ESTIMATION OF LEAF AREA INDEX (LAI) THROUGH THE ACQUISITION OF GROUND TRUTH DATA IN YOSEMITE NATIONAL PARK

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ABSTRACT

Leaf area index (LAI) is an important indicator of ecosystem condition and an important input to many ecosystem models. Remote sensing offers the only feasible method of estimating LAI at regional scales, and land managers can efficiently monitor changes in vegetation condition by using satellite data products such as estimates of LAI from the MODIS instrument onboard Terra and Aqua. However, many ecosystem processes occur at spatial scales finer than those available from MODIS. We investigated different techniques for mapping LAI at multiple temporal and spatial scales, and created high-resolution (30m) LAI maps for Yosemite National Park using Landsat data in combination with ground-based measurements collected using three optical in-situ instruments: LAI-2000, DHP, and the TRAC instrument. We compared in-situ data with three spectral vegetation indices derived from Landsat Thematic Mapper imagery: RSR, SR, and NDVI to identify statistical relationships that could be applied to map LAI for the park at higher spatial resolutions to supplement observations available from MODIS. Pixel values from the Landsat-derived LAI map were resampled to 1km and compared to LAI estimates from MODIS to assess agreement between LAI estimates derived from the two sensors. We found reasonable agreement considering the limited number of field sites and land cover types sampled, and further field measurements would likely improve agreement. The MODIS LAI product is particularly useful because of its high temporal resolution and when supplemented with periodic, higher resolution mapping using Landsat data, can be used to efficiently monitor current and future vegetation changes in Yosemite.

INTRODUCTION

In order to manage resources of our Nation’s parks, it is necessary for the National Park Service (NPS) to track changes in key ecological indicators and incorporate that information into decision-making. Leaf area index (LAI) is an important indicator of ecosystem condition and is a key input in ecological models because of its relation to photosynthesis, transpiration, carbon and nutrient cycle, and rainfall (Chen and Cihlar 1996).

LAI is defined as one-half the total green leaf area per unit of ground surface area (Chen and Black 1992), and is measured using both direct and indirect methods. Direct methods are extremely labor intensive and involve destructive sampling. Indirect methods include the use of ground-based optical instruments and remotely sensed imagery. However, remote sensing offers the only feasible tool for monitoring LAI at regional scales (Stenberg, Rautiainen et al. 2004).

As part of the Natural Resource Challenge initiated in 1999, the National Park Service expanded the Inventory and Monitoring (I & M) Program which provides scientific information to support park managers. NASA's Terrestrial Observation and Prediction System (TOPS) is a modeling framework designed to integrate and preprocess Earth Observing System (EOS) data in order to support retrospective analysis, tracking of current conditions, and forecasts of ecological conditions. The Ecological Forecasting Lab at NASA Ames Research Center is working with the NPS to incorporate data products from the TOPS modeling framework into the I & M system to support NPS monitoring efforts (Nemani, White et al. 2003), particularly for landscape change, climate, phenology, snow cover, and fire. TOPS has developed automated data retrieval, processing, integration, and modeling systems for NASA EOS datasets. In collaboration with the NPS, Montana State University, Woods Hole Oceanographic Institution, and University of Colorado, TOPS data is planned to be implemented for four National Parks (Yosemite, Yellowstone, Rocky Mountain, and Delaware Water Gap) as part of a prototype data system that will provide automated ecosystem assessment tools for use by NPS ecologist and resource managers.

NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the Aqua and Terra satellites provides daily, global estimates of LAI which are then processed into standard global 8-day composite datasets with a spatial resolution of 1km. These 8-day composites are key inputs to many of the component ecosystem models within the TOPS framework. The MODIS LAI product is advantageous to use because of its high temporal resolution, allowing the NPS to monitor Yosemite's vegetation on a weekly basis. In contrast, the Landsat Thematic Mapper (TM) has a coarser temporal resolution of 16 days, but a relatively high spatial resolution of 30m. Utilization of both of these instruments as part of a monitoring and decision support system (DSS) is beneficial to park managers because it allows them to monitor the park weekly with MODIS and investigate persistent anomalies or trends with higher spatial resolution observations from Landsat.

There are no published, comprehensive studies evaluating MODIS LAI estimates in the Sierra Nevada mountain range. The heterogeneous landscape and steep terrain of Yosemite make it difficult to ground-truth satellite data there, and a need exists for field-based LAI estimates for use in mapping and monitoring LAI at multiple temporal and spatial scales. During the summer of 2007, interns from the NASA DEVELOP Program at Ames Research Center conducted a 10-week research project in Yosemite National Park. The objectives of this study were to: 1) collect ground-based LAI values in Yosemite; 2) provide ground-based observation for use in estimating LAI from Landsat scenes over Yosemite; and 3) assess the agreement between the LAI estimates derived from the two different sensors. LAI estimates derived from historical Landsat data can provide baseline information that will be valuable for calibrating and testing TOPS component ecosystem models and will improve modeling of ecosystem processes within the park.

STUDY AREA

The study area for this project was Yosemite National Park (Figure 1). Yosemite National Park is located in the Sierra Nevada Mountains and covers 1,189 mi² (3,081 km²) of Tuolumne and Mariposa Counties in the eastern portion of central California. Current methods employed by the park to collect vegetation information include plot-based studies of vegetation growth, burn scar mapping using Landsat TM data, and vegetation mapping produced from aerial photography. These methods can be both expensive and labor-intensive.

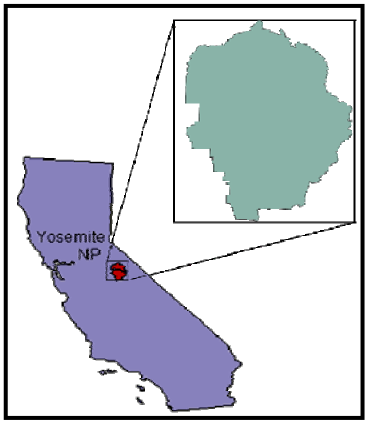

Figure 1. Yosemite National Park, CA.

METHODOLOGY

Field Site Selection

Seven sites of 150m by 150m were selected for the collection of LAI measurements in the park. The sites varied in elevation and included the following dominant species: lodgepole pine (*Pinus contorta*), Jeffrey pine (*Pinus jeffreyi*), ponderosa pine (*Pinus Ponderosa*), sugar pine (*Pinus lambertiana*), California red fir (*Abies magnifica*), white fir (*Abies concolor*), and incense-cedar (*Calocedrus decurrens*). Sites were selected on the basis of reduced simple ratio (RSR) values calculated for Yosemite from a July 30, 2004 Landsat scene, and sites were selected to span the range of RSR values. GIS data including a road shapefile and a 30m digital elevation were used to select sites that were easily accessible and with average slopes of 15%. In addition, GIS data layers including fire boundaries, snow cover, and insect infestation were used to assess the history of each site. Each site was examined at 30m and 1km resolution to represent the Landsat TM and MODIS LAI resolution, respectively. The standard deviation of RSR values in a 240m x 240m window centered around candidate sites were also used to identify sites with the most homogeneous vegetation cover.

Fieldwork

Digital hemispheric photography (DHP) and LI-COR's LAI-2000 Plant Canopy Analyzer are ground-based optical instruments which indirectly measure LAI, and assume a random foliage spatial distribution. Both DHP and LAI-2000 provide ground measurements of effective LAI (LAI_e), which tend to underestimate true LAI in coniferous canopies due to the clumped distribution of foliage (Stenberg 2004). We used both DHP and the LAI-2000 to provide two different estimates of LAI, as no reference measurements from destructive sampling or previous studies were available. The TRAC (Tracing Radiation and Architecture of Canopies) instrument is designed to provide a foliage clumping index, OmegaE(Ωe), which quantifies the effect of the nonrandom distribution of coniferous foliage (Chen, Rich et al. 1997; Leblanc and Chen 2005). Chen provides the following equation to derive LAI from effective LAI (Chen 1996):

$$L = (1-\alpha)L_e/\Omega$$

The formula calculates LAI (L) using the woody-to-total area ratio (α), LAI measurements from either the LAI-2000 or DHP (L_e), and the clumping index (Ω). The value (1- α) is used to remove the contribution of non-leafy materials. The clumping index Ω is defined by the formula,

$$\Omega = \Omega_e/\gamma_e$$

where Ω_e is the clumping index obtained from the TRAC instrument and γ_e is defined as the needle-to-shoot area ratio, which quantifies the effects of foliage clumping within a shoot. Default values for γ_e of 1.0 for broadleaf trees and 1.57 for conifers, as well as the value of 0.1 for α, were obtained from the TRAC manual and used in this study (Leblanc and Chen 2005). Default values were used because this project did not include conducting destructive sampling.

The TRAC manual recommends transects of 100-300m placed perpendicular to the sun. This was accomplished with a N-S, E-W orientation. At each site a 150m X 150m grid was laid out with a flag placed at 30-meter intervals (for a total of 25 pixels), to facilitate comparison with data from Landsat (Figure 2).

The dominant overstory species was recorded at each sample site, along with measurements on the vegetation species, diameter at breast height (DBH) of nearest tree, needle color, and visually estimated needle-to-shoot ratio. In addition, the percent cover, height, and genus information were collected for the understory within a 15-meter radius of the center of the sample site. Photos were taken of the canopy and the understory at each flag.

The TRAC instrument was used in direct sunlight, optimally when the sun angle was between 30 and 60 degrees to minimize shadows.

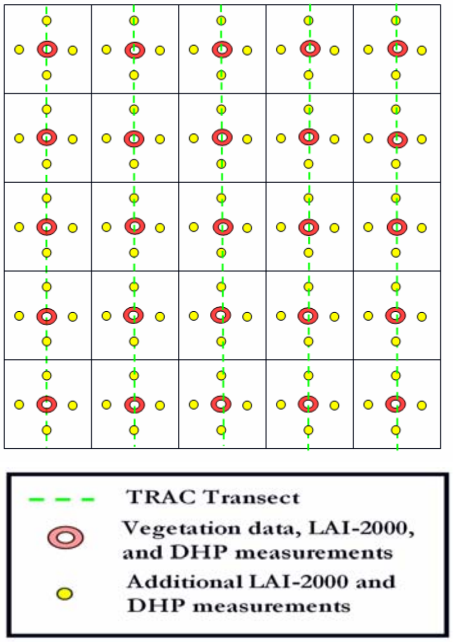

Figure 2. 150m X 150m Sampling Grid representing 25 Landsat pixels.

All TRAC measurements were made in cloudless conditions. TRAC measurements were collected by walking at least two and ideally five of the 120m transects.

Two LAI-2000 units were used to collect LAI measurements at dusk because direct sunlight can cause the sensor to mistake shiny foliage for sky. One instrument was set in a large clearing and used continuously for ambient readings, and the second instrument was used to collect canopy measurements. LAI-2000 measurements were collected at a minimum in the center of each sampling site for as many sampling locations as possible before the light completely faded. If time permitted, four additional measurements were made at each location (7 meters S, N, E, and W and at center).

Digital hemispherical photographs were also used to collect LAI measurements with a Canon Rebel Xti digital SLR camera and a 8mm Sigma fish eye lens. Photographs were taken at dusk in order to minimize the possibility of light scattering caused by direct sunlight , which can cause foliage pixels to be mistaken for sunlight , and were taken at one photograph per sample location, and four additional photos (7 meters S, N, E, and W and at center) at each site if time permitted.

Data Processing

LAI data from the LAI-2000 and DHP were processed with the FV2000 program (LI-COR, Inc, Lincoln, NE) and the DHP 4.5 program (LeBlanc, 2006), respectively. TRAC clumping index data were processed with TRACwin 3.9.1 (LeBlanc, 2006) software. ERDAS IMAGINE 9.1 and ESRI ArcMap 9.2 were used for image processing and analysis. Each digital hemispheric photograph was manually adjusted to the correct threshold setting for each ring using a histogram. LAIe values from both the DHP and LAI-2000 instruments were corrected using the OmegaE values from the TRAC instrument.

Satellite Image Processing

A Landsat TM scene acquired on July 7, 2007 was atmospherically corrected using the COST method (Chavez 1996) and following the Protocol for Landsat-based Monitoring of Landscape Dynamics at North Coast and Cascades Network Parks (Kennedy et al., 2006). Minimum values were determined manually for each band and placed into the COST model, as well as the sun zenith angle and gains and bias listed in the header file. After the image was run through the COST model, 30 ground control points were used to georectify the July 7, 2007 Landsat scene to the original July 30, 2004 scene used for site selection. The July 30, 2004 scene was obtained from NPS and had been orthorectified and terrain corrected at the USGS EROS Data Center (EDC) Land Process Distributed Active Archive Center (DAAC). For comparison, a pre-processed subset of an 8-day composite LAI MODIS tile was obtained for Yosemite from TOPS for July 3 – 10, 2007.

Spectral Vegetation Indices

Ground based measurements of LAI collected between July 1, 2007 and July 15, 2007 were compared to three different Spectral Vegetation Indices (SVI) calculated from the July 7, 2007 Landsat scene: Normalized Difference Vegetation Index (NDVI), Simple Ratio (SR), and Reduced Simple Ratio (RSR). These indices were calculated using the following formulas:

$$\mathrm{NDVI} = \frac{\rho_{TM4} - \rho_{TM3}}{\rho_{TM4} + \rho_{TM3}}$$

$$\mathrm{SR} = \frac{\rho_{TM4}}{\rho_{TM3}}$$

$$\mathrm{RSR} = \frac{\rho_{TM4}}{\rho_{TM3}} * \frac{\rho_{TM5\,max} - \rho_{TM5}}{\rho_{TM5\,max} - \rho_{TM5\,min}}$$

We used linear regression techniques to identify the best fit relationship between the field observations and each of the spectral indices. We then applied the regression equations to derive 30m LAI maps for YNP based on the three spectral indices calculated from the July 30, 2007 Landsat scene. These maps were resampled to 1km resolution using bilinear interpolation. We also resampled data using nearest neighbor and cubic convolution methods but found bilinear interpolation had the best line of fit with our data. The 1km LAI maps were compared with the MODIS LAI map on a pixel-by-pixel basis and the RMSE was calculated for each pixel pair.

RESULTS

Ground-based estimates of LAI using LAI-2000 and DHP techniques differed significantly. A paired *t*-test on the two sets of LAI values revealed a mean difference of 0.62 ($P < 0.0001$). Values obtained from the LAI-2000 were generally greater than those obtained through DHP. When comparing data from pixels where both instruments were used, 78% of the LAI measurements made using the LAI-2000 instrument were greater than those made using the DHP technique. In addition, LAI estimates of zero were occasionally obtained using the LAI-2000 instrument, whereas the DHP-based method always provided a non-zero estimate of LAI. Despite this, the relationship between data collected by these two methods is positive and strong (R= 0.92). A least squares regression describing the relationship is shown in Figure 3.

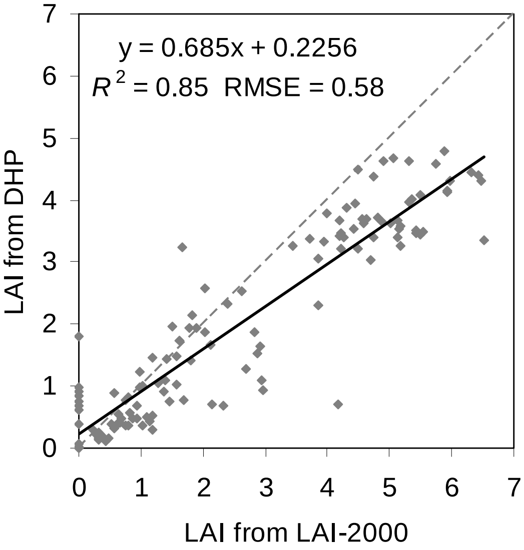

Figure 3. Relationship between LAI values obtained using the LAI-2000 and DHP. The dashed line represents a 1:1 relationship, and illustrates that the LAI-2000 generally obtains higher values than DHP.

Using the July 7, 2007 Landsat scene, values for the three spectral vegetation indices (NDVI, RSR, and SR) were calculated for each pixel that corresponded to a location where field measurements were made. We evaluated the relationship between the ground-based measurements and each of the three spectral indices using a least squares regression (Fig. 4). Quadratic models were considered given the bowed shape of the data, but the R^2 and RMSE values were found to be comparable between quadratic and linear fits. A first-order model was chosen to eliminate bias associated with more complex equations. While no effective difference was observed between R^2 and RMSE for first-order and polynomial models, further work may be done to identify potential effects when using higher-order models.

The strongest relationship (i.e., highest R^2) occurred when using LAI estimates obtained using the DHP-based method. R^2 values for each method of LAI estimation were comparable when regressed against RSR and SR (Figs. 4a, 4c; Figs. 4b, 4d). The lowest R^2 values were obtained when field estimates were regressed against NDVI (Figs. 4e, 4f). Therefore, regressions with RSR and SR were chosen over NDVI in extrapolating the ground-based measurements to create a park-wide LAI map derived from spectral indices calculated from the Landsat scene. The strongest overall relationship identified was between LAI estimates obtained using the DHP-based technique and RSR, where the regression produces the equation:

$$\mathrm{LAI} = 0.6789\times\mathrm{RSR} - 0.001$$

Similar formulas can be created for different vegetation indices and ground-based methods of LAI estimation by using LAI as the dependent variable y and either RSR or SR as the independent variable x in the equations shown in Figure 4. The final results obtained from these relationships are 30m spatial resolution LAI maps of Yosemite (later resampled to 1km for comparison to 1km MODIS LAI maps) based on the best fit lines obtained from our regression analysis (Figure 5).

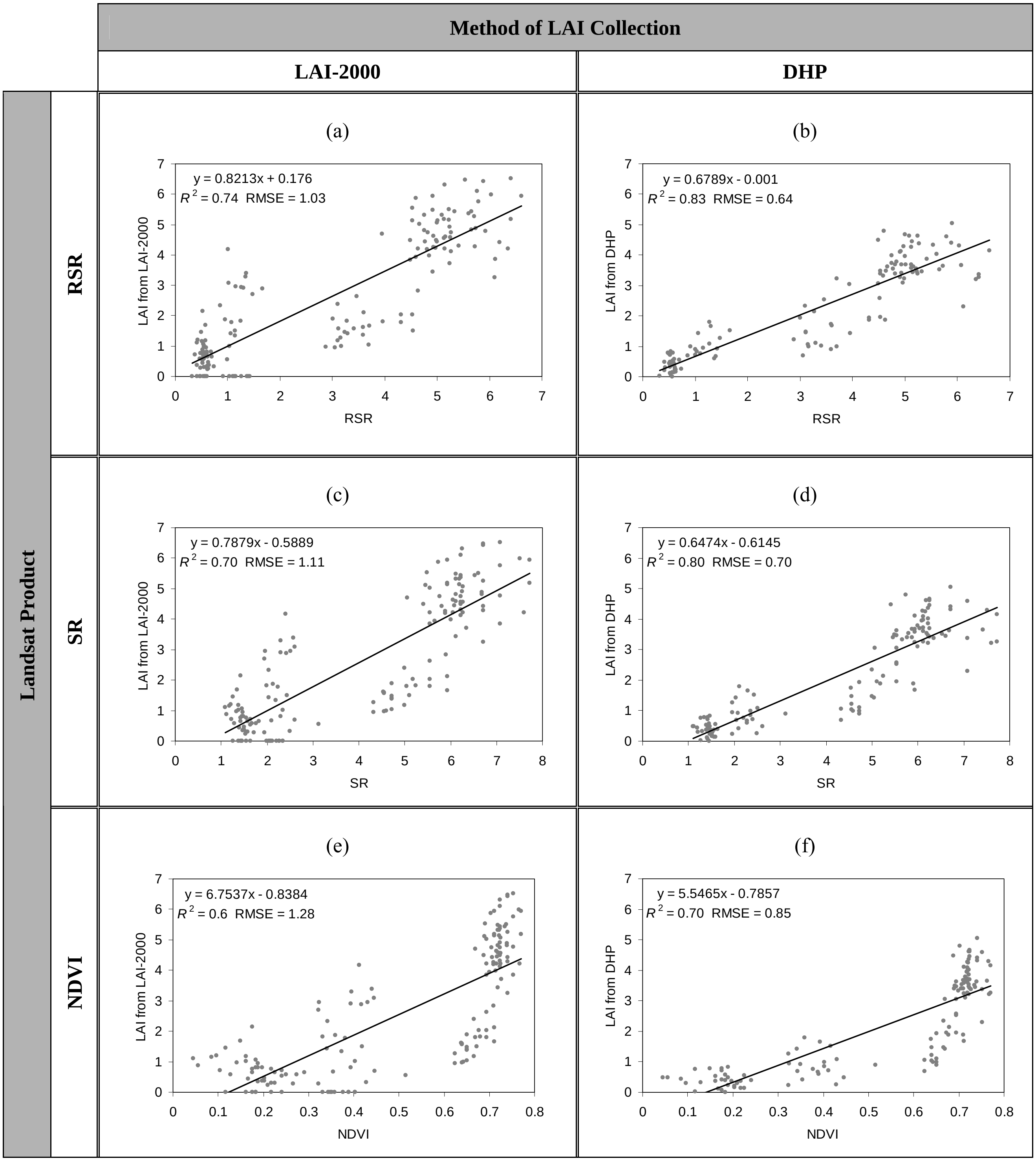

Figure 4. LAI values obtained using the LAI-2000 instrument and DHP-based methods regressed against the RSR, SR, and NDVI vegetation indices derived from the Landsat scene.

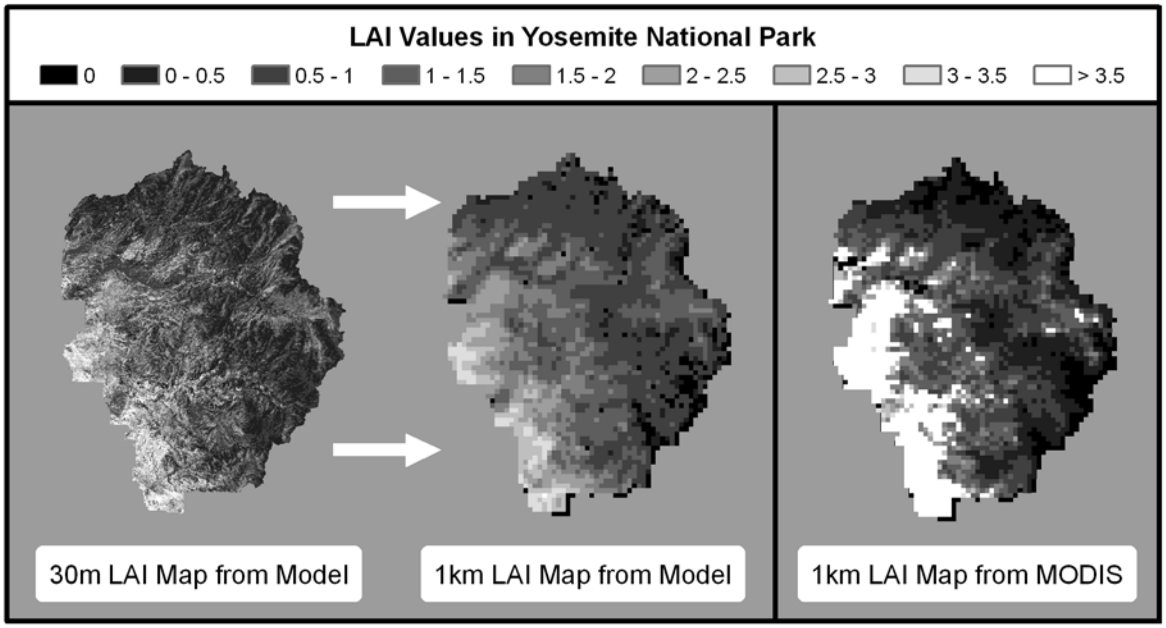

Figure 5. An example of a 30m LAI map and its resampled 1km counterpart (left box). The maps were resampled so that their LAI values could be compared against the 1km MODIS LAI values (right box) to test for differences in estimated LAI values. The contrast between the 1km LAI maps shows the relatively wider range of LAI estimates in the MODIS product compared to the Landsat-based estimates.

Four 30m resolution LAI maps were produced for the park, derived from the following relationships from the regression analyses: RSR/LAI-2000, RSR/DHP, SR/LAI-2000, and SR/DHP. After resampling each map to 1km resolution, LAI values for individual pixels were compared to the LAI values estimated in the 1km pixels of the MODIS LAI map to determine whether or not a one-to-one relationship exists between a model's LAI output and the MODIS estimates. A root mean square error (RMSE) was calculated between the MODIS estimates and values from each map (Table 1). An ideal 1:1 relationship between our models and the MODIS product would yield RMSE values of 0, but the smallest average RMSE was 0.5463 for DHP method and RSR model. This RMSE is approximately 44% of the mean LAI of 1.24 from the MODIS LAI map of Yosemite National Park.

Table 1. Models are written in the form *method*(*index*) where *method* refers to the method of LAI field collection and *index* refers to a spectral vegetation index to indicate the different models. The RMSE calculated with MODIS estimates is shown for each model, along with a percentage of our model values that were larger, smaller, or equal to MODIS estimates.

Model ***method*****(*****index*****)**	**Root mean square error (RMSE)**	**% of MODIS estimates smaller than model values**	**% of MODIS estimates larger than model values**	**% of MODIS estimates equal to model values**
DHP(RSR)	0.5463	57%	34%	9%
DHP(SR)	0.5496	47%	42%	11%
LAI-2000(RSR)	0.7165	85%	12%	3%
LAI-2000(SR)	0.6595	79%	16%	5%

Figure 6 shows plots of MODIS LAI values against LAI values estimated using the relationships between the two field-based methods (LAI-2000 and DHP) and the two spectral indices from Landsat (RSR and SR). While the MODIS LAI product tended to overestimate LAI when using LAI-2000 estimates as a reference (Table 1), the models created using DHP data appear to straddle the 1:1 line. This pattern suggests that while the values vary from each other widely, a positive correlation does exist between the models, and particularly for lower LAI values. The trend does not appear to continue for higher values because DHP based data do not exceed 4 LAI units and LAI-2000 based data do not exceed 5 LAI units. Further work will need to be done to determine the reason that these data appear to overestimate and underestimate LAI almost symmetrically, as well as to explain either the absence of high LAI values for field collected data or the presence of such values for MODIS LAI estimates.

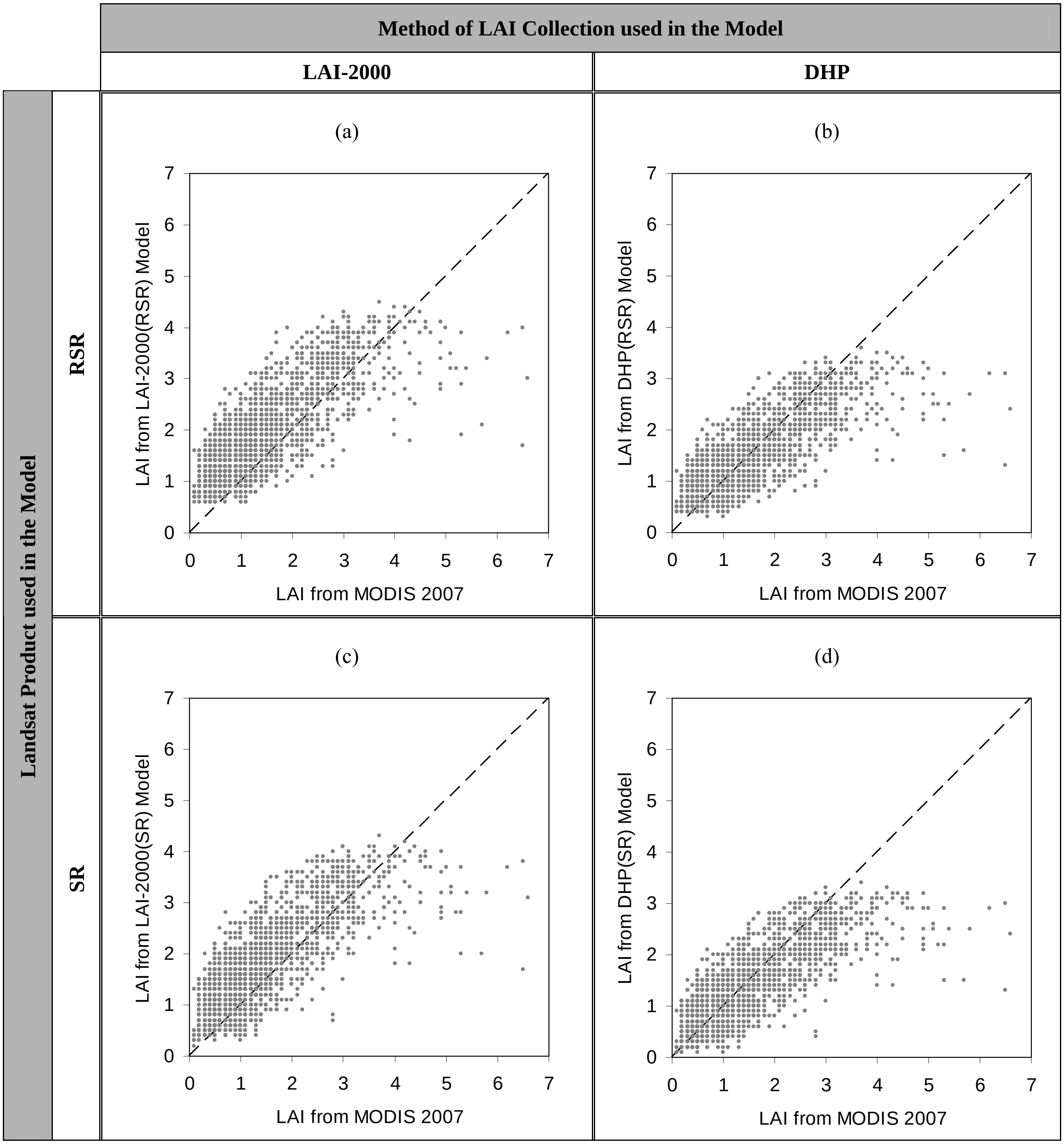

Figure 6. Values for the four 1km LAI maps plotted against MODIS LAI values with a dashed 1:1 line in gray. The *y*-axis labels in these graphs are written in the form "LAI from *method*(*index*) Model" where *method* refers to the method of LAI field collection and *index* refers to a spectral vegetation index to indicate the different models.

Average LAI values from field plots as well as the confidence intervals associated with the averages are listed in Table 2. Overall, our field observations recorded average LAI values ranging from a low of 0.32 to a high of 5.3.

We did not observe good agreement between the average LAI value at each field site and the corresponding MODIS LAI value for the pixel containing the field site, likely due to the extensive heterogeneity of the Sierra landscape.

Table 2. Sample sites listed with average LAI values and associated confidence intervals, and corresponding MODIS LAI values.

LAI-2000 measurements				
Site	**Sample size (*N*)**	**Mean LAI**	**95% Confidence Interval**	**MODIS LAI**
A06b-l	25	0.92	+/- 0.22	1.1
A08c-l	25	0.39	+/- 0.11	2.3
A10-ml	25	1.58	+/- 0.58	1.1
A16-mh	15	4.37	+/- 0.28	2.5
A17c-m	23	1.61	+/- 0.19	1.6
A27b-h	25	4.81	+/- 0.25	3.8
A35-h	20	5.3	+/- 0.46	3.3

DHP measurements				
Site	**Sample Size (*N*)**	**Mean LAI**	**95% Confidence Interval**	**MODIS LAI**
A06b-l	16	0.49	+/- 0.08	1.1
A08c-l	19	0.32	+/- 0.13	2.3
A10-ml	15	1.06	+/- 0.21	1.1
A16-mh	15	3.84	+/- 0.28	2.5
A17c-m	22	1.65	+/- 0.29	1.6
A27b-h	15	3.5	+/- 0.13	3.8
A35-h	25	3.85	+/- 0.31	3.3

DISCUSSION

Our results showed the spectral vegetation indices to be more strongly correlated with the DHP LAI measurements than with the measurements made using the LAI-2000 instrument. However, we did not obtain reference measurements through destructive sampling methods and no previous estimates have been reported for sites within the central Sierra, and therefore our study could not evaluate the absolute accuracy of the LAI measurements made using the different in-situ methods. In terms of usability, however, DHP holds several advantages over the LAI-2000: 1) It allows manual correction of the threshold values to distinguish foliage from the sky; 2) It allows an image to be divided into 10 rings to improve the calculation of LAI; 3) The ability to store the digital image which allows the data to be retained for future re-analysis (Chen, Rich et al. 1997). DHP is also far less expensive than the LAI-2000 instrument, which makes it more accessible, especially for use in student projects. However, a disadvantage of using the DHP-based method for calculating LAI is that processing photographs is significantly more labor-intensive than processing LAI-2000 data.

DHP field measurements of LAI data were more strongly correlated with RSR, followed by SR and NDVI with R^2 values of 0.83, 0.80, and 0.70 respectively. In a comparison of Landsat SR and NDVI, Chen and Cihlar (1996) found Landsat SR to correlate more closely with LAI. In a later comprehensive study, RSR was found to be better correlated with LAI than both NDVI and SR (Stenberg, Rautiainen et al. 2004). There are two major advantages of RSR over SR: 1) the difference between cover types is reduced which improves the accuracy of using a single model for mixed cover types, and 2) the background reflectance, such as understory, litter, and soil, is reduced (Chen, Pavlic et al. 2002).

Our comparison of MODIS LAI values with LAI values estimated using the relationships between spectral indices from Landsat and ground-based measurements of LAI showed that the MODIS product underestimated LAI at low values and overestimated LAI at high values relative to the Landsat-derived values. However, we were only able to sample seven field sites, and due to limitations of terrain and access, field observation were only collected at sites dominated by conifer, shrubland, and mixed land cover types (Table 2). However, for our study the LAI estimates derived were extrapolated across all land cover types for the entire park. Due to practical limitations of time in a 10-week student project, as well as difficulties posed by accessibility, slope, and poison oak, separate estimates for deciduous trees, chaparral, and meadows were not obtained. Additionally, because no destructive sampling was performed, we were not able to obtain definitive reference measurements for absolute LAI to calibrate our field methods, or specific values for needle-to-shoot ratio. As such, it is difficult to draw definitive conclusions about the relative accuracy of the different techniques for mapping LAI using the current data set.

Further research is needed in order to assess the accuracy of LAI maps derived from Landsat spectral indices in the steep terrain and heterogeneous land cover of the Sierra Nevada region. With additional field measurements and collection of measurements of needle-to-shoot ratios, it will be feasible to map LAI for Yosemite National Park using Landsat, thus providing an important additional monitoring and management tool. Some recommendations for future research include: 1) A longer sampling period with more sites to sample all land cover types found in Yosemite; 2) Breaking up each site by land cover type and obtaining a regression equation specific to each type; 3) Use of destructive sampling in plots outside of park boundaries to obtain reference measurements of absolute LAI in order to calibrate field instruments; 4) Sampling in the spring months instead of the summer months because the effect of the understory is minimized in the spring as many of the plants have not yet experienced full annual growth (Chen and Cihlar 1996); 5) Using only DHP in conjunction with the TRAC instrument instead of using both the LAI-2000 and DHP, due to its ease of use in the field, its significantly lower cost, and the fact that the relationships between DHP estimates of LAI and spectral indices from Landsat TM are as robust as those calculated using estimates from the LAI-2000 instrument.

CONCLUSION

In-situ measurements of LAI were made at seven sites in Yosemite National Park over a two-week period in July, 2007, and provide the first in-situ data set for evaluating techniques for mapping LAI at different temporal and spatial scales. Least squares regression was used to identify best-fit relationships between the field observations and three spectral indices (SR, RSR, and NDVI) calculated from a Landsat TM scene acquired on July 7, 2007. The relationships were used to extrapolate the measurements made at the seven field sites to create 30m resolution park-wide LAI maps. The maps were resampled to 1km spatial resolution to facilitate comparisons between estimates of LAI derived from the MODIS and Landsat TM.

Due to the limited time available to the project for field sampling and the absence of reference data, comparisons between ground-based LAI estimates, the LAI estimates derived from the Landsat TM spectral indices, and the MODIS LAI product were inconclusive. In order to draw more definitive conclusions, further sampling needs to be done. However, our study did find good agreement between the RSR index calculated from the Landsat TM scene and the LAI estimates obtained using DHP ($R^2 = 0.83$), providing an initial technique for estimating LAI from Landsat TM data at finer scales than available from MODIS. This technique can be applied to historical Landsat TM data to generate 30m resolution LAI maps, which in turn can be used as inputs for ecological and hydrological modeling, as well as to establish LAI baselines from which to detect future trends and anomalies, providing a convenient indicator of changes in ecosystem condition.

Data from NASA satellites offer great promise for the National Park Service to monitor vegetation trends both within the park and in the surrounding greater park ecosystems. Remote sensing offers the only feasible tool for monitoring LAI in Yosemite due to its heterogeneous landscape and steep topography. Although the MODIS sensor's resolution of 1km is coarse, it has a high temporal resolution (daily, with 8-day composites available from the NASA DAACs) which allows park managers to monitor conditions in the park on a weekly basis. Any vegetation changes detected with the MODIS sensor can be investigated further using Landsat TM 30m resolution imagery. Further study will contribute to evaluation of different techniques for mapping LAI at multiple scales. These LAI estimates, in combination with other satellite and ground-based measured, can be used as inputs to modeling frameworks such as TOPS, which can be applied to provide Yosemite and other National Parks with ecological forecasts of gross primary productivity (GPP), evapotranspiration, soil moisture, phenology, and other measures of ecosystem condition.

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