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Original Research

Relationships Between Landscape Greenness and Condition of Elk, Mule Deer, and Pronghorn in New Mexico☆

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A B S T R A C T

Nutritional condition drives large herbivore population performance and is related to precipitation and forage quality in the arid Southwest. Because precipitation is difficult to measure at home-range scales, we tested whether satellite-derived vegetation indices of landscape greenness (i.e., indices of vegetation phenology or photosynthetic activity including normalized difference vegetation index [NDVI], soil-adjusted vegetation index [SAVI], and enhanced vegetation index [EVI]) were correlated to the condition of three species of large herbivores (elk, mule deer, pronghorn). We used canonical correlation analysis to relate seasonal landscape greenness with several measures of large herbivore condition. We also used linear mixed models to relate each measure of condition to seasonal landscape greenness separately for each herbivore population-year to see if any patterns were masked by multivariate analysis. Landscape greenness indices were only weakly related to condition of large herbivores, and the effect of landscape greenness on condition was always weaker than lactation status with the exception of pronghorn, an income breeder. Different indices also frequently gave highly variable and conflicting relationships between seasonal landscape greenness and condition of large herbivores. Overall, expected positive relationships between herbivore condition and landscape greenness indices were seen in only 8% of 2 988 possible outcomes. Because indices of landscape greenness are increasingly being used to relate wildlife population demographics to precipitation through a presumed effect on forage quality and resultant nutritional condition, we caution this use in arid environments unless a direct landscape greenness-forage quality or greenness-condition link is demonstrated.

Introduction

Nutritional condition is the driver of large herbivore population performance in the arid Southwest (Bender et al., 2007a, 2012a, 2013a; Hoenes, 2008; Bender and Piasecke, 2010; Halbritter and Bender, 2011a) and is related to precipitation and forage quality (McKinney, 2003; O'Gara, 2004a; Halbritter and Bender, 2015). Precipitation affects large herbivore condition but is problematic to measure within smaller areas like the individual home range. Consequently, precipitation data are usually taken from a limited number of sites scattered throughout a study area, which may be near, but seldom within, home ranges (e.g., Bender et al., 2011; Halbritter and Bender, 2011a). However, precipitation patterns at different points on a landscape may not accurately reflect the precipitation that occurs within individual home ranges (Stubblefield et al., 2006; Caltrider, 2012). This is especially true in arid landscapes, where precipitation is highly variable both spatially and temporally (Pennington and Collins, 2007; Caltrider, 2012).

Satellite-derived vegetation indices, including the normalized difference vegetation index (NDVI), soil-adjusted vegetation index (SAVI), and enhanced vegetation index (EVI), measure vegetation reflectance as an index of photosynthetic activity or plant phenology (hereafter, landscape greenness; Tucker, 1979; Huete, 1988; Huete et al., 1997, 2002). For example, photosynthetically active vegetation reflects much of the near-infrared light that strikes it, while absorbing much of the red light. In contrast, senesced vegetation reflects more red light and less near infrared light. Thus, landscape greenness indices are able to index photosynthetic activity by measuring the fraction of photosynthetically active solar radiation absorbed (Tucker, 1979; Huete, 1988; Huete et al., 1997, 2002; http://www.landscapetoolbox.org/). Although many vegetation greenness indices have been developed, NDVI, SAVI, and EVI have been the most commonly available preprocessed data (although red and near-infrared imagery is readily

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available for processing into any vegetation index). Consequently, they, especially NDVI, have been mostly commonly used in natural resources management (Pettorelli et al., 2011).

By indexing photosynthetic activity or plant phenology, these indices may allow inferences between precipitation and large herbivore condition because they may correlate with forage quality (Kerr and Ostrovsky, 2003; Pettorelli et al., 2005a; Ryan et al., 2012). Landscape greenness indices thus may provide a tool to indirectly measure the effects of precipitation on large herbivore condition at spatial scales such as the home range (Pettorelli et al., 2005a, 2005b; Ryan et al., 2012). To test this hypothesis, we related landscape greenness indices to multiple indices of condition of elk *(Cervus elaphus)*, mule deer *(Odocoileus hemionus)*, and pronghorn *(Antilocapra americana)* from several populations covering an array of habitat conditions in arid and semiarid New Mexico. Our objective was to determine whether landscape greenness indices were correlated to nutritional condition of large herbivores, as well as to assess the generality of results among species differing significantly in dietary quality requirements.

Study Areas

Our study populations occurred in five locations within New Mexico (Table 1). The San Andres Mountains (SAM) site covered approximately 11,000 km^2 in south-central New Mexico, approximately 40 km east of Las Cruces. Chihuahuan desert scrub is the major vegetation type, with pinyon (*Pinus edulis* Engelm.)-juniper (*Juniperus* spp.) associations at higher elevations (Hoenes and Bender, 2012). The Chaco Culture National Historical Park (CCNHP) site covered 308 km^2 in northwestern New Mexico approximately 30 km southwest of Nageezi. This site is desert grassland with scattered juniper woodlands (Bender et al., 2012b). The Sacramento Mountains (LNF) site encompassed approximately 1 800 km^2 in the southern Sacramento Mountains of southcental New Mexico west of Alamogordo. The vegetation communities in the Sacramento Mountains are extremely diverse due to differences in elevation and precipitation and included pinyon-juniper and Gambel oak (*Quercus gambelii* Nutt.) woodland; ponderosa pine (*P. ponderosa* Doug. ex Laws.) typically mixed with pinyon-juniper or Douglas fir (*Pseudotsuga menziesii* [Mirb] Franco); mixed conifer forest with pockets of aspen (*Populus tremuloides* Michx.); and numerous mountain meadows (Halbritter and Bender, 2011b). The Corona Range and Livestock Research Center (CRLRC) site encompassed 113 km^2 approximately 23 km northeast of Corona, New Mexico. Vegetation was composed of perennial short grasses with an overstory of sparse to dense pinyon-juniper woodland (Bender et al., 2013b). The pronghorn on CRLRC were bounded by impassible fences that did not allow them to actively select different areas of the ranch for foraging; thus they utilize the entire pasture in which they occur. Consequently, we evaluated pronghorn by pastures rather than within home ranges. The north-central New Mexico (NC) site encompassed approximately 4 860 km^2 in Colfax County, New Mexico. Vegetation types are varied in the area, although most of the mule deer in this study site were associated with lower elevation short grassland, oakbrush shrubland, and pinyon-juniper woodlands (Bender et al., 2007b).

Methods

Nutritional Condition

Methods for animal capture and condition assessment were identical among populations (see Bender et al., 2007a, 2012a, 2013a; Bender and Piasecke, 2010; Halbritter and Bender, 2011a for additional details). Briefly, we captured adult (age 1.5 or older) females by darting or net gun from a helicopter. Darted individuals were immobilized with a mixture of carfentanil citarate and xylazine hydrochloride. All individuals were treated with vitamin E/selenium, vitamin B, an 8-way *Clostridium* bacterin, and penicillin G procaine to alleviate capture stress.

We measured condition at the local seasonal peak at the end of the spring–autumn season (SSA) in late November–early December. We measured rump fat thickness at its thickest point immediately posterior to the cranial process of the tuber ischium (pin bone; MAXFAT) using a SonoVet 2000 (Medison, Seoul, South Korea) portable ultrasound with a 5-mHz probe. For mule deer, we estimated body fat (BF) using $BF = 5.68 + 5.93 \times MAXFAT$ (cm; Stephenson et al., 2002). If no subcutaneous fat was present, we used a rump body condition score (rBCS) to determine BF, where $BF = 4.014 \times rBCS - 2.021$ for female desert mule deer (*O. h. eremicus*; Bender et al., 2012a) and $BF = 3.444 \times rBCS - 0.746$ for female Rocky Mountain mule deer (*O. h. hemionus;* Bender et al., 2007a). We estimated rBCS by palpating the sacral ridge and soft tissue along the sacrosciatic ligament and scored on a scale of 1–5 in intervals of 0.25, where 1 = emaciated and 5 = obese (Bender et al., 2007a).

We estimated body fat of elk similarly except that we combined MAXFAT and rBCS measures into a combined measure (rLIVINDEX), where rLIVINDEX = rBCS when MAXFAT < 0.3 cm and rLIVINDEX = (MAXFAT − 0.3) + rBCS when MAXFAT > 0.3 cm (Cook et al., 2001). We then estimated BF from rLIVINDEX using the following: $BF = -7.15 + 7.32 \times L - 0.99 \times L^2 + 0.06 \times L^3$, where L = rLIVINDEX (Cook et al., 2001). If MAXFAT was not measured, we calculated BF from rBCS using the following: $BF = 4.478 \times rBCS - 4.618$ (Cook et al., 2001).

For pronghorn, we measured MAXFAT and rBCS identically to mule deer. However, we did not estimate BF for pronghorn because no predictive models have been developed for pronghorn.

For each species, we also estimated a withers body condition score (wBCS) by palpating the top of the withers posterior to the shoulder hump and scoring the amount of sacral ridge discernable on a scale of 1.0–5.0 (Cook, 2000; Bender et al., 2007a). We used an ultrasound to measure the thickest point of the longissimus dorsi (loin) near the spine between the 12th and 13th ribs (Cook, 2000; Cook et al., 2001). We also measured heart girth as the circumference of the chest cavity immediately behind the legs and ventral to the peak of the shoulder hump (Bender et al., 2007a) and body mass by using a spring scale or estimated mass from girth regression models (Cook, 2000).

Home Ranges

We located radio-collared individuals ≥ 1 time per week (see Bender et al., 2007b, 2012b, 2013a; Halbritter and Bender, 2011b). We used locations from April to November to create a SSA seasonal home range

Table 1
Mean annual precipitation (cm), mean high temperature in July (°C), mean low temperature in January (°C), number of years of data for a species at a site (population-years), annual sample sizes, and total sample size of individuals used in analyses for elk, mule deer, and pronghorn populations.

Site	Species	Precipitation	Mean temperature		Population-yr	Annual *N*	Total *N*
		Annual	July high	January low			
San Andres	Deer	20-35	35	−3	4	10-26	72
CCNHP	Elk	23	32	−11	3	14-23	52
LNF	Elk	67	22	−7	1	25	25
CRLRC	Pronghorn	40	29	−6	3	14-25	47
CRLRC	Deer	40	29	−6	1	17	17
Northcentral	Deer	44	28	−8	1	13	13

CCNHP, Chaco Culture National Historical Park; LNF, Sacramento Mountains; CRLRC, Corona Range and Livestock Research Center.

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