SCIENCE QUESTION 1: Validation of Moderate Resolution (~1km) Satellite LAI and FPAR Products

"Validation" is the process of assessing by independent means the accuracy of data products. In general, validation refers to assessing the uncertainty of satellite derived products by analytical comparison to reference data (e.g., in situ, aircraft, and high-resolution satellite sensor data), which are presumed to represent the target values.

Our objective is to validate the 1km LAI and FPAR values derived from MODIS data [Myneni et al., 2002] through comparison with field measurements. The biggest challenge for validation of moderate (100-1000m) and coarse (>1km) resolution LAI/FPAR products is the scarcity of ground-truth measurements. Considering the scale of in situ measurement (generally <10m per sample) and the large amount of work associated with field measurements, it is unrealistic to expect sufficient data for a pixel-by-pixel comparison. An alternative is to employ both field measurements and high resolution satellite data to derive an accurate fine resolution LAI map over a sufficiently extended area (say, 10x10 or 20x20 km), degrade it to the coarse resolution, and compare this map with that derived from the moderate resolution imagery.

Based on our previous studies [Shabanov et al., 2002, Tian et al., 2002], we propose the following sampling and validation strategy:

1. Obtain an ETM+ image of the area (200x200 km) with Flakaliden in the center (approximately).

2. Assess the distribution of LAI-correlants, such as Reduced Simple Ratio (RSR), Simple Ratio (SR), NDVI etc. to get an idea of the distribution of LAI and FPAR values in the entire 200x200 km image.

3. Select 5 pairs of 1km regions in this 200x200 km area. Hopefully these are not too far off. Each pair should be more or less identical in terms of vegetation type, LAI and FPAR distributions because we will one for tuning and one for validation. The 5 pairs should cover a range of LAI and FPAR values.

4. Segment the 1km regions into vegetation patches. The patches will have a resolution coarser than the ETM+ 30m resolution.

5. Collect sufficient LAI and FPAR values in each of the patches such that patch average LAI and FPAR can be estimated with good accuracy. Need to do this in all patches in all 5 pairs of 1km regions.

6. Use the field LAI and FPAR data from the 5 tuning 1km regions to tune the LOOK-UP-TABLES of the LAI/FPAR algorithm such that measured patch average LAI and FPAR values can be reproduced with the algorithm when the algorithm is given patch average ETM+ reflectances.
(7) Validate the tuning by comparing the algorithm produced patch LAI and FPAR values with field measured patch average LAI and FPAR values from the 5 validation 1km regions.

(8) Produce LAI and FPAR maps for the entire 200x200 km region. How? First, segment the ETM+ image of the whole region. Aggregate the ETM+ reflectances over the patches, run the algorithm with the tuned LOOK-UP-TABLES patch by patch.

(9) We will also try other methods of producing 200x200 km LAI and FPAR maps. For example, we can directly try to correlate RSR, SR, NDVI evaluated from 30m ETM+ reflectances to ground measurements of LAI and FPAR, assuming that the geolocation of ETM+ is accurate and the ground measurements reflect 30m averages. Use these regression models to create 200x200 km LAI and FPAR maps by applying it ETM+ pixel by pixel. This step (9) is alternative to steps (3) to (8).

(10) Create 1km LAI and FPAR maps from the patch level (steps 3-8) or 30m pixel level (step 9) maps by simple aggregation. Compare these to MODIS 1km LAI and FPAR values.

(11) Important to know the uncertainties in ground measurements, pixel and patch level LAI/FPAR values in order to specify the uncertainties in 1km MODIS LAI/FPAR values.

**Data Needs**

(1) Existing ETM+ images to study the site. This is being presently done by the Boston University group.

(2) LAI and FPAR measurements in all patches in the ten 1km patches. Need to determine how many such patches exist and how many measurements per patch. This information will be available soon.

(3) Hemispherical photos of all patches in the 1 km pixel.

(4) Continuous measurements of the radiation spectrum incident on the vegetation canopy at a few open areas, depending on how far apart the ten 1km regions are. At the very least, we should total incident solar radiation, the diffuse fraction, and the total PAR.

(5) Transmission measurements under the canopy, preferably under the over- and understory. These should be ideally ASD measured spectra. Or, at the very least light bar measurements of PAR. Need these in all patches in the ten 1km regions (several per patch).

(6) Canopy reflectance spectra. At least once, we should have such data from an ASD mounted on a helicopter for all patches in the ten 1km regions. If at all possible, we should try to obtain these data for the entire 200x200 km area.

(7) Leaf/Needle optical Properties of all dominant species in our study area.
(8) Basic study site information such species distribution, age structure, soils, hydrology, topography, etc. Will be valuable to have access to key data sets and research papers describing previous efforts in our study area.

References


SCIENCE QUESTION 2: Optical Properties of Vegetation Canopy at Leaf and Canopy Scales

1. Introduction

Interaction of photons with a host medium is described by a linear transport equation. This equation has a very simple physical interpretation; it is a mathematical statement of the energy conservation law. Its use to derive biophysical parameters from remotely sensed data guarantees the consistency between retrievals and the distribution of solar radiation among the canopy, the understory, and the ground.

Solar radiation scattered from a vegetation canopy and measured by satellite-borne sensors results from interaction of photons traversing through the foliage medium, bounded at the bottom by a radiatively participating surface. Therefore, to estimate the canopy reflectance, three important variables must be carefully formulated: the architecture of the canopy, the optical properties of foliage elements, and the background surface reflectance properties [Ross, 1991]. Specification of the first two variables depends on the definition of the foliage element or scattering center. An individual leaf, for example, should be taken as the basic foliage element to describe photon transport in a vegetation canopy of a small area (e.g., ETM resolution). Optical properties of tree crowns and their distribution in the canopy space can be used to estimate the radiation regime in an extended canopy. In both cases, the three-dimensional transport equation relates properties of the scattering centers to the radiative regime of the medium. The former allows estimation of the radiation field at the leaf scale, while the latter describes the interaction of photons with trees, which is appropriate for interpretation of reflectances at coarse resolution. The reflective properties of the tree crown are determined by its leaf optical properties and architecture. Therefore, solutions of the transport equation that describe canopy radiation regime at the leaf and crown scales are not independent. This allows us to relate these solutions to the biophysical parameters defined at different scales, or spatial resolutions. The major issue is, of course, how the coefficients appearing in the transport equation vary with spatial resolution. Our objective is to collect data needed to address this question.

2. Canopy spectral invariant

The canopy spectral invariant for canopy interception [see definition h, section 4] states that the variable $p_i$ defined as

$$p_i = \frac{\omega_L(\lambda_i)i(\lambda_i) - \omega_L(\lambda_0)i(\lambda_0)}{\omega_L(\lambda_0)i(\lambda_0) - \omega_L(\lambda_1)i(\lambda_1)},$$

remains constant for any arbitrary chosen wavelengths $\lambda_0$ and $\lambda_1$ [Knyazikhin et al., 1998; Panferov et al., 2001; Shabanov et al., 2002]. Here $i(\lambda)$ and $\omega_L(\lambda)$ are the canopy interception [see definition h, section 4] and leaf albedo [see definition e, section 4]. The spectral canopy transmittance $t(\lambda)$ possesses a similar property. However, the variable
\[ p_1 = \frac{t(\lambda_n) - t(\lambda_i)}{\omega_L(\lambda_n)t(\lambda_n) - \omega_L(\lambda_i)t(\lambda_i)} \]  

(2)

may take on several values depending on whether the canopy transmittance is a multi- or single-value function with respect to the single scattering albedo. Figure 1 illustrates this criterion. Note that \( p_1 \) depends on the solar direction and the ratio \( f_{\text{dir}} \) of direct to total incident solar radiation.

![Figure 1. Canopy hemispherical transmittance (dotted line) as a function of the single scattering albedo (section 3) for the Solling site, Goettingen, Germany. Three single-value curves \([t(\lambda), \omega(\lambda)]\) corresponding to three intervals 487 ≤ \( \lambda \) < 555 nm, 555 ≤ \( \lambda \) < 650 nm, and \( \lambda \) ≥ 650 nm, can accurately be approximated with equation (2) using \( p_1 = 0.10, 0.85 \text{ and } 0.48 \), respectively (solid lines). It means that the spectral invariance (2) takes place for each of these intervals. In this example, the canopy transmittance corresponding to the interval 400 ≤ \( \lambda \) < 487 nm can vary considerably with the single scattering albedo essentially unchanged [from Panfirov et al., 2001].

There are several interpretations of the parameters \( p_1 \) and \( p_2 \) reported in literature. First, \( p_i \omega_L(\lambda) \) and \( p_i \omega_L(\lambda) \) are the maximum positive eigenvalues of linear operators describing canopy transmittance and radiation field in the vegetation canopies [Knyazikhin et al., 1998; Zhang et al., 2002]. Panferov et al. (2001) found that \( p_i = 1 - N_1/N_2 \) where \( N_1 \) and \( N_2 \) are counts of photon interactions with absorbing (\( \omega_L = 0 \)) and scattering (\( \omega_L = 1 \)) leaves, respectively (the parameter \( p_i \) can be interpreted in a similar manner, Panferov et al., [2001]). Shabanov et al. [2002] treated these variables as follows. For a purely absorbing medium, i.e., \( \omega_L = 0 \), the canopy transmittance \( t \) coincides with the uncollided canopy transmittance \( q \) [see definition \( f \), section 4], while the
interception $q_i = 1 - q$ is the canopy absorptance. Substituting $\omega_L(\lambda_0) = 0$, $q_t$ and $q_i$ into (1) and (2), one obtains

$$t(\lambda) = \frac{1}{1 - p_t \omega_L(\lambda)} q, \quad i(\lambda) = \frac{1}{1 - p_i \omega_L(\lambda)} (1 - q).$$

(3)

Solving these equation for $p_t \omega_L(\lambda)$ yields $p_t \omega_L(\lambda) = \frac{[t(\lambda) - q]}{t(\lambda)}$ and $p_i \omega_L(\lambda) = \frac{[i(\lambda) - q_i]}{i(\lambda)}$. Thus, $p_t \omega_L(\lambda)$ and $p_i \omega_L(\lambda)$ are portions of collided radiation in total radiation transmitted and intercepted by the vegetation canopy, respectively. This interpretation will be used in further discussions here.

*It should be emphasized that the canopy spectral invariant specifies the relationship between the spectral properties at the leaf and the canopy scale.*

**3. How big is the "leaf scale"?**

The magnitude of scattering per element foliage volume is described using single scattering albedo, $\omega(\lambda)$, which is defined as the ratio of energy scattered by the elementary volume to energy intercepted by this volume. The single scattering albedo depends on the definition of the scattering center and the size of the elementary volume. For example, if a cube of 50x50x50 cm is taken as an elementary volume in a coniferous forest, a one-year shoot of 5-7 cm should be taken as a scattering center [Knyazikhin et al., 1997]. The single scattering albedo, in this case, characterizes scattering properties of the 50x50x50 cm cube filled with one-year shoots, i.e., the single scattering albedo describes spectral properties of the vegetation canopy at "shoot scale."

The canopy spectral invariant (3) is formulated for the single scattering albedo. The left-hand side of equations (3) can be directly derived from field measurements irrespective of the definition of the single scattering albedo. It means that the coefficients $p_t$ and $p_i$ depend on the definition of the scale at which the single scattering albedo is introduced. Thus, we have two variables to characterize "the leaf scale," namely, the single scattering albedo and the coefficients $p_t$ and $p_i$. Note that the products $p_t \omega(\lambda)$ and $p_i \omega(\lambda)$ [portions of collided radiation in total radiation transmitted and intercepted by the vegetation canopy, respectively] became scale independent variables. The following three problems will be examined during this field campaign.

**Problem 1: Scaling from the "single scattering albedo" to the entire vegetation canopy**

Given single scattering albedo, derive the coefficients $p_t$ and $p_i$ using canopy spectral transmittances and reflectances. In the case of coniferous forest, $p_t$ and $p_i$ corresponding to needle and shoot scales will be specified.

Such an experiments was carried out by Panferov et al [2001] at the Solling Site (Germany) representative of temperate coniferous forests. A one-year shoot of size 5-7 cm was taken as the basic foliage element (scattering center) and its spectral transmittance and reflectance were measured using the LI–1800 with the LI–1800–12 External Integrating Sphere. The coefficients
\( p_t \) and \( p_i \) were derived from measured canopy spectral interception and transmittance using Eqs. (1) and (2), respectively (Figures 1 and 2).

\[ \begin{align*}
\text{Canopy interception} & \quad \text{Leaf albedo} \\
0.5 & \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9
\end{align*} \]

\( 0.5 \) \( 1 \) \( 1.5 \) \( 2 \) \( 2.5 \) \( 3 \) \( 3.5 \) \( 4 \) \( 4.5 \)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{(a) Measured and calculated with Eq. (3) canopy spectral interception and (b) their correlation for the Solling site; \( p_i = 0.94 \). The portion \( p_i \) of collided radiation in total radiation intercepted by the vegetation canopy normalized by the single scattering albedo is 0.94. One can see from Panel (a) that the mean number of photon interactions with shoots before either being absorbed or exiting the canopy is an increasing function with respect to the single scattering albedo [from Panferov et al., 2001].}
\end{figure}

\textbf{Problem 2: Scaling from the entire vegetation canopy to the "single scattering albedo"}

Given canopy spectral transmittance and reflectance, derive the single scattering albedo and coefficients \( p_t \), \( p_i \) and \( q \) (uncollided canopy transmittance, see definition \( f \), section 4).

Such an experiment was carried out by Wang et al [2002] at the Ruokolahti site (Finland) representative of coniferous forests. The coefficients \( p_t \) and \( q \) are shown in Table 1. Figure 3 shows the retrieved spectrum of the single scattering albedo. One can see that the retrieved spectrum has the basic scattering features of a green leaf; that is, local minimum at blue and red wavelengths, local maximum at green, and a sharp jump at \( \lambda = 700\text{nm} \). Because optical properties of individual phytoelements were not measured during the Ruokolahti field campaign, the scale to which the single scattering albedo refers was not specified. We believe that this spectrum corresponds to the shoot single scattering albedo.

\begin{table}[h]
\centering
\caption{Retrieved values of \( q_t \) and \( p_t,BS \)}
\begin{tabular}{lcccc}
\hline
Retrieved Parameters & 400-487nm & 487-555nm & 555-650nm & 650-900nm \\
\hline
\( q_t \) & 0.235 & 0.255 & 0.275 & 0.275 \\
\( p_t,BS \) & - & 0.3 & 0.05 & 0.45 \\
\hline
\end{tabular}
\end{table}
Problem 3: Scaling from needle to shoot

Given needle spectral transmittance and reflectance, derive the shoot single scattering albedo and the coefficient $p_{sh}$.

This information is required to specify a relationship between the spectral properties at the needle, shoot and canopy scales as well as to interpret retrievals described in Problem 2. S. Smolander and Stenberg [2002] showed that the shoot single scattering albedo $\omega_{sh}$ is related to the needle albedo $\omega_L$ as

$$\omega_{sh} = \omega_L e_{sh}$$

(4)

where $e_{sh}$ is the radiation interception efficiency defined as the probability that photon will escape the shoot as a result of one intercation with needles,

$$e_{sh} = \frac{1 - p_{sh}}{1 - p_{sh} \omega_L}.$$  

(5)

The interpretation of the product $\omega_L p_{sh}$ is similar to $p_i \omega(\lambda)$ discussed earlier; that is, $\omega_L p_{sh}$ is the portion of collided radiation in total radiation intercepted by needles on the shoot. The
coefficient $p_{sh}$ is the probability that a photon scattered by a needle will undergo interaction with needles in the same shoot again. This probability inversely related to the STAR [S. Smolander and Stenberg, 2002]. For the computer simulated shoot shown in Figure 4, the probability $p_{sh}$ and the shoot single scattering albedo were evaluated using a Monte Carlo technique [S. Smolander and Stenberg, 2002]. Figure 5 demonstrates the shoot single scattering albedo as a function of the needle albedo derived from Monte Carlo simulation and predicted by Eqs. (4)-(5).

Figure 4. Silhouettes (SSA) of the model shoot as seen from (A) side, (B) 45° angle, and (C) axially [from Smolander and Stenberg, 2002].

Figure 5. Shoot single scattering albedo as a function of the needle albedo derived from Monte Carlo simulation (dots) and predicted by Eqs. (4)-(5) (bold line). The coefficient $p_{sh} = 0.446$ [from Smolander and Stenberg, 2002].

Thus, as in the case of Problem 1, we have two variables to characterize spectral properties of needles and shoots, namely, the needle albedo (scattering center albedo) and the coefficient $p_{sh}$. A question then arises as to how this result can be used to specify the scale at which the retrieved single scattering albedo (see Problem 2) is defined as well as to derive a relation between scattering properties of needles and the entire canopy.
4. Definition of variables

(a) The hemispherical canopy transmittance, $t(\lambda)$, [reflectance, $r(\lambda)$] for nonisotropic incident radiation is the ratio of the mean downward radiation flux density at the canopy bottom (mean upward radiation flux density at the canopy top) to the downward radiation flux density above the canopy.

(b) The hemispherical surface reflectance, $\rho_{\text{surf}}(\lambda)$, for nonisotropic incident radiation is the ratio of the mean upward to the downward radiation flux density at the surface level.

(c) The hemispherical-directional reflectance factor (HDRF) for nonisotropic incident radiation is the ratio of the mean radiance leaving the top of the plant canopy to radiance reflected from an ideal Lambertian target into the same beam geometry and illuminated under identical atmospheric conditions [Martonchik et al., 1998].

(d) The hemispherical leaf transmittance, $\tau_L(\lambda)$, [reflectance, $\rho_L(\lambda)$] is the portion of radiation flux density incident on the leaf surface that the leaf transmits (reflects).

(e) The hemispherical leaf albedo, $\omega_L(\lambda)$, is the sum of the hemispherical leaf transmittance and reflectance.

(f) Uncollided canopy transmittance, $q$, is the probability that a photon in the incident radiation will arrive at the bottom of the canopy without suffering a collision.

(g) Collided canopy transmittance, $t(\lambda) - q$, is the probability that a photon in the incident radiation will arrive at the canopy bottom as a result of multiple (one or more) interactions with phytoelements.

(h) Canopy interception, $i(\lambda)$, is the mean number of photon interactions with leaves at wavelength $\lambda$ before either being absorbed or exiting the canopy and can well be approximated as the ratio of the canopy absorbance $a(\lambda)$ to leaf absorption $1 - \omega_L(\lambda)$ [Panfyorov et al., 2001]. In the case of "purely absorbing leaves," the canopy interception coincides with $1 - q$.

Variables (a)-(e) depend on the wavelength and the direction of incident radiation.

The ASD with a standard cosine receptor will be used to collect spectral up- and downward fluxes below the canopy from 350 nm to 1085 nm, at 1.6 nm.

The upward radiation field above the canopy will be measured by mounting the ASD on a helicopter. The ASD field of view should be set to 25 degrees.

The LI–1800 Spectroradiometer with Standard Cosine Receptor will be used to measure spectral variation of incident radiation flux density in the region from 400 nm to 1100 nm, at 1 nm resolution.
A technique developed during Ruokolahti, Finland, June 14-21, 2000 [Wang et al., 2002] will be used to calibrate the ASD and LI-1800 spectroradiometers.

The measured HDRFs will be taken as the hemispherical canopy reflectance $r(\lambda)$.

Leaf spectral transmittances and reflectances will be measured in a laboratory, using the LI−1800 with the LI−1800−12 External Integrating Sphere. We follow measurement methodology proposed by Panferov et al. [2002].

The LAI-2000 plant canopy analyzer composed of a LAI-2070 control unit and a LAI-2050 sensor head. The sensor head projects the image of its nearly hemispheric view onto five detectors arranged in concentric rings (approximately 0-13, 16-28, 32-43, 47-58, 61-74 degrees). The LAI-2000 measures in the blue portion of the spectrum (below 490nm) that is transmitted by the vegetation canopy. In this region, foliage reflect and transmit relatively little radiation and thus data collected with the LAI-2000 can be used to derive the uncollided canopy transmittance (variable $f$).

5. Data Needs

(1) Existing ETM+ images to study the site. This is being presently done by the Boston University group.

(2) Continuous measurements of the radiation spectrum incident on the vegetation canopy at a few open areas, depending on how far apart the ten 1km regions are. At the very least, we should total incident solar radiation, the diffuse fraction, and the total PAR.

(3) Hemispherical photos of all patches in the 1 km pixel.

(4) Transmission measurements under the canopy, preferably under the over- and understory. These should be ideally ASD measured spectra. Or, at the very least light bar measurements of PAR. Need these in all patches in the ten 1km regions (several per patch).

(5) Canopy reflectance spectra. At least once, we should have such data from an ASD mounted on a helicopter for all patches in the ten 1km regions. If at all possible, we should try to obtain these data for the entire 200x200 km area.

(6) Leaf/Needle optical Properties of all dominant species in our study area.

(7) Basic study site information such species distribution, age structure, soils, hydrology, topography, etc. Will be valuable to have access to key data sets and research papers describing previous efforts in our study area.

References

Knyazikhin, Y., J.V., Martonchik, R.B. Myneni, D.J. Diner, and S.W. Running, Synergistic algorithm for estimating vegetation canopy leaf area index and fraction of absorbed


SCIENCE QUESTION 3: Is the MODIS FPAR suggestive of vegetation gross production?

Canopy gross production, at time scales of days and weeks, is perhaps most closely associated with absorbed PAR, under conditions of optimal water and nutrient availability and non-limiting temperatures. Is this true? Can we check this statement with data from the Flakaliden site during the growing season of 2002?

Are year-to-year changes in gross production related closely to year-to-year changes in growing season length and/or total growing season absorbed PAR? Can we check this with data from the Flakaliden site, which happens to be a Euroflux site and must have data from five or more years?

Is it possible to estimate gross production from the flux tower measurements? If so, these estimates would be representative of the vegetation in the tower footprint. The question is, how to obtain the absorbed PAR for the same footprint? We suppose that the incident PAR was measured at the tower site. If we know the spatial distribution of LAI in the footprint, and its seasonal course, it should be possible to estimate the absorbed PAR over a time period (daily, weekly, or seasonal). Is this a possible strategy to address the above questions?

If there is indeed a good relation between vegetation gross production and absorbed PAR, then the question is, how to obtain the latter from satellite FPAR? Ecosystem production models tend to use satellite estimates of FPAR to evaluate daily, weekly, or monthly absorbed PAR and convert this to vegetation production using certain conversion factors or efficiencies. Our goal is to assess the validity of such an approach and to quantify the uncertainties.

Flakaliden is an excellent study site for such a study with all the requisite data likely to be available.

Data Needs

(1) Continuous measurements of incident solar radiation, diffuse fraction, the total PAR, and possibly the spectrum.

(2) Spatial distribution of LAI in the tower footprint. Seasonal course of LAI. Possibly from satellite data. If direct measurements exist, and or can be assembled from alternate non-satellite sources, that is valuable, too.

(3) Estimates of daily course of gross production from tower CO2 data, during the season, for several seasons.

(4) Characterization of light-photosynthesis response variability at leaf/shoot scale within a stand and between stands of different species.