Science of the Total Environment 921 (2024) 170750

Contents lists available at ScienceDirect

Science of the Total Environment

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

Effects of large-scale gold mining on habitat use and selection by American pronghorn

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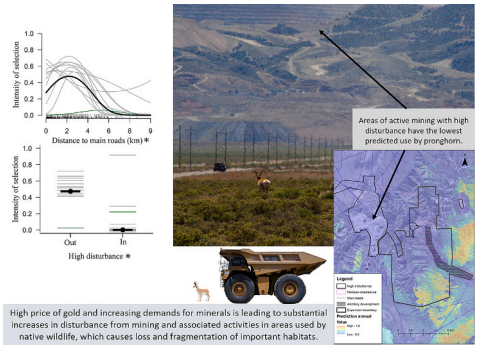
HIGHLIGHTS

- High demands for minerals have led to rapid increase in mining around the world.
- Little information exists on the effects of mining on wildlife populations.
- We documented habitat selection by pronghorn near an open-pit mine.
- Resource selection functions identified areas of important habitats for pronghorn.
- Location or expansion of mines needs to include conservation of wildlife and habitat.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Rafael Mateo Soria

Keywords:
Anthropogenic disturbance
Antilocapra americana
Great Basin
Mining
Pronghorn
Resource selection

ABSTRACT

Anthropogenic disturbances, including extraction of natural resources and development of alternative energy, are reducing and fragmenting habitat for wildlife across the globe. Effects of those disturbances have been explored by studying populations that migrate through oil and gas fields or alternative energy facilities. Extraction of minerals, including precious metals and lithium, is increasing rapidly in remote areas, which results in dramatically altered landscapes in areas of resident populations of wildlife. Our goal was to examine how a resident population of American pronghorn (*Antilocapra americana*) in the Great Basin ecosystem selected resources near a large-scale disturbance year around. We investigated how individuals selected resources around a large, open-pit gold mine. We classified levels of disturbance associated with the mine, and used a random forest model to select ecological covariates associated with habitat selection by pronghorn. We used resource selection functions to examine how disturbances affected habitat selection by pronghorn both annually and seasonally. Pronghorn strongly avoided areas of high disturbance, which included open pits, heap leach fields, rock disposal areas, and a tram. Pronghorn selected areas near roads, although selection was strongest about 2 km away. We observed relatively broad variation among individuals in selection of resources, and how they responded to the

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https://doi.org/10.1016/j.scitotenv.2024.170750
Received 29 August 2023; Received in revised form 28 January 2024; Accepted 4 February 2024
Available online 8 February 2024

mine. The Great Basin is a mineral-rich area that continues to be exploited for natural resources, especially minerals. Sagebrush-dependent species, including pronghorn, that rely on this critical habitat were directly affected by that transformation of the landscape, which is likely to increase with expansion of the mine. As extraction of minerals from remote landscapes around the world continues to fragment habitats for wildlife, increasing our understanding of impacts of those changes on behaviors of wildlife before populations decline, may assist in the mitigation and minimization of negative impacts on mineral-rich landscapes and on wildlife populations.

1. Introduction

Human developments are increasing across the globe causing fragmentation and loss of important habitats for many species of wildlife. Indeed, habitat loss resulting from anthropogenic development has been described as the single most important impact on wildlife today (Barnosky et al., 2011; Drolet et al., 2016). Those developments include gas and oil extraction (Sawyer et al., 2006; Sawyer et al., 2009; Lendrum et al., 2012; Christie et al., 2017), mining for minerals and precious metals (Boulanger et al., 2012; Blum et al., 2015), residential development (Polfus and Krausman, 2012; Johnson et al., 2017; Wyckoff et al., 2018), fencing (Xu et al., 2021), and alternative energy (Lovich and Ennen, 2011; Agha et al., 2020; Sawyer et al., 2022). Anthropogenic structures fragment habitat and reduce both availability and quality of habitat and for wildlife populations. Energy development and mining for minerals and other natural resources has been rapidly expanding across the Western United States over the past several decades (Beckmann et al., 2012; Blum et al., 2015; Martins-Oliveira et al., 2021). Although human developments are increasing across the landscape, our understanding of the corresponding effects on wildlife populations and their habitats, especially from large-scale mining, is limited (Blum et al., 2015, Martins-Oliveira et al., 2021).

Global demand for precious metals and minerals for electronic devices and electric vehicles are rapidly increasing all over the world. Extraction of natural resources, such as fossil fuels, precious metals, and minerals often occur at large spatial scales causing disturbances that affect entire landscapes. Mining, especially, has increased exponentially over the last decade with increasing price and demand for mineral commodities as well as improved techniques for extracting those resources (Blum et al., 2015; Martins-Oliveira et al., 2021). Mining has high economic importance for many countries, including Australia, Canada, Russia, Chile, the United States, and many others, with corresponding concerns about land disturbance and associated waste (Söderholm and Svahn, 2015; Martins-Oliveira et al., 2021). A major impact to natural landscapes worldwide is open-pit mining for precious metals, including gold and silver, and more recently minerals, such as lithium, which are important components of electronic devices and batteries (Kaunda, 2020). In the United States, gold mining is a nearly $9 billion industry, with large open-pits located throughout the western states and especially in the Great Basin ecosystem (Blum et al., 2015). Open-pit mining causes large-scale disturbances on the landscape because large volumes of earth are removed using drill rigs, explosives, and other heavy machinery (Kaunda, 2020). Landscape disturbances associated with large-scale mining include large, open pits, heap-leaching facilities, rock disposal areas, networks of roads for hauling materials, and exploration sites. Many of those activities, including moving materials away from the mines *via* roads operate continuously, 24 h a day and 7 days per week (Blum et al., 2015).

Open-pit mining is an extreme example of landscape change resulting from anthropogenic activities (Cristescu et al., 2016), and there is a paucity of information on the corresponding effects on wildlife populations during and following mining and energy development, especially for wide-ranging mammals (Beckmann et al., 2016; Cristescu et al., 2016; Martins-Oliveira et al., 2021). As developed mines increase in number and size, land that overlaps with critical habitat for wildlife is changed, often permanently, causing fragmentation and loss of habitat. Mule deer that migrated through a gold mine in eastern Nevada avoided high levels of disturbance and occupied the few remaining patches of undisturbed habitat within the mine complex (Blum et al., 2015).

Large-scale loss and fragmentation of habitat from disturbances negatively affect wildlife populations, causing direct declines in population size through reduced survival and recruitment of young (Andrén, 1994). Those disturbances also affect movement patterns and selection of resources by wildlife populations inhabiting areas near large-scale disruptions to landscapes. Habitat fragmentation and loss resulting from anthropogenic development is especially concerning for species that require large, continuous areas of habitat, such as American pronghorn (*Antilocapra Americana*) or saiga antelope (*Saiga tatarica*) (Reinking et al., 2019; Sawyer et al., 2019). Habitat loss and fragmentation change forage availability and quality and alter how populations and individuals use the landscape. As patches of habitat decrease in size, those species that need large areas of intact habitat tend to decline or disappear, and smaller habitat patches may not be suitable to support many wildlife species (Terborgh et al., 2001). Limitations in the size and interspersion of habitat may affect movements, selection of resources, and interactions among and within species (Hagen et al., 2012). Some disturbances result in direct loss of habitat (Sawyer et al., 2006; Sawyer et al., 2009; Sawyer et al., 2022) that affect demographic processes, such as fecundity, survival, and recruitment of young (Beckmann et al., 2016; Johnson et al., 2017; Peterson et al., 2018). Whereas indirect losses, caused when anthropogenic stimuli decrease habitat quality, change behavior or movements eliciting an avoidance response (Sawyer et al., 2006; Sawyer et al., 2009; Drolet et al., 2016; Sawyer et al., 2017). Additionally, indirect effects are likely to be more widespread even if they are more difficult to detect (White and Gregovich, 2017).

American pronghorn are large herbivores that inhabit grassland, shrub steppe, and desert ecosystems across North America (Byers, 1997; O'Gara and Yoakum, 2004). They are selective foragers adapted to open habitats, which allows large-scale movements and for detection and escape from predators. Pronghorn currently occupy fragmented parts of their original ranges since the western expansion and settlement by European humans (O'Gara and Yoakum, 2004). Pronghorn are sensitive to small-scale anthropogenic features on the landscape, such as fences, roads, and other semi-permeable barriers (Seidler et al., 2018; Jones et al., 2019; Sawyer et al., 2019; Robb et al., 2022). Those features, especially highways with fences, can serve as physical barriers to the extent that they reduce gene flow (Dodd et al., 2010; Sprague, 2010, but see LaCava et al., 2020). Pronghorn also avoid large-scale disturbances such as gas and oil fields (Beckmann et al., 2012; Sawyer et al., 2019) and possibly wind energy facilities (Milligan et al., 2021). Gold mining operations are typically an extreme disturbance and modification of the landscape, even if that effect is lower in overall area than oil and gas developments, which creates substantial barriers to movement of animals attempting to navigate through them (Blum et al., 2015). There is a paucity of information on the effects of landscape-scale disturbance from mining, such as open-pits and adjacent exploration sites, on populations and habitat use by large mammals (Martins-Oliveira et al., 2021). Additionally, resident populations of wildlife are affected by those disturbances year around.

We examined the effects of two open-pit gold mines, the Cortez and Pipeline mines (hereafter Cortez mine) that are adjacent to one another in Central Nevada, on a resident population of American pronghorn

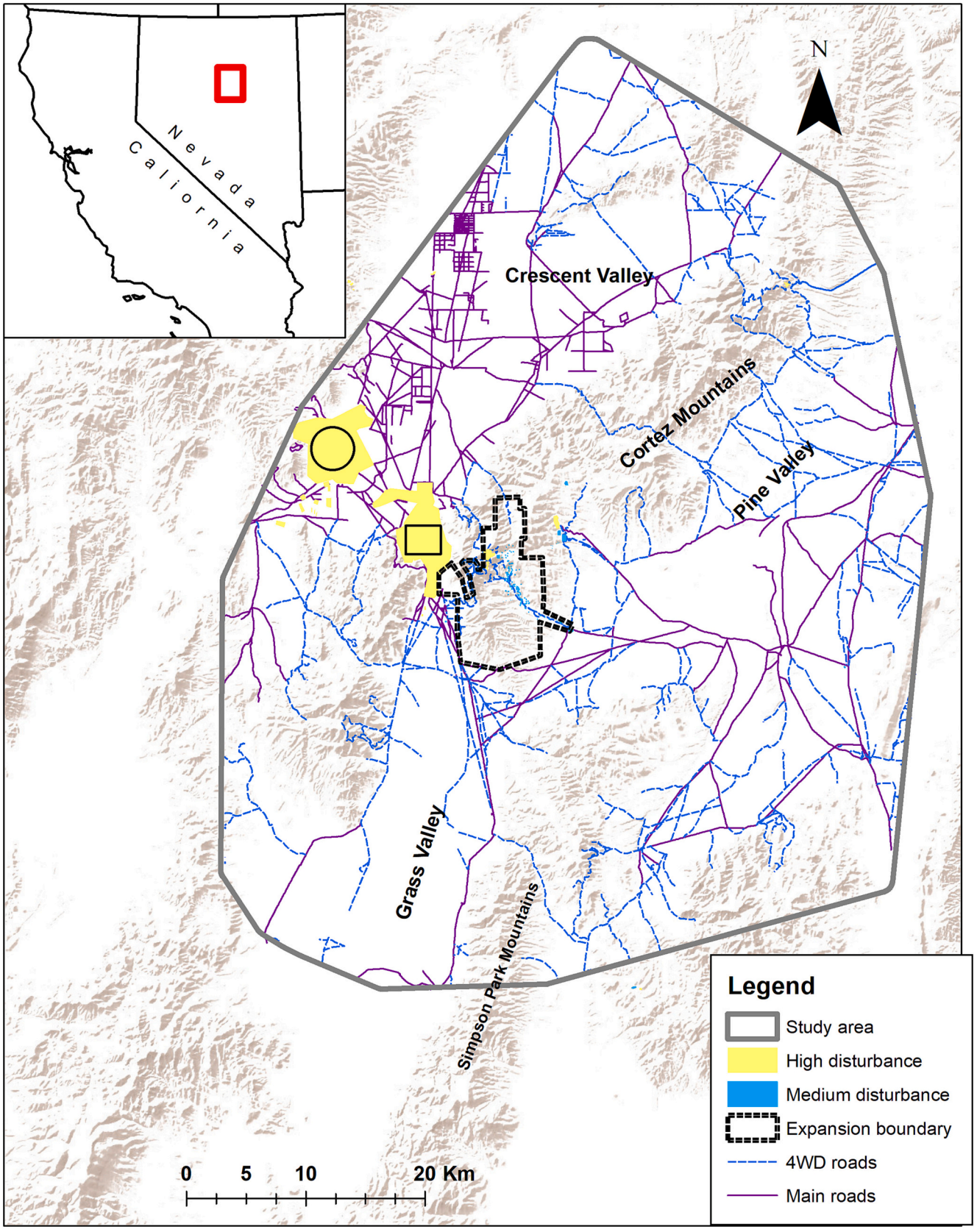

Fig. 1. Map of the study area around the Cortez and Pipeline mines in central Nevada. The gray line represents the minimum convex polygon of all used locations of adult female pronghorn from January 2018 to June 2021. The black square depicts the Cortez mine and the black circle depicts the Pipeline mine.

(Fig. 1). Those mines have been present on the landscape for >30 years, but have recently been approved to expand. Our objective was to evaluate how those mines and the process of expansion with test drilling affects selection of resources by a resident population of pronghorn inhabiting the area around the mine prior to expansion. Further, we wanted to understand to what extent pronghorn avoided disturbance associated with the mine relative to other components of habitat in the area. We hypothesized that, relative to other components of habitat, pronghorn avoid disturbances associated with mining activities and there is variation among individuals in how they react to disturbance and select resources on the landscape relative to the mine. Further, we hypothesized that, despite this being a resident population, pronghorn vary seasonally in selection of resources in the area around the mine. Finally, we created annual and seasonal prediction maps of the study area to identify key areas of pronghorn habitat, which may be altered with expansion of mining activity in the future.

2. Methods

2.1. Study area

The Great Basin is characterized by basin and range topography, which is alternating mountain ranges and valleys (Grayson, 1993; Andreasen et al., 2018). This arid environment is dominated by sagebrush (*Artemisia spp.*) communities at mid and upper elevations. Basins are inhabited by salt desert shrub communities, and alpine areas are characterized by conifer forests (Grayson, 1993). Single-leaf pinyon pine (*Pinus monophylla*) and Utah juniper (*Juniperus osteosperma*) occupy mid-elevation area, but are infilling and encroaching into lower elevations (Romme et al., 2009). Annual plants in the area have become dominated by invasive species including: cheatgrass (*Bromus tectorum*) and medusahead (*Taeniatherum caput-medusae*). Perennial plants include crested wheatgrass (*Agropyron cristatum*), bottlebrush squirreltail (*Elymus elymoides*), and Indian ricegrass (*Achnatherum hymenoides*). Many species of wildlife, including sagebrush-dependent species, such as greater sage grouse (*Centrocercus urophasianus*), pygmy rabbits (*Brachylagus idahoensis*), and American pronghorn (Rowland et al., 2006) are widespread.

Large fires have burned about 1821 km^2 of the study area since 1999. Invasive plants, mostly cheatgrass, established after the fire in the lower elevations and have outcompeted the native sagebrush species (Grayson, 1993). The Bureau of Land Management (BLM) and the Nevada Department of Wildlife (NDOW) seeded the burned areas with a mixture of forage kochia (*Bassia prostrata*) and crested wheatgrass in 2000 and 2001. Forage kochia is an important resource for pronghorn and is used extensively for habitat improvement across the Great Basin (Cox et al., 2021).

Our study area encompassed 3560 km^2 and is within Crescent, Pine, and Grass valleys in Central Nevada (Fig. 1). The three valleys intersect at the western base of the Cortez Mountains with the Simpson Park range bordering Pine and Grass valley. This area is typical of the climate in cold deserts of the Great Basin, with hot dry summers and cold winters with most precipitation falling as snow (Flaschka et al., 1987). The lowest elevation is 1435 m and the highest elevation in the Cortez range is Mount Tenabo at 2887 m. We obtained seasonal weather data from National Centers for Environmental Information (NCEI) and created a climograph by plotting mean monthly precipitation and temperature and defined seasons as months clustered together (Stewart et al., 2002; McKee et al., 2015). Our seasonal delineations were summer: June–September, autumn: October, winter: November–February, and spring: March–May.

The Cortez range is mineral rich and has been mined since 1862. Open-pit and underground mines began operating in the 1930s, and today there are multiple large scale open-pit gold mines located in the Crescent Valley area (Fig. 1; Muntean, 2018). Nevada Gold Mines has been approved to expand current operations to the east of the open pits, on the south side of the Cortez Mountains. There is a proposal to modify the approved expansion plans. The Bureau of Land Management (BLM) has published an Environmental Impact Statement (EIS) for the expansion plans with the name "Gold Rush" (DOI-BLM-NV-B010-2021-0006-EIS). Expansion plans encompass 80 km^2 of land, with 77 km^2 of public land managed by BLM and 3 km^2 owned by Nevada Gold Mines. An additional open pit was ruled out by the EIS because of the negative impact to wildlife in the area and the proposed plans are for an underground mine, which includes aboveground facilities and surface disturbance.

Our study area is inhabited by a resident population of pronghorn that have been steadily increasing over the past 40 years. The Nevada Department of Wildlife estimated the population to be about 100 individuals in the 1980s (Cox et al., 2021). In 2018, the population had increased to approximately 2700 individuals, and in 2021 that had grown to 3900 individuals. This growth resulted from high recruitment of young; with an average ratio of 41:100 young to adult females between 2016 and 2021 (Cox et al., 2021).

2.2. Animal capture and handling

Nevada Department of Wildlife captured 10 adult female pronghorn using helicopter-netgun capture in January 2018, and an additional 2 individuals in January 2019 (Krausman et al., 1985). Individuals were fitted with Global Positioning System (GPS) collars (Vectronic Aerospace GmbH, Berlin, Germany); those collars were programmed to collect five locations per day and to drop after two years. There were two mortalities during the first spring and summer; therefore sample sizes are 11 for summer and 10 for autumn. All collars had dropped as a result of mortality or programming by June 2021. All capture and handling was approved by the Institutional Animal Care and Use Committee at the University of Nevada, Reno (Protocol #21-04-1145 exp.:4/20/2024) and followed guidelines established by the American Society of Mammalogists for care and use of wild mammals in research (Sikes, 2016).

2.3. Analyses

We defined the study area and available habitat by creating a 100 % minimum convex polygon (MCP) of all GPS locations with a 1000 m buffer (ArcMap 10.8.1, Environmental Systems Research Institute [ESRI], Redlands, California, USA, Shoemaker et al., 2018) (Fig. 1). All locations with 3-dimensional fixes and <3.1 dilution of precision were included in the data to increase accuracy of locations (D'Eon and Delparte, 2005). We identified environmental and anthropogenic covariates that have been significant in resource selection functions (RSFs) for

Table 1
Descriptive statistics for continuous variables of all used (n = 37,347) and available locations (n = 97,347) for adult female pronghorn (n = 12) associated with the Cortez gold mining operations in central Nevada, USA, 2018–2021.

Habitat characteristics	Used locations		Available locations	
	$\bar{x}$	*SD*	$\bar{x}$	*SD*
Continuous variables				
Elevation (m)	1883	162.1	1794	237.8
Slope (°)	6.9	4.97	6.5	7.77
Aspect (°) sine transformation	0.90	0.743	0.97	0.735
Aspect (°) cosine transformation	1.09	0.655	1.07	0.673
Perennial forbs and grasses cover (%)	23.0	10.62	16.8	12.69
Annual forbs and grasses cover (%)	21.3	14.06	14.6	16.15
Shrub cover (%)	13.4	6.66	18.2	10.49
Tree cover (%)	0.89	0.775	3.6	9.41
Distance to water (km)	2.8	1.81	3.8	2.44
Distance to 4WD roads (km)	1.2	1.07	1.8	1.98
Distance to main roads (km)	2.4	1.45	2.3	1.97
Binomial variables (no. of locations)	**In**	**Out**	**In**	**Out**
Seeded areas	16,119	21,228	12,272	85,075
Medium disturbance	1615	35,732	1240	96,107
High disturbance	585	36,762	3986	93,3361

pronghorn and other large ungulates (Beckmann et al., 2012; Christie et al., 2017; Milligan et al., 2021) (Table 1). We modeled selection of resources at the population level (2nd order (Johnson, 1980)) using random-forest machine learning techniques to identify important resources to this population. Next, we used RSFs with environmental and anthropogenic covariates in a use-available design (Manly et al., 2002; Johnson et al., 2006). We used random locations within the study area to quantify available resources (Fieberg et al., 2021). Following Northrup et al. (2013) we determined that ~5000 points/individual was the appropriate minimum number of random points (all relevant coefficient estimates had achieved stability on the basis of visual inspection of rarefaction curves). To ensure robust model results, we generated at least 8000 random points for each individual in the study for a total of 97,347 random points (Northrup et al., 2013; Gerber and Northrup, 2020).

We created raster layers for elevation (m), slope (°), and aspect (°) from a Digital Elevation Model of the study area from the United States Geological Society (USGS). Because aspect is a circular variable, we applied a transformation by cosine (north-south) and sine (east-west) function (Stewart et al., 2002; Heffelfinger et al., 2020). We obtained information on vegetation cover from the Rangeland Analysis Platform (RAP), which included cover of perennial and annual grasses and forbs, shrubs, and trees (www.rangelands.app). The RAP layers are estimated from models using Landsat imagery combined with thousands of vegetation measurements (Allred et al., 2021). We calculated Euclidean distance to water and roads from each used and available location. We downloaded Topologically Integrated Geographic Encoding and Referencing road shapefiles from the Census Bureau (www.census.gov/geographies/mapping-files) and split them into two categories: 1) primary gravel roads and the highway that have higher levels of traffic and speed, including vehicles associated with mining, hereafter main roads, and 2) four-wheel drive roads that are less traveled than main roads and are traveled at lower speeds, hereafter 4WD roads.

We obtained layers of all mining activity in the study area from USGS Mineral Resources Data (https://mrdata.usgs.gov/mrds) and supplemented them by digitizing aerial imagery. We classified disturbance resulting from mining (hereafter disturbance) into three levels of intensity (high, medium, and low) following methods from Blum et al. (2015). High disturbance included open-pits, heap leaching pads, rock disposal areas, and a tram that connected the two open-pit mines. The tram has spaces for animals to pass underneath, although it is lined with fences on both sides. Therefore, we classified the tram as high disturbance because pronghorn have shown avoidance of semi-permeable barriers (Robb et al., 2022). Medium disturbance included exploratory pads and ancillary activities defined in the EIS, and low disturbance were drilling sites and adits (horizontal passages leading to the mines for purposes of access or drainage). We excluded the low disturbance from the analysis because there were no locations of low disturbance within the minimum convex polygon we used to define our study area. Medium disturbance was present in the study area near and within the boundary of the expansion, but it was much lower in area than high disturbance in our study area (Figs. 1 and 2). Total area of high disturbance polygons was 59.7 km^2 and medium disturbance polygons totaled 0.68 km^2. We applied a buffer around medium and high disturbance using the average distance traveled, 787 m, by pronghorn between GPS locations. That distance accounted for individuals that may have been within the disturbance area when locations were not recorded. We represented mining disturbance with binomial variables, such that locations within the buffered disturbance areas were coded with a 1 and locations outside of the buffer were coded with a 0. We included a third binary variable to represent whether an area was part of the forage kochia seeding treatments to reestablish forage for pronghorn following fires. Seeded areas were largely in the foothills on the southwest side of the Cortez Mountains and the north side of the Simpson Parks Mountains. All rasters for our study were projected to NAD 83 Zone 11 N with a spatial resolution of 30 m.

To test our hypotheses, we evaluated avoidance of disturbances relative to other characteristics on the landscape that affected use by pronghorn. We tested for collinearity between covariates using Pearson correlation and removed any variables with correlation coefficients $\geq$0.65 (Zar, 2009; Morano et al., 2019). None of our covariates were correlated at that level. We used a random-forest machine learning model to identify variables of importance, and to investigate potential non-linear functional relationships (Shoemaker et al., 2018). Machine-learning methods often yield important ecological insights about the importance of covariates and the shapes of key functional relationships (Breiman, 2001; Elith et al., 2008; Shoemaker et al., 2018; Heffelfinger et al., 2020). To prepare our data for a random forest model, we created a random subset of data of 100 observations per individual per season. We used a recursive feature elimination (RFE) procedure ("RFE" function, with "Random Forest" method) implemented in the "caret" package in R (Kuhn et al., 2020) to identify the set of predictor variables that optimized predictive performance under repeated cross-validation. Then, we fitted a final random forest model using the R package "ranger" (Breiman, 2001; Wright and Ziegler, 2017) and used this model to visualize effects plots for potential non-linear responses.

We estimated annual and seasonal RSFs by fitting generalized linear mixed-effects models with a binomial error distribution and logit-link function (Gillies et al., 2006; Bolker et al., 2009; Long et al., 2014; Harrison et al., 2018). We included variables of importance identified using RFE and included the disturbance variables associated with the mines to test our hypotheses. All continuous variables were standardized (zero-centered and scaled to represent standard deviations from the mean) prior to analyses. In some instances, random forest models indicated that the shapes of the relationships of some variables were unimodal; therefore, we included quadratic terms on those variables for our RSF models. All models included a random intercept and random slopes for individual pronghorn on all variables to account for variation in selection among individuals (Gillies et al., 2006; Muff et al., 2020). All RSF models were fitted in R using the package "glmmTMB" (Brooks et al., 2017).

We ran multiple goodness-of-fit tests implemented in the 'DHARMa' package in R (Hartig, 2022), including tests for uniformity of residuals, outliers, and overdispersion. We assessed model performance using k-fold cross validation with the Boyce Index as our primary metric of performance (Boyce et al., 2002; Johnson et al., 2006); specifically, we used population-level resource selection patterns from the model (setting all random slope and intercept terms to zero) to predict resource use by each individual pronghorn (n = 12). We computed the Boyce Index separately for each individual (assessing the degree to which population-level resource selection patterns were useful in predicting individual-level resource selection patterns) and we computed an average Boyce Index across all individuals (assessing the degree to which modeled population-level resource selection patterns successfully predicted resource use across all individuals in our study). We visualized the effect of each covariate on resource selection propensity using partial-dependence plots (model predictions displayed across the observed range of each predictor variable, with all other variables held at their mean value).

We used resource selection functions to generate maps representing the relative predicted intensity of selection for pronghorn across the landscape. We digitized the expansion area using maps from the Goldrush EIS created by BLM. For simplicity, we digitized the boundary of the underground mine and the ancillary activity aboveground, but excluded the additional expansion areas. Finally, we overlaid the expansion plans on our prediction rasters to represent areas of high use by pronghorn that would likely be affected by expansion of the mines.

3. Results

We had a total of 37,409 locations used by 12 individual pronghorn between January 2018 and June 2021 (Fig. 2). Because of the open

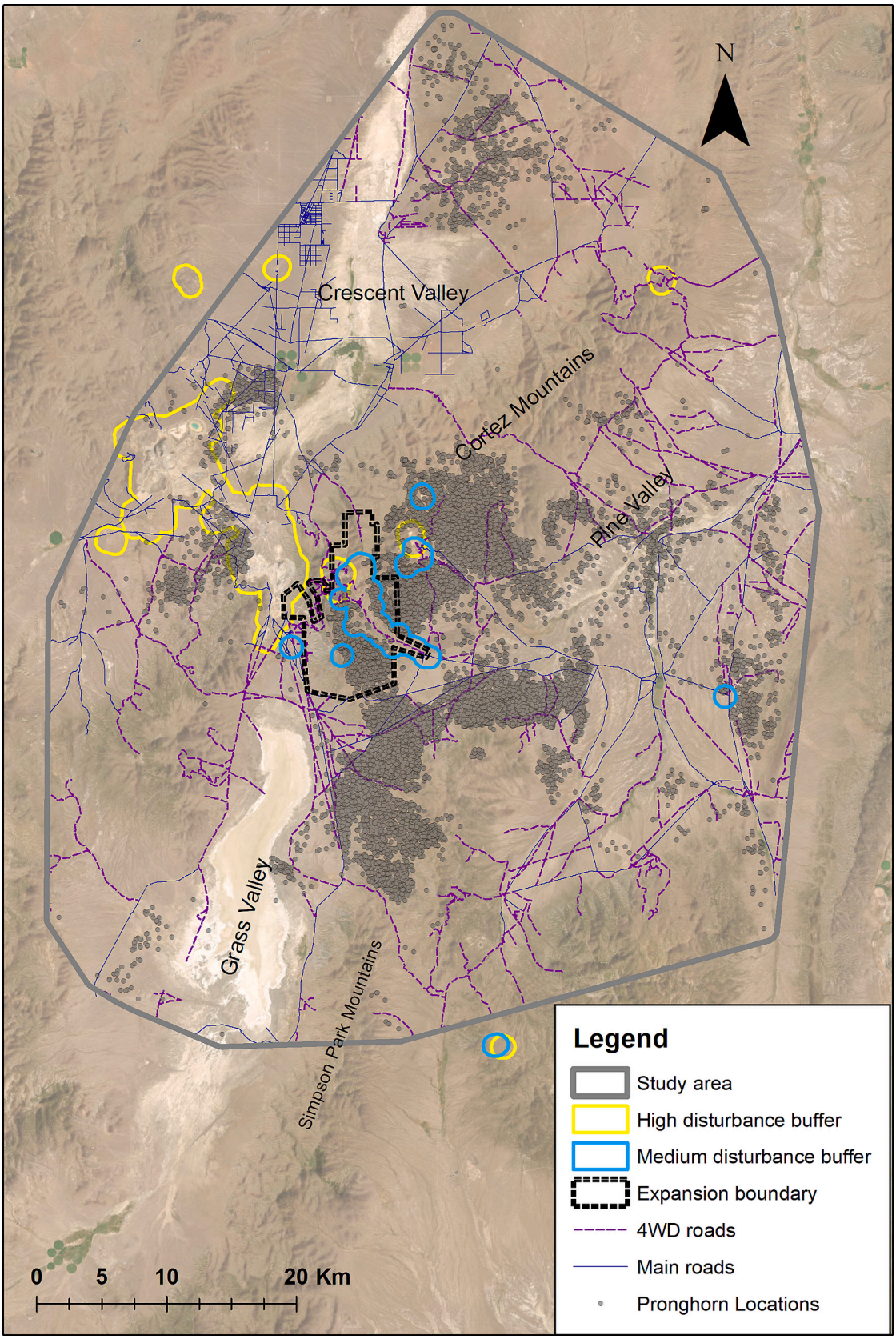

Fig. 2. Terrain map of the study area, which depicts locations of adult female pronghorn with GPS collars, as well as 787 m buffer around areas of medium and high disturbance near the Cortez gold mines in central Nevada, 2018–2021.

landscapes that pronghorn typically inhabit, locations had minimal error and we omitted only 62 locations from the dataset. We had 37,347 used locations and 97,347 randomly generated points to characterize resources available in the study area. We included 14 habitat covariates, and identified 7 characteristics of the habitat as most important for our population as indicated by the recursive feature elimination from random forest analysis (Table 1).

Resource selection functions for both annual and seasonal models indicated quadratic relationships in selection for elevation, slope, distance to 4WD roads, distance to main roads, and cover of annual vegetation (Fig. 3, Supplemental Table 1). DHARMa tests were not significant ($p > 0.05$) for annual and seasonal models, indicating the model fit was appropriate. Model evaluation indicated a strong predictive ability ($r_s = 0.748$, SE = 0.43) of our models. When evaluating predictive ability at the individual level, all $r_s > 0.782$ except for one individual in which $r_s = 0.359$ reflecting low predictive ability, which corresponded to the individual with the fewest locations. One individual $r_s = -0.725$ had very poor predictive ability, and that individual inhabited the most northern portion of the study area and appears to use somewhat different habitats than the rest of the animals in the study.

We observed substantial variation among individuals in selection of resources in annual and seasonal models (Figs. 4–5). We saw the greatest variation among individuals in selection for elevation, with the mean about 60 % of 2000 m of elevation, but individuals varied widely in use of elevation between 1800 and 2300 m (Fig. 4a). Pronghorn showed selection for moderate cover of annual plants, which was strongest at 25 % cover (Fig. 4c). Pronghorn showed strongest selection for low cover of shrubs; but intensity of selection also varied among individuals and declined slowly with increasing shrub cover to about 40 % (Fig. 4d). All individuals avoided high cover of trees, which was indicated by strongest selection for areas of tree cover close to 0, which dropped off rapidly with each 1 % increase in tree cover until about 20 % tree cover, when use became nonexistent (Fig. 4e).

Pronghorn selected locations relatively close to roads and intensity of selection was about 20 % adjacent to the roads, but peaked at about 50 % selection 2-km from both main and 4 wheel drive roads. (Figs. 4f, g). We observed strong avoidance of areas of high disturbance in the annual model, although again we observed substantial variation among individuals within our buffered areas around high disturbance (Figs. 4 h,i). Indeed, one individual showed strong selection for areas within the high disturbance buffers (Figs. 2 and 4h). Although there was substantial variation among individuals with respect to high disturbance during spring, summer, and winter, we observed no significant selection or avoidance during autumn (Fig. 5).

Our model indicated some avoidance of areas with medium disturbance in the annual model, but those confidence intervals overlapped zero (Figs. 3 and 4i; Supplemental Table 1). Confidence intervals for medium disturbance in our seasonal models overlapped zero for all seasons except winter, when pronghorn avoided areas of medium disturbance (Fig. 5; Supplemental Table 1). Similar to the annual model, we observed substantial variation among individuals relative to both the medium and high disturbance (Fig. 5)

Our relative prediction map shows high disturbance areas and the valley to the northeast of the open pits has the lowest probability of use within the study area (Fig. 6). The highest, relative probability of use is largely within the foothills on the south side of the Cortez range and the north side of the Simpson Park range (Fig. 6). Additionally, areas with high relative probability of use surround the edges of the expansion boundary and the edges of the existing high disturbance. Relative probability of use of the disturbed areas varied by season, within the expansion boundary the highest probability of use occurred during winter (Figs. 5 and 6). The expansion boundary overlapped with areas of high, relative probability of use by pronghorn in the area, but showed the strongest effect during winter, which was the only time we observed

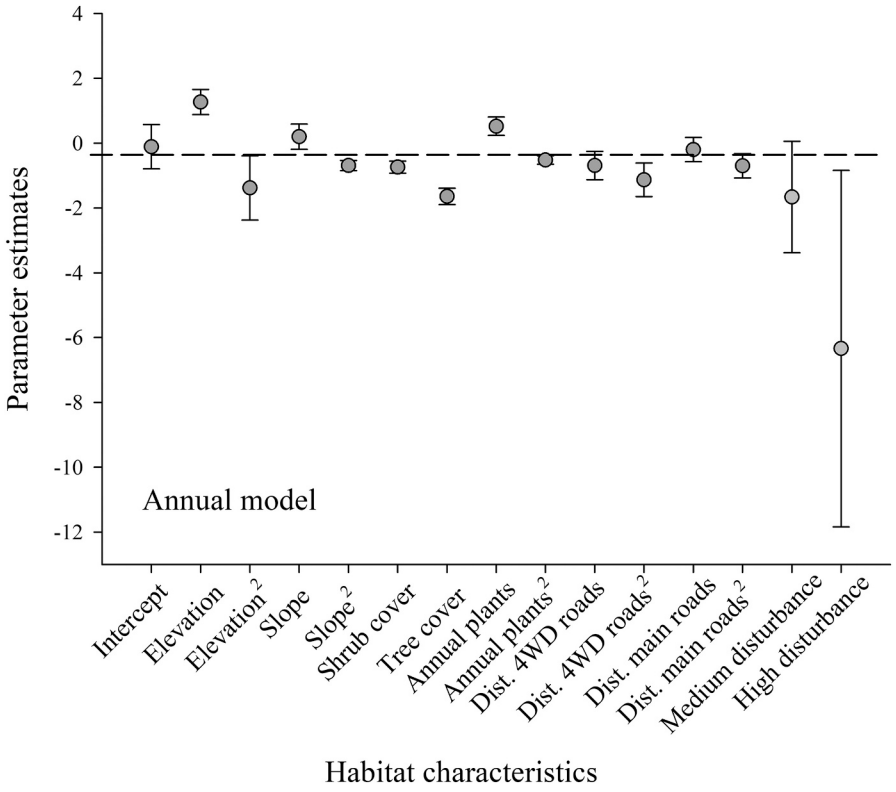

Fig. 3. Parameter estimates with 95 % confidence intervals for standardized habitat variables from annual model of resource selection functions with random intercepts and slopes for adult female pronghorn ($n = 12$) near the Cortez gold mine in central Nevada, 2018–2021. Note that for distance variables negative parameter estimates indicate selection because estimates are closer to roads than is available. For all other variables positive parameter estimates represent selection and negative estimates represent avoidance.

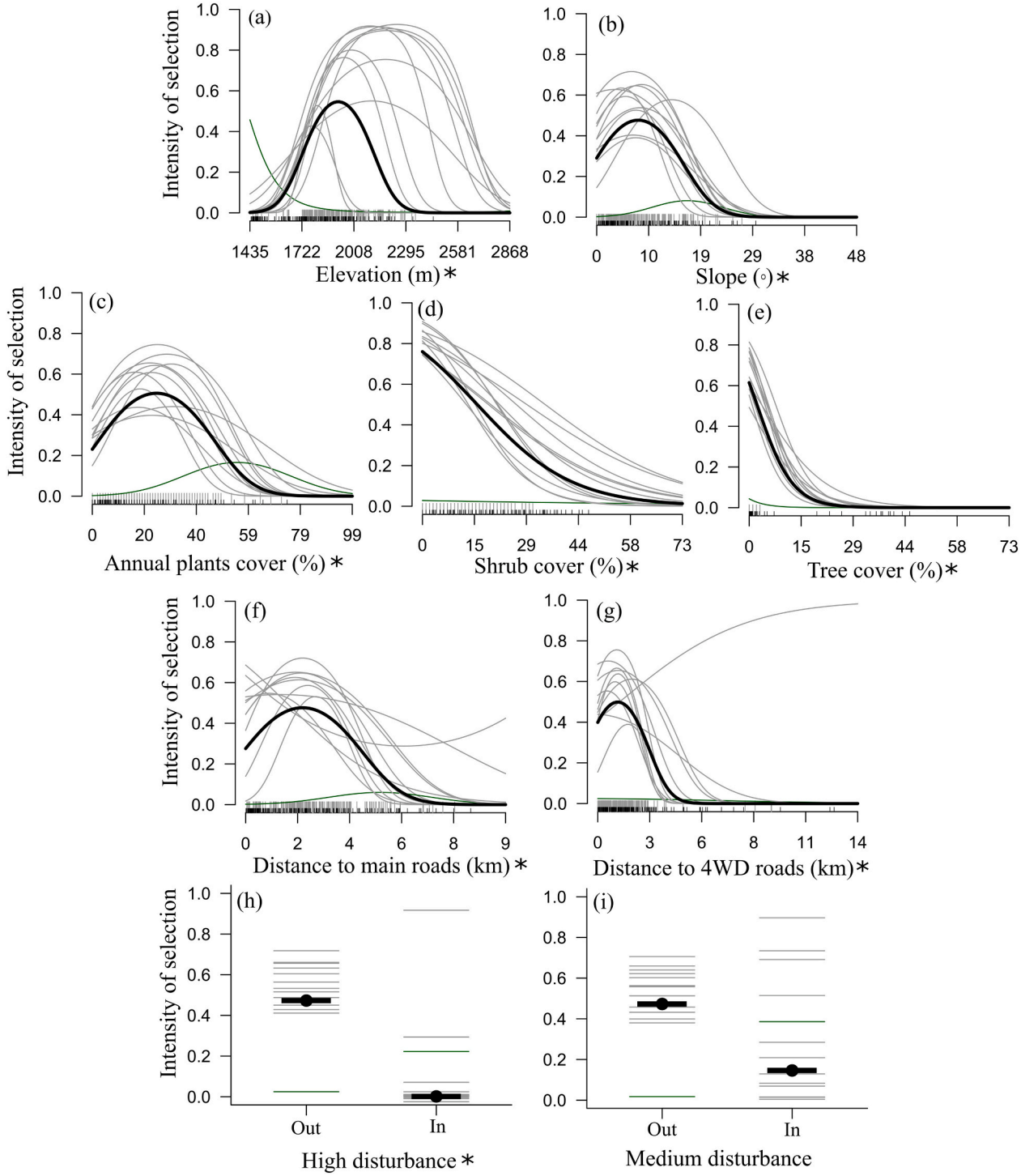

Fig. 4. Annual plots of resource selection by adult female pronghorn (n = 12) associated with the Cortez gold mine in central Nevada, 2018–2021. Visualizations were derived from the annual non-linear mixed effects model with random intercepts and slopes on each variable. In each plot, solid black line represents the population mean and individuals are shown as the gray lines. Tick marks at the bottom of the plot represent every 200th used location. The x-axes for our disturbance variables represent locations inside or outside the disturbance areas with a solid black circle to represent the population mean and individuals represented by each gray line (h and i). Note that the asterisks (*) depict significant relationships.

significant avoidance of medium disturbance (Figs. 5 and 6). The areas of medium disturbance had low relative probability of use even when they were near areas of high predicted probability of use (Fig. 6).

4. Discussion

Pronghorn in our study avoided areas close to high disturbance annually, but we observed strong variation in avoidance of disturbance seasonally even though our population occupied the study area year around. Additionally, we observed substantial variation among individuals in selection of resources in the area, especially for effects of roads and disturbances associated with the mine. Some individuals avoided the mine completely, others were relatively close to the buffered area around both the high and medium disturbances, and 1

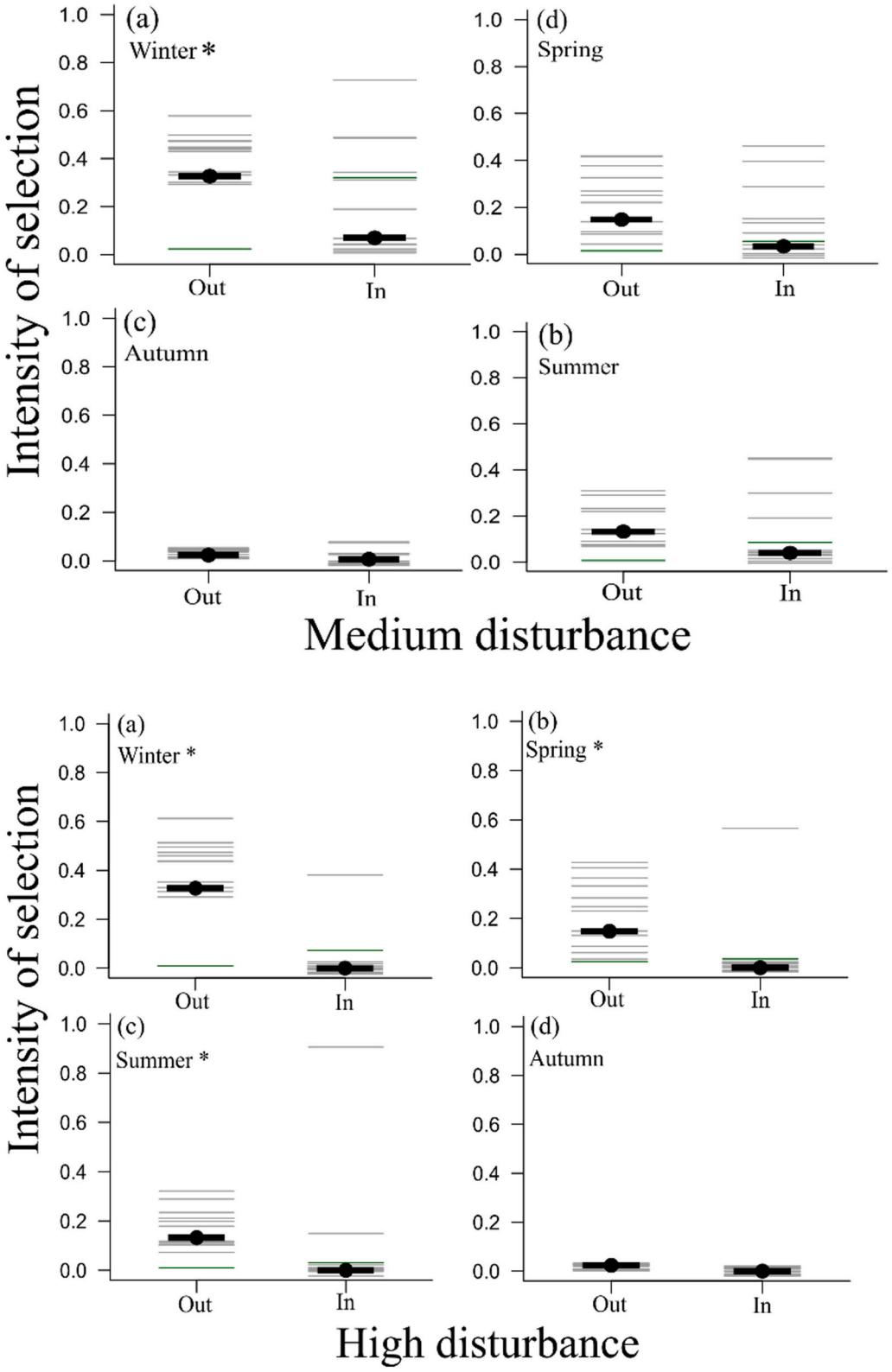

Fig. 5. Intensity of selection plots for medium and high disturbance by season for pronghorn (winter $n = 12$, spring $n = 12$, summer $n = 11$, autumn $n = 10$) associated with the Cortez gold mine in central Nevada 2018–2021. Visualizations were derived from the seasonal non-linear mixed effects models with random intercepts and slopes. X-axes represent locations inside or outside the disturbance areas and y-axes represent intensity of selection (0 to 1). A solid black circle represents the population mean and individuals are represented by each gray line. Note that an asterisk (*) indicates a significant relationship for that season.

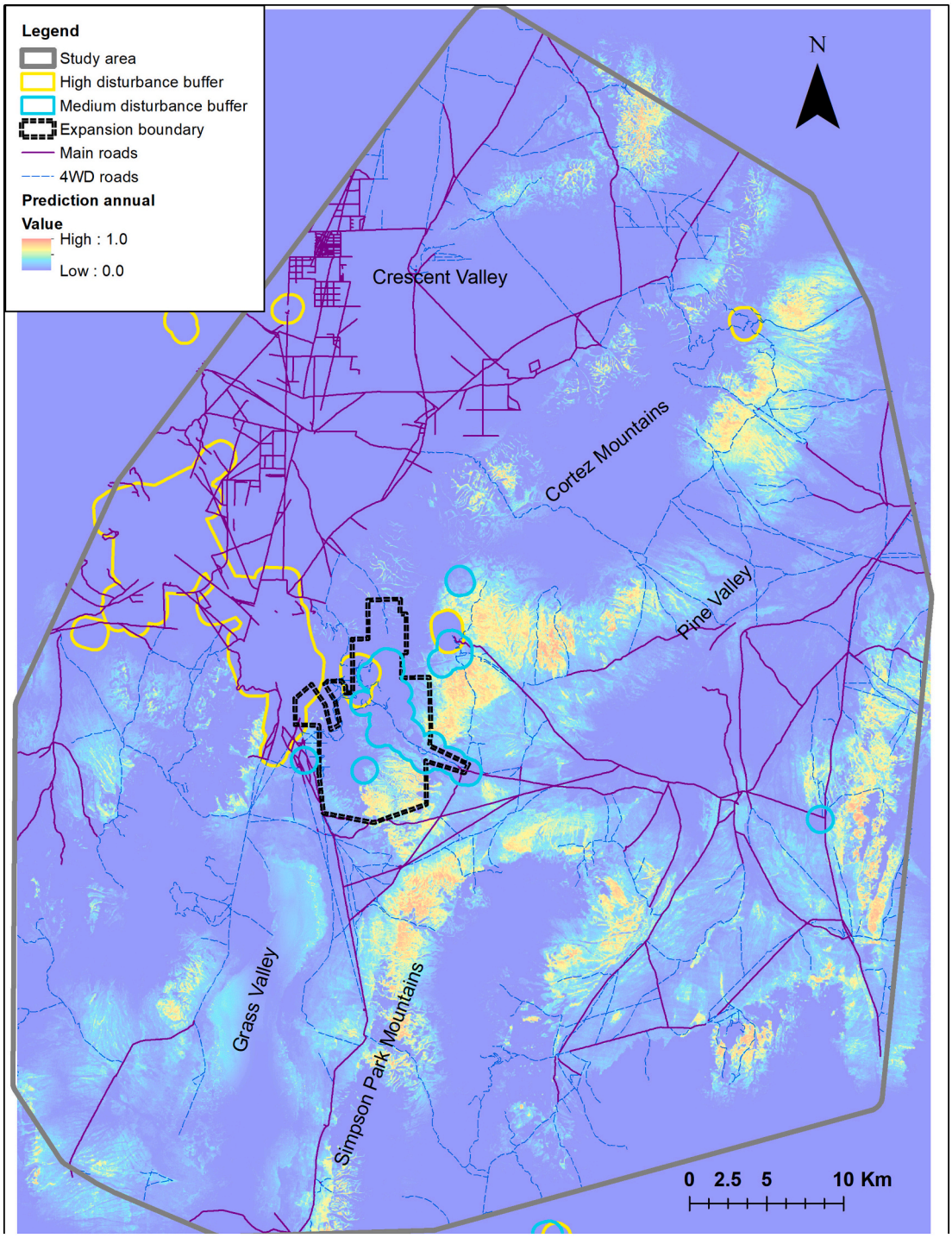

Fig. 6. Prediction raster derived from annual resource selection functions for pronghorn around the Cortez gold mine in central Nevada (2018–2021). Boundaries for expansion of the mine were obtained from the Goldrush Environmental Impact Statement for the proposed underground mine.

individual had locations within the high disturbance area. Pronghorn were not affected by medium disturbance in the annual models, but showed strong avoidance of medium disturbance during winter especially at the south end within the expansion boundary, which had the highest relative, predicted probability of use. That result may be because high disturbance in our study area was a much larger impact to the landscape, and thus was avoided to a greater extent than was the medium disturbance. Medium disturbance occupied a smaller part of the study area and pronghorn may avoid that level of disturbance at a finer scale than we were able to detect, whereas the large disturbance comprised larger and more contiguous areas. The paucity of data relative to medium disturbance also may have limited our power to detect an effect of medium disturbance in our study region.

Many populations of pronghorn exhibit seasonal migration (Sawyer et al., 2005; Jakes et al., 2018; Jones et al., 2019). Our study population, however, is resident and remains within the study area near the mine year-round, likely because of the relatively mild winters compared to areas with migratory populations of pronghorn. Central Nevada is frequently subjected to drought, but abundant precipitation during three winters prior to the study resulted in good habitat with flowing

springs and seeps (Cox et al., 2021). Moreover, the population in our area has been reported to be increasing between 2018 and 2021 (Cox et al., 2021). Beckmann et al. (2012) suggested that as habitats become more fragmented over time, wildlife populations may show changes in selection of resources or movement patterns even if sufficient food is available. While our study area currently has accessible food resources year around, individuals may be forced to use areas closer to disturbance if resources become more limited. Blum et al. (2015) noted that during migration, mule deer used habitat patches in relatively undisturbed areas within a mining complex that overlapped their migration route. Conversely, bighorn sheep spent less time foraging when they were near a mine in southern California than farther away from it (Oehler Sr. et al., 2005). Krausman et al. (2005) reported that Sonoran pronghorn, occupying habitat associated with military activity, selected for disturbed areas that had been subjected to fire from explosions. Pronghorn have been observed using water that collected in the resulting depressions (Krausman et al., 2005). In our study area, there could be patches of high-quality habitat near the medium disturbance that individuals need for nutritional requirements, such as high protein forage and minerals. Although we were unable to test this idea directly with our current data.

Contrary to other studies, pronghorn in our study selected areas relatively close to both main and 4 wheel drive roads. Results from previous research that show strong avoidance of roads, were from areas with high levels of traffic, such as highways and interstate freeways (Christie et al., 2017; Robb et al., 2022). The main roads in our study area included a two-lane paved highway (70 MPH speed limit), gravel roads with high mining traffic, and a network of 4 wheel drive roads that received lower amounts of traffic throughout the study area. Berger et al. (1983) found that pronghorn displayed greater vigilance when exposed to heavy traffic associated with mining activities. Levels of traffic, in our study, likely varied substantially among the main roads included in our study region. We were unable to access traffic data in association with the mine, which would have allowed us to compare selection for locations near main roads across varying levels of traffic. Moreover, our model also does not account for temporal variation in the locations so there may be higher selection at night or during crepuscular hours when traffic was low. Additionally, roads in our study area were not lined with fences, which contrasts with major highways described in other studies, which contributed to avoidance (Dodd et al., 2010). Nonetheless, most roads in the study area were gravel, and the mining company sprayed roads with water to prevent large dust clouds. Watering can contribute to vegetation growth along roadways and earlier green-up during late winter and spring, which might provide useable forage and thus drive selection for areas near the roadways. Additionally, snow melts faster along roadways because of the thermal conductivity of concrete and rocks (Clauser and Huenges, 1995), which can create easier paths of travel during winter.

While our results do not support the hypothesis that pronghorn avoid medium disturbance, except during winter. Individual location data indicated that pronghorn used the land surrounding disturbance within our buffered areas, although no locations were within the actual medium disturbance. Additionally, our relative prediction map identified areas with high probability of use for land that falls within the expansion boundary of the mine. If expansion of the Cortez mine occurs aboveground in this medium disturbance area, it will likely transition to a high disturbance area. Although the current plan for expansion in that area is supposed to primarily be underground. Based on our data, we predict that the increased disturbance will have a strong effect on pronghorn by reducing habitat quality and fragmenting the portion of the study area with some of the highest probability of use. Beckmann et al. (2012) noted that pronghorn are tolerant of some levels of human activities, the Cortez mine complex has been in the area for over 30 years, and potentially modifications to human activity may preclude demographic impacts of expansion if we can minimize disturbance in areas of highest relative probability of use.

Expansion of the mine into that area of high concentration of use by pronghorn could lead to population declines. As we mentioned previously, NDOW has reported high recruitment and population growth in this population, but the impact of a high-level disturbance in the area currently occupied by most of the individuals in our study will most likely have negative effects on the population, especially during years when forage may be more limiting than occurred during the years of our study. Demand for precious metals, such as gold and silver, and minerals, such as lithium, is leading to an increase in mining in the Great Basin and in mineral rich countries around the world (Martins-Oliveira et al., 2021). Expansion of areas of high disturbance, which were strongly avoided by pronghorn in our study, will undoubtedly result in further fragmentation and loss of habitat. As the Great Basin and land across the world continues to be altered by anthropogenic changes, increasing our understanding of possible impacts of those changes in behaviors of wildlife, before populations decline may assist in the mitigation and minimization of negative impacts on mineral-rich landscapes and on wildlife populations.

Additional supporting information may be found in the online version of the article at the publisher's website. Supplementary material includes information on both fixed and random effects of our annual and seasonal models of resource selection, including coefficient estimates (with standard error, t statistic, *p* values) for all fixed effects, and standard deviation and correlation coefficients for all random effects. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170750.

Funding

This project was funded by a Hatch grant from the Agriculture Experiment Station at the University of Nevada, Reno. Nevada Gold Mines provided funding to Nevada Department of Wildlife for the purchase of GPS radio collars for this project. Neither funding source was involved in study design, collection, analyses, interpretation of results, writing, or decision to submit this article for publication.

CRediT authorship contribution statement

Megan J. Osterhout: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Kelley M. Stewart:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Brian F. Wakeling:** Writing – review & editing, Funding acquisition, Conceptualization. **Cody A. Schroeder:** Writing – review & editing, Data curation, Conceptualization. **Marcus E. Blum:** Writing – review & editing, Formal analysis. **Julia C. Brockman:** Writing – review & editing, Formal analysis. **Kevin T. Shoemaker:** Writing – review & editing, Methodology, Formal analysis, Conceptualization.

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.

Data availability

Data is available through request from the Nevada Department of Wildlife

Acknowledgements

We thank S. Hale and J. Lutz of Nevada Department of Wildlife for sharing insight on the study area and population. P. Williams, M. Lohman, and J. Vasquez of the University of Nevada, Reno helped with problem-solving during the analysis stage. We thank T. Dilts for

troubleshooting all things ArcGIS. We also thank M. Branch and B. Schultz of the University of Nevada, Reno for their contributions in editing.

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