Validation of ASTER and MODIS surface temperature and vegetation products with surface flux applications

Final Report for NASA
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Final Report Summary

Highlights and milestones of the EOA-VAL project were:

1. Development of a geostatistical sampling scheme to estimate vegetation characteristics for validating remotely sensed products (Burrows et al. 2002).

2. Spatial measurements of NPP and LAI for three years (Burrows et al. 2003a-b). The geostatistical approach yielded a LAI estimate of 3.5 for the 2 x 3 km study area centered on the tall tower, while MODIS peak LAI estimate was approximately 6, or a 40% overestimate. The average aboveground and belowground NPP estimate for the 2 x 3 km study area were 2.6 and 1.8 tC/ha/yr, respectively for a total NPP of 4.4 tC/ha/yr. Our estimate of NPP was approximately 30% less than the MODIS derived estimate of NPP (5.9 tC/ha/yr). The greater NPP is likely explained by the overestimate of LAI.

3. Field-based estimates of annual and growing season light use efficiency coefficients for the major forest types in northern Wisconsin (Ahl et al. 2003). Light use efficiency varied among forest types and year. NPP estimates derived from a light use efficiency model driven by various land cover classification and LAI schemes for the 2 x 3 km study area varied from 3.9 to 4.2 tC/ha/yr. The estimates of NPP were also smaller than MODIS-derived estimates of NPP.

4. Evaluation of the effect of different land cover classifications and sensor (Atlas, LandSat TM, and MODIS) on spatial estimates of NPP (Ahl et al. 2003b). Landcover classification and sensor did not have a pronounced effect on NPP estimates,

5. Complete a sensitivity analysis of the effects of aerosols on vegetation indices and NPP modeling (Ahl et al. 2003c). Aerosol optical depth significantly affected vegetation indices (normalized difference vegetation index, enhanced vegetation index, and dark-targeted vegetation index), and the effect was not consistent among vegetation indices. As a result, estimates of NPP derived from vegetation indices were affected by aerosol optical depth.

6. Conducted a field campaign to examine use of MODIS to accurately quantify canopy phenology of a deciduous forest in northern Wisconsin. We successfully developed an automated system to measure FAPAR and LAI continuously, and we used this approach along with periodic LAI-2000 measurements to measure vegetation phenology. Ground based measurements of LAI during the growing season were in good agreement with MODIS LAI products.

Objective 7. Measuring and validating vegetation surface temperatures using ASTER. We were unable to derived ASTER data and successfully deploy an automated infra-red thermometer to measure canopy temperature.

RESULTS:

Objective 1. Developing a robust sampling scheme to validate vegetation products derived from remote sensing.

Burrows et al. (2002) developed and tested a cyclical sampling design to be used to quantify vegetation characteristics such as vegetation cover and leaf area index. The approach was more efficient and accurate than other more traditional random and grid sampling techniques. Using this approach, we estimated the average LAI for the tall tower area was 3.51 – a value 40% lower than derived directly from MODIS. The cyclical sampling design was been adopted by BigFoot scientists and geostatistical and by many international scientists developing Terrestrial Carbon Observing sites.

Objective 2. Measure vegetation cover, leaf area index, and net primary production for the Chequamegon tall tower area.

We completed two years of field measurements and all data have been submitted to the ORNL DAAC. Burrows et al. (2003a-b) sumarizied the spatial and temporal patterns of LAI and NPP, respectively. LAI differed among the major cover types and averaged 3.45, 3.57, 3.82, 3.99 and 1.14 fopr northern hardwoods, aspen, forested wetlands, upland conifers and grass, respectively. Other major sources of variation in LAI and NPP were time sine forest management, soil drainage, and soil type.

Objective 3. Estimate Light Use Efficiency (ε) for major vegetation types in northern Wisconsin.

Among Forest Cover Types

Growing season light use efficiency (ε_{gs}) differed significantly (p=0.05) among all forest cover types tested in 1999. In 1999, (ε_{gs} ranged from 0.52 gC MJ^{-1} for northern hardwoods to 0.31 gC MJ^{-1} for upland conifer (Table 1). Aspen ε_{gs} was significantly greater than forested wetland and upland conifer, while northern hardwood was significantly greater than upland conifer.

There was weak evidence to suggest that ε_{gs} differed (p=0.12) among all forest cover types tested in 2000. In 2000, ε_{gs} ranged from 0.56 gC MJ^{-1} for northern hardwoods 0.35 gC MJ^{-1} for upland conifer (Table 1). Only the pair aspen and upland conifer were significantly different.

In 1999, annual light use efficiency (ε_a) differed significantly ($p \leq 0.001$) among all forest cover types tested and ranged from 0.49 gC MJ^{-1} (northern hardwood) to 0.18 gC MJ^{-1} upland conifer (Table 1). Aspen ε_a in 1999 was significantly greater than forested wetland and upland conifer, while hardwoods were significantly greater than upland conifer.

In 2000, ε_a differed significantly ($p \leq 0.001$) among all forest cover types tested and ranged from 0.53 gC MJ^{-1} for northern hardwoods) to 0.21 gC MJ^{-1} for upland conifer (Table 1). All paired comparisons differed significantly with the exception of aspen and hardwood, forested wetland and red pine, and red pine and upland conifer.

Variability Between 1999 and 2000

Mean annual air temperature across all three micrometeorological stations decreased from 5.1 °C in 1999 to 4.3 °C in 2000. Mean annual soil temperature at 10 cm across all three stations decreased slightly from 7.2 °C in 1999 to 6.9 °C in 2000. Annual precipitation was 970 mm in 1999 and 730 mm in 2000. Total annual PAR was 1983 MJ m^{-2} in 1999 and 1922 MJ m^{-2} in 2000.

Mean $□_{gs}$ across all plots was significantly less (p□0.001) in 1999 (0.42 g C MJ^{-1}) than in 2000 (0.47 g C MJ^{-1}). Mean $□_{a}$ across all plots was significantly less (p□0.001) in 1999 (0.33 g C MJ^{-1}) than in 2000 (0.36 g C MJ^{-1}).

Table 1. Annual (ε_a) and growing season (ε_{gs}) light use efficiency (gC MJ^{-1}) for the five major forest cover types. One standard error in parentheses (s.e.). Results are from a mixed linear model, NPP=APAR, using net primary production (NPP) as the dependant variable with absorbed photosynthetically active radiation (APAR), year, and plot classification as effects. The slope of the model with no intercept was used to determine light use efficiency.

	1999				2000				
	Annual		Growing Season		Annual		Growing Season		
Forest Cover Type	(ε_a)	s.e.	(ε_{gs})	s.e.	(ε_a)	s.e.	(ε_{gs})	s.e.	n
Aspen	0.42	(0.04)	0.47	(0.04)	0.45	(0.05)	0.51	(0.05)	24
Forested Wetland	0.28	(0.03)	0.37	(0.04)	0.31	(0.04)	0.41	(0.05)	17
Northern Hardwood	0.49	(0.07)	0.52	(0.08)	0.53	(0.09)	0.56	(0.10)	6
Red Pine	0.27	(0.05)	0.46	(0.08)	0.30	(0.05)	0.50	(0.09)	7
Upland Conifer	0.18	(0.04)	0.31	(0.06)	0.21	(0.04)	0.35	(0.08)	5
Deciduous Broadleaf[1]	0.45	(0.15)	0.49	(0.17)	0.50	(0.15)	0.54	(0.17)	30
Evergreen Needleleaf[2]	0.23	(0.14)	0.39	(0.17)	0.25	(0.14)	0.42	(0.12)	12

[1] Deciduous Broadleaf calculated using data from Aspen and Northern Hardwoods
[2] Evergreen Needleleaf calculated using data from Red Pine and Upland Conifer

Objective 4. Evaluation of the effect of different land cover classifications and sensor (Atlas, LandSat TM, and MODIS) on spatial estimates of NPP

NPP Maps from Different Scales

NPP for each combination of LAI and land cover map (NPP_{XZ}) was calculated using the following equation:

$$NPP_{XZ} = \varepsilon_X \, f_{APAR} \, PAR \qquad (3)$$

where X denotes the land cover map used, Z denotes the LAI map used, ε_X is the land cover specific LUE factor (Table 1), f_{APAR} was determined using the Beer-Lambert equation and the LAI map, and PAR represents an annual sum taken from onsite micrometeorological data. Total PAR was partitioned according to leaf habit: deciduous or evergreen. For mixed stands, we determined the proportion of leaf area for each leaf habit, and modified LAI accordingly. The forested wetlands class contained 53% deciduous leaf area (mostly speckled alder) and 47% evergreen (mostly white cedar). The same procedure was used for the mixed category in the IGBP classifications. The mixed category consisted of 73% deciduous and 27% evergreen leaf area. The spatial NPP maps were created using ERDAS Imagine/Modeler™ software (ERDAS, Inc, 2000, Atlanta) to process the input maps, LUE, and PAR data using equation (3).

Mean NPP differed significantly among all nine scenarios tested ($p<.001$) (Figure 1, Table 2). Mean NPP in 2000 ranged from 388 gC m^{-2} yr^{-1} (WA) to 431 gC m^{-2} yr^{-1} (MA). The percentage difference relative to AR ranged from –3.8 to 6.8. All mean NPP comparisons to AR differed significantly, except for AA. The largest variation occurred within the WISCLAND-based scenarios because of the misclassification of cropland (high LUE) in the data. The NPP variation due to the LAI maps are seen clearly among the MODIS based NPP maps.

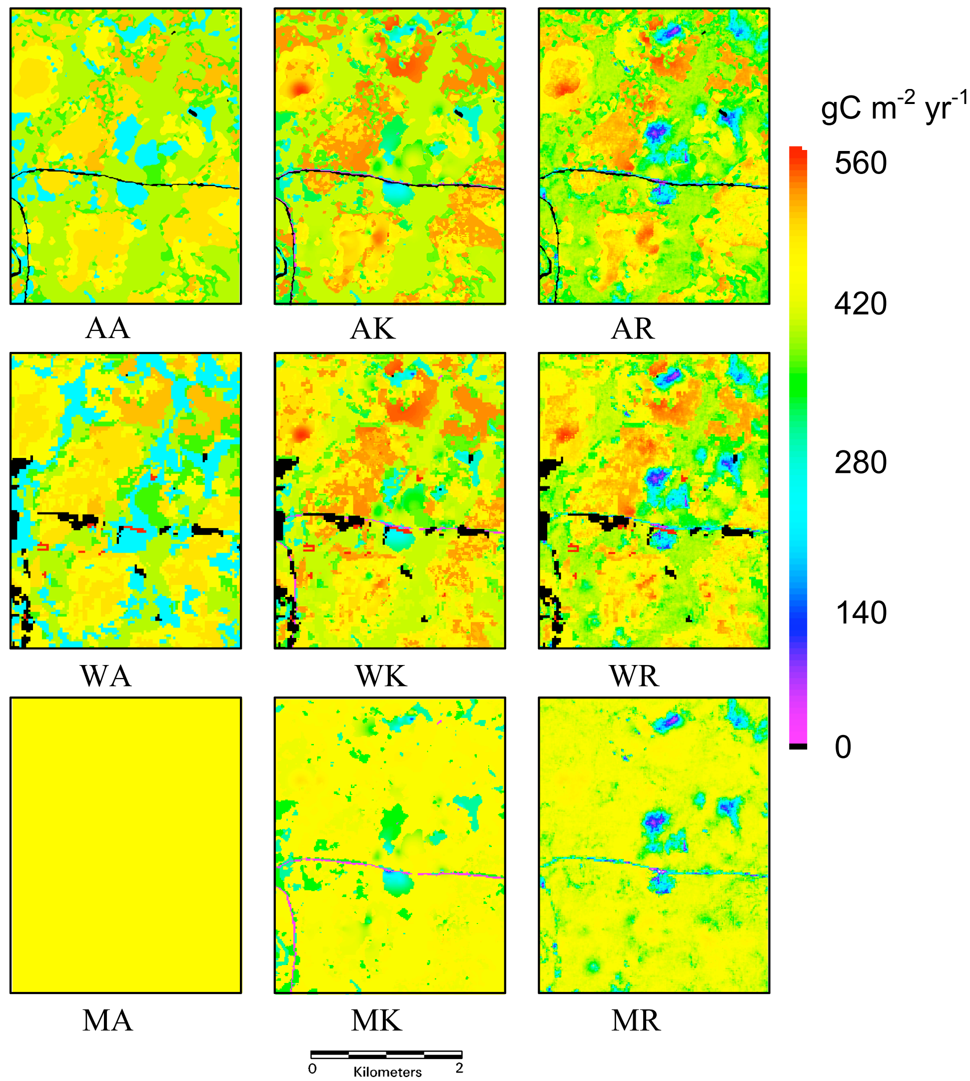
Table 2. Net primary production (NPP) estimates for nine different scenarios in a 10 km^2 study area. Differences (%) are relative to scenario AR. Mean NPP one standard deviation in (). Sensor indicates the remote sensing data used to derive the land cover classification used to model NPP.

Scenario	Sensor type	Sensor Resolution (m)	Mean NPP gC m^{-2} yr^{-1}	Range	% difference
AA	ATLAS	15	402 (86)	0 - 505	-0.3
AK	ATLAS	15	419 (83)*	0 - 555	4.0
AR	ATLAS	15	403 (86)	0 - 560	---
WA	TM	30	388 (182)*	0 - 2603	-3.8
WK	TM	30	424 (165)*	0 - 2780	5.2
WR	TM	30	410 (164)*	0 - 2747	1.6
MA	MODIS	1000	431 (0)[1]	431	6.8
MK	MODIS	1000	426 (56)*	6 - 486	5.6
MR	MODIS	1000	411 (55)*	2 - 487	1.8

* Significantly different from AR at 95%.

[1] Not tested due to lack of variance.

Figure 1. Net primary production (NPP) maps derived using land cover specific light use efficiency values and spatial leaf area index (LAI) maps.



Objective 5. Evaluate the sensitivity of Vegetation Indices and NPP Modeling to Aerosols

MODIS Data

MODIS reflectance values were collected from the MOD04 L2 product available from the Goddard Space Flight Center - (http://modisatmos.gsfc.nasa.gov/MOD04_L2/index.html). Mean reflectance values were extracted for blue, red, NIR, and mid-infrared MODIS bands of a $10km^2$ area around the EOS validation site for 2001. MODIS derived AOD data were also tabulated.

Vegetation Indices

We used four vegetation indices in this study including NDVI, ARVI, EVI and DVI. NDVI was calculated as (Rouse et al., 1973):

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \quad (5.6)$$

The atmospheric resistant vegetation index (ARVI) was calculated as (Kaufman and Tanre, 1992):

$$ARVI = \frac{\rho_{NIR} - \rho_{rb}}{\rho_{NIR} + \rho_{rb}} \quad (5.7)$$

where

$$\rho_{rb} = \rho_{red} - \gamma(\rho_{blue} - \rho_{red}) \quad (5.7a)$$

We used a value of 1.0 for the coefficient γ based on Kaufman and Tanre (1992). EVI was calculated as (Huete et al., 1997):

$$EVI = G\frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + C_1\rho_{red} - C_2\rho_{blue} + L} \quad (5.8)$$

where G is a gain coefficient, C_1 and C_2 adjust for atmospheric effects, and L is a canopy adjustment coefficient. Based on Huete et al. (1997), we used G=2.5,

C_1=6, C_2=7.5, L=1. Miura et al. (2001) compared the sensitivity of these indices after performing the dark target-based atmospheric correction (Kaufman and Sendra, 1988). The dark target method is based on observations that relative atmospheric effects on the signal are greater over vegetated surfaces in the visible wavelengths than over bright surfaces (Kaufman et al., 1997). The path radiance is then estimated from the vegetated surface reflectance to derive AOD and used in atmospheric correction of an image (e.g. Ouaidrari and Vermote, 1999). To derive the surface reflectance of the vegetated pixel, it has been shown that for vegetated surfaces, $\rho_{red} = \rho_{MIR}*0.5$ for AVIRIS, MODIS and Landsat data (Kaufman et al., 1997a; Kaufman et al., 1997b). We substituted this relationship into the NDVI equation and calculated a dark target vegetation index (DVI):

$$DVI = \frac{\rho_{NIR} - \rho_{MIR}0.5}{\rho_{NIR} + \rho_{MIR}0.5} \qquad (5.9)$$

This index assumes the pixel of interest is primarily vegetated with less water and soil background influence.

NPP Modeling

We used equation (5.1) to estimate NPP (gC m^{-2} day^{-1}) using each index for 15 summer days in 2001. We used a constant ε coefficient of 0.5 gC MJ^{-1} based on data for this site (Ahl et al., 2002). We assume that ε varies little due to LAI differences or daily variations in PAR (Norman and Arkebauer, 1991; Field, 1995; Sands, 1996; Sinclair and Muchow, 1999). Daily solar insolation data was derived from the GOES satellite and converted to PAR (MJ m^{-2}) using a factor of 0.47 (Diak et al., 1996; Ahl et al., 2002). Total NPP was calculated as the sum of daily NPP for comparison purposes only.

Statistical Analyses

We restricted the analysis to days where the sun zenith and view angles were < 36° to reduce sun-sensor geometry influence on the indices (Myneni and Williams, 1994). We also restricted the time period to fall within July 4 and August 16 to reduce effects of phenology induced by the beginning and end of the growing season. We assumed that FAPAR remains constant during this period. For the first objective we tested (*F* test) the effects of AOD and PW on the simulated indices for the two surface representations using the SAS/MIXED® software (SAS Institute, Inc., 2000). For our second objective using the MODIS data, the error of the VIs for comparative purposes was calculated from (Miura et al., 2001; Huete and Li, 1994):

$$E_{VI} = \sqrt{\frac{\sum_{d=1}^{n} (VI_d - VI_{ref})^2}{n}} \quad (5.10)$$

where n is the number of observations (=15) and VI_{ref} is the reference VI (=FAPAR=0.88). The same equation was used to compute the relative errors in modeled NPP from each index where NPP_{ref} was computed as 4.74 gC m^{-2} day^{-1}. The percent relative difference in total NPP based on each index was calculated as:

$$E_{NT} = 100 \frac{NPP_t - NPP_{tref}}{NPP_{tref}} \quad (5.11)$$

where NPP_t is the total sum NPP based on a vegetation index and NPP_{tref} is the total sum reference NPP.

Variation can be seen within each VI calculated from MODIS data throughout 2001. A peak in the VI appears in the summer months corresponding to the live green vegetation present. AOD had a significant effect on the VIs for the 15 mid summer days where sun and view angle was less than 35° (Figure 2). Mean VI ranged from 1.02 (ARVI) to 0.69 (NDVI) with a reference value of 0.88 (Table 3). The standard deviation about the mean ranged from 0.02 (DVI) to 0.08 (EVI). The error as compared to the reference ranged from 0.05 (DVI) to 0.20 (EVI).

NPP was estimated for the 15 days using each VI in equation (3). Mean NPP ranged from 3.75 (EVI) to 5.57 (ARVI) gC m^{-2} day^{-1} with a reference value of 4.77 (Table 3). The error as compared to the reference ranged from 0.29 (DVI) to 1.17 (EVI). The percent difference in total NPP from the reference ranged from –21% (NDVI,EVI) to –6% (DVI).

Figure 2. Sensitivity of four vegetation indices to aerosol optical depth (AOD). AOD was derived from MODIS data acquired for 15 days in 2001 in northern Wisconsin. The vegetation indices were also calculated from the same MODIS data.

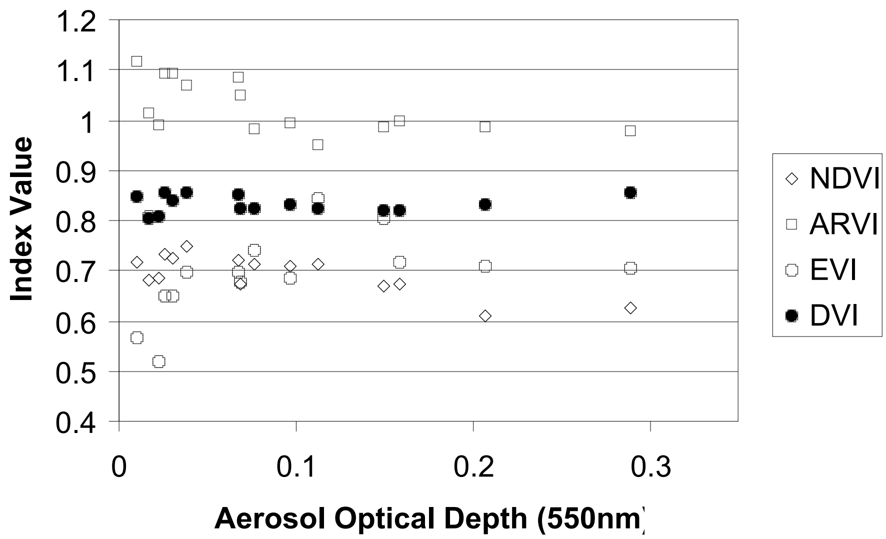


Table3. Results from calculated vegetation indices (VI) and daily net primary production (NPP) from MODIS data for 15 days in 2001. The mean is followed by one standard deviation in parenthesis. E_{VI} and E_{NPP} are the average error compared to the reference VI and NPP respectively. Total is the sum of NPP for 15 days and % difference is the difference of the total NPP from the reference NPP.

	VI		NPP			
Method	Mean	E_{VI}	Mean gC m^{-2} d^{-1}	E_{NPP}	Total	%difference
NDVI	0.69 (0.04)	0.19	3.78 (0.69)	1.02	56.51	-21
ARVI	1.03 (0.05)	0.15	5.57 (1.01)	0.87	83.61	17
EVI	0.70 (0.08)	0.20	3.75 (0.58)	1.17	56.23	-21
DVI	0.83 (0.02)	0.05	4.51 (0.69)	0.29	67.64	-6
Reference	0.88 (0.00)		4.77 (0.73)		71.61	---

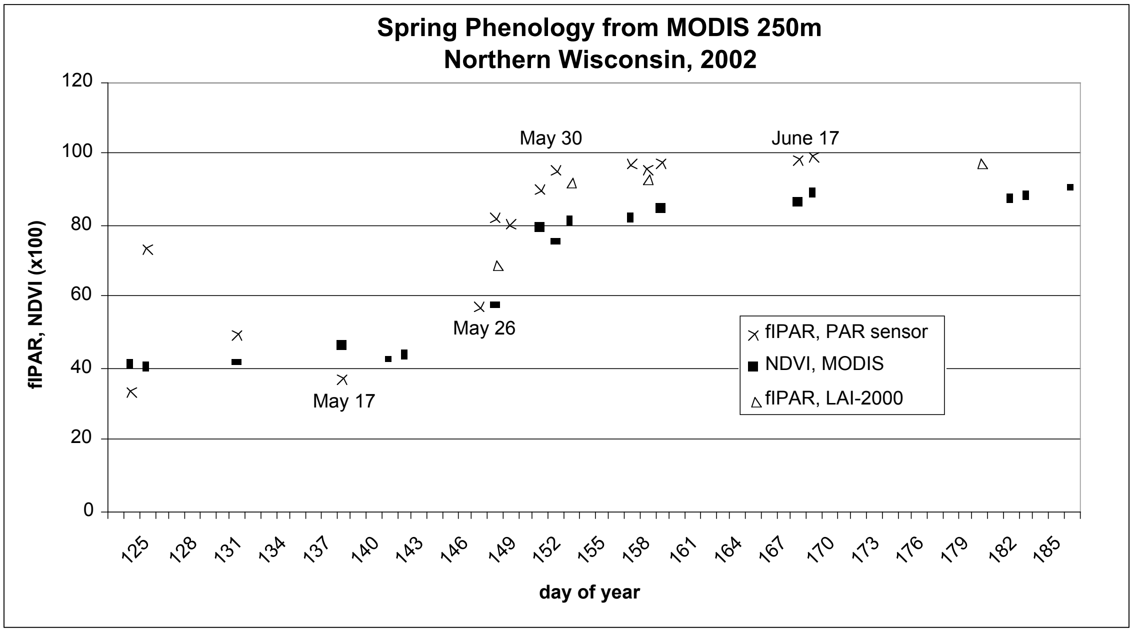
Objective **6. Conducted a field campaign to examine use of MODIS to accurately quantify canopy phenology of a deciduous forest in northern Wisconsin**

Our objective was to gain an understanding of how well MODIS data can monitor the phenology of deciduous species, particularly during leaf expansion. Three separate forest stands consisting primarily of sugar maple were used in the analysis. Each stand was at least 500m in length and width. We measured light transmission with the LAI-2000 in each stand (16 plots per stand) on four different dates in the spring during leaf expansion. PAR was measured in one stand continuously above the canopy and at the bottom of the canopy. The fraction of intercepted light (fIPAR) was calculated separately for the PAR sensor and LAI-2000 data as: 1-x, where x is the light transmission as measured by each sensor respectively. We did not account for scattering or sun-view angle effects on sensor data. Surface reflectance was collected from the MODIS product, MOD09GQK, for all clear days from May- July, 2002. The normalized difference vegetation index (NDVI) was calculated for the center pixel of each stand.

Results indicate that MODIS data are sensitive enough to track phenology during leaf expansion in northern Wisconsin. Important findings and lessons thus far include:

- In 2002, the period from bud burst to near maximum leaf expansion occurred in less than two weeks. Greatest rate of leaf expansion occurred in less than one week, we speculate largely due to a sequence of above normal warm days.
- Satellite data must have a temporal resolution sufficient enough to capture leaf expansion (< 1 week). Although TERRA has near daily repeat coverage at this site, only 1 in 5 days on average will be useful for analysis due to cloud cover.
- Future analysis should include: near daily measurements with the LAI-2000 in Spring for a more complete record; expand site analysis to include heterogeneous cover; examine MOD09GHK (500m) products for similar use; examine phenology corresponding to leaf senescence; examine effects on carbon and water cycling by coupling results with a process model.

Figure 3. Comparison of measured and MODIS-derived LAI for the 2002 growing season.



Objective 7. Measuring and validating vegetation surface temperatures using ASTER.

Despite the many successes, we were unsuccessful at completing the objective to calibrating ASTER observations to measured surface temperature of vegetation. Below we have identified the reasons for our lack of success.

During the first year of the grant, Norman and Diak worked with Dr. John Baker of the USDA/ARS at the University of Minnesota to install three Everest 4000 Infrared thermometers at the 400-m level on the WLEF tower in the summer of 1998. After numerous tests of cell phone coverage at the tower, Norman et al. chose to relay the data from the data loggers monitoring the infrared thermometers at the top of the tower with a cell phone link. Unfortunately we could not collect any data from the instrument package and we could not determine the cause of the problems. After the instrument package was retrieved from the tower, it was determined to be functioning properly so we never could determine the cause of the failure.

We intended to put the Everest 4000 infrared thermometers back on to the tower, but based on other usage, we suspected the accuracy of these instruments. Therefore, before putting the instruments on the tower again we wanted to know how accurate these instruments actually were, even though the manufacture claimed 0.5C accuracy. This meant that we needed an instrument accurate to about 0.2C to evaluate the accuracy of the Everest instruments. We could not purchase such a device. Therefore we designed a new infrared thermometer with an absolute accuracy of 0.05C which we refer to as a Continuously Calibrated Infrared Thermometer (CCIRT) (Baker et al., 2001). We mounted the CCIRT along with the Everest 4000 infrared thermometers and observed unexplainable errors of more than 4C. Therefore, the Everest 4000 infrared thermometers were totally unacceptable for calibrating ASTER from the WLEF tower.

We purchased another instrument from Apogee, Inc., which was calibrated to 0.2 C for target temperatures above 15C. The Apogee infrared thermometer had a wider field of view then the Everest 4000 units and thus had to be installed at 100 m on the tower to view an area about 100 m in diameter on the ground. We also decided to adapt the CCIRT for installation on the tower to get the most accurate calibration of ASTER. Unfortunately funds were never budgeted in the grant to cover the cost of building this instrument so it was funded from other sources. Both the CCIRT and the Apogee instruments were installed in July 2001.

In February of 2001 Norman began trying to register as ASTER users and encountered many unforeseen difficulties. We thought that we were registered users several times but apparently something in the system failed because we could not make requests for observations. After several failures that did not become immediately apparent until some time after attempted registrations, Norman contacted Brandy Adams, who took much time to walk us through the DAR tool and get us registered. In July 2001 we succeeded and set up a three-month window within which ASTER images were to be obtained from the WLEF site. After October the ground target temperatures would be too low for the sensors. After three months we found only two ASTER images that were even worth considering and both had too many clouds in them to be suitable. Additionally, the CCIRT did not function properly while it was on the tower. The problem was not with the cell phone communications as we could communicate adequately with the instrument package and regularly dump data to computers at Madison, WI. When the instrument package was retrieved from the tower after three months of operation, the CCIRT continued to be unreliable. When the CCIRT was turned off and then turned on, it functioned perfectly. Apparently when the instrument was taken up the tower it somehow got into a strange mode and it was not reliable. The Apogee instrument was working perfectly on the tower. However, even if the second ASTER image had been cloudless, the temperature was 10C, too low for the Apogee to achieve its 0.2C accuracy.

The original grant was scheduled to end 6 months after the end of this last test so no more plans were made to install the instrument package on the WLEF tower again. In addition, the acquisition of ASTER data proved so difficult and unreliable that we gave up on trying to do this calibration. Apparently our priority in the acquisition process was so low that in three months at the best time of the year for low cloud cover in northern Wisconsin we did not get a suitable image. Working with the ASTER system was sufficiently cumbersome that I am not even 100% sure that I exhausted the possibilities. Without the ASTER data, we obviously could not calibrate the ASTER sensor; furthermore, without the ASTER data we could not compare ASTER and MODIS. Thus we were prohibited from meeting our objectives, but it was not for lack of trying.

We did develop a novel infrared thermometer (CCIRT) and publish a paper on it. Even though the development costs associated with this CCIRT were not borne by the grant, the EOS Validation project provided the reason for developing the CCIRT so the publication is credited to the grant (Baker et al., 2001).

Publications

Ahl, D., S. T. Gower, D. S. Mackay, S. N. Burrows, J. M. Norman, and G. Diak. 2002. Light use efficiency of a heterogeneous forest in northern Wisconsin: Implications for remote sensing and modeling net primary production, Remote Sensing of Environment. (Submitted)

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THESES

Ahl, D.E. 2002. A measurement and modeling perspective on requirements for future remote sensing vegetation indices and classifications. Department of Forest Ecology and Management. University of Wisconsin, Madison WI. 166p.

Burrows, S.N. 2002. Applications of geostatistics to characterize vegetation characteristics of terrestrial ecosystems. Department of Forest Ecology and Management, University of Wisconsin, Madison, WI.

EOS-VAL Program Metrics

1. *Publications.* EOS-VAL Funding to Gower and Co-PI's has been used to compare MODIS-LAI and NPP products to field-based measurements; this research has resulted in two Ph.D. dissertations, and xx published, in press, and submitted publications (Table 1).
2. *OutReach*. Gower and fellow BigFoot scientists have published the BigFoot field manual that is now used by scientists worldwide to design and implement field measurement and validation programs. The Global Terrestrial Observing System (GTOS) has used the BigFoot manual as a benchmark.
3. *Collaboration*. Gower has attended every MODIS team meeting, where he has made presentations. Furthermore, Gower's team was recognized by Olson (ORNL DAAC) and Morrisette (NASA) has leaders in processing and submitting EOS-VAL data to MERCURY, a data archive system, that is available to all scientists.

4. *Relevance to EOS-VAL and NASA C Cycle Programs*. The proposed study sites are three of the most critical EOS-VAL program sites because of the long-term vegetation cover, leaf area index, and net primary production measurements by BigFoot or EOS-VAL scientists, and the presence of eddy flux towers that have provided several of the longest near-continuous measurements of net ecosystem exchange in the world. A continuous long-term ground measurement, eddy covariance and remote sensing products will provide the necessary tools to quantify inter-annual variation, and determine the processes that are responsible.