Correlation between MODIS LAI, GPP, PsnNet, and FPAR and Vegetation Characteristics of Three Sagebrush-Steppe Sites in Southeastern Idaho

Bhushan Gokhale, Idaho State University, GIS Training and Research Center, 921 S. 8th Ave., Stop 8104, Pocatello, Idaho 83209-8104. E-mail: gokhbhus@isu.edu

Keith T. Weber, GISP, GIS Director, Idaho State University, GIS Training and Research Center, 921 S. 8th Ave., Stop 8104, Pocatello, Idaho 83209-8104. E-mail: webekeit@isu.edu Phone

ABSTRACT

The Moderate Resolution Imaging Spectroradiometer (MODIS) has been used for vegetation monitoring and mapping since February 2000. However, few studies have been conducted that corroborate MODIS data with *in situ* field observations. This study explores the relationship between MODIS products (Leaf area index, gross primary productivity, net Photosynthesis, and fraction of absorbed photosynthetically active radiation) and percent cover and plant biomass for three sagebrush-steppe rangeland sites in southeastern Idaho. Correlations were calculated using data collected between June 2007 and August 2007 with resulting correlation coefficients being very weak in all cases ($R^2 \leq 0.09$). Two of the three sites tested were correlated with percent cover estimates calculated from point intercept transect data while the remaining site was correlated with ocular estimated cover classes. Even though transect data is considered to more precisely describe field plots, their correlations with the MODIS products did not improve relative to the correlations made with ocular estimates. While the spatial distribution of the field observations and various other factors may have affected these results, no significant correlations are expected to emerge due primarily to differences in scale between these data.

KEYWORDS: remote sensing, vegetation monitoring, productivity

INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument specifically designed for improved remote sensing of the land, seas, and the atmosphere. The sensor for land imaging integrates the characteristics of the Advanced Very High Resolution Radiometer (AVHRR) and the Landsat Thematic Mapper. The spatial resolution of the sensor varies from 250 m (bands 1 and 2), to 500 m (bands 3-7), and 1000 m (bands 8-36)(Justice et al 1998; http://modis.gsfc.nasa.gov/about/specifications.php).
MODIS has been widely used for land cover classification since February 2000 because of its enhanced spectral (bandwidth 620-965 nm and 3.6 to 14.3 µm), spatial (250 m to 1000 m resolution at nadir), and temporal (daily to 8-day products) resolution. Further, MODIS enables improved monitoring and mapping of global land cover compared to that offered by AVHRR (Friedl et al 2002) and these studies are important to increasing our understanding of global climate and biogeochemical cycles (Running et al 1994).

Biological productivity is the ultimate source of human civilization; hence accurate estimates of various vegetation parameters (cover and productivity) are increasingly important to our understanding of the carbon cycle, energy balance, environmental impact assessment studies (Tian et al 2000) as well as the effect of global climate change. MODIS provides an array of products that estimate vegetative productivity. The MODIS algorithms use photosynthetically active radiation (PAR) and its relationship with net primary productivity (NPP) to develop a variety of MODIS products. Some of the PAR is absorbed by the vegetation and is known as absorbed photosynthetically active radiation (APAR). APAR is a function of the spatial and seasonal variability of photoperiod, potential incident radiation, and the amount and geometry of displayed leaf material. It is similar to LAI but accommodates the fraction of absorbed photosynthetically active radiation (FPAR) to help define the relationship of APAR and PAR as APAR = PAR * FPAR. The PAR conversion efficiency (ε) is dependent upon vegetation type and can be combined with APAR to estimate gross primary productivity (GPP) as:

$$GPP = \varepsilon * APAR \quad (1)$$

GPP describes the total light energy that has been converted to plant biomass. Some of the energy is lost during plant respiration and this fraction can be derived from GPP. The MODIS product which describes the relationship between GPP and the fraction of energy lost during plant respiration is called net primary productivity (NPP). Yet another MODIS product calculates net photosynthesis (PsnNet) by subtracting leaf maintenance respiration and fine root mass maintenance respiration from GPP (Running et al 1999), while green leaf area index (LAI) - along with FPAR- represents differences in leaf nitrogen content (Heinsch et al 2003).

While MODIS products provide valuable estimates of vegetation productivity, it is important to validate these products with *in situ* measurements. However, uncertainty assessments for coarse resolution satellite imagery presents a host of challenges as field data is not easily compared with satellite imagery (Tian et al 2002). Tian et al (2002) presented a validation method of the MODIS LAI product with emphasis on the sampling strategy for field data collection. They suggest a statistically valid and logistically feasible sampling strategy which would reduce uncertainty based on a hierarchical analysis of LAI obtained from 30 m resolution Landsat ETM+ data. Variance calculations are made for LAI and NDVI with respect to class effect, region effect, and pixel effect (Tian et al 2002).

The validation methods developed by Tian et al is indirect (i.e., they validate one satellite dataset [MODIS] with another satellite dataset [Landsat] with the underlying assumption of accuracy for the Landsat dataset) but other studies have established more direct correlations of MODIS products with ground based data. Barnsley et al (2000) used a model to predict albedo, a parameter that involves understanding both climate and vegetation dynamics, to validate the corresponding MODIS albedo product. In addition, Fensholt et al (2004) studied MODIS LAI and FPAR and the relationship between FPAR and NDVI in a semi-arid environment using *in situ* measurements. They concluded that MODIS LAI was overestimated by approximately 2–15% and the overall level of FPAR was overestimated by 8–20%.

This author's study validates MODIS LAI, GPP, PsnNet, and FPAR products by direct comparison with *in situ* data obtained from three different sagebrush-steppe rangeland sites in southeastern Idaho.

METHODS

Study Area

Three sagebrush-steppe rangeland sites in southeastern Idaho were chosen for this validation study: the USDI BLM Big Desert (Big Desert), USDA ARS US Sheep Experiment Station (USSES), and the ISU O'Neal Ecological Reserve (O'Neal). Each of these sites is part of ongoing rangeland research at the GIS Training and Research Center (GIS TReC) at Idaho State University.

The Big Desert is the largest of the three study sites containing approximately 100,000 ha managed by the Bureau of Land Management (BLM). The area is flat to slightly rolling with abundant lava outcrops. The average annual precipitation in the area is 0.23 m with only 40% falling from April to June (Connelly et al 1991). The Big Desert exhibits a large variety of native plant species as well as numerous invasive species (Anderson et al 2008). The dominant vegetation species in this study area are Wyoming Big Sagebrush (*Artemisia tridentataWyomingensis*) and bluebunch wheatgrass (*Pseudoroegneria spicata*). Other species present are threetip sagebrush (*Artemisia tripartita*), Sandberg bluegrass (*Poa secunda*), and bottlebrush squirreltail (*Sitanian hystrix*) (Fischer et al 1991).

The USSES study site includes nearly 40,000 ha of rangeland with mean annual precipitation significantly changing as site elevation ranges from 1615 to 2900 m. The dominant plant species are Mountain Big Sagebrush (*Artemisia tridentata*), threetip sagebrush (*Artemisia tripartita*), Antelope bitterbrush (*Purshia tridentata*), bluebunch wheatgrass (*Pseudoroegneria spicata*), thickspike wheatgrass (*Elymus lanceolatus*), Sandberg bluegrass (*Poa secunda*), arrowleaf balsamroot (*Balsamorhiza sagittata*), and tapertip hawksbeard (*Crepis acuminata*) (Weber et al 2008).

The O'Neal study site is a 50 ha area along the Portneuf River. This area receives < 0.38 m of precipitation every year and its elevation ranges between 1400 m to 1430 m. The dominant plant species of the area are Big sagebrush (*Artemisia tridentata*) along with other native and non-native grasses that include Indian rice grass (*Oryzopsis hymenoides*) and needle-and-thread (*Stipa comata*) (Weber et al 2007) (Figure 1).

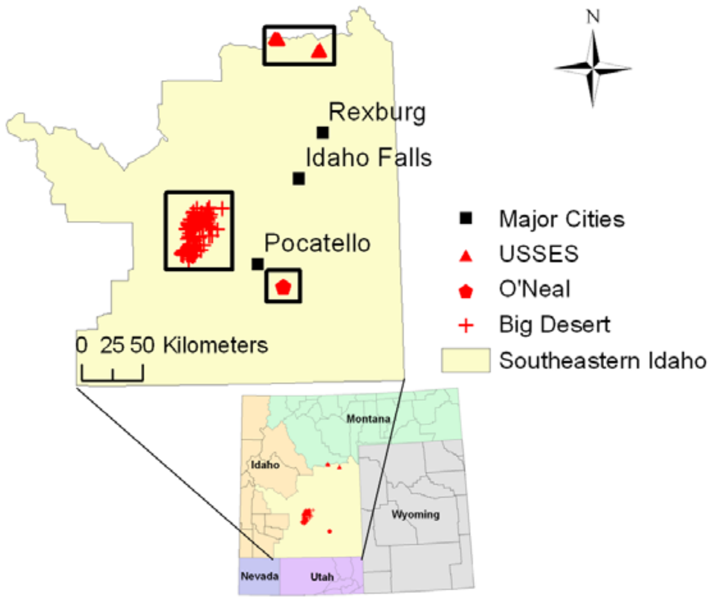

Figure 1. Location of the Three Study Sites in Idaho

Field Sampling Procedures

During the summer of 2007 GIS TReC field personnel collected vegetation data at each of the three study sites. These data (*n*= 347) include ocular estimates for percent cover of grasses, shrubs, litter, weeds, and bare ground at the Big Desert study site, while more precise estimates of percent cover for grasses, shrubs, litter, weeds, and bare ground were made using point-intersect transects at both the USSES and O'Neal sites.

The location of each sample site was recorded using a Trimble GeoXH GPS receiver in latitude-longitude (WGS 84). Points were occupied until a minimum of 60 positions were acquired and the Wide Area Augmentation System (WAAS) was used whenever available. All points were post-process differentially corrected (+/-0.20 m with a 95% CI) using an array of southeastern Idaho GPS base stations each located <80 km from the respective study area. All sample points were projected into Idaho Transverse Mercator NAD 83, using ESRI's ArcGIS (Anderson et al., 2005). These data were stored as three independent feature classes.

Ground Cover Estimation

Visual estimates were made of percent cover for the following; bare ground, litter and duff, grass, shrub, and dominant weed. Cover was classified into one of nine classes (None, 1-5%, 6-15%, 16-25%, 26-35%, 36-50%, 51-75%, 76-95%, and >95%).

Observations were assessed by viewing the vegetation perpendicular to the earth's surface. This was done to emulate what a "satellite sees". In other words the vegetation was viewed from nadir (directly overhead) as much as possible (Anderson et al 2008).

Transects were used to estimate percent cover of bare ground exposure, rock (>75 mm), litter, herbaceous standing dead, dead standing wood, live herbaceous species, live shrubs, and dominant weed. Percent cover estimates were made along two 10 m line transects. Transects were arranged perpendicular to each other and crossing at the center of the plot at the 5 m mark of each line transect. Using the point-intercept method, observations were recorded every 20 cm along each 10 m line, beginning at 10 cm and ending at 990 cm. The cover type (bare ground exposure, rock (>75 mm), litter, herbaceous standing dead, dead standing wood, live herbaceous species, live shrubs, and dominant weed) at each observation point was recorded (Tibbitts et al 2007).

Plant Biomass Measurement

Available forage was measured using a plastic coated cable hoop 2.36 meters in circumference, or 0.44 m^2. The hoop was randomly tossed into each of four quadrants (NW, NE, SE, and SW) centered over the sample point. All grass species within the hoop considered forage for cattle, sheep, and wild ungulates were clipped and weighed (+/-1g) using a Pesola scale tared to the weight of an ordinary paper bag. The measurements were then used to estimate forage amount in AUM's, pounds per acre, and kilograms per hectare (Anderson et al 2008).

Data Processing

MODIS LAI, GPP, PsnNet, and FPAR were acquired for the months of June, July and August 2007. The spatial resolution of all layers was 1km x 1 km, projected into Idaho Transverse Mercator (NAD83). FPAR was estimated over a period of 8 days by the University of Montana NTSG lab. They estimated daily APAR for the pixel by multiplying daily estimated PAR by the FPAR. The APAR values were then used to calculate daily GPP using equation 1. Eight day summations of GPP were then calculated and used in the study. The subsequent products (i.e. PsnNet and LAI) were also estimated over a period of 8 days. Hence, all MODIS products used in this study had a temporal resolution of 8 days (Heinch et al 2003).

Landscape-scale validation

Each MODIS product was independently tested for correlation with percent cover and plant biomass. Since the Big Desert study site field data were collected during the first two weeks of June 2007, MODIS products for the first two weeks of June 2007 were chosen to correlate with these data. Similarly MODIS products for the first two weeks of July 2007 were chosen for the O'Neal study site and MODIS products for the first two weeks of August 2007 were similarly chosen for the USSES study site.

Using ESRI ArcGIS, the value of the MODIS pixel at each sample site (n=347) was extracted and stored in a database table. These results were then converted to a file format usable by MS Excel. The resulting spreadsheet contained percent cover and plant biomass attributes along with the extracted LAI, GPP, PsnNet, and FPAR pixel values. The extracted data for each MODIS product was correlated against percent cover and plant biomass values across each of the three study sites (e.g., percent cover was correlated with LAI for the Big Desert). The R^2 value for the model (using exponential, linear, logarithmic, polynomial, power or moving average lines of best fit) that consistently produced the best fit between these data is reported below.

Pixel-scale Validation

While it was procedurally important to extract and analyze the MODIS values at each sample location (n=347), it was equally important to assess just those pixels that contained three or more sample locations (n= 19) to try to capture some of the variability within each pixels and thereby produce a better representative of each pixel's value. This assessment was considered important for coarse resolution imagery such as MODIS as the generalization of *in situ* field observations (using mean or median) may better reflect the characteristics of the landscape. To accomplish this, all pixels for the USSES and O'Neal study sites containing 3 or more sample points per pixel were identified (*n*=19). For USSES and O'Neal average number of samples per pixel were 6 and 35 respectively. When combined; overall average number of samples per pixel was 12. USSES had the least samples per pixel i.e. 3 whereas O'Neal had the maximum samples per pixel i.e. 86. (Note: the Big Desert study area was not included in this part of the study as these field samples were too broadly distributed). For the USSES study area, FPAR and PsnNet images obtained on 07-28- 2007 were used whereas FPAR and PsnNet images obtained on 06- 26-2007 were used for O'Neal study area analysis. A total of 15 pixels were included from the USSES and 4 pixels were included from the O'Neal study site. Mean and median values for both percent cover and plant biomass (kg/ha) were correlated with FPAR and PsnNet values. These specific products (FPAR and PsnNet) were chosen for pixel scale validation as FPAR is the most basic product (least processed productivity product) whereas PsnNet is the most processed product, hence it was hoped that some relationship would be revealed by these comparisons. The specific differences between these products are the PAR conversion efficiency (ε), leaf maintenance respiration factor, and fine root mass maintenance respiration factor. With this in mind, we anticipated a trend in the correlations between the least processed (FPAR) and most highly processed products (PsnNet). Further, we expected a more direct correlation of percent cover and plant biomass (kg/ha) with FPAR and PsnNet and chose linear regression for all analyses. The coefficient of correlation (R^2) was calculated for each test and reported below.

RESULTS AND DISCUSSION

Landscape-scale Validation

Second order polynomial model results are reported here as they consistently produced the highest R^2 values compared to all other models tested. The R^2 values for correlations of the MODIS products with percent cover and plant biomass for the Big Desert, USSES, and O'Neal study sites are summarized in Table 1, 2 and 3. It can be seen that all R^2 values are below 0.1 indicating very weak correlation among the MODIS products and the percent cover and forage values at the 3 study sites.

Table 1. Correlation coefficient (R^2) between *in situ* field measurements (total percent cover and plant biomass) and various MODIS productivity products (FPAR, GPP, LAI, and PsnNet) for the Big Desert study site.

	Correlation (R^2) of	
Big Desert (06/02/07)	**% Cover**	**Forage (kg/ha)**
FPAR	0.057	0.0508
GPP	0.045	0.0476
LAI	0.0482	0.073
PsnNet	0.018	0.0297
Mean R^2	*0.0421*	*0.0503*
Big Desert (06/10/07)	**% Cover**	**Forage (kg/ha)**
FPAR	0.0433	0.0746
GPP	0.0576	0.0741
LAI	0.0374	0.0607
PsnNet	0.0462	0.0744
Mean R^2	*0.0461*	*0.0710*

Table 2. Correlation coefficient (R^2) between *in situ* field measurements (total percent cover and forage biomass) and various MODIS productivity products (FPAR, GPP, LAI, and PsnNet) for the USSES study site.

	Correlation (R^2) of	
USSES (08/05/07)	**% Cover**	**Forage (kg/ha)**
FPAR	0.0095	0.0911
GPP	0.0121	0.0745
LAI	0.0163	0.0557
PsnNet	0.013	0.0314
Mean R^2	*0.0127*	*0.0632*
USSES (08/13/07)	**% Cover**	**Forage (kg/ha)**
FPAR	0.0179	0.0599
GPP	0.0208	0.0546
LAI	0.024	0.0679
PsnNet	0.0145	0.018
Mean R^2	*0.0193*	*0.0501*

Table 3. Correlation coefficient (R^2) between *in situ* field measurements (total percent cover and forage biomass) and various MODIS productivity products (FPAR, GPP, LAI, and PsnNet) for the O'Neal study site.

	Correlation (R^2) of	
O'Neal (07/04/07)	**% Cover**	**Forage (kg/ha)**
FPAR	0.014	0.0324
GPP	0.0243	0.0352
LAI	0.031	0.0165
PsnNet	0.0409	0.0092
Mean R^2	*0.0276*	*0.0233*
O'Neal (07/12/07)	**% Cover**	**Forage (kg/ha)**
FPAR	0.0287	0.0501
GPP	0.0568	0.0523
LAI	0.0384	0.0645
PsnNet	0.0154	0.0657
Mean R^2	*0.0348*	*0.0582*

Although the direct correlation between percent cover and biomass was weak ($R^2 = 0.1211$, n = 347), we assumed the quantity of biomass depended largely on percent cover. This suggests that correlations using either of these field-based productivity measures should result in highly similar (autocorrelated) results. However, since the biomass values used in this study only included grass, total percent cover should have yielded a better relationship with MODIS productivity products. The comparison of MODIS correlations with percent cover and biomass reveals the opposite. The R^2 values for biomass were typically better than the R^2 values for total percent cover (twenty comparisons out of 24 [i.e. 83% of the observations]). The field methods used to measure total percent cover and forage biomass can certainly play a role and these results suggest that the biomass estimation variable may be a more reliable estimate of overall productivity compared to total percent cover.

Correlations between MODIS products and the *in situ* field data for the Big Desert study site were consistently better than found at the other sites (mean R2 = 0.04 for percent cover and 0.06 for biomass [table 4]).

Table 4. Mean correlation coefficient (R^2) between *in situ* field measurements (total percent cover and forage biomass) and various MODIS productivity products (FPAR, GPP, LAI, and PsnNet) for the three study sites.

	Correlation (R^2) of	
	% Cover	**Forage (kg/ha)**
Big Desert (06/02/07)	**0.0421**	**0.0503**
Big Desert (06/10/07)	**0.0461**	**0.0710**
O'Neal (07/04/07)	0.0276	0.0233
O'Neal (07/12/07)	0.0348	0.0582
USSES (08/05/07)	0.0127	0.0632
USSES (08/13/07)	0.0193	0.0501

This is of particular interest, because percent cover at the Big Desert was estimated in ocular fashion using fairly broad classes (approximately 10% cover intervals) compared to point-intercept transect data used at the other two sites.

Pixel-sc ale Validation

The results of validation for those pixels containing 3 or more sample points indicate that percent cover and plant biomass share a weak correlation with FPAR and PsnNet (Table 5). The correlation improves slightly (from 0.0094 to 0.1129 for percent cover and from 0.0549 to 0.1029 for biomass) suggesting a dependence on the level of processing (FPAR being the most basic to PsnNet the most processed) with the more highly processed product being having a slightly higher correlation field data.

Table 5. Pixel scale correlation coefficients (R^2) between *in situ* field measurements (total percent cover and forage biomass) and two MODIS productivity products (FPAR and PsnNet).

	Correlation (R^2) of	
	% Cover (Mean)	**Forage kg/ha (Mean)**
FPAR	0.0094	0.0549
PsnNet	0.1129	0.1029

Past studies suggest that MODIS products will not correlate well at the pixel scale, whereas multi-pixel patch level comparisons have demonstrated improved correlation between field measurements and satellite derived products (Wang et al 2004). The present study suggests that the results of validation for pixels containing 3 or more sample points are slightly better than the results for validation using all pixels across the study's landscape thereby supporting the findings of Wang et al.

The results in Table 5 are combined results for the two sites i.e. O'Neal and USSES. We also examined the individual correlations for the same. The R^2 ranges from 0.00 (for O'Neal - PsnNet and percent cover relationship) to 0.19 (for USSES – FPAR and forage relationship). This implies that none of the study sites possesses a strong correlation with MODIS products.

Assessment of Error and Bias

Heterogeneity in the native vegetation contributes to the variation in the R^2 values especially for LAI values. An effect of foliage clustering and discontinuities is well documented and can significantly affect LAI values (Shabanov et al 2003).

Other spatiotemporal factors may also have contributed to the weak relationship seen in this study. We chose MODIS products acquired on 07- 28- 2007 and 06- 26-2007 for the USSES and O'Neal respectively for pixel scale validation. Although these products should closely represent the field scenario, from the results it is clear that the MODIS products and the field scenario vary from each other. The field attributes (percent cover and forage biomass) for the points in a pixel can be entirely different. Norton and others have reported that there can be significant variability between the field measurements of even two samples made in close proximity (+/- 5 m; (Norton 2008). In this study, we dealt with two vegetation characterization estimates (total percent cover and biomass) and attempted to correlate these over areas that were 1000m in size (1 km MODIS pixels). Not surprisingly then, significant variability was encountered. To better characterize the variability within each pixel, many more sampling points are required with a better distribution d within each pixel.

CONCLUSIONS

Biomass measurements correlated better with MODIS products than did percent cover estimates Forage biomass is defined as all grass species except invasive weeds (Gregory et al 2005) while percent cover included everything except bare ground, litter and rocks. This suggests that non-grass species may have interacted differently with photosynthetically active radiation there by resulting in the poor correlations of percent cover to the MODIS products.

No pattern can be seen for R^2 values for any of the three sites. However distribution of the data points was different for all three sites. The Big Desert data points were well distributed across the study area landscape and exhibit a better range of values for the MODIS products as compared to USSES and O'Neal sites (Figures 2-4).

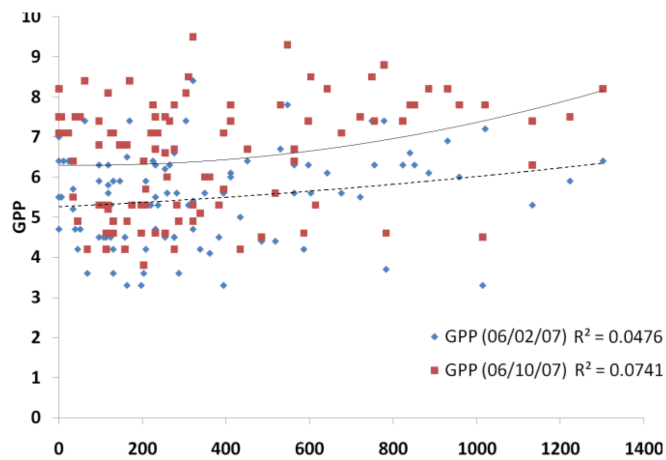

Figure 2. GPP vs. Forage for the Big Desert study area

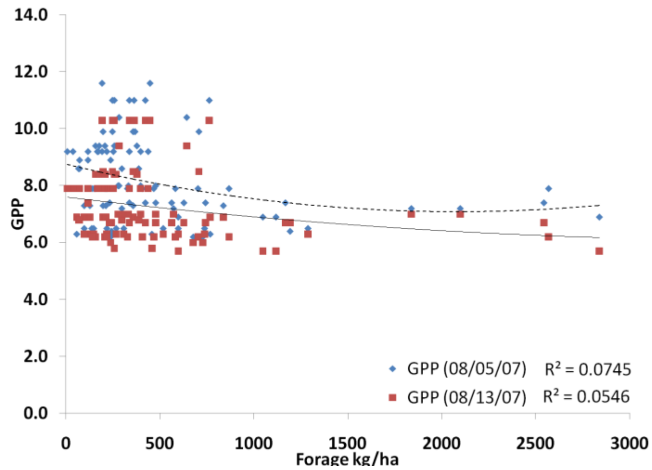

Figure 3. GPP vs. Forage for the USSES study area

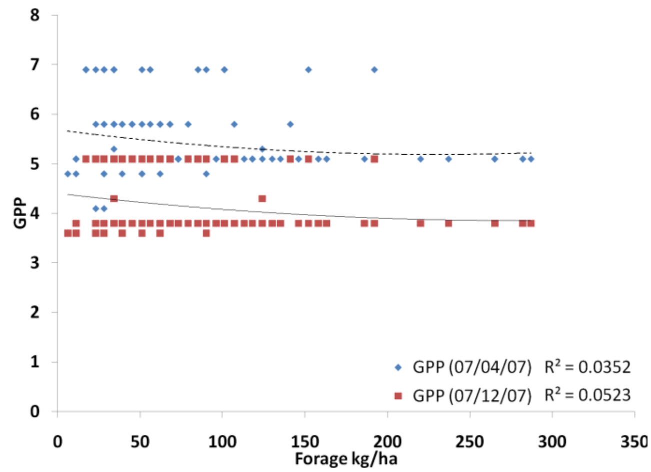

Figure 4. GPP vs. Forage biomass for the O'Neal study area

This study underlines the need to understand potential effect of the spatial distribution of data points with a study area. The Big Desert study area covers over 1000 km^2 which means several MODIS pixels are available for analysis. But the USSES and O'Neal study areas are in the order of only tens of km^2 in size and contain only a few MODIS pixels each.

The importance of this fact is also underlined by revisiting the R^2 values for the Big Desert study site. These values were better --compared to those for USSES and O'Neal—perhaps only because of the better spatial distribution of data points over the study area relative to the size and extent of the MODIS pixels. Pixel-scale validation did not improve the correlation between the MODIS products and field attributes. Spatiotemporal factors and/or the level of MODIS product processing are likely the reason for such poor results.

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