Multi-sensor Analysis of Vegetation Indices in a Semiarid Environment

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ABSTRACT

Multi-sensor comparisons are sometimes used due to limited image availability and temporal coverage by a single sensor. However, multi-sensor comparability is not well documented. Factors affecting direct comparability such as atmospheric conditions, landscape heterogeneity, landscape changes, and sensor characteristics are difficult to quantify. This study compared several vegetation indices (VIs) from multi-sensor data to determine if VIs are comparable across scales and sensors. Within-sensor comparisons demonstrate that VIs are consistent across spatial resolutions indicating a direct multi-scale comparability. However, among-sensor comparisons indicate that VIs calculated from different sensors are not comparable with one another regardless of spatial resolution. Sensor-specific characteristics appear to offer the best explanation for the observed results.

KEYWORDS: satellite imagery, NDVI, scale

INTRODUCTION

Drylands cover 41% of the earth's land surface and are home to one-third of the world population (IUCN, 2007). Vegetation productivity of semi-arid ecosystems is limited by inter-annual variability in precipitation (Holmgren et al., 2006) and is relatively vulnerable to human and natural disturbances. To monitor these vast areas, satellite remote sensing is commonly used. However, remote sensing of semi-arid landscapes is challenging because of the difficulty in detecting low levels of biomass and sparse vegetation (Leprieur et al., 2000) amidst relatively high proportions of exposed soil. The presence of litter and other non-photosynthetic vegetation, which are also common in semi-arid environments, further complicates the issue (van Leeuwen and Huete, 1996). Numerous studies have characterized vegetation in arid and semi-arid environments using vegetation indices (VIs) with spectral data from a single sensor (Elmore et al., 2000; Hunt and Miyake, 2006; Marsett et al., 2006; McGwire et al., 2000; Washington-Allen et al., 2006; Xiao and Moody, 2005). However, data from multiple sensors are sometimes used together (García-Gigorro and Saura, 2005) due to limited data availability from a single sensor, varying temporal coverage by different sensors (e.g. MODIS and AVHRR), and use of high spatial resolution products to validate or calibrate coarse spatial resolution images and models (Hu and Islam, 1997; Leprieur et al., 2000).

Various factors such as the atmospheric conditions during acquisition, landscape heterogeneity, landscape changes, and sensor characteristics influence direct comparability (i.e., scaling) of VIs between different sensors. Their effects on VIs, however, are not well understood and are difficult to quantify. For instance, atmospheric conditions are not consistent over space and time and are difficult to fully correct due to a lack of precise atmospheric parameters at the time of acquisition across the entire field of view, although models such as Cos(t) (Chavez, 1996) are often used to reduce atmospheric effects. Furthermore, sensor characteristics vary between platforms and sensors. Geometric characteristics, such as viewing angle, field of view, and sun elevation may be different in addition to the intrinsic characteristics of the sensor (scanning system construction, band width, band center, signal-to-noise ratio)(Lillesand and Kiefer 2000). The impact of these factors can be reduced by using sensors with similar characteristics (e.g. Landsat MSS and Landsat TM). However, due to limited choices of imagery, images from multiple sensors are commonly used (Buheaosier et al., 2003; Teillet et al., 1997).

The comparison of imagery from multiple sensors typically implies the use of multi-date imagery. As a result, the temporal difference will result in changes on the ground due to plant phenology, weather conditions, and human perturbations. These differences are almost impossible to correct for and minimizing the differences in acquisition times between imagery is the only viable solution.

Several studies have attempted to analyze the effects of scale on vegetation indices directly (Aman et al., 1992; Buheaosier et al., 2003; Goodin and Henebry, 2002; Hu and Islam, 1997; Jiang et al., 2006; Tarnavsky et al., 2008; Teillet et al., 1997; Wood and Lakshmi, 1993) and indirectly using fragmentation indices (García-Gigorro and Saura, 2005; Saura, 2004) or leaf area index estimations (Chen, 1999; Sprintsin et al., 2007). However, these studies focused mostly on NDVI in forested areas with a spatial resolution > 30 meters. To our knowledge, no study has attempted to exclusively examine the comparability of several VIs from multiple sensors in semi-arid environments. The objective of this study was to examine the comparability of multi-sensor imagery to characterize a semi-arid environment by: 1) comparing VI values at the same point locations using increasing pixel sizes *within* the same sensor, and 2) comparing VI values at the same point locations using increasing pixel sizes *across* different sensors.

METHODS

Study area

The study area is located in sagebrush-steppe rangelands of southeastern Idaho (Fig. 1) in the vicinity of the O'Neal Ecological Reserve (property of Idaho State University). The area covers 64 km^2 and is located along the Portneuf River approximately 25 km southeast of Pocatello, Idaho, USA. It contains riparian areas and cultivated crop fields as well as typical sagebrush steppe upland areas located on lava benches. The area receives an average of 0.41 m of precipitation annually (primarily during the winter) and the annual mean temperature is 7.8 °C with a mean of 18.9 °C in the summer and 3.4 °C in the winter (based upon monthly averages) (WRCC, 2007). The terrain is relatively flat with an average elevation of 1400 m. The dominant plant species in the sagebrush steppe is big sagebrush (*Artemisia tridentata*) with various native and non-native grasses such as indian rice grass (*Oryzopsis hymenoides*), needle-and-thread (*Stipa comata*), and cheatgrass (*Bromus tectorum*). The cultivated areas are dominated by wheat and forage such as alfalfa (*Medicago sativa*).

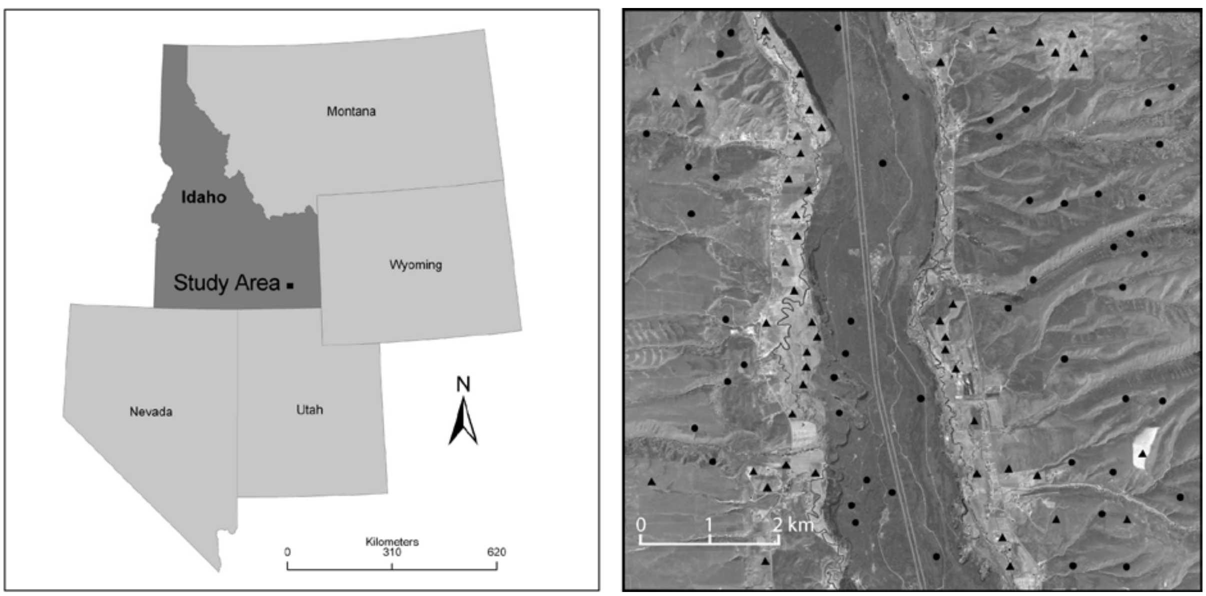

Figure 1. Study area and sampling locations used to calculate vegetation indices. Sampling stratification is shown for shrub/grassland cover type (dots) and cultivated crops/hay land cover type (triangles).

Satellite Imagery

Imagery from four commonly used satellite platforms were selected: QuickBird, SPOT5 HRG (Haute Résolution Géométrique), Landsat5 TM (Thematic Mapper), and MODIS. We selected June 26th 2006 as the target date and imagery from different sensors were acquired to match this date as closely as possible (Table 1). All QuickBird, SPOT5 HRG, and Landsat5 TM images were atmospherically corrected and converted to reflectance using the Cos(t) model (Chavez, 1996) to reduce variability of vegetation indices due to the heterogeneity in the radiometric processing of data (Guyot and Gu, 1994). MODIS imagery was received in reflectance format ("MOD09GQ" data).

Table 1. Description of imagery used in this study

Sensor Name	Acronym Definition	Acquisition Date	Spatial Resolution (m)
QuickBird	-	June-28-2006	2.5
SPOT5 HRG	Satellite Pour l'Observation de la Terre 5 Haute Résolution Géométrique	June-25-2006	10
Landsat5 TM	Thematic Mapper	June-13-2006	28.5
MODIS	Moderate-resolution Imaging Spectroradiometer	June-13-2006 June-25-2006 June-26-2006 June-28-2006	250

All imagery was projected into Idaho Transverse Mercator NAD83 projection and datum using nearest neighbor resampling. Georectification of each image was assessed using 1-m resolution orthorectified aerial images acquired in 2004 as part of the National Agricultural Imagery Program to ensure spatial co-registration consistency between scenes. The assessment indicated that the georectification of MODIS and QuickBird imagery was satisfactory and no additional georectification was performed. However, an additional georectification was performed on both SPOT5 HRG and Landsat5 TM images using ground control points selected from the orthorectified aerial images. The resulting root mean squared errors (RMSE) were 3.80 and 11.27 m respectively.

Image processing

While some VIs that include the mid-infrared band are used in semi-arid environments (Marsett et al., 2006) this band is not available for every sensor (e.g., QuickBird). Therefore, the VIs compared in this study were limited to those derived from the red/infrared bands (Table 2). The spectral and spatial characteristics of the red and infrared bands of the sensors used in this study are presented in Fig. 2 to illustrate band width and band centers.

Table 2. Description of vegetation indices selected in this study for spatial scale comparison

Name	Full name	Formula	Reference
NDVI	Normalized Difference Vegetation Index	$\frac{NIR-R}{NIR+R}$	Rouse et al. (1974)
RVI	Simple Ratio Vegetation Index	$\frac{R}{NIR}$	Richardson and Wiegand (1977)
NRVI	Normalized Ratio Vegetation Index	$\frac{RVI-1}{RVI+1}$	Baret and Guyot (1991)
SAVI	Soil-Adjusted Vegetation Index	$\frac{NIR-R}{NIR+R+L}\times(1+L)$	Huete (1988)
$MSAVI_2$	Modified Soil Vegetation Index	$\frac{2NIR+1-\sqrt{(2NIR+1)^2-8(NIR-R)}}{2}$	Qi et al. (1994)

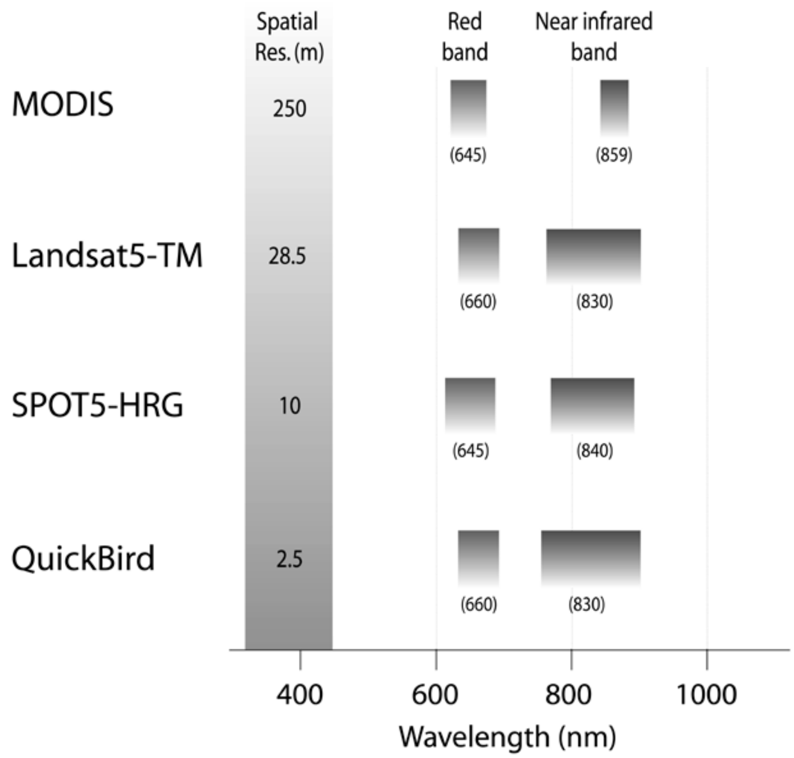

Figure 2. Spatial and spectral characteristics of red and near infrared bands of the sensors used in this study. Wavelengths of band centers are shown in brackets.

VIs were calculated at the native resolution of each sensor (Table 1). These VI images were then re-sampled using a common pixel aggregation function (average) to correspond to the coarser spatial resolutions of the other sensors used in this study. We consistently used only one resampling algorithm, because our goal was not to explore the effect of different resampling algorithms. However, other aggregation functions are available and can produce different results (García-Gigorro and Saura 2005).

Because the study area is heterogeneous and covers different land cover types, the images were stratified to reduce potential variability in VI values due to landscape heterogeneity and thereby better compare the effects of scale. Two land cover types were selected using an independent classification of the area from the National Land Cover Database (NLCD) of 2001 (Homer et al., 2004) and the following criteria: 1) each land cover type was large enough to select 50 independent sample points at the coarsest spatial resolution used (250 m) and, 2) the land cover type was composed of patches larger than the coarsest spatial resolution used (250 m). The selected land cover types were shrub/grassland and cultivated crops/hay. Analyses were performed in these strata using separate masks.

Statistical Analysis

All statistical analysis used samples from 100 randomly-selected point locations. Samples from the two land cover types (50 point locations each) were examined separately in all analyses. One-way analysis of variance (ANOVA) with all pair-wise post-hoc comparisons were used to compare all possible combinations of resolutions and sensors.

First, the VIs were examined across different resolutions within the same sensor to compare VI values at the native resolution to VI values at various aggregated resolutions. In this analysis, NDVI, NRVI, SAVI and $MSAVI_2$ were separately compared across various resolutions. For QuickBird imagery, native 2.5 m, 10 m, 28.5 m, and 250 m resolutions were used, whereas three resolutions were used for SPOT5 HRG imagery (native 10 m, 28.5 m, and 250 m), and two resolutions of Landsat5 TM imagery were used (native 28.5 m and 250 m). The increasing sizes of resolution were the predictor variable and the estimated VI values were the response variable.

Secondly, each VI was compared among different sensors to determine scalability between platforms. In this analysis, NDVI, NRVI, SAVI, and $MSAVI_2$ were separately compared among QuickBird, SPOT5 HRG, Landsat5 TM, and MODIS sensors using their native resolutions as well as their aggregated resolutions to determine if VI values from different sensors were significantly different from each other when using native versus aggregated resolutions. For example, NDVI values from 2.5-m-resolution QuickBird imagery were compared to NDVI values from 10-m-resolution SPOT5 HRG, 28.5-m-resolution Landsat, and 250-m-resolution MODIS images. Similarly, NDVI values from aggregated 10-m-resolution QuickBird imagery were compared to 10-m-resolution SPOT5 HRG imagery, values from aggregated 28.5-m-resolution QuickBird imagery were compared to 28.5-m-resolution Landsat5 TM imagery, and values from aggregated 250-m-resolution QuickBird imagery were compared to 250-m-resolution MODIS values. In this way, all combinations of sensors and resolutions were tested. The native or aggregated resolutions from the different sensors were the predictor variable and the estimated VI values were the response variable.

Finally, complementary analyses were performed to study the effect of image acquisition date on vegetation index values. MODIS images from June 13th, June 25th, and June 28th were acquired to correspond to the same acquisition dates of the Landsat5 TM, SPOT5 HRG, and QuickBird images used in this study, respectively. NDVI and $MSAVI_2$ values from the same point locations used in the analyses above were compared for each date-synchronous pair of images: MODIS from June 13th and Landsat5 TM, MODIS from June 25th and SPOT5 HRG, and MODIS from June 28th and QuickBird imagery. Aggregated 250 m pixels from the finer resolution imagery were used to compare at native MODIS resolution.

RESULTS

Within-sensor comparisons

ANOVA test results indicate that different resolutions of QuickBird, SPOT5 HRG, and Landsat5 TM were not significant as predictor variables ($P > 0.05$) and no statistically significant differences were found in NDVI, NRVI, SAVI, and $MSAVI_2$ values among the four different resolutions of QuickBird, three resolutions of SPOT5 HRG, and two resolutions of Landsat5 TM imagery (Fig. 3 (a, b, c, d, e, and f)) for either land cover type.

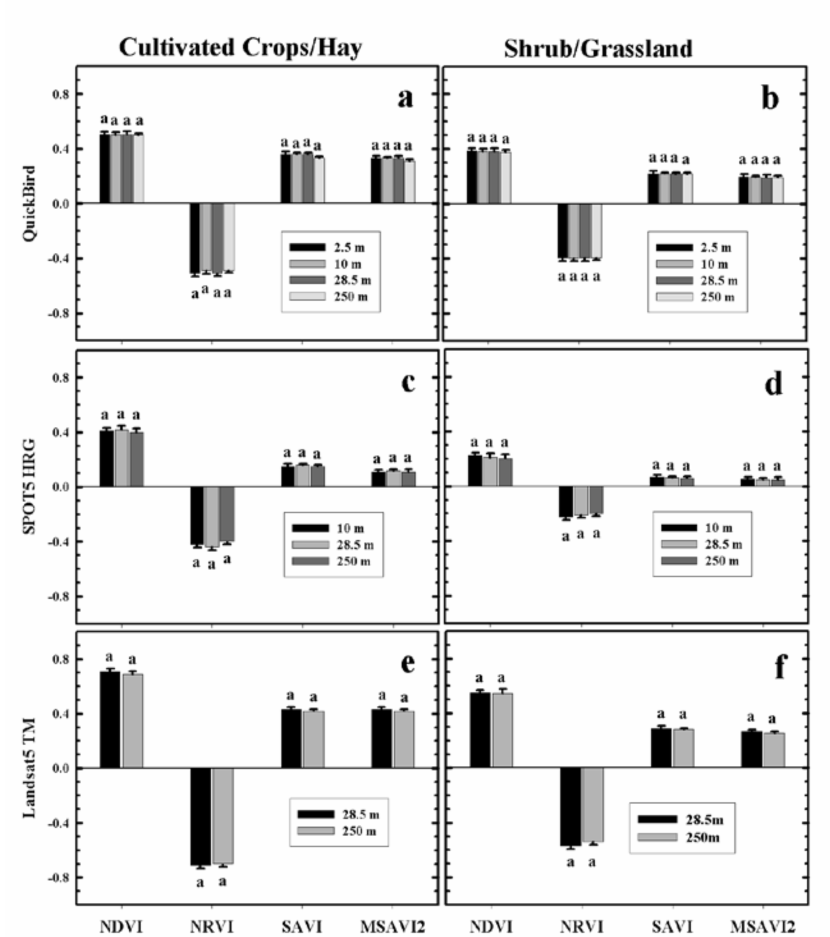

Figure 3. Vegetation index comparisons within sensors. The estimated mean (±SE) value of each vegetation index is separately compared among four different scales for QuickBird imagery (a and b), three different scales for SPOT5 HRG imagery (c and d), and two different scales for Landsat5 TM (e and f). No statistically significant differences were found in any of the comparisons among different scales of each vegetation index.

Among-sensor comparisons

The native and aggregated resolutions from different sensors were significant as predictor variables (P <0.000) and post-hoc comparisons indicated many significant differences (Fig. 4).

- NDVI values from the cultivated crop/hay cover type were significantly different in all pair-wise comparisons (P <0.000), except the comparison between 2.5-m-resolution QuickBird and 250-m-MODIS imagery (P =0.566) (Fig. 4g). NDVI values from the shrub/grassland cover type were also significantly different in all pair-wise comparisons (P <0.000), except the comparison between 28.5-m-resolution Landsat5 TM and 250 m MODIS imagery (*p* =1.000) (Fig. 4h).
- NRVI values from the cultivated crop/hay cover type were significantly different in all pair-wise comparisons (P <0.000), except the comparison between 2.5-m-resolution QuickBird and 250-m–resolution MODIS imagery (P =0.566) (Fig. 4g). NRVI values from the shrub/grassland cover type were also significantly different in all pair-wise comparisons (P <0.000), save for the comparison between 28.5-m-resolution Landsat5 TM and 250-m-resolution MODIS imagery (P =1.000) (Fig. 4h).
- SAVI values from the cultivated crop/hay cover type were significantly different among all resolutions of QuickBird, SPOT5 HRG, and Landsat5 TM images (P <0.000), but no difference was found between

2.5-m-resolution QuickBird and 250-m-resolution MODIS imagery (P <0.064) and between 28.5-m and 250-m-resolution Landsat5 TM images and 250-m-resolution MODIS imagery (P =1.00 and 1.00, respectively) (Fig. 4g). SAVI values from the shrub/grassland cover type were significantly different in all pair-wise comparisons (P <0.000), except the comparison between 28.5–m-resolution Landsat5 TM and 250-m-resolution MODIS imagery (P <0.115) (Fig. 4h).

- $MSAVI_2$ values from the cultivated crop/hay cover type were significantly different in all pair-wise comparisons (P <0.000), except the comparison between 28.5-m- and 250-m-resolution Landsat5 TM images and 250-m-resolution MODIS imagery (P =1.00 and 1.00, respectively) (Fig. 4g). $MSAVI_2$ values from the shrub/grassland cover type were also significantly different in all pair-wise comparisons, except the comparison between 28.5-m-resolution Landsat5 TM and 250-m-resolution MODIS imagery (P =0.06) (Fig. 4h).

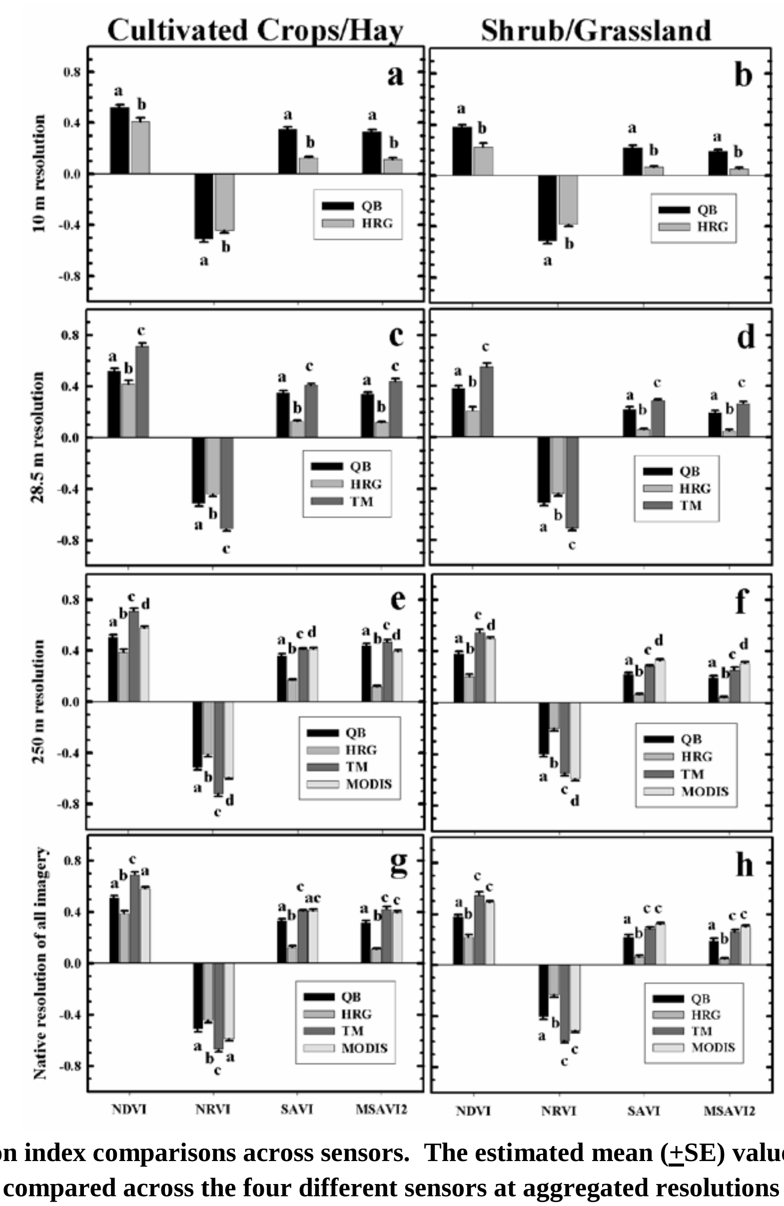

Figure 4. Vegetation index comparisons across sensors. The estimated mean (±SE) value of each vegetation index is separately compared across the four different sensors at aggregated resolutions of 10 m (and b), 28.5 m (c and d), and 250 m (e and f), as well as their native resolutions (g and h). Many statistically significant differences were found in the estimated mean values of the same vegetation index between different sensors.

Date-synchronous comparisons

The comparison between $MSAVI_2$ and NDVI values between data-synchronous pairs of imagery indicated many significant differences (Fig. 5). Comparisons between the June 13th MODIS and Landsat5 TM imagery indicated significant differences for both VIs and cover types ($P < 0.05$). The same results were observed in the comparison between the June 28th MODIS and QuickBird imagery ($P < 0.05$). Significant differences were also found when the June 25th MODIS and SPOT5 HRG imagery were compared ($P < 0.05$), except the NDVI comparison in the shrub/grassland cover type ($P=0.074$) (Fig. 5d) and $MSAVI_2$ comparison from the cultivated crop/hay cover type ($P=0.06$) (Fig. 5a).

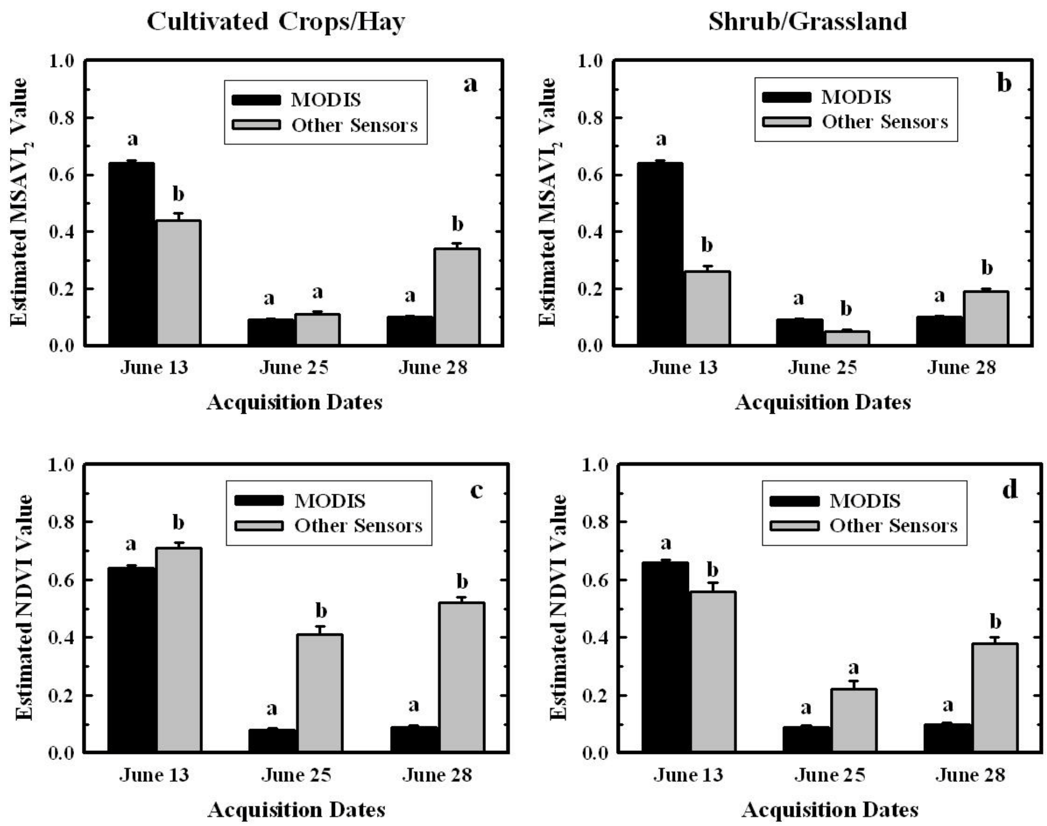

Figure 5. Pair-wise comparisons of MODIS $MSAVI_2$ and NDVI values with $MSAVI_2$ and NDVI values from Landsat5 TM, SPOT5 HRG, and QuickBird images acquired on June 13th, June 25th, and June 28th 2006, respectively. Most pairs of images acquired on the same day had significantly different (indicated by letters) $MSAVI_2$ and NDVI values.

DISCUSSION

Effects of landscape heterogeneity

Results from the within-sensor comparisons indicate no significant effect of scale on VI values. These results suggest that VIs derived from the same sensor are comparable when pixels are aggregated to coarser resolutions. The relatively homogeneous spatial pattern found in the crops/hay cover type can explain the scalability of VIs for this land cover type. The range of spatial resolution used (i.e., 2.5 - 250 m) was smaller than the size of a typical crop field and consequently aggregated pixels at each point were likely located within the same crop field. This ensured relatively stable radiometric conditions resulting in similar VI values. Hu and Islam (1997) identified land surface homogeneity as a condition under which algorithms such as VIs can be "up-scaled" or "down-scaled" without incurring significant differences. In addition, Teillet et al. (1997) found similar results over forested areas with constant NDVI values at different spatial resolutions for the same sensor, except when it reached a scale on the order of the size of land cover patches. In that study, one threshold was approximately 260 m which corresponded to the size of the forest stands evaluated in that study.

In the case of the shrub/grassland cover type, the scalability results were unexpected. Pixels in this environment are relatively heterogeneous with a mix of bare ground, shrubs, and shadow in various proportions and sizes. Significant differences in VIs associated with the change of spatial resolution were expected as shown by Jiang et al. (2006) who found strong spatial scale dependencies of NDVI over heterogeneous surfaces. However, the Jiang et al. study (using simulated data) pointed out that NDVI can be scale invariant over heterogeneous surfaces when the brightness (sum of red and NIR reflectance) of vegetation is equal to that of soil background. This might partially explain our results. Another study from our study area presents spectral signatures of common land cover elements and describes a similar pattern in brightness between bare ground and big sagebrush plants, the dominant vegetation species of the area (Weber et al., 2008).

Most of the literature regarding scale effects on VIs has focused on NDVI. Our study showed that NRVI, SAVI, and $MSAVI_2$ follow the same patterns as NDVI in terms of within-sensor scalability. Our results further suggest that VI layers can be aggregated to fit other GIS layers (e.g., for spatial analysis purposes) in semi-arid environments.

Effects of sensor characteristics

Many statistically significant differences were found when VIs were compared using native and aggregated resolutions across QuickBird, SPOT5 HRG, Landsat5 TM, and MODIS sensors. QuickBird, SPOT5 HRG, Landsat5 TM, and MODIS images did not produce the same VI values at the same locations, except for only a few cases. Further, the finer resolution imagery (QuickBird, SPOT5 HRG, and Landsat5 TM) did not produce the same or even similar VI values, when aggregated to match the pixel sizes of the coarser resolution imagery.

This lack of agreement may be due to sensor-specific characteristics such as systematic, radiometric, and spectral differences as well as differences in scene-specific characteristics such as variations in the atmospheric conditions on the specific acquisition date. Teillet et al. (1997) found similar results over forested areas and noted that even after radiometric calibration and atmospheric correction, NDVI values calculated from medium and low resolution sensors were not comparable. Buheaosier et al. (2003) also found differences in NDVI calculated from sensors with different resolutions over several land cover types. However, they did not test for statistical significance of these differences. The results presented here extend the observations to semi-arid environments for several VIs with the observed differences expressed statistically.

Another sensor-specific difference is the variation in bandwidths and bandcenters for the red and near infrared bands of each sensor. Teillet et al. (1997) conducted a detailed study of the dependence of VIs on the location and width of red and infrared bands over forested areas. They found that an increase in the bandwidth of red and infrared bands leads to a decrease in NDVI values and is mostly influenced by the width of the red band. However, our results don't follow this trend. They indicate that VI values for MODIS (i.e., narrow bands) are not systematically higher than values for the other sensors (i.e., those with larger bandwidths) over the two land cover types examined. Moreover, when comparing results between Landsat5 TM and QuickBird which have identical red and near infrared bandwidth characteristics, we found a significant difference for all VIs calculated over both land cover types. We also found no significant difference between VIs calculated from Landsat5 TM and MODIS over the shrub-grassland cover type despite the fact that these sensors have dissimilar band characteristics. The same pattern was also observed between VIs calculated from QuickBird and MODIS (except $MSAVI_2$) over cultivated crop/hay cover type. These results seem to indicate that even if bandwidth and land cover have an influence on VI values, other factors evidently play a larger role in explaining the differences in VI values calculated from these different sensors.

Effects of landscape changes

Because of limited availability of imagery for the study area on the targeted date (June 26^{th} 2006), imagery was acquired on slightly different dates assuming a minimal change of land characteristics would be observed over this short period of time (15 days). This same assumption is regularly made when using multi-sensor imagery or image mosaics for a target date with various methods of radiometric normalization used to minimize reflectance variations due to factors other than land surface change (Théau and Duguay, 2004). When statistically significant differences were found in VI values among the different sensors used in this study, we then sought to determine if these differences were simply due to the differences in image acquisition dates alone. If this were the case, comparisons between date-synchronous imagery would result in no significant difference between VIs. However, since there are known differences between the sensors, some difference in VIs was expected. Under this scenario, date-synchronous VI comparisons were expected to be more similar than the previous among-sensor VI comparisons which would then suggest a contributory relationship in the "difference budget" described in this paper. An examination of Z-scores from each comparison reveals consistently higher Z-scores for date-synchronous VI comparisons ($\underline{x}$ Z-score = -5.40) relative to the Z-scores from the among sensor comparisons ($\underline{x}$ Z-score = -4.95). This confirms that differences observed are primarily attributable to sensor-specific differences and incompatibilities.

The date-synchronous comparison results indicate statistically significant differences in almost all comparisons between daily MODIS NDVI and $MSAVI_2$ values and the same index values from the other sensors on synchronous dates. This indicates that even when images are acquired on the same day, there are sensor-specific differences affecting VI values. This indicates that direct comparison across sensors is not advisable. Furthermore, this implies that any inferences made using VIs from one sensor are limited.

CONCLUSIONS

The goal of this study was to assess the effect of scale on several VIs in a semi-arid environment by comparing values from the same point locations and increasing pixel sizes within the same sensors, and across different sensors. Results suggest that multi-scale comparability is applicable when aggregating pixels from the same sensor only. While the need to do this is limited, possible applications are the use of VI layers that have been aggregated to facilitate related spatial analyses with other GIS data of coarse resolution, or to complete a time series from different sensors. In contrast, multi-scale comparisons are not recommended when using different sensors. Our results also showed that the reason for these differences is primarily sensor-driven. Further research should focus on the effect of atmospheric correction methods and the effect of various aggregation methods on VI comparability as well as on the temporal variability of VIs in semi-arid environments.

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