Techniques and Technology Article

A Simple Solar Radiation Index for Wildlife Habitat Studies

KIM A. KEATING,[1] *United States Geological Survey, Northern Rocky Mountain Science Center, Montana State University, Bozeman, MT 59717, USA*
PETER J. P. GOGAN, *United States Geological Survey, Northern Rocky Mountain Science Center, Montana State University, Bozeman, MT 59717, USA*
JOHN M. VORE, *Montana Department of Fish, Wildlife, and Parks, P.O. Box 1408, Hamilton, MT 59840, USA*
LYNN R. IRBY, *Department of Ecology, Montana State University, Bozeman, MT 59717, USA*

ABSTRACT Solar radiation is a potentially important covariate in many wildlife habitat studies, but it is typically addressed only indirectly, using problematic surrogates like aspect or hillshade. We devised a simple solar radiation index (SRI) that combines readily available information about aspect, slope, and latitude. Our SRI is proportional to the amount of extraterrestrial solar radiation theoretically striking an arbitrarily oriented surface during the hour surrounding solar noon on the equinox. Because it derives from first geometric principles and is linearly distributed, SRI offers clear advantages over aspect-based surrogates. The SRI also is superior to hillshade, which we found to be sometimes imprecise and ill-behaved. To illustrate application of our SRI, we assessed niche separation among 3 ungulate species along a single environmental axis, solar radiation, on the northern Yellowstone winter range. We detected no difference between the niches occupied by bighorn sheep (*Ovis canadensis*) and elk (*Cervus elaphus*; $P = 0.104$), but found that mule deer (*Odocoileus hemionus*) tended to use areas receiving more solar radiation than either of the other species ($P < 0.001$). Overall, our SRI provides a useful metric that can reduce noise, improve interpretability, and increase parsimony in wildlife habitat models containing a solar radiation component. (JOURNAL OF WILDLIFE MANAGEMENT 71(4):1344–1348; 2007)

DOI: 10.2193/2006-359

KEY WORDS bighorn sheep, *Cervus elaphus*, elk, habitat modeling, mule deer, niche separation, northern Yellowstone winter range, *Odocoileus hemionus*, *Ovis canadensis*, solar radiation index.

Solar radiation affects many biological processes that influence species' distributions and habitat selection, but it seldom appears explicitly as a covariate in habitat studies. Instead, such studies typically employ surrogates such as aspect (e.g., Pereira and Itami 1991, Manly et al. 1993, Anderson et al. 2000) or computer-generated hillshade values (Ciarniello et al. 2005). Unfortunately, neither aspect nor hillshade accounts for effects of both slope and latitude; thus, they may fail to distinguish among areas receiving different amounts of solar radiation. In addition, aspect and hillshade can yield different values for areas receiving equal solar radiation. For example, aspect-based methods distinguish between southeast (135°) and southwest (225°) aspects of equal slope and latitude, even though the amount of solar radiation striking such areas is the same. We show below that the hillshade surrogate of Ciarniello et al. (2005) suffers similar problems. A further issue is that use of aspect generally requires transformations that either discretize (Manly et al. 1993) or linearize (Pereira and Itami 1991) what would otherwise be a continuous circular variable. These transformations burden habitat models with extra parameters that impose added costs in terms of common model selection criteria (e.g., Akaike's Information Criterion; Burnham and Anderson 1998). Discretization also causes information loss.

As an alternative to aspect and hillshade, we construct a simple solar radiation index (SRI) that distills information about slope, aspect, and latitude into a single linear value that researchers can easily incorporate into habitat studies. Derived from first geometric principles, our index is proportional to the amount of extraterrestrial solar radiation theoretically striking an arbitrarily oriented surface during the hour surrounding solar noon on the equinox. Herein, we present the derivation of our SRI, compare it with the hillshade method of Ciarniello et al. (2005), and demonstrate its application in a test of niche separation among 3 ungulate species.

STUDY AREA

We illustrated the use of our SRI in an example application in which we tested for niche separation among bighorn sheep (*Ovis canadensis*), elk (*Cervus elaphus*), and mule deer (*Odocoileus hemionus*) during winter along a single environmental axis, solar radiation. We defined winter as 1 December–30 April. Our tests used data collected previously in the Gardiner Basin area of the northern Yellowstone winter range (NYWR), USA. Houston (1982) and Despain (1990) gave detailed descriptions of the area. Elevations in the 104,771-ha Gardiner Basin ranged from about 1,500 m to 3,350 m. This area encompassed the lowest elevations on the NYWR, which were dominated by sagebrush (*Artemisia* spp.)–grassland, Rocky Mountain juniper (*Juniperus scopulorum*), and Douglas-fir (*Pseudotsuga menziesii*) communities that were vital to wintering ungulates, especially during severe or late-winter conditions. Straddling the northern boundary of Yellowstone National Park, the Gardiner Basin comprised state, federal, and private lands. Knowledge of ungulate habitat-use patterns in this area, and the factors governing them, is key to devising effective and cooperative conservation strategies.

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[1] *E-mail: kkeating@usgs.gov*

METHODS

Solar Radiation Index

We derived our SRI from the general equation for hourly extraterrestrial radiation striking an arbitrarily oriented surface (Iqbal 1983:72):

$$\begin{aligned} I_{0\beta\gamma} = I_{sc}E_0\{&[\sin(\varphi)\cos(\beta) - \cos(\varphi)\sin(\beta)\cos(\gamma)]\sin(\delta) \\ &+[\cos(\varphi)\cos(\beta) \\ &+\sin(\varphi)\sin(\beta)\cos(\gamma)]\cos(\delta)\cos(\omega_i) \\ &+\cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega_i)\}, \qquad (1) \end{aligned}$$

where

$I_{0\beta\gamma}$ = total hourly extraterrestrial radiation striking the surface;

I_{sc} = solar constant, in energy units;

E_0 = eccentricity correction factor;

φ = latitude (degrees; north positive, south negative)

β = inclination of the surface from the horizontal position (degrees);

γ = surface azimuth angle (degrees; east positive, west negative);

δ = declination (degrees; north positive, south negative);

ω_i = hour angle at the middle of the ith hour.

By definition, $E_0 = (r_0/r)^2$, where r_0 is the mean sun–earth distance, and r is the actual sun–earth distance on a given day (Iqbal 1983). Equation 1 can be greatly simplified by judicious choice of a reference time. Note that $\omega_i = 0$ for the hour surrounding solar noon, and $r = r_0$ (thus, $E_0 = 1$) on the equinox. Further, the declination (δ; which defines the tilt of the earth relative to the ecliptic plane) is zero on the equinox. Therefore, choosing solar noon on the equinox as the reference time for our index yields $E_0 = 1$, $\sin(\omega_i) = 0$, $\cos(\omega_i) = 1$, $\sin(\delta) = 0$, and $\cos(\delta) = 1$. Substituting these values into equation 1 and expressing hourly irradiation as a proportion of the solar constant, I_{sc}, equation 1 reduces to the nondimensional index,

$$\begin{aligned} \mathrm{SRI} = I_{0\beta\gamma}/I_{sc} &= \cos(\varphi)\cos(\beta) + \sin(\varphi)\sin(\beta)\cos(\gamma) \\ &= \cos(\text{latitude})\cos(\text{slope}) \\ &\quad + \sin(\text{latitude})\sin(\text{slope})\cos(\text{aspect*}), \qquad (2) \end{aligned}$$

where aspect* = 180° − aspect, so that south is 0°, westerly aspects range between 0° and −180°, and easterly aspects range between 0° and +180°. The index is constrained to the domain $-1 \leq \mathrm{SRI} \leq 1$, but not all values are possible everywhere because of the effect of latitude. For example, SRI values at 45° latitude range between −0.707 and +1 (Fig. 1).

Relationship to Hillshade

Ciarniello et al. (2005) calculated hillshade values using a digital elevation model (DEM) and ArcGIS Version 8.3, and used those values as a surrogate for solar radiation. Although intuitively reasonable, the relationship between solar radiation and the hillshade index of Ciarniello et al. (2005) is difficult to evaluate analytically because the algorithm for calculating hillshade is not given, nor have researchers empirically demonstrated its relationship to true solar radiation. To understand whether SRI values offer a gauge of solar radiation that is fundamentally different from that obtained via the hillshade method, we conducted 2 simple empirical comparisons. In our first comparison, we used a 10-m DEM for Glacier National Park, Montana, USA, and calculated hillshade using ArcView Version 3.3, specifying azimuth = 225° and elevation = 45°, as per Ciarniello et al. (2005). In our second comparison, we specified azimuth = 180° and slope = 45°, reasoning that an azimuth of 225° might result in a poor correlation between hillshade and true solar radiation because, in the northern hemisphere, south-facing (180°) slopes receive the most solar radiation (Fig. 1). Using information about latitude, together with slope and aspect calculated from the DEM, we also computed SRI (eq 2). For each of our comparisons, we recorded SRI and hillshade for 1,000 locations randomly selected using the ArcView Animal Movement extension (Hooge and Eichenlaub 1997). To judge whether SRI and hillshade values provide equivalent information, we plotted hillshade on SRI and examined the correlation (Zar 1984) between them.

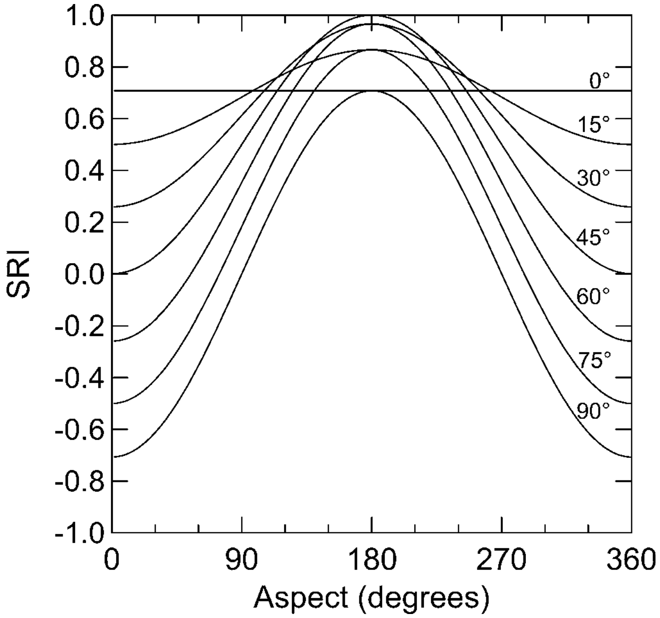

Figure 1. Solar radiation index (SRI) values associated with different slopes and aspects at 45° latitude. Individual curves depict values for slopes of 0–90°. Values for slopes of 0° are constant and are shown for comparison, recognizing that aspect for such areas is undefined.

Ungulate Niche Separation

In our example application, we calculated SRI (eq 2) for the Gardiner Basin using latitude and a 30-m DEM, from which we computed slope and aspect. We determined density of use by bighorn sheep, elk, and mule deer from radiotelemetry data gathered in previous studies during 1979–1997 (Keating 1982; Vore 1990; Legg 1996; Ostovar 1998; P. J. P. Gogan, United States Geological Survey, unpublished data). In those studies, researchers relocated radiocollars primarily using fixed-wing aircraft. The bighorn sheep and elk data also included locations of collared animals sighted following ground-based radiotracking. In the bighorn sheep and elk studies, researchers estimated coordinates after plotting locations on United States Geological Survey 7.5-minute topographic maps. Researchers determined mule deer locations using a Global Positioning System, as described by Olexa et al. (2000). We assigned SRI values associated with individual telemetry locations using ArcView Version 3.3, under the assumption that telemetry locations were strictly accurate. Violations of this assumption clearly contributed noise to our analyses, thereby making niche separation more difficult to detect, but we assumed that telemetry locations were not systematically biased with respect to SRI values. Because researchers gathered data over an 18-year period, it is reasonable to ask whether significant vegetation changes occurred that might affect our analyses. We believe that such an effect is unlikely because 1) all 3 species concentrated their winter use on slopes with relatively high SRI values (i.e., on xeric slopes where plant succession tends to be quite slow), and 2) winter ranges in the Gardiner Basin were not affected during this period by major events such as the 1988 Yellowstone fires.

For each pair-wise combination of our 3 study species, we used a Kolmogorov–Smirnov procedure (Zar 1984) to test for differences in density of use with respect to SRI values. Although our data derived from repeated measures of the same individuals, we nonetheless assumed that, for each species, telemetry locations provided a simple random sample of use by the population with respect to solar radiation. We justify this assumption on 3 grounds. First, the data seem likely to be representative of the population as a whole because researchers sampled relatively large numbers of individuals of each species ($n = 50$ bighorn sheep, $n = 38$ elk, $n = 85$ mule deer). Second, all 3 species are gregarious; thus, location data are likely to be representative of larger groups, not just single animals. Third, not considering repeated measures among individuals would tend to result in estimated standard errors and, in turn, P-values that are too small. This concern would be bothersome if P-values associated with our results were only marginally significant, but all P-values were either >0.05 or very near zero. Thus, the assumption of a simple random sample is unlikely to affect our conclusions.

RESULTS

Relationship to Hillshade

Comparison showed that hillshade values calculated using azimuth = 225° and elevation = 45° were correlated with SRI values (Pearson's $r = 0.70$), but provided a much less precise surrogate (Fig. 2a). Calculating hillshade using azimuth = 180° and elevation = 45°, hillshade and SRI provided nearly identical indices of solar radiation (Pearson's $r = 0.98$; Fig. 2b). However, in both comparisons we observed inexplicable behavior in hillshade values. In our first comparison, hillshade values of zero were associated with SRI values in the range −0.46 to +0.77, whereas in our second they were associated with SRI values in the range −0.46 to +0.62 (Fig. 2a, b). Expressed in more familiar metrics, the hillshade algorithm yielded values of zero for terrain as diverse as aspect = 107° and slope = 45°, or aspect = 334° and slope = 58°. In both of our comparisons, cases where hillshade equaled zero accounted for only about 4% of the sample. Nonetheless, confidence in index performance is undermined by such behavior.

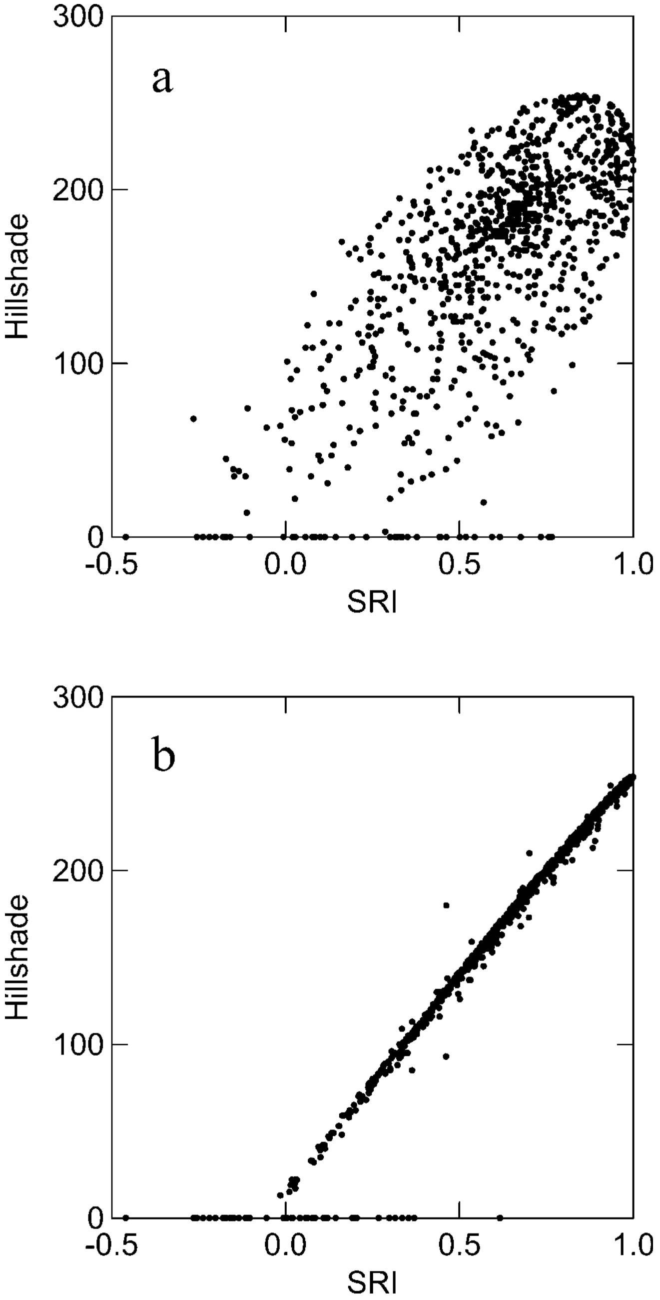

Figure 2. Relationship between solar radiation index (SRI) and hillshade values for 1,000 randomly selected locations in Glacier National Park, Montana, USA. We calculated hillshade values in (a) using azimuth = 225° and slope = 45°, and in (b) using azimuth = 180° and slope = 45°.

Ungulate Niche Separation

For all species examined, winter use was concentrated in locations receiving relatively high levels of solar radiation (Fig. 3). We found no difference in allocation of winter use by bighorn sheep and elk, with respect to solar radiation (D

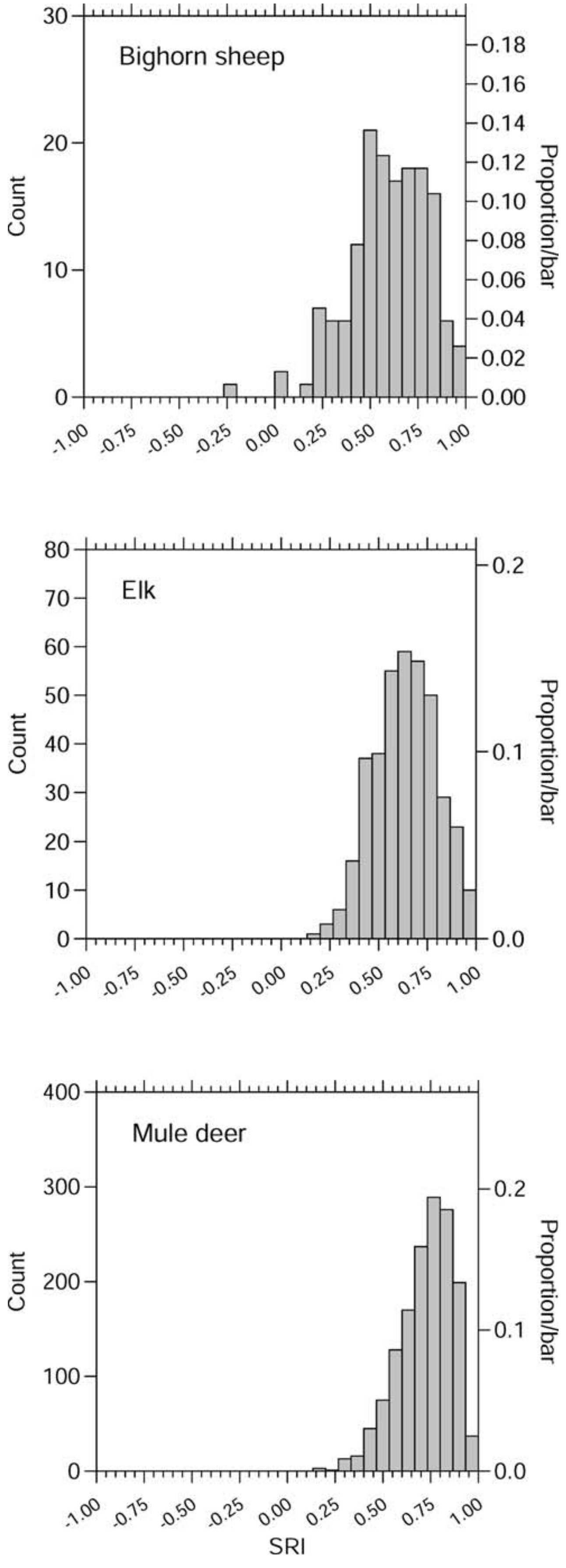

Figure 3. Observed density of winter use by bighorn sheep (n = 154 locations of 50 individuals), elk (n = 393 locations of 38 individuals), and mule deer (n = 1,533 locations of 85 individuals) in studies conducted during 1979–1997 in the Gardiner Basin area of the northern Yellowstone winter range, USA. Densities are plotted relative to solar radiation index (SRI) values.

$= 0.116$, $P = 0.104$). Thus, our data provide no evidence of niche separation between these species during winter along this particular environmental axis. There were, however, clear differences in habitat use by mule deer and bighorn sheep ($D = 0.324$, $P < 0.001$), and mule deer and elk ($D = 0.270$, $P < 0.001$). Relative to bighorn sheep and elk, mule deer tended to use areas receiving more solar radiation (Fig. 3; median SRI = 0.61, 0.64, and 0.75 for bighorn sheep, elk, and mule deer, respectively).

DISCUSSION

Solar radiation is a potentially important covariate in many wildlife habitat studies, but most researchers include it in their analyses only via problematic surrogates like aspect or hillshade. Drawing from the engineering literature, in which issues related to solar radiation have received more rigorous attention, we devised a simple SRI that derives from first geometric principles. Consequently, our SRI offers a more direct approach than other surrogates and dispenses with problems caused by the circular distribution of aspect and by difficulties in accounting simultaneously for effects of aspect, slope, and latitude. It also dispenses with the sometimes inexplicable and undesirable behavior of the hillshade surrogate, whereby 4% of the locations we sampled were inappropriately assigned a value of zero. The utility of our SRI is illustrated in our example application, where we show that mule deer in the Gardiner Basin area of the NYWR tend to use areas receiving more solar radiation than areas used by bighorn sheep or elk. All else being equal, areas receiving more solar radiation should experience shallower snow depths. Thus, our findings are consistent with Houston (1982), who concluded that mule deer are less suited than elk or bighorn sheep to dealing with deep winter snow.

Although we believe that SRI values should be broadly useful, users should remember that SRI is more tightly correlated with solar radiation than are aspect or hillshade. Thus, SRI is less likely to behave as an unintended surrogate for factors other than solar radiation. This has ≥ 2 important and perhaps unobvious implications.

First, use of SRI should improve our ability to distinguish between different effects of slope. Slope affects the amount of solar radiation striking a particular site, but it also can impose physical limitations on habitat use that are independent of solar radiation. For example, winter habitat use by mule deer might correlate with slope because of its relationship to solar radiation and, in turn snow depth, but that correlation might also reflect the species' physical inability to use the same steep terrain as bighorn sheep. Thus, it may be appropriate to include both SRI and slope in habitat-use analyses, even though slope is a component of

SRI. Indeed, if use is correlated with slope, then doing so may allow for more refined interpretations as to why that correlation exists.

A second, counterintuitive observation about SRI is that because it is more tightly correlated with solar radiation it may yield models with less predictive power than other surrogates. This observation merits careful consideration because it illustrates a more general cautionary tale about the use of surrogates in habitat modeling. To see how an SRI-based model might be less predictive than an aspect-based model, imagine a species that concentrates its use on southwest (225°) aspects, but avoids those to the southeast (135°). Imagine also that the terrain is a simple cone, so that all southwest and southeast aspects receive identical amounts of solar radiation, and disparities in use are not due to differences in slope or availability. Consider 2 competing models of species occurrence. Using SRI to indicate solar radiation would yield a model that correctly predicts avoidance of northerly aspects but incorrectly predicts equal use of southwest and southeast slopes. In contrast, using aspect as our surrogate would yield a model that correctly predicts avoidance of northerly and southeast aspects, as well as concentrated use of southwest slopes. Clearly, the aspect-based model would have greater predictive power, even though SRI better indexes solar radiation. This occurs because the correlation between use and aspect is not due solely to solar radiation; thus, interpreting aspect strictly as a surrogate for solar radiation may lead to erroneous conclusions about causes of the observed pattern. This example underscores the fact that surrogates for habitat variables can also serve as unintended surrogates for other factors that the researcher may or may not explicitly recognize or understand.

When using SRI, researchers also should recognize certain limitations. Users should remember that SRI is an index, designed to be proportional to the amount of solar radiation that would theoretically be received in the absence of factors like atmospheric interference, cloud or vegetation cover, or shading due to topography. It is not a measure of the amount of solar radiation actually striking a given surface. In addition, time is held constant to simplify calculation of SRI, thereby rendering SRI inappropriate for some applications. Consider, for example, a hypothetical species that seeks out direct sunlight, causing it to move from eastern aspects in the morning toward western aspects in the afternoon. To study this phenomenon, SRI provides an inadequate gauge of solar radiation because it does not account for changes in solar radiation during the day. For such an application, a more sophisticated measure would be needed.

MANAGEMENT IMPLICATIONS

Our SRI is designed to enhance wildlife habitat models containing a solar radiation component by reducing noise, improving interpretability, and minimizing the number of model covariates (thereby increasing parsimony). Ultimately, this promotes greater understanding of the determinants of wildlife–habitat relationships and, in turn, improved decision-making by wildlife managers.

ACKNOWLEDGMENTS

The United States Geological Survey funded this work. We appreciate access to the bighorn sheep telemetry data created jointly by L. R. Irby, K. A. Keating, K. L. Legg, and K. Ostovar. We thank L. A. Landenburger for Geographic Information System assistance, E. M. Olexa for radio-tracking mule deer, R. K. Menicke for the Glacier National Park DEM, and the Northern Yellowstone Cooperative Wildlife Working Group for archiving the telemetry data used in this study. We also thank the Associate Editor J. J. Millspaugh and 2 anonymous reviewers, whose comments helped improve the manuscript.

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