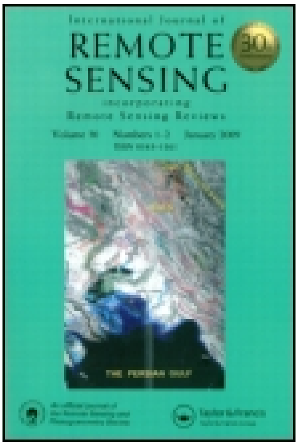

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A comparison of Landsat TM and MODIS vegetation indices for estimating forage phenology in desert bighorn sheep (Ovis canadensis nelsoni) habitat in the Sonoran Desert, USA

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A comparison of Landsat TM and MODIS vegetation indices for estimating forage phenology in desert bighorn sheep (*Ovis canadensis nelsoni*) habitat in the Sonoran Desert, USA

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Sonoran Desert bighorn sheep (*Ovis canadensis mexicana*) occupy rugged upland areas that experience irregular periods of vegetation growth associated with precipitation events. These episodic and often spatially limited events provide important forage and preformed water resources that may be important drivers of animal movement and habitat use. Habitat-use models that incorporate forage phenology would broaden our understanding of desert bighorn ecology and have considerable potential to inform conservation efforts for the species. Field-based methods are of limited utility to characterize vegetation phenology across large areas. Vegetation indices (VI) derived from satellite imagery are a viable alternative, but may be confounded by areas of high relief and shadow effects that can degrade VI values. The varying spatial and temporal resolutions of readily available satellite sensors, such as the Landsat thematic mapper (TM) and moderate-resolution imaging spectrometer (MODIS), present additional challenges. In this study, we sought to minimize degrading effects of terrain on TM- and MODIS-based estimates of vegetation phenology. We compared effects of high topographic relief on time series MODIS- and TM-based VI such as the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) using VI departures from average (DA) in shaded and unshaded areas. Sun elevation angle negatively impacted TM-derived NDVI and EVI values in areas of steep terrain. In contrast, MODIS-derived NDVI values were insensitive to sun elevation and terrain effects, whereas MODIS-derived EVI was degraded in areas of steep terrain. Time series MODIS NDVI and EVI DA values differed significantly during months of low sun elevation angle. Average MODIS EVI departure values were $\geq$20% lower than NDVI under these conditions, confounding time series estimates of plant phenology. Our best results were obtained from MODIS 16-day composited NDVI. These remote-sensing-based VI estimates of seasonal plant phenology and productivity can be used to inform models of habitat use and movements of desert bighorn over large areas.

1. Introduction

Desert ungulates occupy diverse habitats that provide various life history requirements, such as foraging, escape from predators and reproduction (Marshal *et al*. 2005,

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Bleich *et al*. 2010). In the Sonoran Desert, bighorn sheep (*Ovis canadensis mexicana*) are associated with rugged upland areas that experience irregular periods of vegetation growth triggered by precipitation events. These episodic and often spatially limited events provide important forage and preformed water resources and may be important drivers of animal movements and habitat use. Habitat use models that incorporate vegetation phenology would broaden our understanding of desert bighorn ecology and have considerable potential to inform conservation efforts for the species. Field-based methods are of limited utility to characterize vegetation phenology over large areas, particularly rugged and often inaccessible terrain commonly used by desert bighorn. Remote-sensing data are a potential alternative, providing a means to characterize vegetation phenology of Sonoran Desert vegetation over large areas and multiple years. These data can potentially be integrated with radio telemetry data collected for desert bighorn sheep to model sheep movements and foraging patterns in the Sonoran Desert.

Multispectral and multitemporal satellite imagery from Landsat thematic mapper (TM) and the moderate-resolution imaging spectrometer (MODIS) satellites provide time series data on vegetation parameters related to seasonal productivity and distribution (Zhang *et al*. 2003, Pennington and Collins 2007, van Leeuwen *et al*. 2010). Each of these sensors produces data in the red and near-infrared (NIR) spectral regions that distinguish photosynthetically active plant material. Spectral vegetation indices (VIs) are a ratio or combination of spectral bands which typically are used to enhance the sensitivity of remotely sensed data to vegetation characteristics such as plant greenness, vigour, productivity, biomass and leaf area index (Huete *et al*. 2002). Numerous VIs exist; however, the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) are standard satellite data products used for regional- to global-scale vegetation monitoring (Jensen 2007, van Leeuwen *et al*. 2010). EVI (equation (1)) is often used in place of NDVI (equation (2)) because it contains empirically derived correction factors accounting for canopy background (e.g. soil and bare earth) and atmospheric effects and is more sensitive to high biomass conditions. However, NDVI has been shown to potentially reduce terrain effects on VI values (Matsushita *et al*. 2007). EVI and NDVI are calculated as follows:

$$\mathrm{EVI} = G\frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + C_1\rho_{\mathrm{red}} - C_2\rho_{\mathrm{blue}} + L}, \tag{1}$$

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}}, \tag{2}$$

where ρ represents atmospherically corrected reflectance in the NIR, red and blue spectral regions, and coefficients $C_1 = 6.0$ and $C_2 = 7.5$, soil adjustment factor $L = 1.0$ and gain factor $G = 2.5$ (Jensen 2007).

Soil effects are particularly important in desert environments with low vegetation cover and high albedo from land surfaces. Several VI derivatives contain soil correction features similar to EVI (Jensen 2007), but can show greater sensitivity to terrain effects and sun angle differences, which vary throughout the year and during satellite image acquisition (figure 1). For example, TM viewing geometry and low sun elevation angle ($\leq 30°$) in the month of January result in shadows in areas of steep terrain with north to north-western aspects that are illuminated in other months of the year.

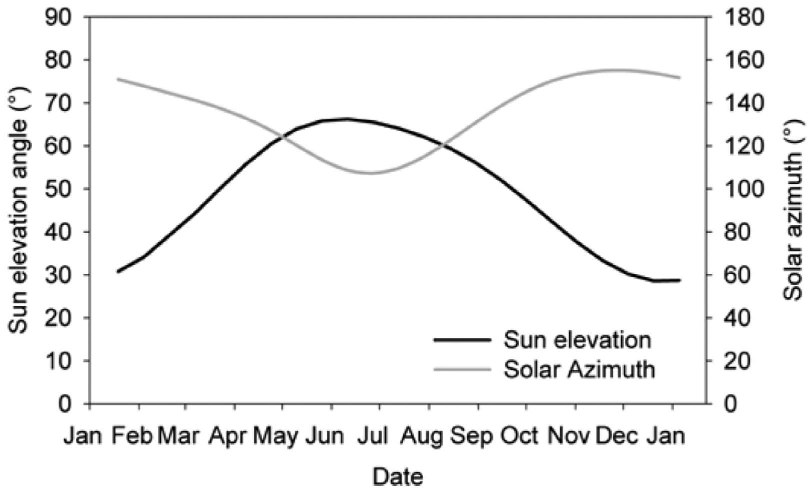

Figure 1. Year 2008 sun elevation (black line) and solar azimuth (grey line) values at the time of image acquisition for the Landsat TM sensor.

TM and MODIS satellite imagery offer different spatial and temporal resolutions. TM produces 30 m pixel resolution imagery every 16 days, in which each scene represents a snapshot on the given acquisition date. MODIS has lower spatial resolution (250 m pixel), greater field of view and higher frequency of acquisition, covering the same location at least once per day, at differing viewing geometries. To account for the wide range of viewing geometries and potential cloud cover, MODIS 16-day composite images are corrected for spatial variation in the bidirectional reflectance distribution function, to accommodate anisotropic reflectance from land surfaces, and remove clouded pixels. MODIS VI data products are systematically derived using the constrained view angle – maximum value composite algorithm designed to reduce terrain and atmospheric impacts (http://tbrs.arizona.edu/project/MODIS/MOD13.C5-UsersGuide-HTML-v1.00/index.html). TM provides high spatial resolution (30 m pixels) data useful for determining fine-scale vegetation patterns and phenology, but typically at lower temporal resolution due to cloud cover during image acquisition.

Our primary research objective was to identify the best available VI and image data source to estimate annual and seasonal vegetation phenology in areas of steep terrain occupied by desert bighorn sheep. We also explored image-processing methods to reduce atmospheric and terrain impacts on TM data and determined relationships between 2007 and 2008 weather patterns and VI variability.

2. Methods and materials

2.1 *Study area*

The study area includes the Kofa National Wildlife Refuge and the Yuma Proving Ground in South western Arizona (figure 2). Elevation ranges from 54 to 1730 m in numerous rugged mountain ranges that comprise the principal habitat for desert bighorn sheep. Native vegetation across the study area comprises the Lower Colorado

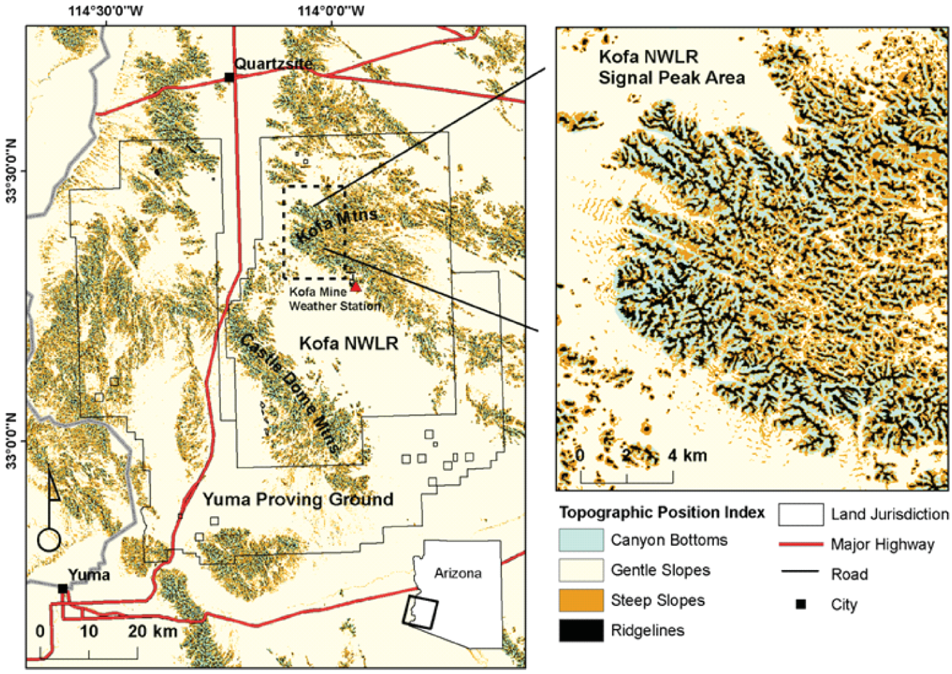

Figure 2. Study area and level of terrain variability characteristic of locations occupied by desert bighorn sheep. Topographic position index (TPI) was used to indicate areas of extreme terrain variability (Dickson and Beier 2007).

River Valley and Arizona Upland subdivisions of the Sonoran Desert, dominated by creosote bush–white bursage and Palo verde cacti series (Brown 1982).

Mean annual rainfall and temperature are 18 cm and 22.4°C, respectively. However, precipitation and air temperature vary strongly on an annual and inter-annual basis (Western Regional Climate Center, http://www.wrcc.dri.edu/). Rainfall can be too low to measure in any given month of the year and mean minimum and maximum monthly temperatures range between 7°C and 40°C during January and July, respectively. Growth and productivity of annual and perennial plants is strongly tied to fall–winter rainfall and summer monsoon thunderstorms. Inter-annual variability in the amount of rainfall is the primary factor affecting forage availability for bighorn sheep in a given season or year (Bleich *et al*. 2010). Forage productivity also varies spatially and temporally according to site biophysical factors such as topography, solar radiation and soil substrate, but is more tightly coupled with rainfall patterns in the arid south-western USA (Halvorson and Patten 1975, Allen 1991).

2.2 *Data processing*

An annual time series of VI values between January and December of 2008 were used to estimate phenologic cycles and periods of increased plant productivity (green-up) for single image dates relative to average annual vegetation conditions. Pixel values for a given date indicate either a greener than average (positive departure from the annual average) or less green (negative departures) time periods for locations on the ground. Departures from average (DA) values, described below, provide a standardized scale to quantitatively compare different VI for characterizing vegetation green-up and senescence periods.

A total of 13 cloud-free TM images and 23 MODIS 16-day VI were downloaded from the USGS Global Visualization Viewer (http://glovis.usgs.gov/) for mapping vegetation phenology between January and December of 2008. An atmospheric correction was applied to TM images using ENVI v. 4.5 software and the fast line-of-sight atmospheric analysis of spectral hypercubes model (ITT Visual Data Solutions 2008) prior to deriving VI. Fast line-of-sight atmospheric analysis of spectral hypercubes processing also corrects upwelling path radiance scattered from adjacent pixels. To assess the atmospheric correction, we compared corrected and uncorrected red and NIR TM bands used to derive VI for invariant sand targets (pixels) on relatively level terrain within the study area.

To examine terrain effects on VI, NDVI and EVI values were compared using the percentage departure value of pixels for areas potentially shaded during some months of the year, in addition to locations unlikely to be shaded by surrounding terrain at any time of the year. Our assumption was that although the amount of plant production differs among sites, temporal patterns in plant phenology, driven by seasonal rainfall and increased photosynthetically active vegetation, would be similar. For example, low-productivity sites characteristic of arid lands will be likely to show positive departures from the annual average VI values when even minor increases in green vegetation occur (van Leeuwen *et al*. 2010).

DA values were calculated as follows:

$$\mathrm{DA} = \frac{\mathrm{VI_s}}{\mathrm{VI_m}}, \tag{3}$$

where $\mathrm{VI_s}$ is the VI value for a single image date, $\mathrm{VI_m}$ is the mean pixel value for the time series. DA′ is the DA for a particular image date in the series multiplied by 100 to estimate each pixel's percentage departure from the annual average (Beck and Gessler 2008).

To estimate locations potentially shaded during satellite image acquisition, we developed a hillshade model using a 30 m digital elevation model and spatial analyst extension in ArcGIS v. 9.3. Shading was based on the predicted shadows cast at the lowest sun elevation angle (28.7°) and highest solar azimuth (151.7°), coincident with a January 2008 TM image date. Areas greater than 5 ha in size having a hillshade value of 0 (shaded areas) were used to extract shaded VI pixels from all image dates. A total of 17% of daily sheep locations were within these highly shaded areas according to telemetry data collected from individuals ($n = 27$) monitored during 2008 with global positioning system collars. To identify unshaded pixels, an initial set of 100 random points were distributed across the study area on slopes <1%. Each point was buffered with a 1500 m radius polygon. Polygons located over areas of contiguously low slope angle ($n = 27$) were used to extract non-shaded VI pixels from the image time series.

Data on monthly air temperature and precipitation during the study period are important to understanding vegetation green-up patterns and its connection to climate in the study area. Temperature and precipitation data collected between January 2007 and December 2008 were used to determine linkages between VI and periods of increased desert vegetation productivity and green-up.

To determine the sensitivity of VI to highly varied topography and terrain effects, quantitative comparisons were made between (1) mean NDVI and EVI DA′ values extracted from shaded areas at each image date and (2) mean VI values extracted from each shaded area during the month of January, when sun angle was lowest. Data were evaluated for normality using a Kolmogorov–Smirnov test and compared using non-parametric Mann–Whitney rank sum or *t*-tests ($\alpha = 0.05$) using the SigmaPlot v. 11 statistics software package (Systat Software 2008). MODIS VIs were also compared by examining residual DA values for each month on both shaded and unshaded terrain. The absolute difference between EVI and NDVI departure values in shaded areas were compared to the absolute difference between the two VIs in unshaded areas using a Mann–Whitney test.

3. Results and discussion

Reflectance of invariant targets should remain constant over time. Atmospheric and other noise contributes to errors that result in variable reflectance over time (figure 3(*a*)). The atmospheric correction minimized this variance, as evidenced by clustering of pixels from three dates in corrected scenes (figure 3(*b*)). No additional corrections were applied to MODIS VIs that were pre-processed with the constrained view angle – maximum value composite algorithm to reduce atmospheric and terrain effects.

Increased plant production is more tightly coupled with periods of increased precipitation in arid desert lands than other biomes (Allen 1991). When winter–early spring precipitation is sufficient, annual plants initiate growth between October and November and mature between February and April depending on the amount and duration of precipitation. Precipitation for Kofa National Wildlife Refuge prior to and during the study period show increased monthly rainfall during late fall 2007 and early 2008 (figure 4), characteristic of winter frontal systems that can bring widespread rainfall to the Sonoran Desert (Hanson and Hanson 2000). While monthly average temperatures were relatively consistent, precipitation in 2007 and 2008 was highly

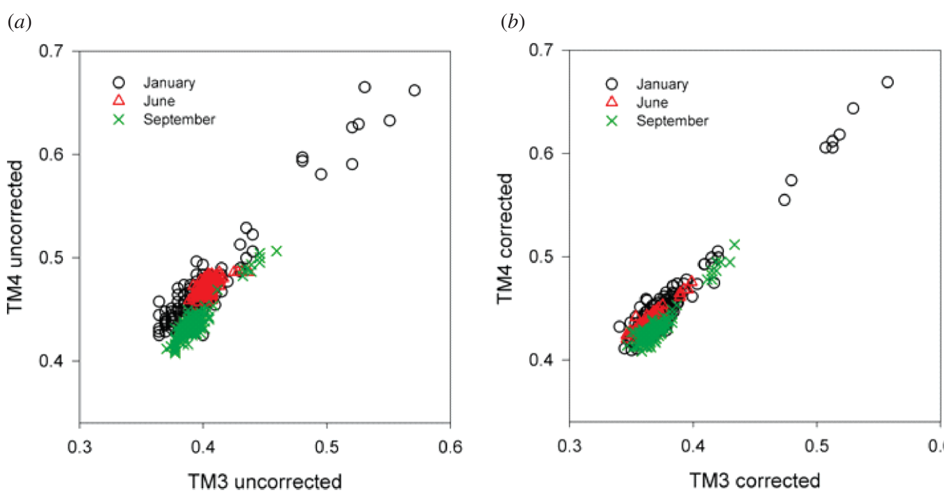

Figure 3. Red (TM3) and NIR (TM4) reflectance values for (*a*) uncorrected sand pixels ($n = 200$); and (*b*) atmospherically corrected sand pixels ($n = 200$) from winter, summer and fall 2008 Landsat image dates.

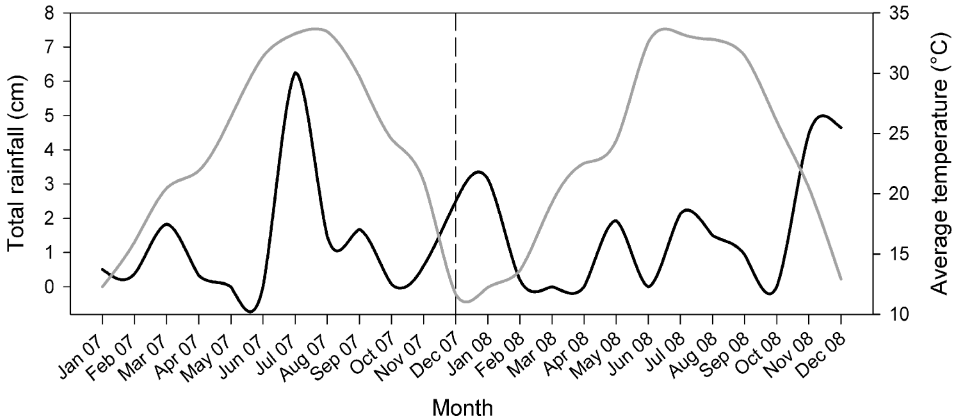

Figure 4. Monthly average temperature (grey line) and total rainfall (black line) for 2007 and 2008 from the Kofa Mine Meteorological Station located in Kofa National Wildlife Refuge.

varied between the years (figure 4). These conditions typified the high inter-annual variability of rainfall in this region.

The number of available cloud-free Landsat TM image dates was less than the number of MODIS 16-day composited scenes (13 vs. 23). Consequently, TM presented a less-complete record of plant phenology and productivity. Of the TM-derived VI values, EVI appeared less sensitive to areas of steep rocky terrain shadowed during image acquisition (figure 5). Departure values greater than 100% of the annual average were considered green-up events or periods of increased plant productivity (Pennington and Collins 2007, Beck and Gessler 2008, Mildrexler *et al*. 2009, van Leeuwen *et al*. 2010). Monthly DA below 100% represents lower productivity periods where annual plants are in an early-germination stage or have undergone senescence. EVI departure values were, in general, more consistent with green-up events corresponding to November to January rainfall during 2007 and 2008 and increased spring temperature in February and March 2008 (figure 4).

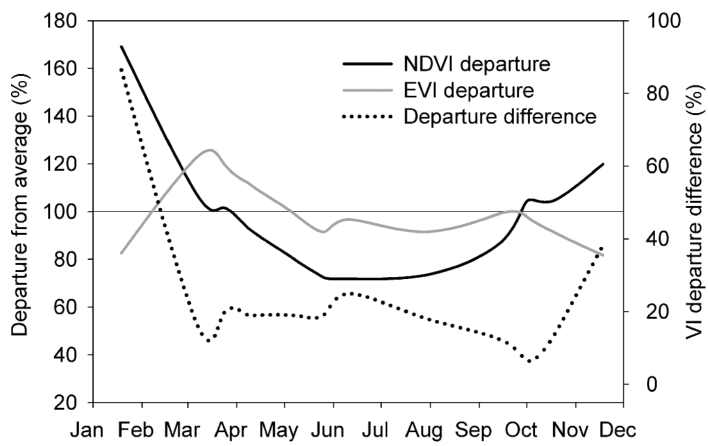

Figure 5. Monthly departure from average Landsat NDVI and EVI values for steep shaded terrain across the study area. The dotted line (black) represents the percent difference between TM NDVI and EVI values.

However, both NDVI and EVI produced inordinately high or low departure values for image dates with a low sun elevation angle (<40°). A comparison of mean VI departure values from pixels within shaded areas showed a significant difference between EVI and NDVI ($U = 213$, $p < 0.001$) with a median DA of 83 and 170%, respectively, for the month of January.

North-east facing slopes and canyon areas with a lower amount of annual solar radiation typically maintain ephemeral herbaceous plants and deciduous shrubs in the study area (personnel observation). In areas of steep and shaded terrain, visual comparisons indicated that MODIS NDVI DA was less sensitive to terrain and shadow effects than was EVI DA (figure 6 (*a*)–(*c*)). EVI- and NDVI-derived departure values for shaded terrain in mountainous areas also showed a statistically significant difference ($U = 101080.5$, $p < 0.001$) for months such as January with a low sun elevation angle (figure 7(*a*)). In contrast, areas of low topographic variation showed nearly identical MODIS VI departure values, further indicating greater sensitivity of EVI to terrain effects (figure 7(*b*)). Areas of steep shaded terrain also showed significantly higher residual departure values than did values from level terrain (figure 7(*c*), $t = 347.0$, $p < 0.001$).

This is particularly important when calculating DA values as a measure of annual and inter-annual green-up events in areas of steep topography. Extremely low EVI departure values, ≥20% lower than NDVI DA attributable to terrain and sun angle effects, negatively impacted time series data, erroneously indicating above-average greenness during hotter and drier months of the year that are typically associated with low productivity and senescence of winter annual grasses and forbs. Falsely low EVI values in shaded areas produced low annual average values for these pixels, resulting in higher than expected DA values for summer months (figure 7(*a*)).

4. Conclusions

Sensor viewing geometry can impact index values in areas of rugged mountain topography, which comprises a large portion of desert bighorn sheep habitat in the Sonoran Desert. TM-derived NDVI was more sensitive to terrain effects than EVI, however both indices either under- or over-estimated VI values in areas of steep topography. This is particularly problematic for TM images acquired during months when sun elevation angle is very low (<40°). Terrain-affected VI values subsequently impact DA values for any given date in the time series producing artificially high or low DA values. A further limitation of TM imagery is that fewer cloud-free dates are typically available as compared to MODIS composite images. In contrast, MODIS composite images provided regular bimonthly time series VI. MODIS NDVI values were notably insensitive to areas of steep topography that are most likely to impact VI during months with poor viewing geometry. MODIS EVI greatly underestimated VI values under these conditions. Results from our VI comparisons are consistent with Matsushita *et al*. (2007) who demonstrated terrain impacts on MODIS EVI and other VI where a soil adjustment factor has been used. Our results suggest that MODIS NDVI is best suited for evaluating vegetation phenology in the rugged desert terrain present on our study area. Such information may be useful for developing models that incorporate the inherent spatial and temporal variability in habitat quality for desert bighorn sheep, and assessing potential impacts of climate change and other factors on this and other species of concern.

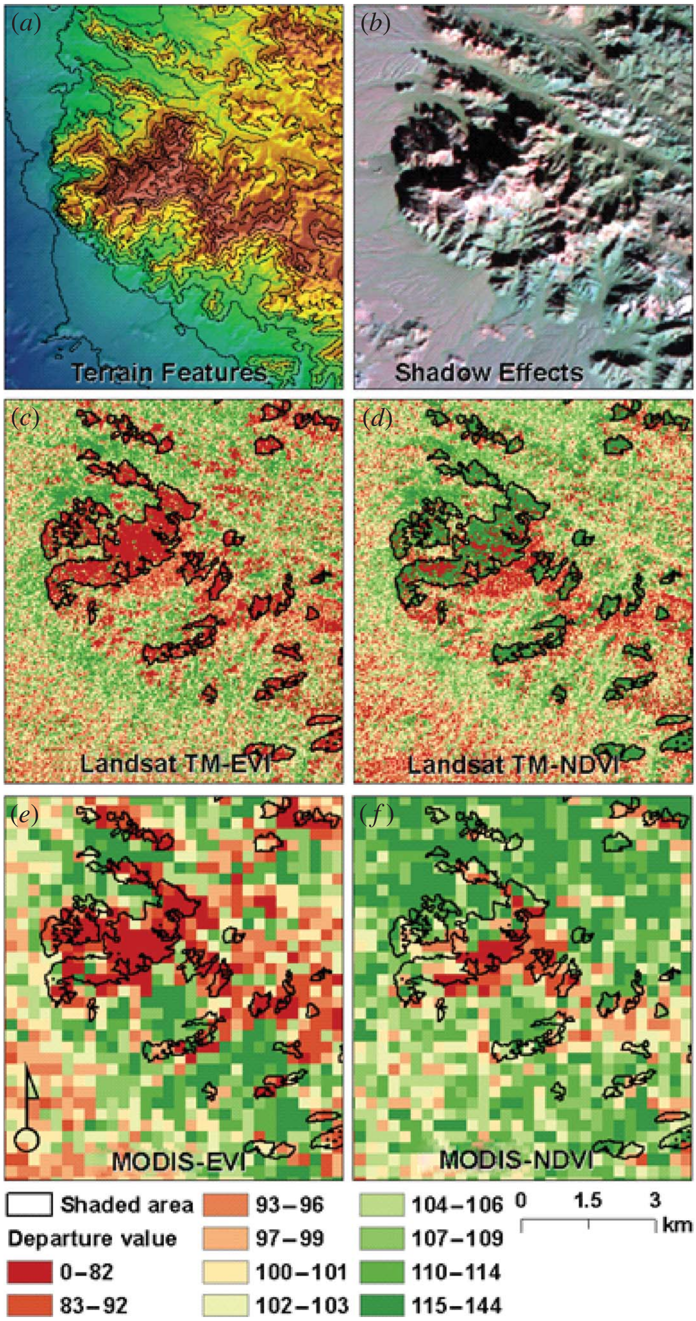

Figure 6. (*a*) A contour map (100 m contours) and overlaying a coloured digital elevation model show the location of steep terrain (yellow to red) for each of the preceding images in the Signal Peak area shown in figure 2. (*b*) The January 2008 TM image (bands 4, 3, 2) indicates the shadowed portion of the landscape (black) corresponding to very low or high departure from average (DA) values depending on the VI used. The TM-derived (*c*) EVI DA and (*d*) NDVI DA from a January image in a location of highly shaded topography shows a strong difference in the impact of shadow effects on DA values. The MODIS-derived (*e*) EVI DA and (*f*) NDVI DA for January indicates that NDVI appears to be less affected by steep terrain and shaded slopes in the study area than EVI.

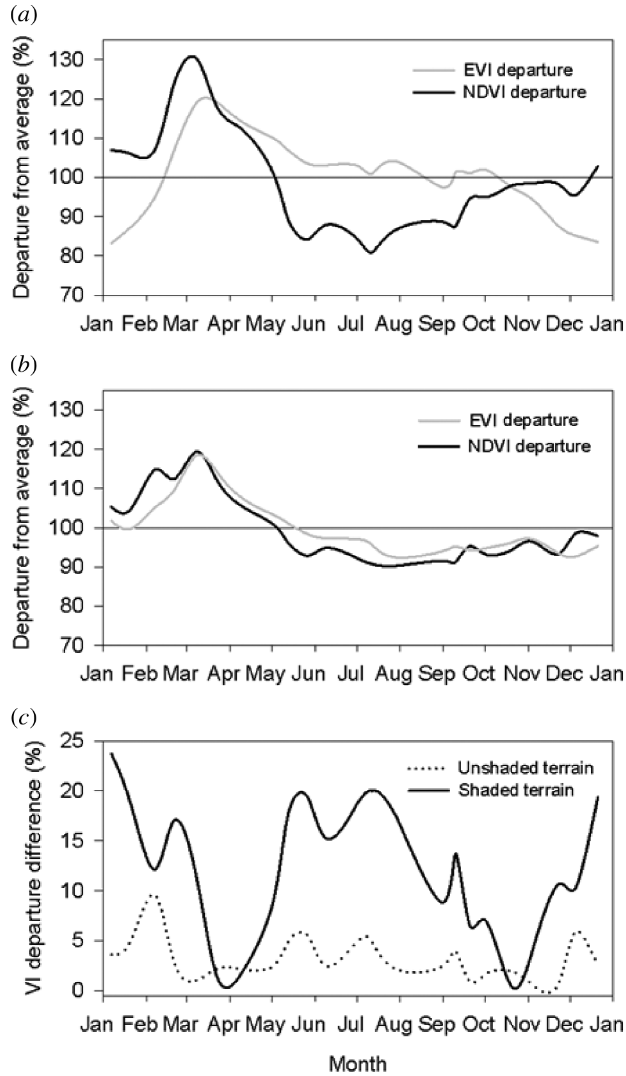

Figure 7. Monthly departure from average values from (*a*) MODIS NDVI and EVI from shaded terrain; and (*b*) MODIS NDVI and EVI for unshaded level topography. (*c*) Graph showing the difference in VI departure values for shaded versus unshaded level topography.

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