Comparison of MODIS fPAR Products with Landsat-5 TM Derived fPAR over Semiarid Rangelands of Idaho

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ABSTRACT

While validation of the MODIS fPAR product is well behind that of the LAI product, it is recently receiving more attention. In this study, MODIS fPAR and Landsat-5 TM derived fPAR (TM fPAR) were calculated and quantitatively compared using imagery from 2005 to 2008 for the semiarid rangelands of Idaho, USA. fPAR change maps were calculated between active growth and late-summer senescence periods. Accuracy of the MODIS fPAR and TM fPAR were determined indirectly by incorporating field-based measurements of above-ground forage biomass and percent ground cover from a variety of sites (*n* = 442).

KEYWORDS: Rangelands, fraction of photosynthetically active radiation absorbed by vegetation (fPAR), Moderate Resolution Imaging Spectroradiometer (MODIS), remote sensing, Idaho

INTRODUCTION

Live vegetation responds to radiation, heat, and water balance interactions between the land surface and the atmosphere (Bonan, 1995; Sellers et al., 1997). Currently, most interaction simulation models, including carbon budget models, climate cycle models, and ecosystem productivity models require quantitative vegetation information as a modeling input (Dickinson et al., 1998; Running et al., 1999; Feng et al., 2007). In each case, the fraction of photosynthetically active radiation absorbed by vegetation (fPAR) is a key biophysical parameter (Asner et al., 1998; Running et al., 2004). Many techniques have been developed to measure fPAR and most can be categorized as either a field-based or satellite-based methodology. For example, field-based measurements from flux towers have been widely used to derive fPAR in various ecological environments (Baret et al., 2006; Morisette et al., 2006). Although field-based methods are straightforward and accurate for small scale studies they are also difficult to apply for spatial pattern studies at regional scales.

When it is important to have global or regional measurements of fPAR (e.g., for effective application of interaction simulation models over large areas and long time periods), satellite remote sensing has the advantage of acquiring land surface imagery at broad-spatial scales and frequent temporal periodicity. In addition, satellite based methods provide a unique way to extend the estimations of fPAR into additional productivity metrics such as gross primary production (GPP), net primary production (NPP), and net ecosystem exchange (NEE) (Zhao et al., 2005; Turner et al., 2009).

Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument aboard the Terra and Aqua satellites. The MODIS Land Discipline Team (MODLAND) has developed leaf area index (LAI) and fPAR products that provide global 1 km spatial resolution LAI/fPAR images at 8 day intervals (Knyazikhin et al., 1998; Cohen et al., 2003; Morisette et al., 2006). Since the launch of the Terra satellite in December 1999, MODIS LAI/fPAR products have been widely used in many global ecosystem interaction studies including forest (Shabanov et al., 2003; Chen et al., 2008), cropland (Chen et al., 2006; Yang et al., 2007), and grassland ecosystems (Fensholt et al., 2004; Hill et al., 2006).

Experience from previous generations of satellite imaging systems suggests that an independent assessment of product quality is a critical step to the success of MODIS product usage (Justice et al., 2002; Morisette et al., 2002; Turner et al., 2003). For this purpose, the MODIS Science Team has developed several validation projects. "BigFoot" is one such project which provides validation of MODLAND science products (http://www.fsl.orst.edu/larse/ bigfoot/index.html.), including land cover, LAI, fPAR, and NPP (Morisette et al., 2003; Turner et al., 2006). The "Bigfoot" project includes nine carbon flux tower sites (seven in the USA, one in Canada, and one in Brazil) that cover eight major biomes from desert to tundra, and tropical rainforest. fPAR surface images are derived by linking *in situ* measurements to data from Landsat-7 ETM+ and various independent ecosystem process models. Based on validation data from "BigFoot ", the quality of MODIS fPAR products and their source error have been assessed, concluding that while it is not possible for a single MODIS pixel accurately estimate fPAR, multiple pixel estimations within and across sites can be accurately estimated (Gower et al., 1999; Milne and Cohen, 1999). The Validation of Land European Remote sensing Instruments (VALERI) project is another project to evaluate the absolute accuracy of the biophysical products (e.g., LAI, fPAR) derived from satellite observations (Garrigues et al., 2007; Baret et al., 2009). More than twenty counties (e.g., Argentina, Australia, China, England, Finland, France, Germany, Spain) collaborate in VALERI project and MODIS fPAR product is inter-compared with other different sensors and algorithms (Gobron et al., 2006; Weiss et al., 2007). In general, these MODIS validation projects participate in existing long-term ecological research programs (Franklin et al., 1990), scientific data networks such as AERONET (Holben et al., 1998) and FLUXNET (Heinsch et al., 2006), and international validation activities (Swap et al., 2000).

The validation of MODLAND science products is also accomplished by comparison with field measurements or cross-sensor comparison with other satellite sensors. The advantage of field-based validation is that abundant land surface information, such as the exchange of carbon dioxide, water vapor, and energy, across a spectrum of temporal and spatial scales can be used to support the validation. Cross-sensor comparison is another important part of MODLAND science product validation. CYCLOPES LAI/FPAR products (Weiss et al., 2007) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) fPAR data (Gobron et al., 2006) have been used for the purpose of understanding the difference between MODLAND science products and analogous biophysical parameters derived from other sensors (Garrigues et al., 2008).

Validation of the MODIS LAI/fPAR products have mostly focused on LAI (Tian et al., 2002; Cohen et al., 2003; Shabanov et al., 2003), yet it is important to extend validation to the fPAR product across all biomes. Semiarid rangeland ecosystems (an anthropogenic biome comprising a number of ecological biomes such as semiarid deserts, dry steppes, grasslands and savannas) cover approximately 40% of the earth's terrestrial surface and play an important role in global ecosystem productivity (Breman and de Wit, 1983; Huntsinger and Hopkinson, 1996). Validation of the MODIS fPAR product in semiarid rangeland ecosystems is important part of the overall product validation.

In September 2006, MODLAND released a new version of MODIS Land Data Products (Collection 5) providing greater data quality than available from Collection 4. Although there are MODIS fPAR validation studies in other semiarid rangelands, (Fensholt et al., 2004; Weiss et al. 2007), previous validation studies were specific to the earlier MODIS fPAR Collection 4 product. To date there have been no papers published for studies of fPAR Collection 5 product validation in the semiarid rangelands of North America.

In this study, fPAR was derived using Landsat 5 TM data following the SR-fPAR retrieval algorithm proposed by Sellers et al. (1992). A cross-sensor comparison was made using MODIS fPAR Collection 5 products and Landsat 5 TM-derived fPAR products. The accuracy of these fPAR products was indirectly determined by incorporating field-based measurements of aboveground forage biomass and percent ground cover from a variety of sites in the semiarid sagebrush-steppe rangelands of Idaho.

MATERIALS AND METHODS

Study area

The study area, known as the Big Desert, lies in southeast Idaho, USA, approximately 71 km northwest of Pocatello. The center of the study area is located at 113° 4' 18.68" W and 43° 14' 27.88" N (Figure 1). This area is managed by the Bureau of Land Management (BLM) and exhibits a large variety of native as well as invasive plant species. The Big Desert is a semiarid sagebrush-steppe ecosystem with a high proportion of bare ground ($\bar{x}$ bare ground > 17%), and is classified as a Wyoming big sagebrush/blue bunch wheatgrass habitat type. Annual precipitation is 23 cm with 40% of the precipitation falling from April through June (Yanskey et al., 1966). The area is bordered by geologically young lava formations to the south and west and irrigated agricultural lands to the north and east. Sheep grazing is the primary anthropogenic disturbance to the study area with semi-extensive continuous/seasonal grazing systems used on allotments ranging in size from 1100 to over 125,000 ha. The set stocking rate is low across the study area (>19 ha/animal unit [AU]) with actual utilization approximately 40% of the set stocking rate. Wildfire is a common disturbance and nearly 40% of the study area has burned in the past 10 years.

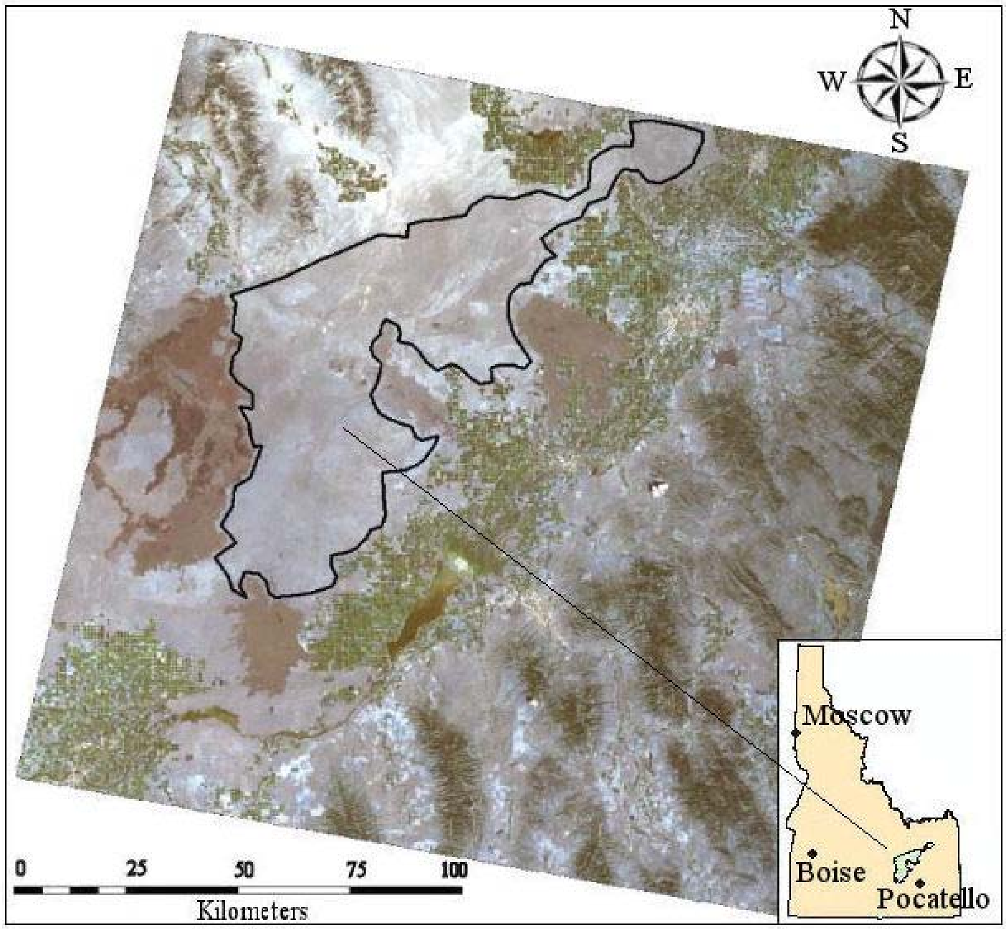

Figure 1. Location and general characteristics of the Big Desert in southeastern, Idaho, USA. The true color composite of Landsat-5 TM: band3=red, band2=green, band1=blue.

Sample design and field measurements

A total of 442 sample points were randomly generated across the Big Desert study area between 2005 and 2008 (Table 1). Each point met the following criteria; 1) >70 meters from an edge (road, trail, or fence line) and 2) < 750 meters from a road. The location of each sample point was recorded using a Trimble Geo XT (2005) or Geo XH (2006-2008) GPS receiver using latitude-longitude (WGS 84) (Serr et al., 2006). Points were occupied until a minimum of 60 positions were acquired for averaging and the Wide Area Augmentation System (WAAS) was used whenever available to improve baseline accuracies. All sample point locations were post-processed differentially corrected (horizontal positional accuracy = +/-0.70 m (2005) and +/-0.20 m (2006-2008) after post-processing with a 95% CI) using continuously operation reference stations (CORS) each located <80 km from the study area. All sample points were projected into Idaho Transverse Mercator NAD 83, using ESRI's ArcGIS for datum transformation and projection (Gneiting, et al., 2007).

Table 1. Dates and numbers of field sample plots used for validation.

Year	Sampling dates	Number of sample plots
2005	01-June to 15-July	88
2006	05-June to 10-July	175
2007	29-May to 13-June	97
2008	10-June to 11-July	82

Ground cover estimations were made within 10x10m square plots centered over each sample point with the edges of the plots aligned in the cardinal directions. Estimates of percent cover were made for bare ground, litter and duff, grass, shrub, and dominant weed. Cover was classified into one of nine general cover classes (None, 1-5%, 6-15%, 16-25%, 26-35%, 36-50%, 51-75%, 76-95%, and >95%). Available above-ground forage biomass was measured using a plastic coated cable hoop 2.36 meters in circumference. The hoop was randomly tossed into each of four quadrants (NW, NE, SE, and SW) centered over the sample point. All herbaceous species within the hoop that were 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 expressed in kilograms per hectare.

Landsat-5 TM imagery

Based upon four years of field survey data (2005-2008), it was determined that grasses, shrubs, and dominant weeds tended to be green and most actively growing, resulting in high fPAR values, during spring and early summer (i.e., June) time periods. Later in the summer, high temperatures hasten the desiccation of plants and in contrast to the active growing period, fPAR values are reduced and substantially different at this time. Therefore, we selected Landsat-5 TM and MODIS imagery from these two time periods (henceforth referred to as the active growth and late-summer senescence periods) to optimally detect fPAR changes and thereby better understand seasonal productivity within semiarid rangelands.

Four Landsat-5 TM scenes, path/row 039/030, were collected on 13-August-2005, 13-June-2006, 03-August-2007, and 18-June-2008. Two scenes were acquired during the active growth period of early June 2006 and 2008, while the other two scenes were acquired during the late-summer period when grasses senesced in August 2005 and 2007. Digital Number (DN) values were transformed into radiance using gain and offset coefficients from the metadata of the imagery. The images were then atmospherically corrected based on the dark object subtraction (DOS) method (Chavez, 1996; Song et al., 2001). All imagery was projected into Idaho Transverse Mercator (IDTM), NAD 83 and georectified to < 0.3 pixel root mean square error (RMSE) (Weber, 2006).

Landsat-5 TM fPAR calculation

Recently, two primary approaches have been used to retrieve fPAR from remotely sensed data. The most common approach has been to establish an empirical relationship between NDVI and fPAR through fitting ground-based measures of fPAR to corresponding remotely sensed data (Myneni and Williams 1994; Chen, 1996). The limitation of relationship-based approaches is that the resulting formulas are influenced by vegetation type and soil background. Another important fPAR retrieval approach is based on bidirectional reflectance distribution function (BRDF) models (Tian, et al., 2000, 2002; Hu et al., 2007). The model-based approach may be more accurate from a theoretical basis, however it requires lengthy calculation time and is difficult to obtain sufficient model input parameters.

In this study, with limitations on field fPAR measurement data and model input parameters, TM fPAR estimations were developed by applying the SR-fPAR algorithm. To specifically assess the ability of the SR-fPAR retrieval approach for fPAR estimation in semiarid rangelands ecosystems, field-based measurements of aboveground forage biomass and percent ground cover were used to better indirectly assess TM fPAR. Recently, empirical relationship based empirical algorithms are highly site- specific and always emphasizes on forest ecosystem, however SR-fPAR algorithm described by Sellers et al. (1992) is a straightforward fPAR retrieval approach and is considered applicable within a variety of biome types (e.g., broadleaf evergreen trees, needle leaf deciduous trees, and grassland) (Paruelo et al., 1997; Los et al., 2000; Hassan et al., 2006).

Assuming a nearly linear relationship between fPAR and simple ratio (SR) (Equation 1), fPAR can be calculated when two known points are determined. The value of the 98th percentile from a normalized difference vegetation index (NDVI) distribution was assumed to represent vegetation at full cover and maximum photosynthetic activity with fPAR values close to unity (0.950). The 5th percentile value is assumed to represent no vegetation photosynthetic activity with an fPAR of 0.001. The relation between fPAR and SR is then given by

$$SR = \frac{1+NDVI}{1-NDVI} \qquad (1)$$

$$fPAR = fPAR_{min} + (SR - SR_{i,min})\frac{(fPAR_{max} - fPAR_{min})}{SR_{i,max} - SR_{i,min}} \qquad (2)$$

where the maximum ($fPAR_{max}$ =0.950) and minimum ($fPAR_{min}$ =0.001) values of fPAR are independent of vegetation type. $SR_{i,max}$ and $SR_{i,min}$ correspond respectively to the 98th and 5th percentile of the NDVI data population for type *i* (sagebrush-steppe) vegetation (Sellers et al., 1996).

MODIS fPAR product

The theoretical basis of the MODIS fPAR algorithm is the three dimensional radiative transfer theory (Myneni et al., 1999). The inversion of the 3D Radiative transfer is accomplished with Look-Up Table approach (Knyazikhin et al., 1998). A back up method based on the relationship between NDVI and fPAR, used together with a biome classification map, is applied when the primary algorithm fails. In this study, four the Collection 5 MODIS fPAR (MOD15A2) scenes were selected on the basis of temporal coincidence with existing Landsat-5 TM imagery. All MODIS fPAR imagery (1 km spatial resolution) used in this study represent a time interval of eight days. All imagery was projected into ITDM, NAD 83, using ESRI's ArcGIS 9.3 for datum transformation and projection. Using quality control (QC) layers, MODIS fPAR data were screened to reject fPAR data of insufficient quality. Only pixels with the best possible quality (i.e., values on all bit fields are equal to zero) under the QC definition table were retained

(Table 2). The QC filter includes pixels with good quality and removes pixels which were not produced due to cloud or other reasons.

Table 2. MODIS fPAR general quality control definitions for collection 5 data.

Bit No.	Parameter Name	Bit Comb.	Description of Bitfield(s)
0	MODLAND_QC_bits	0	Good quality (main algorithm with or without saturation)
		1	Other Quality (back-up algorithm or fill values)
1	Sensor	0	Terra
		1	Aqua
2	DeadDetector	0	Detectors apparently fine for up to 50% of channels 1,2
		1	Dead detectors caused >50% adjacent detector retrieval
3-4	CloudState (inherited from Aggregate_QC bits {0,1} cloud state)	00	0 Significant clouds NOT present (clear)
		01	1 Significant clouds WERE present
		10	2 Mixed cloud present on pixel
		11	3 Cloud state not defined, assumed clear
5-7	SCF_QC (five level confidence score)	000	0, Main (RT) method used, best result possible (no saturation)
		001	1, Main (RT) method used with saturation. Good,very usable
		010	2, Main (RT) method failed due to bad geometry, empirical algorithm used
		011	3, Main (RT) method failed due to problems other than geometry, empirical algorithm used
		100	4, Pixel not produced at all, value coudn't be retrieved (possible reasons: bad L1B data, unusable MODAGAGG data)

fPAR comparison

MODIS fPAR and TM fPAR imagery were first compared to determine general similarity. To enable quantitative assessment of MODIS fPAR distributions, all TM fPAR layers were averaged resampled to 1 km spatial resolution in ESRI's ArcGIS 9.3. A total of 350 independent randomly distributed test points were generated using Hawth's analysis tools for ArcGIS. Of these, 302 test points were finally available for analysis after removing all points falling within the “no-retrieve” areas of the imagery. Pixel values were extracted using the ArcGIS "Sample" tool, and correlation coefficients were calculated to evaluate the relative agreement between MODIS fPAR and TM fPAR values.

TM fPAR change layers were calculated using TM fPAR values for 13-August-2005 subtracted from TM fPAR values for 13-June-2006. Similarly, TM fPAR values for 03-August-2007 were subtracted from TM fPAR values for18-June-2008. The resulting change layers were assumed to represent vegetation growth that occurred following the end of the previous growing season and prior to periods of active livestock grazing in the study area. MODIS fPAR change layers were calculated in the same way. Finally, fPAR distribution layers and change layers were compared with field-based measurements of aboveground forage biomass and percent ground cover to further indirectly validate these data.

fPAR indirect-validation

There were no flux tower sites in or surrounding the Big Desert study area and no ground-measured fPAR data were available for the study area. Because actual fPAR values must be considered unknown, direct validation from field measured fPAR was unavailable in this study. For this reason, we consider the seasonal characteristics of fPAR change over semiarid rangelands. Grasses, shrubs, and dominant weeds tended to be green during active growth periods (June). In contrast, most shrubs maintained greenness throughout much of the year while grasses and weeds became senescent, resulting in substantial fPAR reduction (e.g., fPAR value of grass is close to 0) in late summer (August). fPAR difference between late-summer senescence periods (e.g., primarily resulting from shrubs) and the next active growth periods (e.g., resulting from grasses, weeds, and shrubs) describes the amount of grasses and weeds available during the active growth period. Therefore, fPAR change values can be indirectly validated through a careful assessment of the spatial variability of grasses and weeds.

Based upon the reported data, the authors observed that 1) in areas where the percent cover of shrubs and above-ground forage biomass were similar, the area with the higher percent cover of grasses and weeds during the active growth period consistently resulted in higher fPAR change; 2) when the percent cover of shrub and grass functional groups were similar, the area with more above-ground forage biomass during the active growth period lead to higher fPAR change. As a result, the relationship between percent ground cover and fPAR change, and the relationship between above-ground forage biomass and fPAR change was established and fPAR values indirectly validated by comparing changes in fPAR with changes in above-ground forage biomass and percent ground-cover.

RESULTS

MODIS fPAR values and TM fPAR values were relatively similar (Figure 2). The results of quantitative comparisons among aggregated TM fPAR and MODIS fPAR products (1 km spatial resolution in both cases) across the study region from 2005 to 2008 indicate MODIS fPAR values were relatively close to TM fPAR values and a weak relationship between MODIS fPAR and TM fPAR was also noted ($R^2 \leq 0.51$) (Figure 3). In general, MODIS fPAR depicts the same overall trend and offers the advantage of acquiring reliable fPAR data at broad-scales and frequent periodicity.

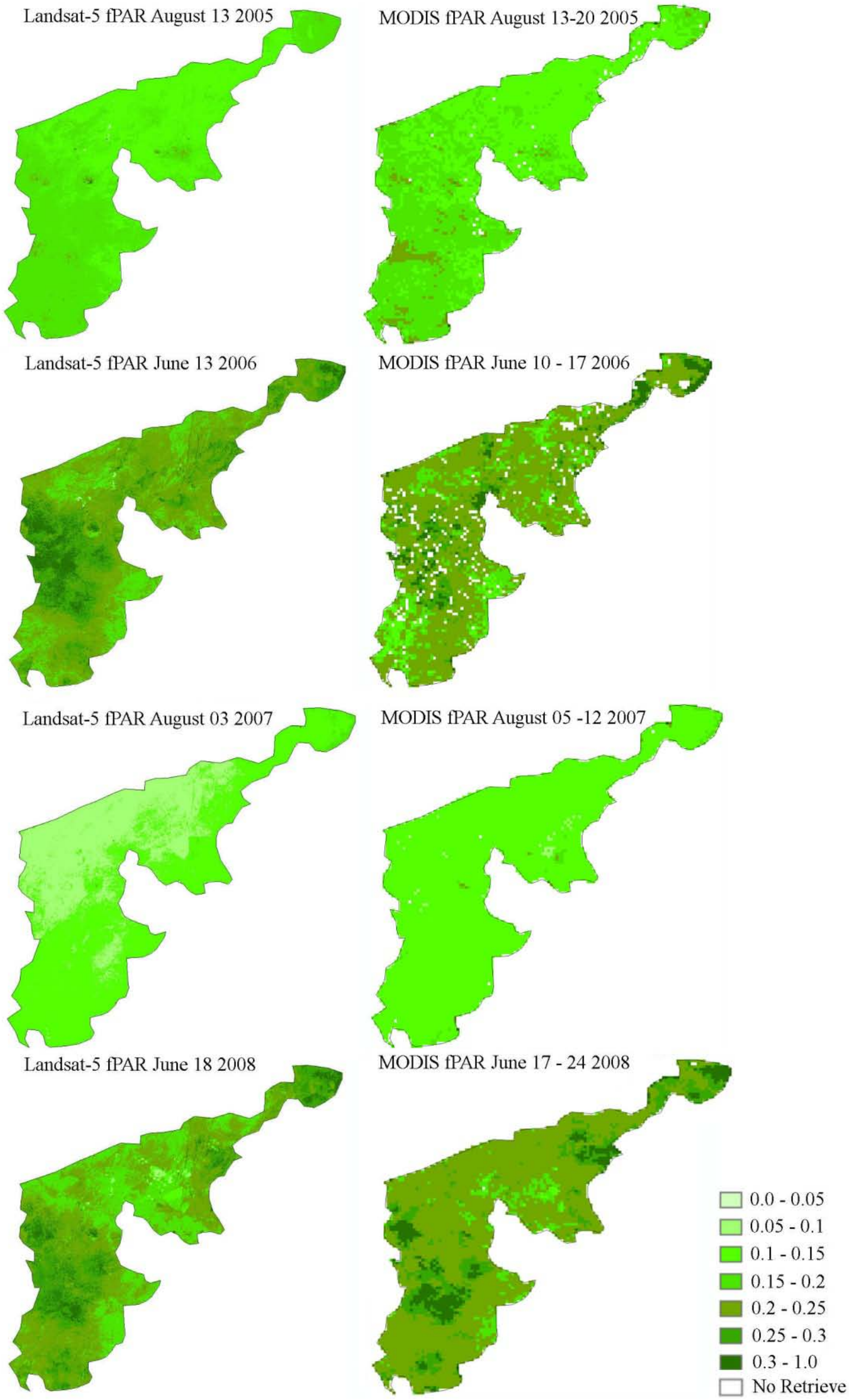

Figure 2. Landsat-5 TM fPAR (30 meters per pixel [mpp]) and eight-day composite MODIS fPAR (1000 mpp) layers.

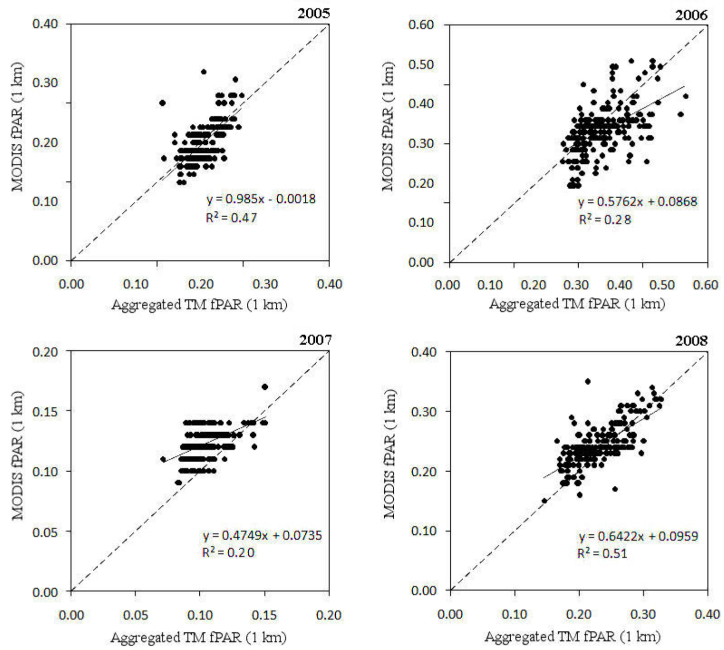

Figure 3. The comparison of aggregated Landsat-5 TM fPAR to the MODIS fPAR product at 1 km resolution.

TM fPAR change layers were nearly identical to MODIS fPAR change layers (Figure 4). Using fPAR change results, areas of major negative change (-1 < fPAR change < -0.05), minor change (-0.05 < fPAR change < 0.05) and major positive change (0.05 < fPAR change < 1) were delineated. A major positive change (MPC) area was defined as an area where fPAR values increased. Similarly, a major negative change (MNC) area was an area where fPAR values substantially decreased, while minor change (MINC) areas were areas where fPAR values changed only slightly.

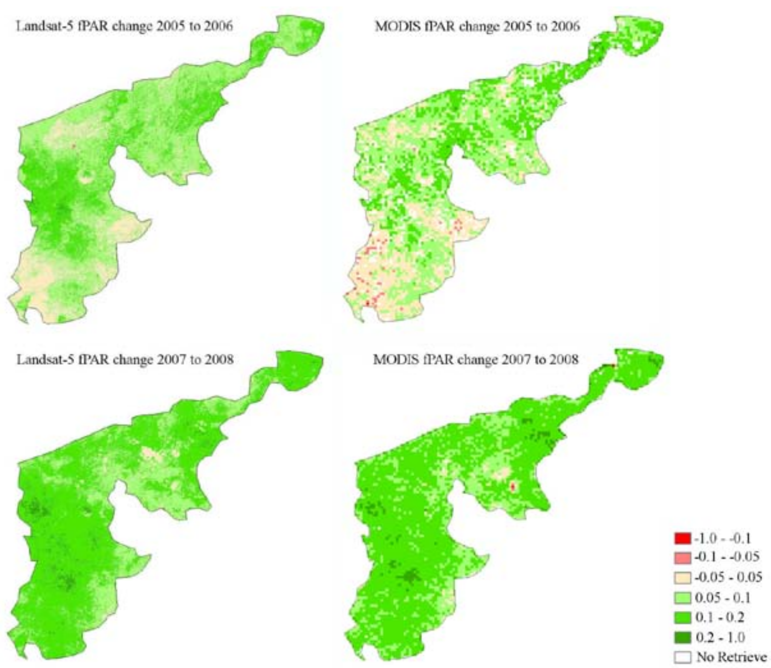

Figure 4. The fPAR change maps of Landsat-5 TM and MODIS.

Field-based measurements of above-ground forage biomass and percent ground-cover in MPC, MNC, and MINC areas are summarized in Table 3 and Table 4. In 2006, average percent shrubcover in MPC areas was similar to that in MINC areas, while higher percent grass cover was present in MPC areas than MINC areas over the same time period. Mean and maximum forage biomass was greater in MPC areas ($\bar{x}$ = 496 Kg/Ha; maximum = 1668 Kg/Ha) than in MINC areas ($\bar{x}$ = 328 Kg/Ha; maximum = 1065 Kg/Ha) in 2006, while mean forage biomass reduced in both MPC areas (-115 Kg/Ha) and MINC areas (-223 Kg/Ha) between 2005 and 2006. The reduction of forage biomass in MINC areas was greater than the reduction of forage biomass in MPC areas, , hence a major negative change was detected in the MINC areas.

Table 3. Percent ground cover for fPAR change analysis.

	Average ground percent cover (%)					Number of sample plots
	Shrub	Grass	Litter	Bare ground	Weed	
MINC areas 2005	5-13	5-13	2-7	49-71	1-6	21
MPC areas 2005	5-13	5-14	2-7	47-69	2-7	67
MINC areas 2006	15-23	6-16	27-37	17-27	6-15	36
MPC areas 2006	14-23	16-25	17-26	16-25	5-14	139
MPC areas 2007	4-9	14-22	6-16	33-46	2-7	97
MPC areas 2008	2-7	14-23	16-26	27-36	5-12	82
Changes in MINC areas 2005-2006	10	1-3	25-30	-(32-44)	5-10	N/A
Changes in MPC areas 2005-2006	9-10	11	15-19	-(31-44)	3-7	N/A
Changes in MPC areas 2007-2008	-(3-5)	0-1	10	-(6-10)	3-5	N/A

Note: no MINC areas were delineated in 2007 or 2008 and no sample plots was available within MNC area. SD stands for standard deviation.

Table 4. Aboveground forage biomass for fPAR change analysis.

	Forage biomass (Kg/Ha)				Number of sample plots
	Mean	Max.	Min.	SD	
MINC areas 2005	551	2524	34	562	21
MPC areas 2005	612	3138	34	297	67
MINC areas 2006	328	1065	62	249	36
MPC areas 2006	496	1668	51	346	139
MPC areas 2007	356	1302	11	309	97
MPC areas 2008	249	975	11	208	82
Changes in MINC areas 2005-2006	-223	-1459	28	N/A	N/A
Changes in MPC areas 2005-2006	-115	-1470	17	N/A	N/A
Changes in MPC areas 2007-2008	-107	-345	0	N/A	N/A

Note: no MINC areas were delineated in 2007 or 2008 and no sample plots was available within MNC area. SD stands for standard deviation.

Analysis of field-based measurements of ground cover and forage biomass between 2005 and 2006 suggest MPC areas should exhibit greater fPAR change trends relative to MINC areas. Furthermore, comparing the change of mean forage biomass in all MPC areas from 2005 to 2006 (-115 Kg/Ha) to the change of mean forage biomass in all MPC areas from 2007 to 2008 (-107 Kg/Ha) revealed very similar change patterns. The information describing field-based above-ground forage biomass and percent ground-cover follow the same distribution and trend as indicated by both the MODIS and TM fPAR change maps.These results support the hypothesis that the seasonal characteristics of fPAR change over semiarid rangelands can be used as an indicator for the relative abundance of grasses and herbaceous weeds.

DISCUSSION

Many MODIS fPAR validation studies noted that MODIS seems to overestimate fPAR in many regions. Fensholt et al. (2004) demonstrated that in comparison to field measured fPAR the overall level of MODIS fPAR is overestimated by approximately 0.06 - 0.15 in the semiarid grasslands of West Africa and Senegal. Weiss et al. (2007) compared MODIS fPAR and CYCLOPES fPAR products and also concluded that MODIS estimates higher fPAR values than CYCLOPES in grasslands. Similar to grassland, Steinberg et al. (2006) indicated the MODIS fPAR algorithm overestimates fPAR when compared to Landsat-7 ETM derived fPAR in the boreal forests of Alaska (i.e., MODIS approximately overestimated fPAR by up to 0.2). However, in this study the difference between MODIS fPAR values and TM fPAR values contradicted previous findings ($\overline{x}$ difference < 0.05). The reduction in MODIS fPAR values may be attributed to the improvement in the Collection 5 MODIS fPAR retrieval algorithm (e.g., all previous MODIS fPAR validation studies used Collection 4 product but this study used Collection 5 product) (Steinberg and Goetz, 2009).

Field sampling was conducted between June and early July throughout this study (2006-2008). This corresponds with the period of peak biomass production in the study area. Remote sensing imagery was acquired during this same time period to similarly capture the active growth period and allow comparison with known field conditions. Imagery for the years 2005 and 2007 were chosen to capture late-summer senescence and thereby better assess changes in fPAR over the growing season. In semiarid rangelands ecosystems, plant growth rates dramatically decrease following the active growth period in early June. However, plant growth does continue and in some years exhibits a spike of activity if sufficient autumn precipitation is present. Therefore, vegetation change derived from field measurement data provided an estimate of growth for the entire summer and following spring, whereas the fPAR change layers developed in this study did not include vegetation changes that occurred between June and early August. Following this approach, the resultant change layers describe the amount of green biomass available (e.g., actively growing grasses) as the difference between the estimated total above-ground biomass during the active growth period (i.e., actively growing grasses, accumulated litter, and residual plant matter) and the estimated total above-ground biomass at the end of the previous growing season.

In this study, fPAR change values help describe the spatial variability of grasses and weeds based on the seasonal characteristics of fPAR change over semiarid rangelands. For example, a positive fPAR change indicates more grasses and weeds would be found during the growing period (i.e., increased spatial distribution). Similarly, a negative fPAR change indicates fewer patches of grasses and weeds would be found in an area during the growing period. fPAR images were selected to represent the active growth and late-summer senescence periods, therefore fPAR change layers do not reflect an entire year of vegetation change (e.g., from June 2005 to June 2006). Hence, a positive fPAR change between 2005 and 2006 does not necessarily mean there was an increase in grass and weed biomass production in June 2006 than June 2005 but that the spatial distribution of grasses and herbaceous weeds was increased across the area. In addition, while the summary of field sample data and fPAR change levels describe the spatial variability of grasses and weeds, differences between years should not be used to quantify inter-annual variability of grasses and weeds. For example, changes in above-ground forage biomass in MPC and MINC areas for the periods 2005-2006 and 2007-2008 (Table 4) showed a reduction in both cases. However, compared to MINC areas, MPC areas showed less of a reduction in above-ground forage biomass. This example supports the use of fPAR change as an indicator of changes in the spatial variability of grasses and weeds and furthermore, demonstrates that more grasses were produced in MPC areas relative to the MINC areas.

Because each MODIS pixel can contain many different types of ground features (e.g., shrubs, grasses, and weeds) the field measurements used in this study represent only a portion of a MODIS pixel's information. It would be inappropriate to directly link a specific MODIS fPAR value to above-ground forage biomass values for an individual sample plot. In addition, since different years' statistics were based on a different number of sample plots, which consist of different percentages of shrubs, grasses, litter, weeds, and bare ground, we cannot obtain field measured above-ground forage biomass change and percent cover change at a given sample plot across time. For these reasons, the study area was categorized into areas of different fPAR change levels which were indirectly validated using above-ground forage biomass statistics to represent the spatial variability of grasses and weeds. In future field surveys, we plan to measure above-ground biomass for additional functional groups (e.g., forbs) at the same sample plot each year and use composited above-ground biomass values to provide a better link with MODIS fPAR data.

Measurement of field fPAR is an arduous task and an insufficient number of field sites (e.g., flux tower) make field fPAR data unavailable to many studies. Ideally, field measured fPAR data would have been available for this study. However, in lieu of these data, we used an accumulation of 10 years of field data (above-ground biomass and percent cover) for this study. In addition, TM fPAR estimations were developed using the SR-fPAR retrieval algorithm to provide a cross-sensor comparison of fPAR.

The seasonal characteristics of fPAR change over semiarid rangelands (e.g., herbaceous plants have a late-summer senescence period and fPAR values of herbaceous plants in this period declined) were considered in this study, and these fPAR change trends exhibited a positive relationship with changes in above-ground forage biomass and percent cover of grasses and weeds. These results were used to indirectly assess the MODIS fPAR product and the SR-fPAR retrieval algorithm used to produce a Landsat 5 TM fPAR product. The methodology presented herein was specifically designed for use within the semiarid sagebrush-steppe rangelands of southeastern Idaho, and should not be directly applied to other ecosystems. This is because there may be little difference in fPAR between the active growth and late-summer senescence periods in more humid rangelands or woodland ecosystems where precipitation is more uniformly distributed throughout the year and distinct growing seasons/dry seasons are not present. However, similar studies should be undertaken to further validate the MODIS fPAR product.

CONCLUSION

This study focused on the comparison and assessment of the MODIS fPAR product for semiarid rangelands using cross-sensor comparisons with TM fPAR values as well as field-based observations and measurements. Landsat-5 TM and MODIS fPAR data were compared between active growth periods (June) and late-summer senescence periods (August) using measurements of above-ground forage biomass and percent ground-cover from 2005, 2006, 2007, and 2008. Observed fPAR changes appear to be a function of changes in the composition and percent cover of grasses and weeds within the study area as grasses and weeds are more ephemeral and dynamic in nature relative to shrubs. In contrast to previous MODIS fPAR validation studies, which noted that MODIS overestimated fPAR in many regions, this study validated Collection 5 MODIS fPAR products and found the difference between MODIS fPAR and TM fPAR values were very small small ($\bar{x}$ difference < 0.05). This may be the result of improvements in the Collection 5 MODIS fPAR retrieval algorithm.

Rangeland ecosystems are very important in the assessment of global ecosystem productivity, and abundant field-based measurements are crucial to the validation of satellite-based fPAR products. Future work will aim to collect additional field data to improve MODIS and TM fPAR applications for semiarid rangelands.

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