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Research Paper

Habitat selection by Rocky Mountain Population greater Sandhill Cranes (*Antigone canadensis tabida*) during spring and autumn migration at a key stopover area

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ABSTRACT. The San Luis Valley (SLV), Colorado is a critical stopover area for Rocky Mountain Population greater Sandhill Cranes (*Antigone canadensis tabida*). During spring and autumn, cranes use crops for foraging and water resources adjacent to foraging areas for roosting and loafing. However, surface water is becoming increasingly limited in the SLV. Understanding the factors that affect use by roosting, loafing, and foraging cranes and where habitat is the most limiting will inform water and habitat management under changing conditions. We used mixed-effects models to determine the effects of habitat variables, ownership, and landcover type on the selection of roosting, loafing, and foraging areas by cranes marked with GPS transmitters (2015–2021). We found that Sandhill Cranes selected for areas with a high amount of water, relatively short vegetation (< 5 m in autumn, < 10 m in spring), close to grain fields (< 5 km), and areas identified as open water for roosting. Loafing Sandhill Cranes also selected for areas with short vegetation and close to grain fields but that had less water and more sandbar and were identified as pastures or wetlands. Although selection was higher for private land overall, we found evidence of avoidance of private lands and a stronger preference for public lands with increasing surface water for roosting in spring. For foraging areas, selection was highest for barley in both seasons, but triticale and other grains had relatively high selection in autumn. Our research confirms the importance of providing roosting and loafing areas on both private and public lands close to foraging areas and provides evidence that roosting and loafing opportunities may be most limited on public lands in the SLV.

Sélection de l'habitat par la Grue du Canada de la population des Rocheuses (*Antigone canadensis tabida*) pendant les migrations printanière et automnale dans une halte migratoire clé

RÉSUMÉ. La vallée de San Luis (VSL), au Colorado, est une halte migratoire cruciale pour la population des Rocheuses de la Grue du Canada (*Antigone canadensis tabida*). Au printemps et à l'automne, les grues y fréquentent les cultures pour se nourrir et les ressources aquatiques adjacentes pour dormir et se reposer. Cependant, les eaux de surface sont de plus en plus limitées dans la VSL. La détermination des facteurs qui influent sur l'utilisation des dortoirs et des secteurs de repos et d'alimentation par les grues, ainsi que des endroits où l'habitat est le plus limité, permettra aux spécialistes d'orienter la gestion de l'eau et de l'habitat dans des conditions changeantes. Nous avons utilisé des modèles à effets mixtes pour déterminer l'effet des variables liées à l'habitat, à la propriété et au type de couverture végétale sur la sélection des dortoirs et des secteurs de repos et d'alimentation par des grues munies d'émetteurs GPS (2015-2021). Nous avons constaté que les Grues du Canada choisissaient des secteurs riches en eau, à végétation relativement courte (< 5 m en automne, < 10 m au printemps), proches de champs de céréales (< 5 km) et identifiés comme zones d'eau libre pour dormir. Les Grues du Canada se reposant choisissaient également des secteurs à végétation courte et proches de champs de céréales, mais qui avaient moins d'eau et plus de bancs de sable et qui étaient identifiés comme pâturages ou milieux humides. Bien que l'habitat sélectionné se trouvait sur terres privées dans l'ensemble, nous avons constaté une tendance à éviter les terres privées et à préférer les terres publiques dont les eaux de surface augmentaient pour y dormir au printemps. Quant aux secteurs d'alimentation, les grues choisissaient d'abord l'orge au cours des deux saisons, mais aussi le triticale et d'autres céréales en automne. Notre étude confirme l'importance de fournir des secteurs pour dormir et se reposer sur terres privées et publiques à proximité des secteurs d'alimentation, et indique que les dortoirs et les secteurs de repos peuvent être plus limités sur terres publiques dans la VSL.

Key Words: *resource selection; San Luis Valley; Sandhill Cranes; stopover*

INTRODUCTION

Animals face survival and reproductive consequences depending on the type and quality of habitat and resources that they use (Matthiopoulos et al. 2015). Resources include biotic and abiotic items, such as food or nesting material, and space needed for reproduction and survival (Johnson 1980, Aarts et al. 2008, Beyer et al. 2010, Gaillard et al. 2010). Theory predicts that individuals should use resources and thus habitat patches in such a way that their fitness is maximized (Fretwell 1969, Rosenzweig 1981, Northrup et al. 2022). Their requirements will influence how they move across the landscape, and movements will be further impacted by individual condition and the presence of other conspecifics or species (Avgar et al. 2020). Habitats or resources are selected when they are used disproportionately to their

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availability (Manly et al. 2002). An understanding of habitat use can inform management of populations, so habitat selection is of interest to managers and researchers.

An important consideration in habitat selection studies is that resource needs will change in seasonal environments, and animals will use different habitats depending on their stage in the annual cycle (Newton 2007, McLoughlin et al. 2010, Stanley et al. 2021). The seasonal changes in resource availability in time and space are ultimate reasons for the evolution of migratory behavior, particularly in birds (Cristol et al. 1999, Chapman et al. 2011). Migrants respond to environmental and habitat changes on their wintering and breeding areas to, in part, initiate migration, while stopover areas are used along the migration route and influence migratory decisions and duration (Newton 2007, Warnock 2010). Stopover areas are used for replenishing energy reserves through foraging and resting and sometimes as refugia from harsh conditions or predators (Schmaljohann et al. 2022). The energy acquired at stopover areas is critical for completing migration and, for some species, reproducing successfully during the following breeding season (Alisauskas 2002, Baker et al. 2004, Drent et al. 2007, Devries et al. 2008). Managing habitat or resources associated with energy acquisition and maintenance is of concern to many managers in key stopover areas for species of interest (Albanese and Davis 2015, Ballard et al. 2021).

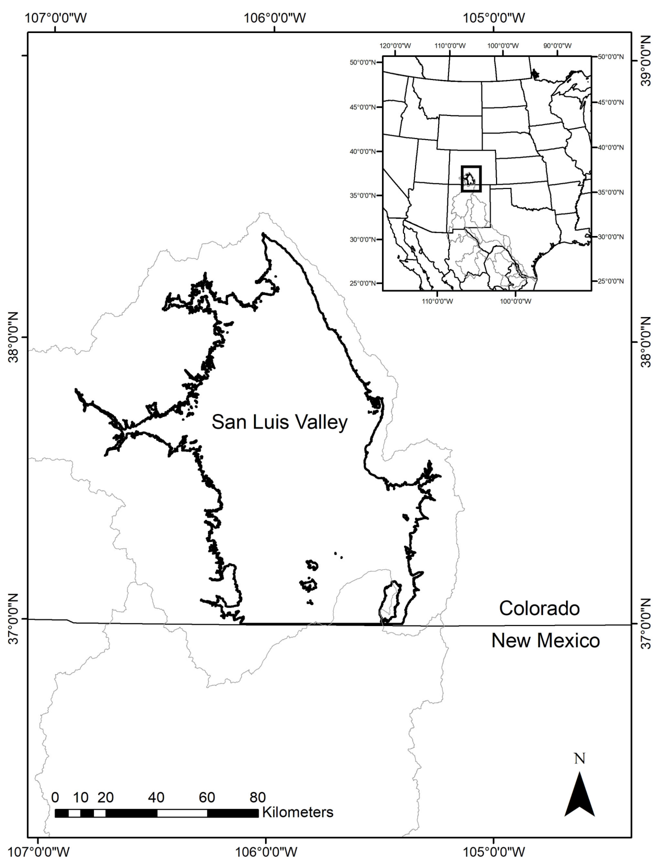
In North America, there are six migratory populations of Sandhill Cranes (*Antigone canadensis*) managed by state and federal agencies (Collins et al. 2016, Gerber et al. 2020), and all of them use stopover areas during autumn and spring migration (Drewien and Bizeau 1974, Krapu et al. 2011, Fronczak et al. 2017). Several populations show high fidelity to certain stopover areas each year and season, and these areas have been the target of research and management (e.g., Krapu et al. 1984, Iverson et al. 1987, Bunting et al. 2022). For example, the San Luis Valley in Colorado is an important and well-known spring and autumn stopover area for Sandhill Cranes of the Rocky Mountain Population (RMP; Drewien and Bizeau 1974, Donnelly et al. 2021, Vanausdall et al. 2024). Sandhill Cranes rapidly increase lipid levels in spring by foraging on grain leftover from harvest, and these reserves are used to fuel the remainder of migration (Kauffeld 1981, Krapu et al. 1985) and, in part, assist in reproduction and egg laying (Krapu et al. 1985). Because of their status as a game species, a charismatic species, and a success story in terms of recovery from near-extirpation (Walkinshaw 1949), Sandhill Cranes and their use of stopover areas have been of interest in recent decades.

The habitat requirements of Sandhill Cranes during the non-breeding period have been well documented, with a particular emphasis on spring migration owing to its potential impact on reproduction (Lovvorn and Kirkpatrick 1982, Krapu et al. 1984, Boggie et al. 2018). Slightly less work has examined habitat selection for Sandhill Cranes in autumn (but see Littlefield 1992, Donnelly et al. 2021), but there is evidence to suggest that preferred habitat in autumn is more variable among individuals when compared to spring (Lovvorn and Kirkpatrick 1982). The distribution of Sandhill Cranes is largely determined by the proximity of roosting areas and foraging areas (Iverson et al. 1987, Sparling and Krapu 1994). Roosting habitats at stopover areas include wetlands, wet meadows, and riverine habitats with shallow water (approximately 30 cm deep or less) and low vegetation, channel widths wider than 200 m, and at least 25 m from disturbance (Kinzel et al. 2009, Kruse et al. 2017, Pearse et al. 2017). Sandhill Cranes will also use wetlands and pastures in between foraging bouts to loaf, which refers to behaviors such as resting, preening, and overall maintenance (Iverson et al. 1987, Tacha et al. 1987, Aborn 2010). Foraging habitat tends to include agricultural grains, but habitats such as wetlands, grasslands, and wet pastures are also important for providing other nutrients and minerals (Armbuster and Farmer 1982, Reinecke and Krapu 1986, Rowland et al. 1992). Sandhill Cranes show a preference for foods high in carbohydrates, such as corn and barley during migration, which allows for the synthesis and deposition of lipids (Krapu et al. 1985, Reinecke and Krapu 1986). Other crops, such as potatoes and alfalfa shoots, are also consumed in some areas (Kauffeld 1981, Armbuster and Farmer 1982, Walker and Schemnitz 1985). Sandhill Cranes will also forage on invertebrates and other plant parts during migration and these items provide protein, calcium, minerals, and other nutrients that agricultural crops do not (Lewis 1979, Walker and Schemnitz 1985, Reinecke and Krapu 1986).

The San Luis Valley (hereafter, SLV) in south-central Colorado is of key interest for the RMP because most of the population is in the SLV during peak migration in spring and autumn (Drewien and Bizeau 1974), and it is an area critical to the migratory connectivity of the RMP (Donnelly et al. 2021). The RMP is composed solely of the greater Sandhill Crane (*A. c. tabida*), but lesser Sandhill Cranes (*A. c. canadensis*) from the Midcontinent Population also use this area during autumn and spring migration (Krapu and Brandt 2008, Krapu et al. 2011). A challenge facing the management of the RMP is the increasingly limited water resources due to over-appropriation, prolonged drought, and warming temperatures (Barnett et al. 2005, 2008, Mix et al. 2011, Dettinger et al. 2015). Irrigated agriculture is an important economic driver in the SLV (San Luis Valley Development Resources Group and Council of Governments 2023), and most fields are irrigated using surface water runoff from the surrounding mountain ranges, along with water pumped from underground aquifers. Because of increased groundwater pumping in response to prolonged drought and lowered aquifer levels in the early 2000s, groundwater subdistricts were created and tasked with bringing groundwater levels back to a sustainable level (Rio Grande Basin Roundtable 2015, 2022, Cody et al. 2015). An irrigation season also limits the time that most irrigators can divert surface water, with diversions generally restricted to between 1 April and 31 October for most users (Rio Grande Basin Roundtable 2015). At the same time, public areas in the SLV distribute water on the landscape for migrating waterbirds, including Sandhill Cranes. The Monte Vista National Wildlife Refuge has adjudicated water rights to pump and divert water outside the irrigation season to provide roosting and foraging habitat for migrating Sandhill Cranes and waterbirds (U.S. Fish and Wildlife Service 2015). As a result, water availability differs spatially and temporally across the landscape in the SLV and can be dependent on whether property is privately or publicly owned. Temperatures are predicted to continue to increase in many parts of the Intermountain West, which will further reduce snowpack, the main provider of surface water for basins in the Southwest (Llewellyn and Vaddey 2013, Bureau of Reclamation 2021). Earlier spring runoff has already been documented (Barnett et al. 2008, Llewellyn and Vaddey 2013), which has the potential to create a mismatch between migration patterns and water availability in the SLV (Donnelly et al. 2019). Efficient management of water resources at a landscape scale on both public and private land will thus be important for migrating RMP Sandhill Cranes.

Examination of RMP habitat selection patterns at a key stopover area will provide a better understanding of where and when Sandhill Cranes most utilize habitat and inform how habitat could be managed to optimize limited resources (e.g., water) during the migratory period. Given continued water limitations, it would also be informative to understand the importance of publicly and privately managed lands to Sandhill Cranes, as the habitat management of each will require different strategies and include different stakeholders. We used data from global positioning system (GPS) transmitters fitted to RMP Sandhill Cranes between 2015 and 2022 to (1) identify habitat attributes and landcover types that influence selection of roosting, loafing, and foraging Sandhill Cranes in the SLV, (2) determine if there is a preference for private or public lands for roosting and loafing, and (3) identify areas with the strongest selection strength throughout the SLV. For the first objective, we predicted that surface water would have a positive influence on selection by both roosting and loafing RMP Sandhill Cranes. We expected distance to grain and surrounding vegetation height to be negatively correlated with roosting and loafing selection, with a stronger selection strength in autumn for distance to grain because of the depletion of grain resources closer to roosting and loafing sites over time. We also expected Sandhill Cranes to use a greater diversity of landcover types while loafing than while roosting, with a greater selection strength for pastures and grasslands for loafing and for open water and wetlands for roosting. In terms of foraging, we expected barley to be the crop type with the greatest selection strength in both seasons. For the second objective, we predicted Sandhill Cranes to use private areas (i.e., where more water is likely to be available) more than public areas for roosting and loafing because of limited water resources on public lands.

Fig. 1. The study area used by greater Sandhill Cranes (*Antigone canadensis tabida*) during autumn and spring, 2015–2022. The solid black line outlines the San Luis Valley, and the light gray lines in the subset map outline the Rio Grande Basin.



METHODS

Study area

The SLV is in the Upper Rio Grande Basin in southcentral Colorado, situated between the San Juan Mountains to the west and the Sangre De Cristo Mountains to the east (Fig. 1). The area of the valley floor is approximately 8200 km² and the average elevation is 2100 m (Emery et al. 1969). The average temperature is 6 °C but it can range between -20 °C and 20 °C throughout the year (Western Regional Climate Center 2013). Winds primarily come from the southwest and are highly variable. Considered an arid region, the SLV receives less than 20 cm of precipitation annually, while the surrounding mountains receive 115–127 cm per year (Cooper et al. 2006). Hydrology in the SLV is driven by runoff from snowpack in the mountains, along with water coming from and discharging to underground aquifers (Emery et al. 1969, Bexfield and Anderhold 2010). The headwaters of the Rio Grande are in the San Juan Mountains, and runoff from this mountain range provides 80% of the total runoff for the entire Upper Rio Grande Basin (Elias et al. 2015). Peak runoff occurs between April and June, but this has been shifting to earlier in the year in the Upper Rio Grande Basin and other parts of the Intermountain West (Barnett et al. 2008, Ficklin et al. 2013, Chavarria and Gutzler 2018). Monsoonal rains in the summer months can provide additional water, but surface water availability generally declines in autumn.

Agriculture is an important economic industry in the SLV. The main crops grown include alfalfa, potatoes, and barley. The main source of irrigation water in the Upper Rio Grande Basin comes from the Rio Grande but use in the last century has led to decreased water levels and depleted groundwater supplies utilized to compensate (Rio Grande Basin Roundtable 2022). Wetlands and wet meadows were historically more abundant throughout the SLV, but now large wetland complexes are mostly restricted to state and public lands (Beeton and Johnson 2020). Cottonwoods (*Populus deltoides*) and willows (*Salix* sp.) occur along riparian areas, and emergent vegetation, such as cattails (*Typha* sp.) and bulrush (*Scirpus* sp.), occur in wetlands. Wet meadows include moist, short grass areas near riverine habitat or as part of wetlands, and many occur in areas used for ranching, which is also common in the SLV.

GPS deployment and formatting

Sandhill Cranes were captured and fitted with global system for mobile communication (GSM) platform transmitter terminal (PTT) tags (*n* = 95; Evolution Series-400, 15-g; Cellular Tracking Technologies, Rio Grande, NJ, USA) or GPS PTT tags (*n* = 38; PTT-100, 22-g Solar Argos/GPS PTT, Microwave Telemetry, Columbia, MD, USA) between 2015 and 2022. Most Sandhill Cranes were captured in wintering areas in New Mexico at the Bosque del Apache National Wildlife Refuge and Bernardo Wildlife Area in Valencia and Socorro Counties, but a few were captured in Arizona, Colorado, Idaho, and Montana. Details on the capture methods can be found in Collins et al. (2016) and Boggie et al. (2018). Data were acquired at different rates between the two types of transmitters, as the original acquisition and use of the transmitters were for different projects. The GSM units acquired locations at 15- to 30-min intervals, and we resampled these to approximately two-hour intervals. The GPS units were programmed to acquire points at scheduled times (07:00, 08:00, 10:00, 14:00, 18:00, 24:00) and applied to data gathered between the spring of 2015 and the spring of 2017. The location error for the GSM units was ±22 m for the GSM units and ±18 m for the GPS units.

Sandhill Cranes in the SLV have predictable movement patterns during the autumn and the spring and this influenced how we formatted GPS data. Their behavior patterns at different times of the day, namely roosting, loafing, and foraging, are also distinct in terms of behavior and, generally, habitat preference. We separated locations into either roosting, loafing, or foraging, depending on the time of day (Table 1) and analyzed models separately for each behavior (Suraci et al. 2019). Sandhill Cranes roost along rivers and in wetlands at night and fly to foraging locations around sunrise to begin feeding. After about 2–3 hours, flocks will fly to nearby wetlands, ditches, pastures, or moist grassy areas to loaf, where they rest, preen, drink water, and socialize with some occasional foraging. Approximately 2–3 hours before sunset, they will go back to foraging areas before returning to a roost around sunset. These patterns were observed in the field, but we also examined trajectories of Sandhill Cranes with transmitters to confirm their movement patterns. Specifically, we examined the hourly average movement of Sandhill Cranes and identified times of the day when their movements were minimal (i.e., when they were roosting and loafing; see Appendix Fig. 1 for an example). We considered the roosting period to be between one hour after sunset and 1.5 hours before sunrise. However, Sandhill Cranes moved an average of 140.52 m (SE = 6.65 m) in autumn and 36.27 m (SE = 1.72 m) in spring per night, indicating that movement is minimal once they choose a roost. As a result, we used one location per crane per night for each season. We used the location acquired at or closest to midnight. We defined the foraging period to be between sunrise and two hours after sunrise and between two hours before sunset to sunset. The time in between was the loafing period, but we found considerable variation in the average distance moved during this period. The average distance between loafing locations within a day was 353.85 m (SE = 14.57 m) in autumn and 670.95 m (SE = 25.37 m) in spring. Sandhill Cranes were sometimes observed moving to different loafing locations during this time frame, which likely explains the greater movement between these locations. Additionally, the difference in distances between the seasons is likely due to within-season and individual variation in the timing of Sandhill Crane departure from and arrival to foraging locations. As a result, we decided to use one loafing location per day per individual at or closest to the time of day when movement was minimal, which was around noon. The remaining locations were considered foraging locations, and we resampled these locations to every two hours. The average distance between foraging locations within a day was 971.21 m (SE = 10.03 m) in autumn and 2505.58 m (SE = 39.77 m) in spring.

Table 1. The number (n) of unique telemetered Rocky Mountain Population Sandhill Cranes (*Antigone canadensis tabida*) and the mean number ($\bar{x}$) and standard deviation (SD) of roosting, loafing, and foraging locations they used in the San Luis Valley, Colorado.

	Roosting			Loafing			Foraging		
Year	*n*	$\bar{x}$	SD	*n*	$\bar{x}$	SD	*n*	$\bar{x}$	SD
Autumn									
2015	9	16.44	10.22	10	11.80	6.27	11	36.55	20.09
2016	14	18.71	14.90	14	17.07	13.05	14	25.29	14.79
2017	9	22.78	16.98	9	25.67	12.48	10	37.30	25.31
2018	6	16.00	11.61	7	31.86	12.06	10	86.60	65.75
2019	10	18.90	13.06	15	29.27	19.90	17	102.65	80.82
2020	12	19.00	13.54	27	27.56	19.37	32	100.81	78.72
2021	14	24.57	19.96	16	31.56	22.71	22	95.09	94.07
2022	9	23.00	18.52	9	31.00	15.39	12	108.08	75.65
Spring									
2015	29	13.86	8.86	26	12.69	7.58	29	41.17	22.77
2016	23	12.78	12.30	21	16.14	12.68	21	30.52	12.03
2017	16	14.19	10.89	15	16.80	9.58	15	32.00	17.99
2018	14	16.07	12.33	15	26.47	12.11	14	70.14	51.55
2019	13	13.92	14.14	10	21.10	7.67	13	75.46	41.91
2020	46	19.89	14.79	46	22.91	13.69	48	94.02	53.76
2021	57	23.00	13.71	56	24.43	13.05	57	104.39	50.09
2022	31	19.90	15.07	29	22.52	11.30	31	96.68	54.18

Habitat covariates

To estimate surface water and sandbar for roosting and loafing areas, we used constrained spectral mixture analysis (SMA), which is a technique that uses remotely sensed images to determine the proportional amount of habitat classes within image pixels (Adams et al. 1995, Adams and Gillespie 2006). We used Landsat 8 and 9 satellite imagery corrected for surface reflectance for the years 2015–2022. Landsat images have a spatial resolution of 30 x 30 m, so our estimates of water and sandbar are the proportion of a pixel classified as those habitat types. To determine the fractional amount of habitat classes within pixels of an image, SMA requires reference endmembers, which are representative areas composed of pure or well-characterized habitat classes. All pixels must also be classified to a habitat type, but it is recommended to not use more habitat classes than the number of wavelength bands in an image (Adams and Gillespie 2006). We chose the classes shrub, soil, sandbar, water, and vegetation, but our main interests were in water and sandbar. For surface water and vegetation, endmembers were generated using the median band values of images for each season and year. Although Landsat images are available approximately every 16 days, there can be considerable variation in the quality of the images because of cloud cover and other factors. To account for this variation, we chose to take the median of all images for each season and year during the periods between 1 October and 15 November for autumn and 15 February and 1 April for spring. We used the 98th percentile of Normalized Difference Water Index (NDWI) values to generate endmembers for each season-year. We used a similar approach for vegetation using the Normalized Difference Vegetation Index (NDVI). The endmembers for the remaining habitat classes were determined using static endmembers. Based on examination of various areas in the SLV, we chose polygons that did not significantly change in band values throughout the study period. The proportion of water and sandbar in each 30 x 30 m pixel was used in the resource selection analysis. We completed the SMA in the publicly available Google Earth Engine (Gorelick et al. 2017).

Vegetation height was also calculated using remote sensing techniques. We used Light Detection and Ranging (LiDAR) data collected in the SLV in 2011. To determine vegetation height, we generated a digital elevation model (DEM) and a digital surface model (DSM) at a spatial resolution of 10 m from the LiDAR data. The DEM was subtracted from the DSM to get the height of objects. To smooth out the resulting layer, we used a 3 x 3 cell window around each cell and calculated the majority height value within each window. We excluded urban areas from this analysis. We then estimated the mean vegetation height within a circular buffer with a 100 m radius around each used and available crane location (Boggie et al. 2018).

Distance to the nearest grain field was identified using data from the Rio Grande Water Conservation District (RGWCD) and the Cropland data layer from the National Agricultural Statistics Service (NASS). The RGWCD completes an annual census of crop types in the counties of Rio Grande, Alamosa, and Saguache. We used the Cropland data layer for Costilla County. We considered all the most dominant grain types (i.e., barley, rye, triticale, and wheat) and other grains (e.g., corn) that were not as prevalent. We also identified the crop types used by foraging Sandhill Cranes and included the classes: potatoes, alfalfa, grains, pasture, and other crops.

We classified used and available locations for the roosting and loafing period into other landcover types and into public or private property. Public lands in the SLV included areas owned by U.S. Fish and Wildlife National Wildlife Refuges, Bureau of Land Management, and Colorado Parks and Wildlife. We used both the RGWCD and the National Land Cover Database (NLCD) from 2016 (Dewitz 2019) and 2019 (Dewitz 2021) to determine landcover type: grassland, open water, pasture, wetland, and other. We used the 2016 NLCD data layer for crane locations from the years 2015 to 2017 and the 2019 NLCD layer for the remainder of the years.

Resource selection functions and habitat availability

We designed our study based on a use-availability framework to develop resource selection functions (RSF). A RSF estimates the selection strength by comparing a set of used locations, which were defined above, to a set of available locations (Boyce and McDonald 1999, Manly et al. 2002). Habitats or resources that are used disproportionately to availability are "selected" by that animal (Johnson 1980, Boyce et al. 2002, Manly et al. 2002). To define the available distribution, we examined the average and median distances that RMP Sandhill Cranes moved between roosting or loafing locations on days for each season (Appendix Table 1). Distances were heavily skewed right for both periods and seasons. Although the median values indicated that individuals typically moved within 1 km of roosting or diurnal locations between consecutive days, the average values are influenced by cranes that moved greater distances as they likely continued to migrate south or north in the SLV. We wanted to encapsulate their ability to move greater distances between days, so we used a 5-km buffer around each used location to define the available area for all periods. Although individuals moved less between roosting and loafing areas in autumn than in spring, we decided to keep the available area consistent between seasons. We further restricted the available area for roosting and loafing locations to only include areas defined by a wetland polygon layer that delineated wetland, riparian, and wet meadow features (Fig. 1). Restricting the sample space in this way excluded areas not typically used by roosting or loafing Sandhill Cranes (e.g., crop fields) and improves estimation of habitat features in wetland or similar habitat types, which may have a different spectral signature than crop types, urban areas, or other habitat types. For each used location, individual, season, and year, we randomly placed 20 available locations within the 5-km buffered region (Pearse et al. 2021).

We built RSFs using generalized linear mixed effects models (GLMM) with random intercepts for each location and random slopes for each roosting and loafing individual (Muff et al. 2019). Including random intercepts accounted for the unequal number of used and available locations per individual (Gillies et al. 2006, Muff et al. 2019), while random slopes allowed for individual variation on selection (Gillies et al. 2006, Hebblewhite and Merrill 2008). For roosting and loafing periods, we examined models that included landcover types as dummy covariates (i.e., 1 if the location was the specified landcover type, 0 otherwise), along with ownership type as a dummy covariate (i.e., 1 if location was specified as private, 0 otherwise). We included the habitat covariates proportion of water, proportion of sandbar, vegetation height, and distance to the nearest grain field. Proportions refer to the proportion of water and sandbar in the 30 x 30 m pixel in which the used and available points were located. We examined separate models with a linear effect of water and a quadratic effect of water, but we did not include any other interactions. We used a GLMM with a Poisson distribution and a log link following Muff et al. (2019),

$$\log(\pi_{\mathrm{ntj}}) = \frac{\exp(\alpha_{nj} + \beta_n x_{ntj} + \varepsilon_{ntj})}{\sum_{i=1}^{J} \exp\,(\alpha_{nj} + \beta_n x_{ntj})} \tag{1}$$

where π_{nj} is the probability that point t from the jth set of used and available locations from Sandhill Crane n is used, α_{nj} is the stratum-specific intercept for set j and for Sandhill Crane n where α_{nj}~N(0, σ^2_{α}), β_n is a vector of coefficients for covariates (i.e., sandbar, water, vegetation height, and distance to grain) for Sandhill Crane n where β_n~N(0, σ^2_{β}), x_{ntj} is a vector of covariate values at point t from set j and Sandhill Crane n, and ε_{ntj} is a residual error term where ε_{ntj}~N(0,σ^2). Using a Poisson distribution with a log link has a likelihood equivalent to a conditional logistic regression model that uses matched set data, but GLMMs can more easily be fit with random slope effects (Muff et al. 2019). Our global model could be written as

$$\begin{aligned}\log(\pi_{\mathrm{ntj}}) = \exp\,(&\alpha_{nj} + \beta_{n_1}\mathrm{sandbar}_{ntj} + \beta_{n_2}\mathrm{water}_{ntj} + \beta_{n3}\mathrm{water}^2_{ntj} \\ &+ \beta_{n4}\mathrm{vegetation\ height}_{ntj} + \beta_{n5}\mathrm{distance\ to\ grain}_{ntj} \\ &+ \beta_{n6}\mathrm{ownership}_{njt} + \beta_{n7}\mathrm{barley}_{ntj} + \beta_{n8}\mathrm{alfalfa}_{ntj} \\ &+ \beta_{n9}\mathrm{potato}_{ntj} + \beta_{n10}\mathrm{other\ grain}_{ntj} + \beta n_{11}\mathrm{other}_{ntj} \\ &+ \varepsilon_{ntj})\end{aligned} \quad (2)$$

where we omitted the denominator here for readability. We used Akaike's Information Criterion (AIC; Akaike 1973, Burnham and Anderson 2002) to compare a model with a linear trend for water to a model with a quadratic trend for water. We opted for examining models with all covariates because these habitat covariates are known to influence selection by Sandhill Cranes, and we were interested in the relative selection strength across landcover and ownership type. To examine covariate effects on selection strength, we removed the intercept from the top model, applied the coefficients to the observed values of the covariate of interest while holding the other covariates at their mean (i.e., zero), and exponentiated (Muff et al. 2019, Fieberg et al. 2021). We used the delta method to estimate the variance of the prediction. Next, we used a method described by Fieberg et al. (2021) to calculate the likelihood of a Sandhill Crane selecting one landcover type over another. Specifically, we calculated selection (above) across all observed covariate values and combinations, summed this value across all locations for the landcover type of interest, and divided it by the sum of selection for each of the other landcover types. Finally, using the population-level coefficient estimates to identify areas in the SLV where RMP Sandhill Cranes are most likely to roost and loaf, we projected our models to the most recent year (2022) of environmental data across the SLV. We applied each of the top models for roosting and loafing to the entirety of the SLV and identified areas with relatively high selection strength.

We built a separate, single model for foraging selection. Because we did not have continuous, measurable covariates for foraging areas, we only examined how crop type (alfalfa, potatoes, barley, rye, triticale, wheat, wetland, pasture, other crops) influenced selection in autumn and spring. Our model for foraging selection was

$$\log(\pi_{\mathrm{ntj}}) = \exp(\alpha_{nj} + \beta_1\mathrm{crop\ type}_{ntj} + \varepsilon_{ntj}) \quad (3)$$

where the denominator is again omitted for readability. We predicted that grains would have the greatest selection strength for both seasons, with barley being the highest, followed by other grains, and then potatoes, alfalfa, and pastures.

Model validation

We used methods from Boyce et al. (2002) to ensure that our roosting and loafing models had good predictive capabilities using covariates from the top models. We used cross-validation by splitting the dataset into training and testing datasets, where 80% of the data was randomly assigned to the training dataset and the remainder was assigned to the testing dataset. The training data were used in the top model for each season, and the resulting model generated predictions using the testing data (Boyce et al. 2002, Fieberg et al. 2018). This was repeated for 1000 iterations. We then examined the correlation between the expected and the observed observations and considered a value > 0.90 to indicate a model with adequate predictive capabilities. We did not complete predictive checks for foraging models because we were only able to examine one covariate on selection and did not have continuous covariates.

Functional response

We used methods described by Holbrook et al. (2019) to examine if use of roosting and loafing areas changed with availability on public or private lands. We first converted proportion of water to area by multiplying NDWI values by 900 m² (i.e., area of a 30 x 30 m pixel), and we summed the total area each for used and available points on public and private lands for all individual Sandhill Cranes. We used approach 2 described in Holbrook et al. (2019) and fit a general linear model (GLM) with the log of water area at used points as the response variable and the log of water area at available points as the explanatory variable. We also included ownership type and fit both an additive model and a model with an interaction between water area and ownership type. Thus, our additive model was

$$\begin{aligned}\log(\mathrm{area\ water\ used}_t) = \beta_0 + \beta_1 \log(\mathrm{area\ water\ available}_t) \\ + \beta_2\mathrm{ownership}_t\end{aligned} \quad (4)$$

where covariates were specific to point t. A slope of 1 indicates selection of water (or ownership type) proportional to its availability, but a significant deviation from 1 indicates increasing or decreasing selection as availability of water increases (i.e., a functional response).

RESULTS

Between 2015 and 2022, we used a total of 13,477, 17,953, and 10,357 locations for roosting, loafing, and foraging analyses, respectively, in autumn. We used a total of 29,218, 32,083, and 17,721 locations for roosting, loafing, and foraging analyses, respectively, in spring. Individual RMP Sandhill Cranes were monitored for an average of 2.10 autumn seasons (SD = 1.00 seasons) and 2.19 spring seasons (SD = 1.07 seasons; Table 1).

The roosting model with a quadratic effect of water performed better than the model with a linear effect for both seasons based on AIC (Appendix Table 2). The proportion of water had a positive effect on selection in both seasons (Fig. 2A, Fig. 3A), while the proportion of sandbar also had a positive effect (Fig. 2). Vegetation height had a negative effect on selection for both seasons, but there was a stronger effect in autumn than in spring (Fig. 2, Fig. 4A). Selection strength dropped to zero above approximately 2.5 m in height in autumn, while there appeared to be a greater tolerance for taller vegetation in spring. Distance to the nearest grain field had a negative effect on selection (Fig. 2, Fig. 5A), but the effect was stronger in autumn than in spring. Selection for private land was higher than for public land (Fig. 2). For both autumn and spring, RMP Sandhill Cranes were more likely to roost on open water than other landcover types, followed by wetland habitat (Table 2, Fig. 2).

The loafing model with a quadratic effect of water performed better than the model with a linear effect for both seasons based on AIC (Appendix Table 2). Covariate effects on selection for loafing areas followed similar patterns as for roosting except for proportion of water and landcover type (Fig. 2). In autumn,

Fig. 2. Covariate effects on the selection strength of (A) roosting and (B) loafing areas by Rocky Mountain Population Sandhill Cranes (*Antigone canadensis tabida*) in the San Luis Valley, Colorado 2015–2022 in autumn (•) and spring (▲). The reference level for landcover types (open water, pasture, grassland, other, and wetland) is wetland. The dashed vertical line represents zero, and the horizontal bars represent 95% confidence intervals. Covariates were scaled to have a mean of zero and standard deviation of one.

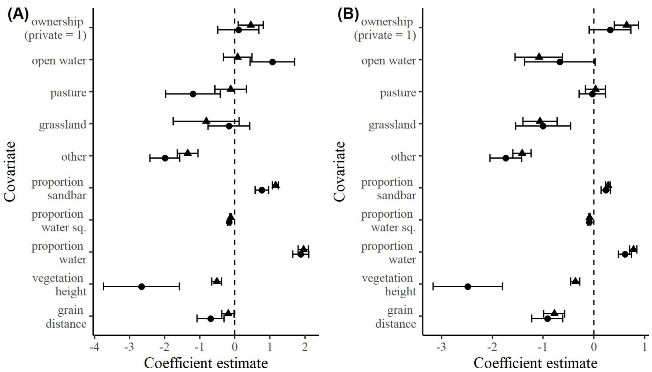
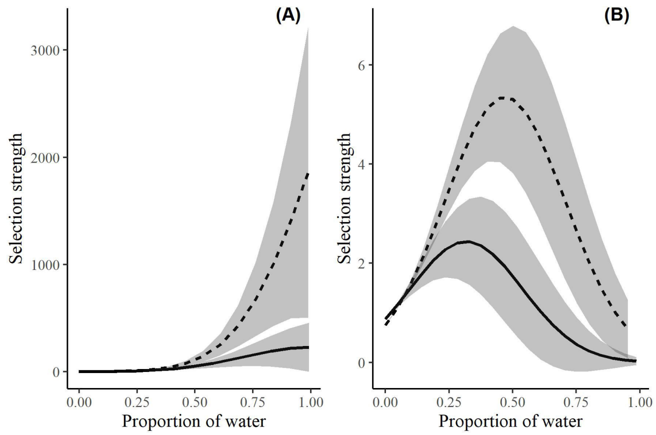


Fig. 3. The effect of proportion of water on selection by (A) roosting and (B) loafing greater Sandhill Cranes (*Antigone canadensis tabida*) during autumn (solid line) and spring (dashed line) migration in the San Luis Valley, Colorado, 2015–2022. The shaded regions are 95% confidence intervals. The y-axes are scaled differently.



selection for the proportion of water peaked around 50% water, while it peaked around 30% water in spring (Fig. 3B). Vegetation height had a negative effect on selection for both seasons (Fig. 2, Fig. 4B). Distance to the nearest grain field also had a negative effect on selection similar to roosting, but selection dropped to zero more quickly (Fig. 2, Fig. 5B). Selection for private land was higher than for public land (Fig. 2). For both autumn and spring, RMP sandhill cranes were more likely to loaf on wetlands than other landcover types, followed by pastures (Table 2, Fig. 2).

Several areas showed a relatively high selection strength for both roosting and loafing in both seasons (Appendix Fig. 2). The MVNWR showed a higher area of locations with high selection strength than the reference private area along the Rio Grande in spring, but this pattern was less pronounced in autumn. Compared to roosting, there were fewer areas that showed a relatively high selection strength to loafing areas across the SLV.

From the foraging model, selection was highest for grain crops overall for both seasons, but there was a difference in the types of grain that had the highest selection strength between autumn and spring (Fig. 6). While barley had the highest selection strength in both seasons, other grains and triticale also had relatively high selection strengths in autumn. Selection for these grains was lower in spring. There was also higher variability among individuals in selection for grains other than barley. Compared to wheat and rye, potatoes, pasture, and alfalfa had higher selection strengths in both seasons.

Model validation

Overall, our models showed a relatively high predictive accuracy with the exception of the autumn roosting model. The correlation coefficient between the expected and observed RSF values for the roosting models were 0.66 and 0.92 for the autumn and spring models, respectively. The loafing models showed correlations of 0.94 for autumn and 0.95 for spring.

Functional response

We detected a functional response (i.e., slope coefficients deviated from 1) to water based on the ownership type for roosting selection in both autumn and spring but not for loafing selection (Fig. 7). In all cases except spring roosting, the model with an interaction between water area and ownership type did not improve model fit based on AIC values, so interpretations are from the additive models (Table 3). For autumn roosting, use was proportional to availability for both private and public land, but the rate of increase declined as availability increased. There was also higher use on private than public land (Fig. 7). We found that roost use also increased as water availability increased on public lands in spring, but use declined with increasing availability on private land, indicating avoidance of private lands and a stronger preference for public lands with increasing surface water. For the loafing period, we found little evidence of use as a function of availability. There was a slight apparent increase in the area used for private over public lands in autumn but no difference in spring.

DISCUSSION

Our results on the resource selection of RMP Sandhill Cranes in the SLV improve our understanding of the habitat features important to this population during autumn and spring migration. Understanding how Sandhill Cranes utilize water in the SLV helps identify where resources can be allocated to provide the most benefit throughout the year. In general, RMP Sandhill Cranes preferred to roost and loaf in wet areas with short vegetation and close to grain fields in both seasons. Roosting cranes showed a stronger selection for open water and wetlands, whereas wetlands and pasture were more preferred for loafing. There were also some differences in the strength of selection when comparing autumn to spring. For example, wetlands were preferred over other habitats for roosting in autumn, whereas there was greater preference for roosting in open water in spring. Wetlands were preferred for loafing in both seasons. Additionally,

Fig. 4. The effect of vegetation height on selection by (A) roosting and (B) loafing greater Sandhill Cranes (*Antigone canadensis tabida*) during autumn (solid line) and spring (dashed line) migration in the San Luis Valley, Colorado, 2015–2022. The vertical bars are 95% confidence intervals. The y-axes are scaled differently.

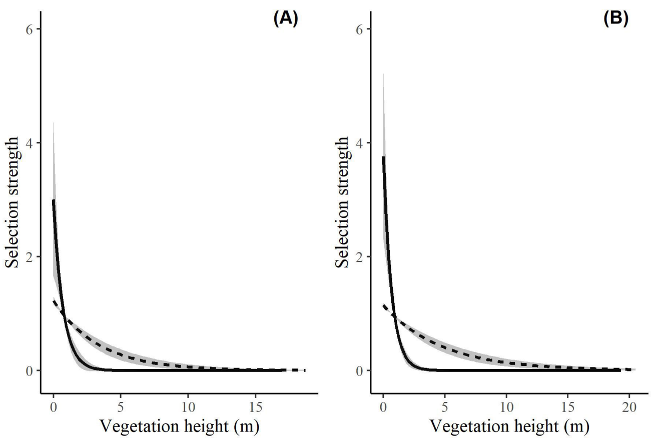
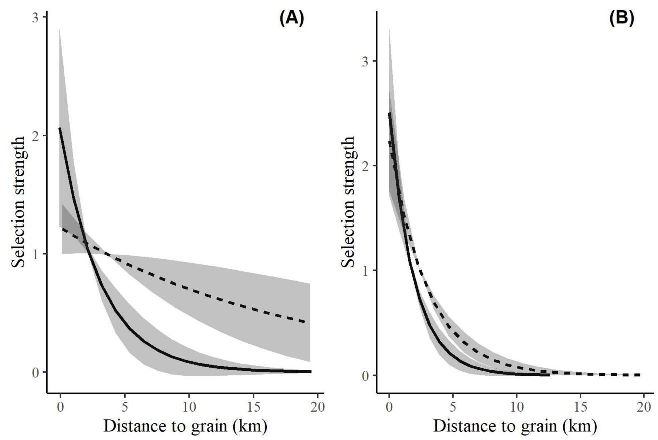


Fig. 5. The effect of distance to the nearest grain field on selection by (A) roosting and (B) loafing greater Sandhill Cranes during autumn (solid line) and spring (dashed line) migration in the San Luis Valley, Colorado, 2015-2022. The vertical bars are 95% confidence intervals. The y-axes are scaled differently.



ownership type influenced selection and indicated that both public and private lands provide roosting and loafing habitat at different times of the year.

Consistent with other studies, vegetation, water, and sandbar influenced selection by roosting and loafing Sandhill Cranes in the SLV. As expected, surface water had an overall positive effect on selection by roosting Sandhill Cranes in both seasons, but selection strength peaked at around 25 to 50% for loafing areas. Surrounding vegetation heights below 2.5 m within 100 m of roosting and loafing locations had the highest selection strength in autumn, while there appeared to be a greater tolerance for taller (but still < 5 m) vegetation in spring. Other studies have identified areas with shallow water, shorter vegetation heights with wide channel or bank widths, and shallow water being selected by roosting Sandhill Cranes (Kauffeld 1981, Krapu et al. 1984, Folk and Tacha 1990, Pearse et al. 2017, Boggie et al. 2018). Loafing RMP Sandhill Cranes also preferred areas with shorter vegetation, but the combination of a positive effect of sandbar and a peak in the selection of proportion of water may indicate a preference for dryer conditions than for roosting areas. Our results indicate that managing the structural aspects of these habitats may not need to differ between seasons. Rather, focusing on providing habitats that meet both their roosting and loafing preferences (e.g., more surface water for roosting than for loafing) will optimize the allocation of resources.

Roosting and loafing Sandhill Cranes also showed preferences for certain landcover types and ownership types in the SLV. Most surface water in the SLV is on privately managed property and is especially limited in autumn compared to spring, when snowmelt provides an influx of available water from the surrounding mountains. Selection was higher for open water areas and for private areas overall for roosting Sandhill Cranes in both seasons, but selection for open water areas was slightly stronger in autumn than in spring. The water that is generally available in autumn tends to be permanent or semi-permanent waterbodies (Donnelly et al. 2021), which characterize open water landcover types. For loafing, pastures or wetland areas were more likely to be selected than open water, and private areas also had a higher selection strength than public areas. Sandhill Cranes have been documented roosting or loafing in areas identified as pasture, wet meadows, and grasslands in other studies (Krapu et al. 1984, Iverson et al. 1987, Davis 2003). Pastures in the SLV are generally characterized by shallow water or moist soil with relatively short vegetation. The reliance on habitat in irrigated pasture is not new for Sandhill Cranes, as their importance is evident during the nesting season in summer (Donnelly et al. 2024).

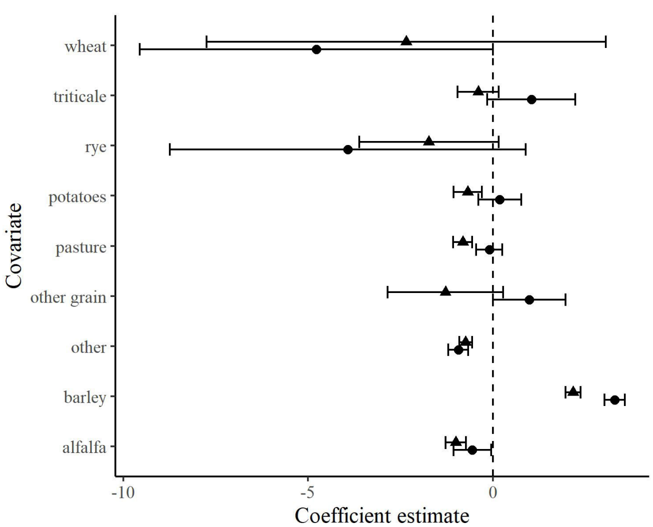
Although selection was higher for private areas, some public areas like the MVNWR manage water specifically for roosting and loafing Sandhill Cranes (U.S. Fish and Wildlife Service 2015, Wetland Dynamics 2019), which may be particularly beneficial for Sandhill Cranes during autumn. Our functional response analysis indicated that Sandhill Cranes in the SLV may be responding favorably to water management on public lands. Despite the high availability of water available on private areas in spring, there appears to be a preference for public areas for roosting RMP Sandhill Cranes, particularly in spring. Selection for loafing areas did not change with water availability, which may be because of less preference for large waterbodies for loafing than for roosting. These results may indicate that public areas play an important role in the roosting and loafing needs of RMP Sandhill Cranes, but private areas may be critical in preserving especially limited surface water used by Sandhill Cranes.

We found distance to grain fields to be influential for both roosting and loafing RMP Sandhill Cranes, with selection decreasing with increasing distance from grain fields. Having both roosting and loafing areas close to foraging areas can reduce energy expenditure during migration (Sparling and Krapu 1994, Jankowiak et al. 2015), which is a time when maintaining adequate

Table 2. The likelihood of Rocky Mountain Population Sandhill Cranes (*Antigone canadensis tabida*) roosting or loafing in one landcover type (rows) over another landcover type (columns) based on the top performing selection model and using methods described by Fieberg et al. (2021). Values with asterisks represent ratios where the value is greater than one, indicating the landcover type in the row is more likely to be selected than the landcover type in the column.

	wetland	grassland	open water	other	pasture	
wetland	1.00	21.57*	0.27	39.64*	25.07*	autumn roosting
grassland	0.05	1.00	0.01	1.84*	1.16*	
open water	3.74*	80.66*	1.00	148.26*	93.77*	
other	0.03	0.54	0.01	1.00	0.63	
pasture	0.04	0.86	0.01	1.58*	1.00	
wetland	1.00	45.33*	0.90	10.83*	4.62*	spring roosting
grassland	0.02	1.00	0.02	0.24	0.10	
open water	1.11*	50.24*	1.00	12.01*	5.12*	
other	0.09	4.18*	0.08	1.00	0.43	
pasture	0.22	9.81*	0.20	2.34*	1.00	
wetland	1.00	22.13*	33.72*	4.72*	3.18*	autumn loafing
grassland	0.05	1.00	1.52*	0.21	0.14	
open water	0.03	0.66	1.00	0.14	0.09	
other	0.21	4.69*	7.15*	1.00	0.67	
pasture	0.31	6.95*	10.60*	1.48*	1.00	
wetland	1.00	51.14*	29.17*	4.02*	4.81*	spring loafing
grassland	0.02	1.00	0.57	0.08	0.09	
open water	0.03	1.75*	1.00	0.14	0.16	
other	0.25	12.73*	7.26*	1.00	1.20*	
pasture	0.21	10.63*	6.06*	0.84	1.00	

Fig. 6. The effect of covariates on the selection strength of foraging areas by Rocky Mountain Population Sandhill Cranes (*Antigone canadensis tabida*) in the San Luis Valley, Colorado 2015–2022 in autumn (•) and spring (▲). The reference level for landcover type was wetland. The dashed vertical line represents zero, and the horizontal bars represent 95% confidence intervals.



energy reserves may be important for reproduction or survival (Ankney and MacInnes 1978, Alisauskas 2002, Devries et al. 2008). For autumn roosting and loafing and spring loafing, distances > 5 km showed a selection strength near zero, whereas the decline was more gradual for spring roosting. A distance of 5 km has been shown to be the maximum distance greater Sandhill Cranes travel between roosting or loafing areas and foraging areas (Sparling and Krapu 1994, Ivey et al. 2015, Boggie et al. 2018). Collins et al. (2023) also found that wintering greater Sandhill Cranes from the Lower Colorado River Valley Population flew farther (up to 10 km) to grain than other potential foraging sites. It may be that the higher tolerance for flying greater distances to foraging areas in spring than in autumn is due to both a higher energy demand and depleting resources near roosting areas. Sandhill Cranes rapidly increase their lipid reserves in spring in preparation for reproduction (Krapu et al. 1985, Reinecke and Krapu 1986). Additionally, departure from the SLV in spring requires Sandhill Cranes to fly over mountain ranges and fly greater distances, whereas there are fewer obstacles and a shorter total distance in autumn on their southbound migration from the SLV to their wintering areas, so energy requirements upon departure are likely lower. The effect of distance to grain fields was lower for choosing loafing areas than for roosting areas. Traveling shorter distances during the day, rather than going back to roosts, can help Sandhill Cranes reduce energy expenditure (Collins et al. 2023). Loafing areas allow Sandhill Cranes to forage on other food sources (e.g., invertebrates) that provide nutrients (e.g., protein, calcium) less available in agricultural foods (Reinecke and Krapu 1986, Ballard and Thompson 2000). Sandhill Cranes engage in other important behaviors during migration, such as courtship, preening, and drinking water, that are often observed more frequently during the loafing period (Tacha 1981, Tacha et al. 1987). Our results provide additional evidence that having adequate foraging areas nearby is important for both roosting and loafing RMP cranes in the SLV.

Grains were the dominant crop type used by foraging RMP Sandhill Cranes in both seasons, but barley was not the only important grain type, which was inconsistent with our original hypothesis. Autumn RMP Sandhill Cranes showed their highest selection strength for barley followed by triticale, while probability was highest for barley in spring. Grains provide a high amount of carbohydrates, which are used to synthesize the

Fig. 7. The log of the mean area of water used by roosting and loafing greater Sandhill Cranes as more water becomes available on private (solid line) and public (dashed line) land in the San Luis Valley, Colorado, 2015-2022. The reference line has a slope of 1 and represents use in proportion to availability.

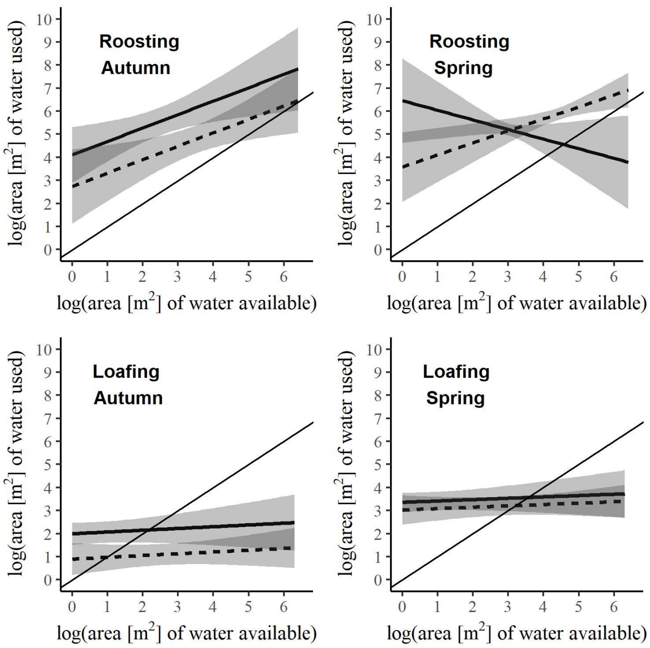


Table 3. Coefficient (β) estimates and their standard errors for the effect of area of water available on the area of water used by roosting and loafing Rocky Mountain Population Sandhill Cranes (*Antigone canadensis tabida*) in the San Luis Valley, Colorado (2015–2022) during the autumn and spring.

	Water area β	Ownership β	Water area*ownership β
Autumn roosting	0.58 (0.22)	1.37 (0.49)	*NA*
Spring roosting	0.52 (0.17)	2.88 (1.21)	-0.94 (0.35)
Autumn loafing	0.08 (0.10)	1.10 (0.38)	*NA*
Spring loafing	0.06 (0.09)	0.33 (0.35)	*NA*

deposition of lipids and often dictate Sandhill Crane distribution throughout their range (Anteau et al. 2011, Boggie et al. 2023, Collins et al. 2023). The difference in the use of triticale in the SLV between spring and autumn is likely due to availability. Of the grains grown in the SLV, triticale makes up only approximately 1% of the total crop area (Rio Grande Water Conservation District 2022). Given the relatively low amount of triticale grown, these fields may be depleted soon after the arrival of Sandhill Cranes in autumn, leaving less triticale available the following spring. Preference for triticale may also be due to the chemical and physical properties of the grain type. Barley and triticale have similar energetic contents, but they can differ in carbohydrate content and other chemical characteristics (Rodehutscord et al. 2016, Siegert et al. 2022), which may make triticale more favorable than barley to Sandhill Cranes.

Although our study focused on the population-level decision patterns of RMP Sandhill Cranes, other methods exist that could elucidate individual-level behaviors related to habitat selection. Several covariates, including vegetation height and landcover type, showed high variation in effects across individuals, indicating that other factors may influence selection by RMP Sandhill Cranes. For example, if pairs of Sandhill Cranes are successful breeders, their offspring will generally stay with the parents until the following spring (Gerber et al. 2020), and adults with young in autumn may select habitat differently than those without young. Additionally, another important consideration is body condition, or the overall health of an individual bird. Body condition can influence habitat selection and overall stopover time, as birds may need to remain at a stopover until they reach a threshold in energetic content and may select habitats that more rapidly increase their lipid accumulation (Hedenström and Alerstam 1997, Alerstam and Hedenström 1998, Eikenaar and Schläfke 2013). Further examination of individual-level habitat use patterns in the future will add to the growing body of work on Sandhill Cranes land use patterns.

Finally, we recognize that there are limitations to our models and acknowledge several other methods exist to determine habitat selection. Our analysis and model building were specific to the SLV in Colorado, and caution should be taken if extrapolating the RSF to other areas. Additionally, we were not able to provide a measure of accuracy in our estimates of habitat covariates (e.g., surface water) derived using SMA. Several other studies have utilized SMA to determine habitat use by animals using similar methods and have reported a high degree of accuracy (Donnelly et al. 2020, Bunting et al. 2022). At the same time, our approach to validating our models showed a high degree of predictive ability in the SLV for spring roosting and both autumn and spring loafing Sandhill Cranes, which may indicate that our estimates for surface water and other covariates are suitable for predicting roosting and loafing areas for Sandhill Cranes in the SLV. However, the low predictive ability of the autumn roosting model could be due to missing covariates that may better explain roost selection during this time, such as disturbance from hunting for waterfowl or other covariates that may better explain roosting in autumn. There are several covariates that we did not consider because of a lack of data availability, but future work could assess the effects of attributes such as channel width and wetland type on habitat selection (Iverson et al. 1987, Pearse et al. 2017).

CONCLUSION

In summary, we identified habitat features important to the selection by RMP Sandhill Cranes for roosting, loafing, and foraging. We also found that ownership type was an important factor to consider, indicating that habitat characteristics and availability differ between public and private lands. Sandhill Cranes in the SLV are selecting for roosting and loafing areas with short vegetation (< 10 m), close to grain fields (< 5 km), and with > 25% open water in both autumn and spring and showed a preference for open water areas, wetlands, and pastures. Our functional response analysis also indicated that RMP Sandhill Cranes select more strongly for public areas for roosting as water becomes more available.

Understanding the factors that drive habitat selection is important because habitat quality and resources may influence fitness components of populations (Alisauskas 2002, Devries et al. 2008, Sedinger and Alisauskas 2014, Matthiopoulos et al. 2015). As a long-lived bird, Sandhill Cranes may be particularly susceptible to habitat changes that affect their ability to meet energetic demands during migration. It is also informative for land managers when resources are limited or costly to obtain and manage. Resources and jurisdictions are often limited for either private landowners or state and federal agencies managing property, which may reduce habitat availability for some species. Management on federal lands in the SLV, for example, is largely focused on Sandhill Cranes and waterfowl, but ranching and grazing greatly influence habitat on private lands even if water is available. Ultimately, we found that both public and private lands are important for the resource selection of RMP Sandhill Cranes, particularly for roosting and loafing cranes, and at different times of the year. Although we did not consider specific management actions, selection for public lands, particularly in spring, may indicate that management on public areas is providing the necessary resources migrating Sandhill Cranes need, particularly for roosting. At the same time, when roosting and loafing habitats are limited on public lands, private areas can potentially provide appropriate habitat conditions throughout the year.

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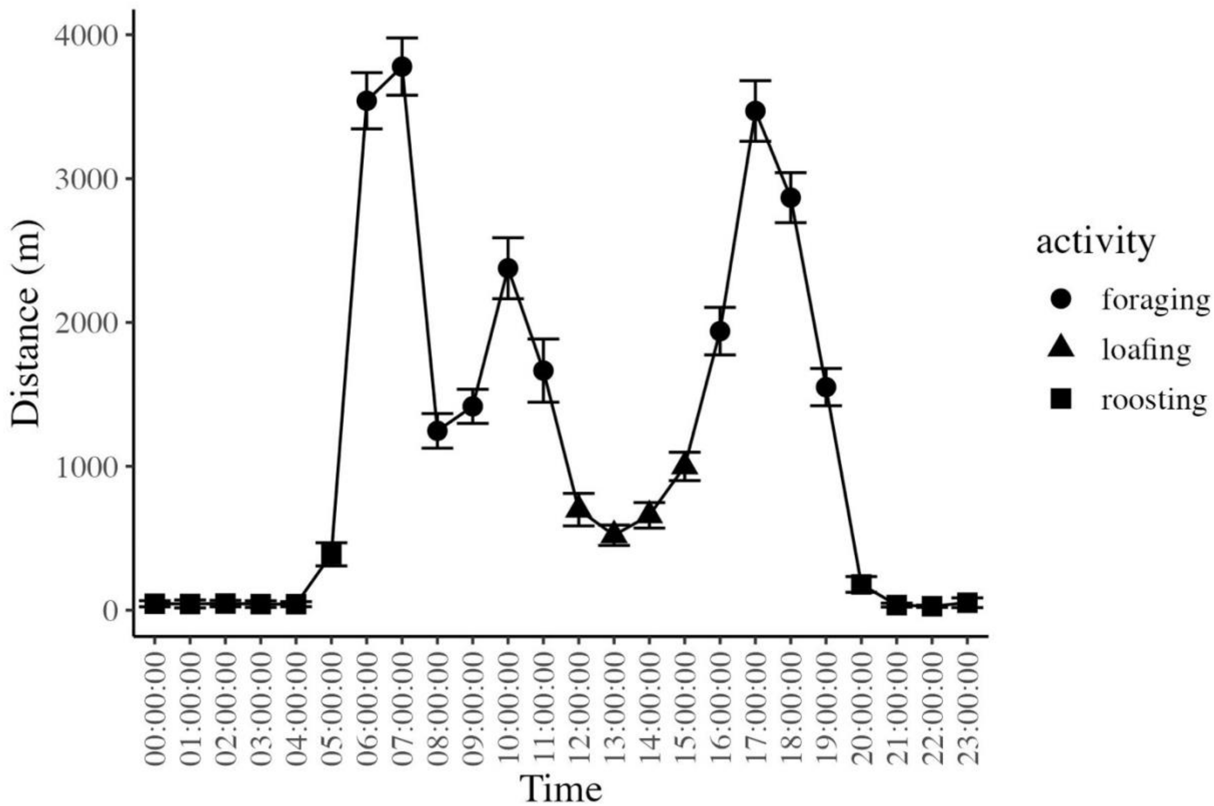
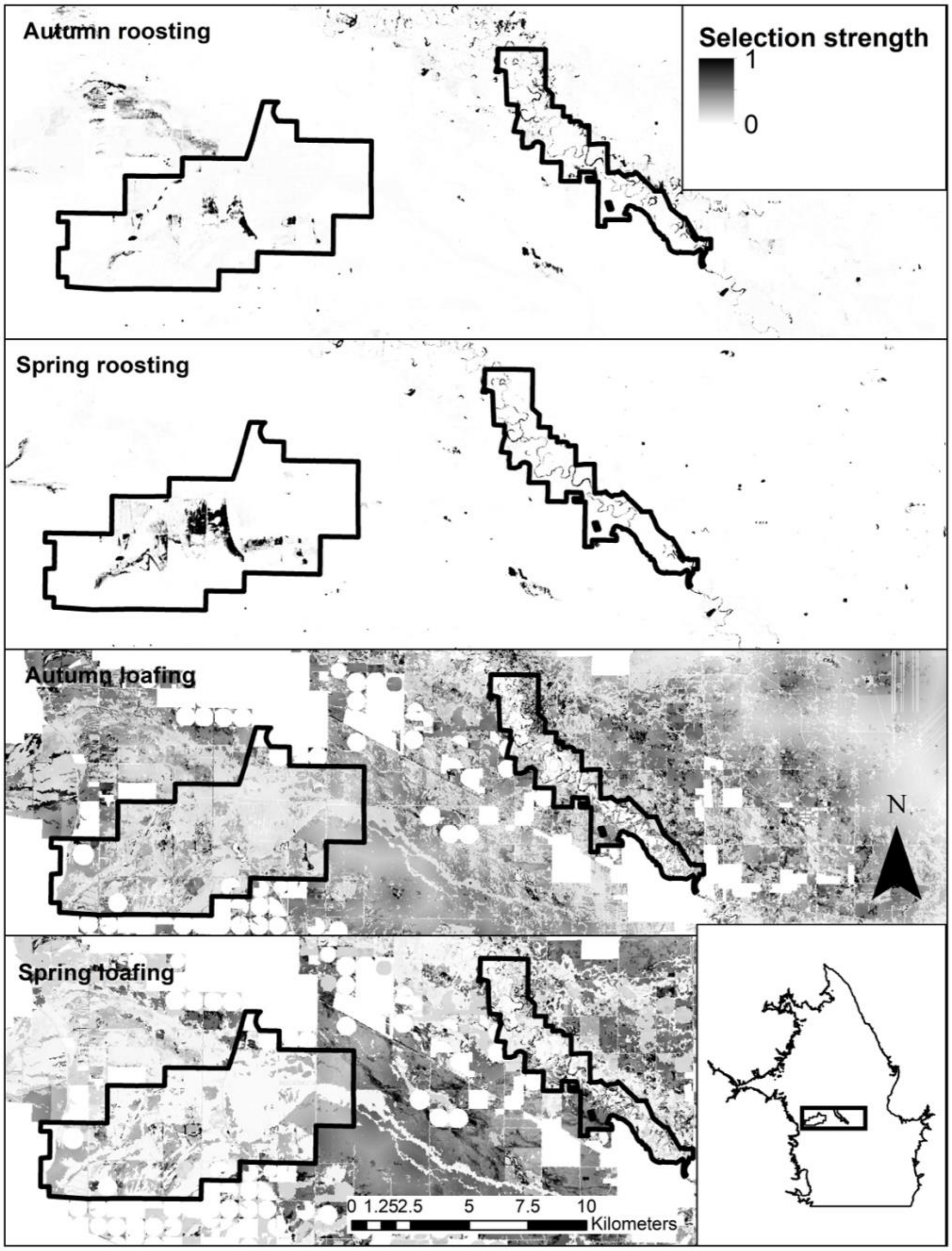
Appendix Figure 1. An example of the average distance moved by hour for Rocky Mountain Population greater Sandhill Cranes (*Antigone canadensis tabida*) marked with Global Positioning System tags in the San Luis Valley, Colorado (2015-2022) in spring. We used these data to initially identify roosting, loafing, and foraging periods. We used a single location for roosting (at or closest to midnight) per night and a single location for loafing (at or closest to 12:00:00) per day. We defined the foraging period to be between sunrise and two hours after sunrise and between two hours before sunset to sunset, but we further resampled these to every two hours.



Appendix Figure 2. he relative probability of use across two example areas in the SLV during the autumn and spring of 2021. The public property is the Monte Vista National Wildlife Refuge (left), while the private property is along the Rio Grande River (right).



Appendix Table 1. The mean, standard error (SE), median, and 95% lower (LL) and upper (UL) confidence intervals for distances (m) moved by Rocky Mountain Population Sandhill Cranes monitored using locations at night (i.e., roosting) and during the day (diurnal) during 2015-2022.

Season	Period	Measurement description	Mean	SE	Median	95% LL	95% UL
Autumn	Roosting	Distance between roost (midnight) locations on consecutive nights (< 1.5 days apart)	2419.39	98.25	157.46	2226.82	2611.96
Autumn	Diurnal	Distance between diurnal locations on consecutive days (< 1.5 days apart)	2130.86	95.48	666.62	1943.719	2318.001
Spring	Roosting	Distance between roost (midnight) locations on consecutive nights (< 1.5 days apart)	5165.03	182.66	373.96	4807.016	5523.044
Spring	Diurnal	Distance between diurnal locations on consecutive days (< 1.5 days apart)	4457.451	150.36	1100.66	4162.745	4752.157

Appendix Table 2. Akaike's Information Criteria (AIC) for models used to estimate the relative selection strength of roosting and loafing Rocky Mountain Population Greater Sandhill Cranes (*Antigone canadensis tabida*) marked with Global Positioning System tags and monitored in the San Luis Valley, Colorado, 2015-2022. The two models for each group differ in whether they include a linear effect of water or a quadratic effect of water, and, therefore, the number of parameters (K).

Model	AIC	K
Spring roosting		
sandbar + water + $water^2$ + vegetation height + distance to grain + ownership + landcover	49600.75	21
sandbar + water + vegetation height + distance to grain + ownership + landcover	49741.17	19
Autumn roosting		
sandbar + water + $water^2$ + vegetation height + distance to grain + ownership + landcover	23000.37	21
sandbar + water + vegetation height + distance to grain + ownership + landcover	23058.76	19
Spring loafing		
sandbar + water + $water^2$ + vegetation height + distance to grain + ownership + landcover	74689.84	21
sandbar + water + vegetation height + distance to grain + ownership + landcover	74962.83	19
Autumn loafing		
sandbar + water + $water^2$ + vegetation height + distance to grain + ownership + landcover	44591.67	21
sandbar + water + vegetation height + distance to grain + ownership + landcover	44703.70	19