electrical stimulus zones are user defined. When an animal enters the audio zone, it hears a 0.5-second electronic tone followed by a 1.5-second pause. This pattern repeats until the animal leaves the auditory zone. When an animal enters the electrical stimulus zone, it receives a 0.5-second shock (800V), followed by a 1-second sound stimulus and then a 3.5-second pause. This level of electrical stimulus is comparable with that delivered by a single wire electric fence (personal communication, Todd Parker, Vence Corp.). If the animal remains in the electrical stimulus zone, this pattern repeats up to 20 times, after which the animal receives no auditory or

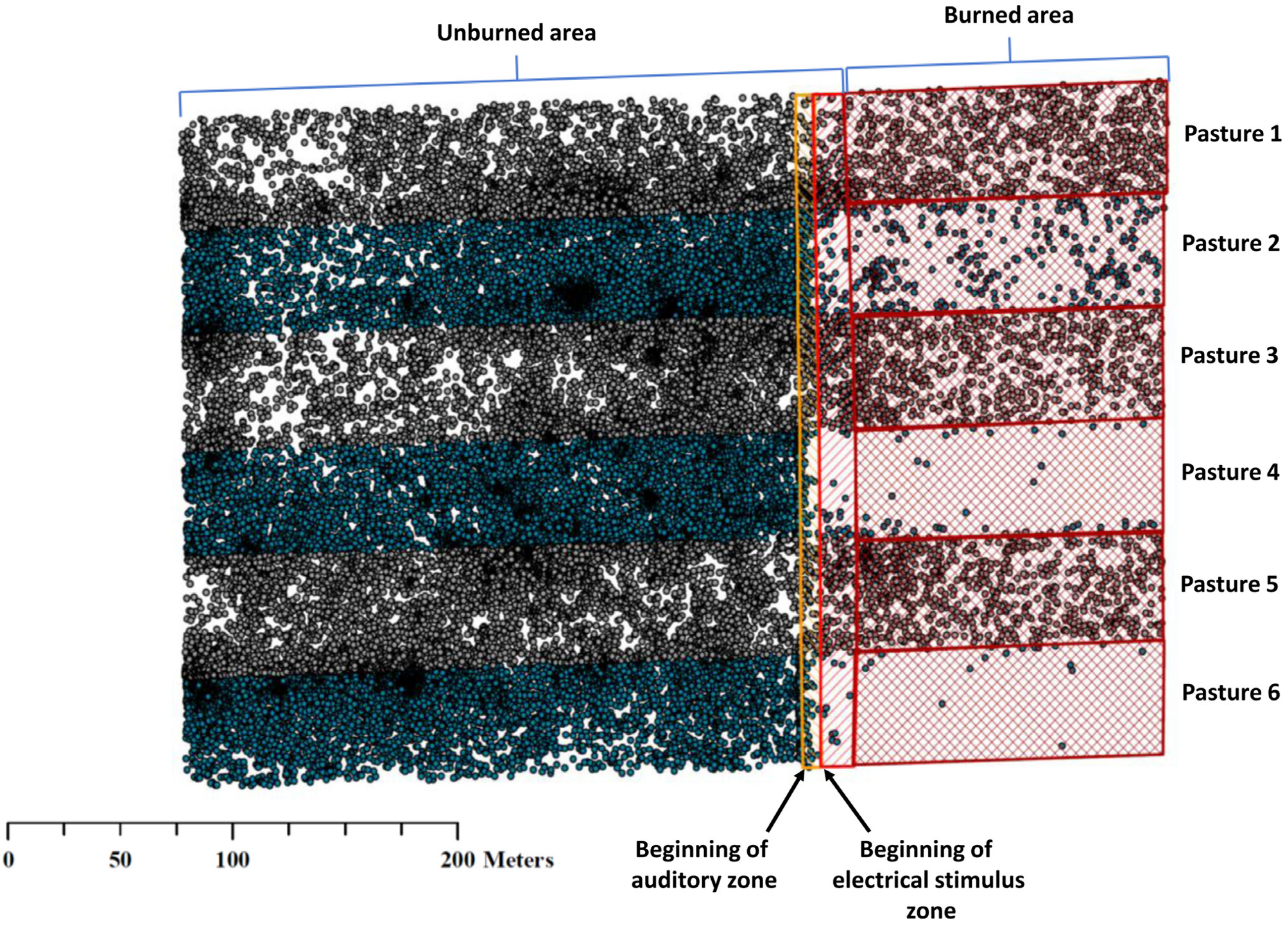

Figure 1. Diagram of 2.1-ha study pastures (numbered 1–6) used in a 14-d virtual fencing trial in southeast Oregon. In pastures 1, 3, and 5 ("Control" pastures), collars were only used to track cattle location (i.e., no auditory or electrical cues). In pastures 2, 4, and 6 ("Virtual fence" pastures), collars were used to track cattle location and administer auditory and electrical cues to discourage use of burned areas. For each pasture in the VF treatment, we employed an electrical stimulus zone that began 20 m from the junction of burned and unburned portions of each pasture. We set the auditory zone to extend inward toward the unburned an additional 10 m from the edge of the electrical stimulus zone. Dots in each pasture represent location data (5-min intervals) for 3 cows for the duration of the trial.

electrical stimulus for a period of 3 minutes. If the animal still remains in the electrical stimulus zone for $>$ 4 such cycles, the collar is disabled and all cues will cease unless the collar is remotely reactivated by the end user. Animal location data are transmitted from the collar to the base station and from the base station to cloud-based storage within HerdManager.

In June 2020 we "trained" 20 mature Angus dry cows with the Vence collars. For training, we placed cattle that had been previously fitted with Vence collars within a rectangular 90 × 120 m pen with stock tank at the NGBER for 6 d. The pen was perimeter fenced with 2-m high wooden fencing. Two conterminous sides of the pen were designated as virtual boundaries. For d 1–3 of training, the virtual boundaries were defined by an electrical stimulus zone that extended 5 m inward from the perimeter fence, and the electrical stimulus zone was bordered by an auditory warning zone that extended inward for 5 m from the edge of the electrical stimulus zone. For d 4–6 of training we expanded the width of the auditory zone inward an additional 10 m.

Immediately after training, 18 of the "trained" cows were randomly selected for use in the study. We placed three cows in each of the study pastures for a 14-d trial period. Water was provided for each pasture in a polyethylene stock tank placed at the end of the pasture opposite the burn. Collars of all animals were set to transmit animal locations at 5-min intervals. For each pasture in the VF treatment, we employed an electrical stimulus zone that began 20 m from the junction of the burned and unburned portions of each pasture (see Fig. 1). We set the auditory zone to extend inward toward the unburned an additional 10 m from the edge of the electrical stimulus zone (see Fig. 1).

The day before the trial, we measured standing crop of herbaceous vegetation by clipping five randomly located 1-m^2 quadrats within burned and unburned portions of all pastures. Clipped materials were oven-dried before weighing. Immediately following the trial, we qualitatively estimated grazing utilization of herbaceous forage using a modification of the Landscape Appearance method (USDA-USDI 1999; Jansen et al. 2021). At each of 10 equally spaced points along the center of the long axis of each burned or unburned pasture subplot, a single observer experienced with the technique visually characterized utilization of perennial grasses within a 2-m radius circle as falling into one of six utilization categories: 1) no use, 2) slight use (1–20%), 3) light use (21–40%, 4) moderate use (41–60%), 5) heavy use (61–80%), or 6) severe use (81–100%). Midpoint utilization values were averaged within pasture and subplot.

Data analysis

Initial data processing was done in ArcGIS (ESRI 2020) and Rstudio v 1.2.5003 (RCore Team 2019) with the tidyverse package (Wickham et al. 2019). Statistical analyses were performed in SAS v 9.4 (SAS Institute Inc., Cary, NC). Total number of cattle locations received from all the collars combined was 50 382 spatial

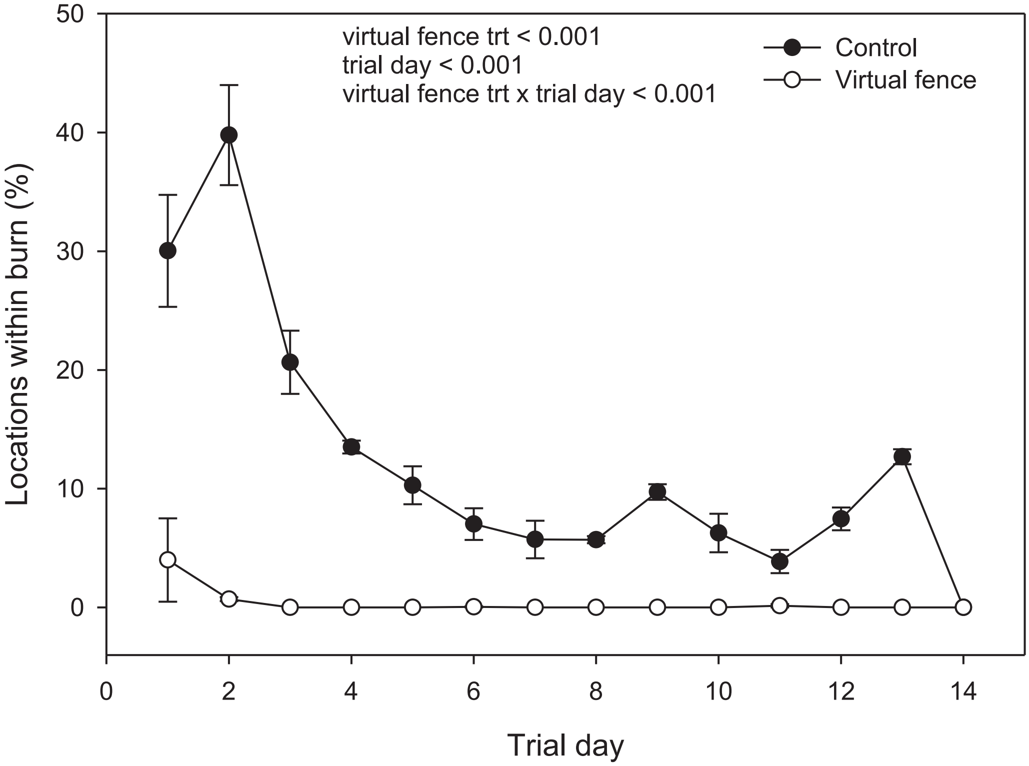

Figure 2. The effect of virtual fencing on percentage of total daily cattle locations within burned subplots of Control and Virtual fence pastures in southeast Oregon. Cattle within Virtual fence pastures had collars designed track animal location at 5-min intervals and to provide auditory and tactile (electrical stimulus) cues to deter use of the burned subplot. Control animals had collars that tracked location at 5-min intervals but did not provide cues to deter use of the burned subplot.

data points. Cattle data locations that were outside of their respective treatment pasture due to setting up the experiment by moving the animals to their respective treatment pastures, or location data that were outside of their respective treatment pastures due to geolocation error, were removed from the analysis. This gave a total of 45 380 location data points across all treatments for the duration of the experiment. Percentage of total locations within the burned portions of a pasture was calculated for each animal, for each day of the trial. We then averaged these values within pasture and trial day for further analysis. The effect of virtual fencing on percentage locations within burned subplots was determined using repeated measures analysis of variance (Proc Mixed) with trial day as the repeated factor and pasture and virtual fencing treatment * pasture as random effects. Values for pretrial standing crop were averaged across pastures and within subplot. Values for post-trial utilization were averaged by virtual fencing treatment and within subplot. The effects of burning and virtual fencing on post-trial utilization measurements were determined using analysis of variance (Proc Mixed) with pasture and virtual fencing treatment * pasture as random effects. Differences between treatment and between subplot means were evaluated using LS Means in SAS. All means are reported with their associated standard errors and effects were considered to be significant at $P \leq 0.05$.

Results

Pretrial standing crop of herbaceous forage was 757 ± 40 kg/ha for unburned subplots and 336.6 ± 77.6 kg/ha for burned subplots. Percent of daily locations within the burned area was affected by virtual fencing treatment ($P < 0.001$), day ($P < 0.001$), and the virtual fencing treatment * day interaction ($P < 0.001$). Animals in the control treatment spent a relatively higher percentage of their time within the burned area, but use of the burned subplots declined over time; by d 14 control animals had stopped using the burned subplot (Fig. 2). Animals in the VF treatment had a relatively low percentage of daily locations within the burn (< 5%) and largely avoided use of the burn after d 2 (see Fig. 2). For animals in the VF treatment, over 90% of initial (trial d 1) locations within the burned subplot were from pasture 2 (Fig. 3). The remaining two VF treatment pastures had little to no animal locations within the burned subplot for the duration of the trial. Relatively high initial use of the burned subplot in pasture 2 was associated with a single animal whose collar had become inverted such that the electrical contacts were pointing outward and not contacting the skin. On trial d 2 we removed this animal from the trial and replaced it with an animal from the same training cohort (see methods section). We elected to replace this animal (i.e., vs. repositioning the collar) because our aim was to test the efficacy of the technology versus factoring in errors associated with incorrect fitting of the color. While the collar was out of position, this animal spent considerable time within the burned area such that if we had repositioned the collar and left the animal in the study, that previous experience could have introduced variability in future behavior that would not be related to membership in a virtual fence treatment (i.e., "on" or "off"). Herbaceous forage utilization within pastures differed by virtual fencing treatment ($P < 0.001$), burning treatment ($P < 0.001$), and their interaction ($P < 0.001$). Percentage utilization of the unburned subplot was slightly higher for the VF treatment, and utilization of the burned subplot was over 25-fold higher for the control treatment compared with the VF treatment (Fig. 4).

Discussion

We found that virtual fencing technology was effective at excluding cattle from burned areas within sagebrush steppe vegeta-

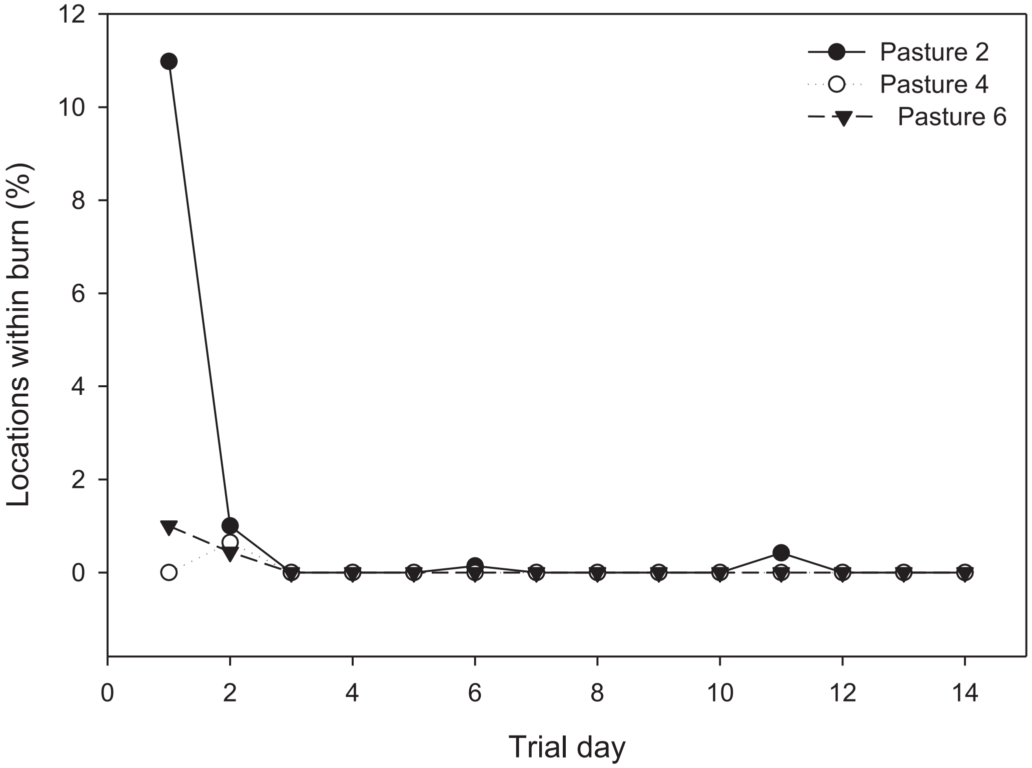

Figure 3. Percentage of daily cattle locations within burned subplots of Virtual fence treatment pastures (i.e., cattle in Control treatment not included) in southeast Oregon. Cattle within these pastures had collars designed to track animal location at 5-min intervals and to provide auditory and tactile (electrical stimulus) cues to deter use of the burned subplot.

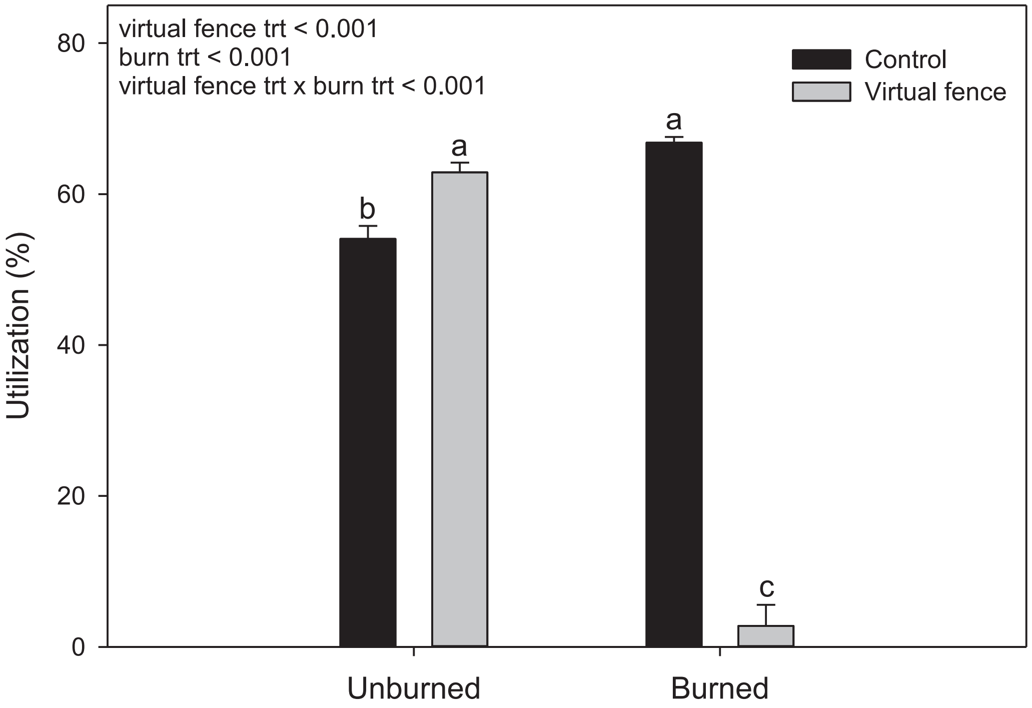

Figure 4. Herbaceous forage utilization of burned and unburned subplots within study pastures in southeast Oregon. Cattle within Virtual fence pastures had collars designed to provide auditory and tactile (electrical stimulus) cues to deter use of the burned subplot. Collars worn by Control animals did not provide cues to deter use of the burned subplot. Bars without a common letter are different ($P < 0.05$).

tion. This exclusion occurred despite strong animal preference for burned areas as demonstrated by 1) greater percentage of daily locations within burned areas by cattle in control pastures, particularly at the beginning of the trial; 2) a higher utilization ratio of burned areas in relation to overall pasture availability when cattle were not excluded by VF technology; and 3) higher end-of-trial utilization of burned subplots by cattle in control pastures. Changes in grazing behavior associated with VF technology resulted in no utilization in two out of three burned areas in our trial and minimal utilization of the third. The utilization in the third was associated with a collar that became inverted after being fitted too loosely and did not provide electrical stimulus to the animal.

Although animals in the VF treatment displayed only limited usage of burned subplots, virtual fencing did not completely exclude use of the burned subplot. In the case of recently burned areas within larger sagebrush steppe pastures, where managers are concerned with the potential impact of grazing on vegetation recovering from burning, 100% effectiveness in excluding animals from burned areas may not be necessary. Others have noted that even in dry Wyoming big sagebrush plant communities, recovery of burned vegetation is possible, even with moderate amounts of livestock use (Bates et al. 2009). As demonstrated by our study, VF technology should not be thought of as an "iron gate" that prevents all animal use of nondesired areas. Instead, it is a technology that uses auditory cues and electrical stimuli to create pressure that helps animals make decisions that are more closely aligned with management expectations, a concept that is similar to the idea of low-stress livestock handling (Grandin 1998).

From a cognitive learning standpoint, VF systems must employ behavioral cues that are both predictable and controllable (i.e., the animal can respond in a manner that eliminates negative stimuli; Lee et al. 2018)—key considerations for both effectiveness of the system and animal welfare. The Vence platform we employed uses both auditory and electrical cues, and in theory the former will help increase predictability of the latter, resulting in reduced electrical stimuli and increased animal welfare. In concurrent work with the Vence platform, Ranches et al. (2021) conducted a feeding attractant trial in which individual naive cattle were repeatedly placed in an enclosure with hay on one end; the initial exposure was without a VF in place, and subsequent exposures employed a VF between the cow and the feed. Results from this trial indicated that cattle quickly learned to avoid the feed area after the VF was activated (i.e., 82% and 91% decrease in auditory and electrical cues, respectively, from first to third exposure) and that the ratio of auditory to electrical stimuli doubled between the first and third exposure to the VF. These results suggest the Vence VF platform has sufficient predictability and controllability to promote cognitive learning over time and that auditory cues help reduce exposure to electrical cues, decreasing concerns over animal welfare.

The VF platform and training/experimental protocols we employed contained a number of design features that can reduce potential for adverse effects to the animal. For example, while animals will receive an electrical stimulus when crossing into the electrical stimulus zone, these stimuli are not continuous (i.e., 0.5-second duration). Using the Vence platform, the electrical stimulus is turned off after a maximum number of deliveries and electrical stimulus will remain off until remotely turned on again by the user. The use of auditory cues in advance of electrical stimuli (as in the current study) decreases reliance on the latter as a means of directing livestock movements (Quigley et al. 1990). While we did not partition the number of auditory and electrical cues received by animals in our trial, Lee et al. (2009) found that the number of electrical stimuli received by heifers was twofold less when electrical stimuli were preceded by auditory cues. Kearton et al. (2020) reported that when electrical stimuli were preceded by auditory stimuli, behavioral and physiological stress indicators of sheep were similar to control (i.e., no cues) animals. In additiony, Vence collars are designed to apply auditory or electrical pressure to only one side of the animal, which may encourage a change in direction of travel, potentially reducing the need for repeated cues. This is consistent with our anecdotal field observations of animals turning away from the electrical stimulus (i.e., turning left, away from probes which were always on the right side of the neck), and in the process, altering their direction of travel away from the burned area boundary. Finally, our use of a training herd and multiple animals within pastures could reduce the number of adverse stimuli received across animals through social facilitation. Keshavarzi et al. (2020) found that animal movements within groups of cattle exposed to VFs were more highly correlated than those in groups without VF and indicated that social interaction alone (i.e., in the absence of receiving cues) was sufficient to contain some animals within inclusion zones in VF pastures.

At peak usage, control animals used burned areas in greater proportion than their availability. That preference decreased over time, presumably in relation to declining forage availability within the burned subplots. Higher utilization of the unburned subplot for VF treatment animals was likely associated with a more spatially confined grazing area due to exclusion from the burned areas. Burned rangeland has been noted as an attractant to herbivores across a wide variety of rangeland systems (Clark et al. 2014; Allred et al., 2011; Burkepile 2016). Herbivores may be attracted to burned areas of the landscape for a variety of reasons including increased forage production, greater proportion of young, succulent vegetation, higher nutrient density, and decreased amounts of tactile interference from nondesired forage components (e.g., shrubs and previous years herbaceous litter; Ganskopp et al. 1992; Ganskopp and Bohnert 2006). In our case, forage standing crop was over twofold less in burned areas, and, although not tested, we suspect that preference for burned areas was a function of a higher proportion of current year vegetation and reduced herbaceous litter from previous years.

The present study and others, (e.g., Campbell et al. 2020) focused on the use of virtual fencing to deter animals from entering a defined area. Another similar use of the technology would be in managing use of rangeland or forested riparian systems by grazing livestock (Rose 1991; Bailey 2004). While these habitats often occupy a small portion of rangeland or forested pastures, concern over the impacts of livestock on riparian channel structure and vegetation attributes often determines grazing management within the remainder of the pasture. Campbell et al., 2018 reported results from a small-scale trial in Australia suggesting that virtual fencing was nearly 100% effective in excluding cattle from a riparian area. Exclusion areas may also have potential in managing invasive species, such as cheatgrass, because invasion vectors into pastures generally occur at subpasture spatial scales where soil factors and high solar exposure serve as vectors. Thus, keeping cattle away from these invasion vectors (Williamson et al., 2020) could reduce the spread of cheatgrass and other exotic annual species present within the sagebrush region. In addition to excluding animals from designated areas, more complex uses of the technology could include "inclusion polygons," in which multiple VF boundaries are simultaneously used to confine animals within a larger management area, and "moving polygons," in which animals may be moved within larger landscapes via turning virtual boundaries on and off in a user-defined sequence (Campbell et al. 2021; Verdon et al. 2021). That said, increases in complexity of usage will be bounded by the ability of the animal to process applied stimulus in a manner that is perceived as predictable and controllable as described earlier (Lee et al. 2018).

One of the limitations of any VF system will be topographic barriers that limit communication with GPS satellites or, in our case, radio and cellular communications between the collars and base station and the base station and offsite data storage. Using the Vence system, collars may continue to operate in the absence of base station to collar communication, so long as the collars maintain contact with GPS satellites. However, the system will be unable to store animal locations, and user input parameters (e.g., frequency of animal data location storage, electrical/auditory stimulus parameters) cannot be changed (Todd Parker, Vence Corp.; personal communication). Another potential limitation of implementing rangeland virtual fencing systems is cost. The collars used in this study were leased from Vence Corp at an annual cost of $40 (USD) per unit. In addition, a Vence solar-powered base station retails for approximately $12,500 (USD) and the number of base stations needed will vary depending on topography, size of the target management area, and flexibility of management objectives. While these costs are far from insignificant, current costs for barbed wire fencing can range up to $8 000 (USD)/km (Burns, OR BLM, personal communication) or more depending on fencing configuration, topography, and soils. Additional operational scale analyses are needed to build context for the economic viability of virtual fencing systems as compared with traditional fencing. These analyses should include the lost opportunity costs that may be incurred with traditional place-based fencing versus the spatially opportunistic (i.e., nonpermanent) nature of virtual fencing.

Management Implications

As demonstrated by our results, use of VF technology is largely effective, but not completely effective, in altering animal distribution to exclude cattle from burned areas. This is an important consideration from a management standpoint, and managers should weigh the level of control over animal distribution needed to meet management objectives with the ability of virtual fencing to achieve those objectives. In addition, managers should weigh efficacy of the technology against the reality that no form of fencing, even traditional wire fencing, is 100% effective. In fact, on the basis of our experience, a fair comparison to traditional wire fencing would be to say that virtual fencing is largely but not entirely effective, and when it does fail it fails on an individual animal basis.

While we focused on the use of VF technology to exclude animals from recently burned areas of sagebrush steppe, there are a plethora of other potential precision rangeland management applications for this technology. For example, the spatially and temporally transitory nature of virtual fences could have strong applicability to rangeland grazing applications that vary in space and time, grazed fuel breaks being a good example. Virtual fences could also be effective in creating exclusion or inclusion zones for use in patch grazing systems and exclusion zones for seasonal avoidance of areas such as locations known to have poisonous plants. Similarly, riparian areas could be excluded to avoid grazing effects on anadromous fish spawning habitat or riparian woody plants during fall. Additional work is needed at larger spatial scales and in more topographically complex environments to more fully frame the utility of virtual fencing in rangeland cattle production systems. However, our initial work suggests that virtual fencing has great potential for increasing management options for controlling rangeland livestock grazing distribution.

Declaration of Competing Interest

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.

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