Validation of MODIS LAI product for the Northern hardwoods forest

of the Upper Peninsula of Michigan

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Abstract

The Moderate Resolution Imaging Spectroradiometer (MODIS) Land Discipline Team produces a suite of global land products whose uncertainty is determined through validation activities. Data validation is an important step because data quality must be understood before these land products can be interpreted correctly. Leaf area index (LAI) collected in the Northern hardwoods forest of the Upper Peninsula of Michigan was used to validate MODIS LAI product. The field-collected data were related to a vegetation index using 30-m resolution images from Landsat 8's Operational Land Imager (OLI) to create a high-resolution LAI map. Comparison of aggregated LAI pixels and corresponding MODIS LAI retrievals at a pixel- and patch-level shows poor agreement. Further investigation of MODIS LAI values revealed temporal variability in the MODIS LAI product. Additional study is needed to find out the reason behind the observed variability.

1. Introduction

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument on board the Terra and Aqua spacecraft used for remote sensing of the Earth's atmosphere, oceans, and land surface (Tan *et al.* 2005). It observes the Earth, with a viewing swath width of 2,330 km and views the entire Earth surface in one or two days. It has the capability to measure up to 36 spectral bands in three spatial resolutions: 250-m, 500-m, and 1,000-m. Since the Terra launch in 1999, MODIS has provided many data products that describe the Earth's land, oceans, and atmosphere (https://lpdaac.usgs.gov). The MODIS Land Discipline Team (MODLAND) produces several land products relevant to the Earth system science and global change. Some of these include:

- Radiation Budget Variables: Surface Reflectance, Land Surface Temperature (LST)/Emissivity, Snow and Ice Cover, Albedo/Bi-directional Reflection Distribution Function (BRDF)
- Ecosystem Variables: Vegetation Indices, Leaf Area Index (LAI)/ Fractional Photosynthetically Active Radiation (FPAR), Vegetation Production: Daily Photosynthesis (PSN)/ Annual Net Primary Production (NPP)
- Land Cover Characteristics: Fire and Thermal Anomalies and Burned Area, Land Cover, Vegetative Cover Conversion and Vegetative Continuous fields (Morisette *et al., 2002*).

As these satellite sensor products become available for public use, the process of quality assurance through validation becomes important. This is because adequate understanding of data quality is required before the various products can be interpreted (Issac and Lynnes, 2003). In general, validation refers to assessing the uncertainty of satellite sensor derived products (e.g. land cover and LAI) by analytical comparison to reference data, which are presumed to represent the target values. It involves the collection of *in situ,* aircraft, and satellite sensor data (Justice *et al*. 2000).

LAI is defined as the total one-sided area of leaf tissue per unit ground surface area (Breda, 2003). This definition can be used for broadleaf canopies; however, for coniferous canopies, projected needle leaf area can be considered (Morisette *et al.,* 2006). Projected needle leaf area is the area of horizontal shadow that would be cast beneath a horizontal leaf from a light at infinite distance directly above it (Barclay 1998). LAI is one of the primary measures used in characterizing plant canopies. It is used as an ecophysiological measure of the photosynthetic and transpirational surface within a canopy and as a remote sensing measure of the leaf reflective surface within a canopy (Chen *et al.,* 1997). LAI also provides key information on the exchange of energy, mass, and momentum flux between the Earth's surface and the atmosphere, having especial importance in ecosystem productivity models and global models of climate, hydrology and biogeochemistry (Morisette *et al.,* 2006).

LAI measurements can be performed either through direct or indirect means. Direct measurements can be obtained through harvesting methods, such as destructive sampling, or by non-destructive litter traps during autumn leaf-fall period in deciduous forests. Because these methods are laborious and time consuming, they are not compatible with the long-term monitoring of spatial and temporal dynamics of leaf area development. However, they remain important for the validation and calibration of indirect methods. Most field campaigns use indirect methods to measure LAI because they are generally faster, amendable to automation, and thus allow for a larger spatial sample to be obtained. Indirect measurements are made through allometric and optical methods. Optical methods relate the amount of foliage to the probability of a beam of light that will pass through the canopy, called gap probability (Yang *et al.,* 2006; Jonckheere *et al*. 2004; De Kauwe *et al*. 2011). Estimates of LAI derived from optical instruments may suffer from two sources of error, if necessary corrections are not made: (1) random distribution of foliage within certain foliage-containing envelopes and (2) radiation interception by wood elements (Gower *et al*. 1999).

The global validation of moderate- to coarse-resolution LAI products is a complicated and challenging task. It involves field measurements of sites representative of various vegetation types and scaling of these measurements from small areas to the resolution of satellite data (1km for MODIS LAI product). Moreover, assumptions made in LAI measurement and uncertainties in satellite data, which result from a variety of sources including imperfect atmospheric correction, and calibration and geolocation errors, must be accounted for (Wang *et al*. 2004; Tan *et al*. 2005).

This study focuses on the validation of MODIS LAI land product for UNDERC (University of Notre Dame Environmental Research Center) and surrounding areas in the Upper Peninsula of Michigan (46'13'N, 89'32'W). The area is covered by an extensive forest, composed of coniferous and deciduous trees, lakes, streams, and wetlands. The location was chosen for validation activities since it fit the following criteria:

- accessibility to researchers
- availability of research facility
- characteristic of the surrounding area
- existence of MODIS data
- long-term commitment to scientific study through land ownership

2. Methods

The validation steps followed in this study involve (1) ground sampling of LAI (2) generation of fine resolution LAI map and (3) comparison of aggregated fine resolution pixel with MODIS LAI product (Fig. 1)

2.1 Ground Sampling

Five sites representing the different forest types of the area were chosen for field data collection (Fig. 2). These sites are maple monoculture (site 1), late successional/old growth forest (site 2), coniferous forest site (site 3), mixed hardwoods forest (site 4), and mixed hardwood and conifer forest (site 5). Sites 1, 2, 4 and 5 were 100 X 100-m in area, while site 3 was 120 X 50-m. A smaller area was chosen for the site 3 because the forest patch was not large enough to fit a 100 X 100-m plot. Site 1 was occupied by sugar maple (*Acer saccharum*); site 2 was dominated by eastern hemlock (*Tusga canadensis*), yellow birch (*Betulla alleghaniensis*) and sugar maple; site 3 mostly contained black spruce (*Picea mariana*); site 4 consisted of aspen (*Populus tremuloides*), ash (*Fraxinus* spp.), and some sugar maple. There was not a dominant species in the mixed hardwoods and conifer site, rather it was mix of spruce, white birch (*Betula papyrifera*), ash, and various shrubs, such as beaked hazel (*Corylus cornuta*), and American fly honeysuckle (*Lonicera canadensis*).

I measured LAI using the LAI-2200C plant canopy analyzer (LI-COR, Lincoln, Nebraska), which consists of LAI-2270C control unit and LAI-2250 optical sensor. The LAI-2200C measures the attenuation of sky radiation at five zenith angles centered at 7°, 23°, 38° 53° and 68°. The optical sensor projects the image of its nearly hemispheric view onto five detectors arranged in concentric rings. I followed the calibration procedure given in the LAI-2200C Plant Canopy

Analyzer Instruction Manual (LI-COR, 2013). I took LAI measurements at the four 100 X100-m sites along 11 transects, which were 10 m apart (Fig. 3). I took readings along each transect at 10 m interval, for a total of 11 readings per transect. I followed the same method for site 3, taking measurements on a total of 6 transects. I used a 270º view cap for all sites, except site 5, to eliminate myself from the sensor's view while taking readings. I used a 45º view cap for site 5 to prevent the sensor from seeing gaps and canopies in the same view, as there were several gaps in the site. This is done to prevent the sensor from over-weighing the canopy gap in the calculation process and giving an LAI value that is an underestimate (LI-COR, 2013).

LAI-2200C calculates LAI values using Miller's (1967) derivation (Equation 1; LI-COR, 2013). However, since this calculation is under the assumption of uniformly distributed leaves and since the instrument cannot distinguish between foliage and woody material, the values from Miller's formula give effective LAI, L_e. L_e can be converted to true LAI using equation 2 (Chen and Cihlar, 1996)

$$Le = 2\int_0^{\pi/2} -lnP(\theta)\cos\theta\sin\theta\, d\theta \qquad (1)$$

$$L = \frac{(1-\alpha)Le\gamma e}{\Omega e} \tag{2}$$

where $P(\theta)$ is the gap fraction, which relates to the probability of beam penetration through a canopy, θ is the view zenith angle, α is the woody-to-total area ratio, γe is the needle-to-shoot area ratio for clumping within shoot, and Ωe is the element clumping index for foliage clumping at scales larger than the shoot. Individual leaves were considered to be foliage elements, so I used γe=1. Table (1) shows the correction factors used for the five sites studied. Since LAI-2200C applies an apparent clumping index defined by Ryu *et al*. 2010, the indices in Table (1), which are species specific, were applied using Eq (3) from the LAI-2200C instruction manual (LI-COR, 2013)

$$Lc = La\; x \frac{ACF}{\Omega e} \tag{3}$$

where Lc is the clumping corrected LAI, La is the LAI value calculated by the LAI-2200C that has the apparent clumping index applied and ACF is the apparent clumping index given by LAI-2200C. Multiplying La by ACF undoes the clumping factor correction inherently applied by the LAI-2200C. No Ωe values were applied for sites 1, 4 and 5 since they do not violate the assumption of random foliage distribution to a significant degree. The presence of yellow birch and maple in site 2 also decreases clumping, so I did not apply any Ωe correction.

2.2 Generation of fine-resolution LAI map

The collection of sufficient data for a pixel-by-pixel comparison of MODIS LAI product is unfeasible because the 1-km MODIS pixel size significantly exceeds the plot size typically used for LAI measurements. An alternative is to use representative field measurements and high-resolution satellite data to derive an accurate fine-resolution LAI map over an extended area. This can then be degraded to moderate resolution and compared with MODIS LAI imagery (Tian *et al*. 2002). This method is based on the principle that green leaves are selective absorbers of solar radiation. Compared with non-vegetative surfaces, green leaves absorb more visible radiation for photosynthesis and less near infrared radiation (Jordan 1969). Reflectance in red and near-infrared wavebands, denoted by ρ_{red} and ρ_{NIR}, can therefore been used to formulate vegetation indices (Chen and Cihlar 1996). The correlation between vegetation indices and ground measurements of LAI can then be used to establish an empirical model, which is used to generate a fine-resolution LAI map.

A July 2012 Landsat 8 image from OLI (Operational Land Imager) sensor was used to generate the fine-resolution map. OLI images consist of nine spectral bands with a spatial resolution of 30-m for bands 1 to 7 and 9 (http://landsat.usgs.gov/). A good quality image (with no cloud cover and a high quality rating) of the UNDERC area was chosen for this study. The vegetation index that was used in this study was the Reduced Simple Ratio (RSR), which can be calculated as (Brown *et al*. 2000)

$$RSR = \left(\frac{\rho\text{NIR}}{\rho\text{red}}\right)\left[1 - \frac{\rho\text{SWIR} - \min(\rho\text{SWIR})}{\max(\rho\text{SWIR}) - \min(\rho\text{SWIR})}\right] \quad (4)$$

where ρ_{SWIR} is the shortwave infrared reflectance, obtained from Band 6 of OLI data, min (ρ_{SWIR}) and max (ρ_{SWIR}) are the minimum and maximum SWIR reflectances in the OLI image. ρ_{red} and ρ_{NIR} were obtained from Bands 4 and 5, respectively, of the OLI image. ArcMap, a GIS (Geographic Information System) software, was used to find the RSR values of the points where LAI measurements were taken. A linear regression was then performed using the RSR values and the corresponding LAI measurements. The relationship from the regression was applied to the area covered in the image to produce the fine-resolution LAI map.

2.3 Comparison of aggregated fine-resolution pixels with MODIS LAI product

ENVI (Environment for Visualizing Images) GIS software was used to aggregate LAI values from the 30-m resolution pixels to 1-km. This was done by averaging all fine-resolution LAI values within each MODIS pixel. The aggregated pixels were then compared to the corresponding MODIS pixels at the pixel- and patch-level. Patch level comparison was performed by dividing the up-scaled LAI map into patches according to the similarity of LAI values. Each patch was then compared to the MODIS pixels in the same spatial area. Pixel-level comparison was done by simply taking a pixel on the up-scaled map and comparing it to the corresponding pixel on the MODIS LAI map.

3. Results

The relationship between RSR and LAI that was used to produce the fine-resolution map (Fig. 4) is shown in Fig 5. and is given by (R^2=*0.52293*)

$$LAI = 0.2524RSR + 1.5454 \quad (5)$$

Fig. 6 shows the fine-resolution map produced by applying this relationship over an extended area of UNDERC. The result of the comparison between the derived LAI and MODIS LAI is shown in Fig 7; 7a. is a pixel-by-pixel comparison and 7b. is a patch-level comparison. Both comparisons were made for the Northwest part of UNDERC. The reason behind this is that MODIS does not recognize most of the lakes at UNDERC and gives an LAI value >0; in order to test its validity over terrestrial surfaces, I chose an area with low water cover.

4. Discussion

The analysis presented shows little correlation between derived LAI and MODIS LAI values. In both the patch-level and pixel-level comparisons, derived LAI values fall within a narrow range, while MODIS LAI values have a wider range (Fig. 7). Wang *et al*. (2004) found similar result (Fig. 8) for a coniferous forest, while De Kauwe *et al*. (2010) found that MODIS LAI was restricted to a narrow range, even though their derived LAI was widespread for a mixed coniferous forest. To check the reason behind the disagreement, I did a Kruskal-Wallis test (Shapiro $p<0.001$) comparing MODIS LAI values for the Northwest part of UNDERC for July 2002, 2003, 2004, 2011, and 2012 ($df=4$), and the result showed they have significant difference ($p<0.001$). The Nemenyi-Damico-Wolfe-Dunn test shows that there is significant difference in the year-to-year MODIS LAI values for the Northwest area of UNDERC (Fig. 9; Table 2). 2012 MODIS LAI value is particularly low from other years' values.

Even though MODIS is unable to recognize most of the lakes in the area studied, this does not explain the temporal variability in LAI values. I would expect this weakness to result in an underestimate of LAI rather than a general increase in variability. The results of this study may inform further research by flagging MODIS' inability to characterize spatially heterogeneous areas. Given the error found in MODIS LAI values, the use of LAI products for such areas must be done with caution to prevent the propagation of similar error in products that depend on these LAI values. Further validation studies are needed to investigate the temporal discrepancy observed in MODIS LAI products.

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Table 1 Clumping index and wood correction used to find true LAI for the 5 sites studied. The values are found by averaging the reported values in the listed literature for the corresponding species. α is the woody-to-total area ratio and Ωe is the clumping index

Site	α	Source	Ωe	Source
Maple Monoculture	0.19	Walter *et al*. 2003; Thomas *et al*. 2010		
Old Growth	0.17	Thomas *et al*. 2010		
Conifer	0.16	Walter *et al*. *2003*; Thomas *et al*. 2010; Ryu *et al*. 2010	0.91	Ryu *et al*. 2010; Walter *et al*. 2003
Mixed Hardwoods	0.19	Walter *et al*. *2003*; Thomas *et al*. 2010		
Mixed Hardwoods and Conifer	0.17	Thomas *et al*. 2010		

Table 2 Nemenyi-Damico-Wolfe-Dunn Test comparing MODIS LAI values for the Northwest part of UNDERC for the years 2002, 2003, 2004, 2011, and 2012

Years	p value
2002-2003	<0.001
2002-2004	<0.001
2002-2012	<0.001
2003-2011	<0.001
2003-2012	<0.001
2004-2011	<0.001
2004-2012	<0.001
2011-2012	<0.001

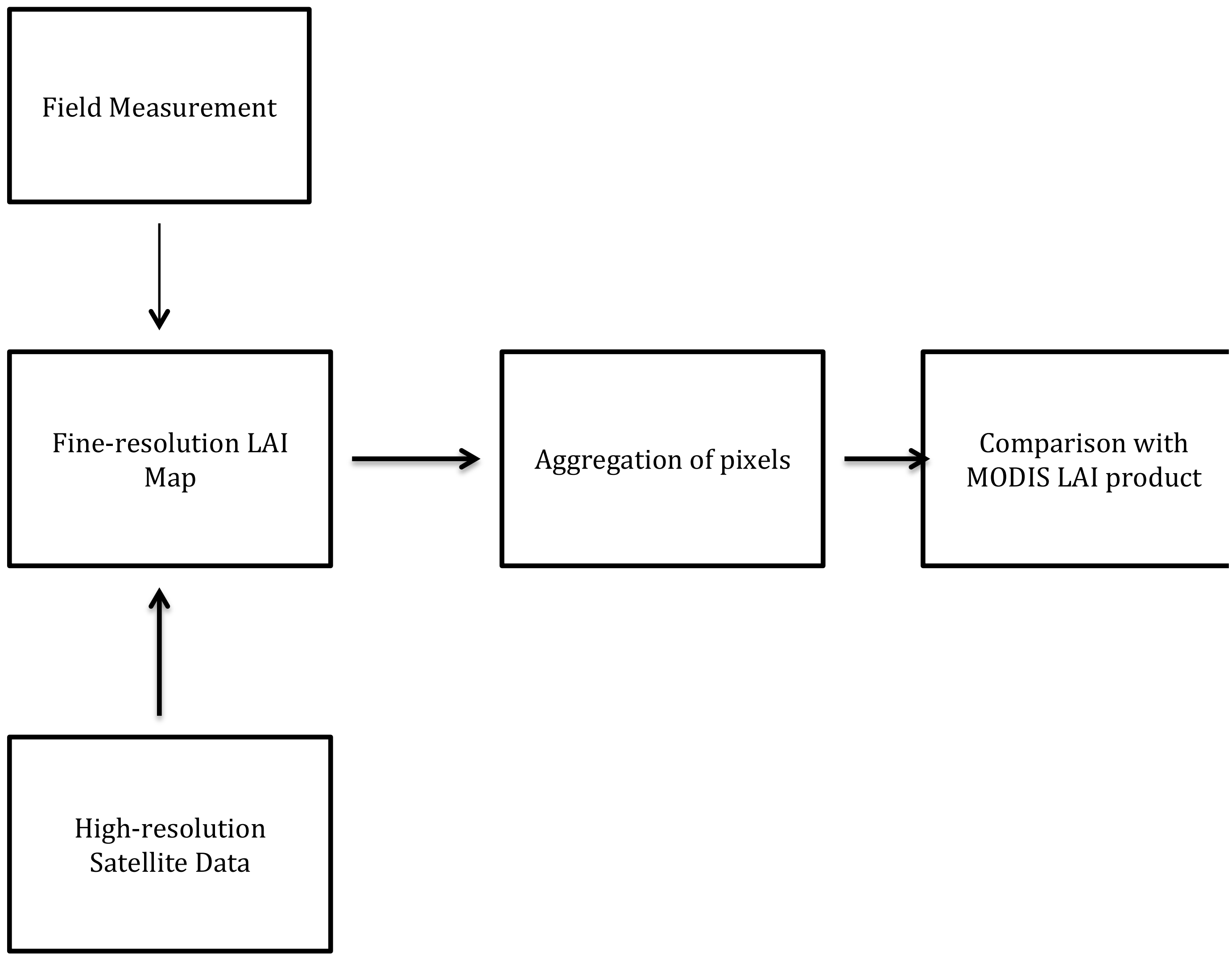


Figure 1 Schematic representation of validation procedure

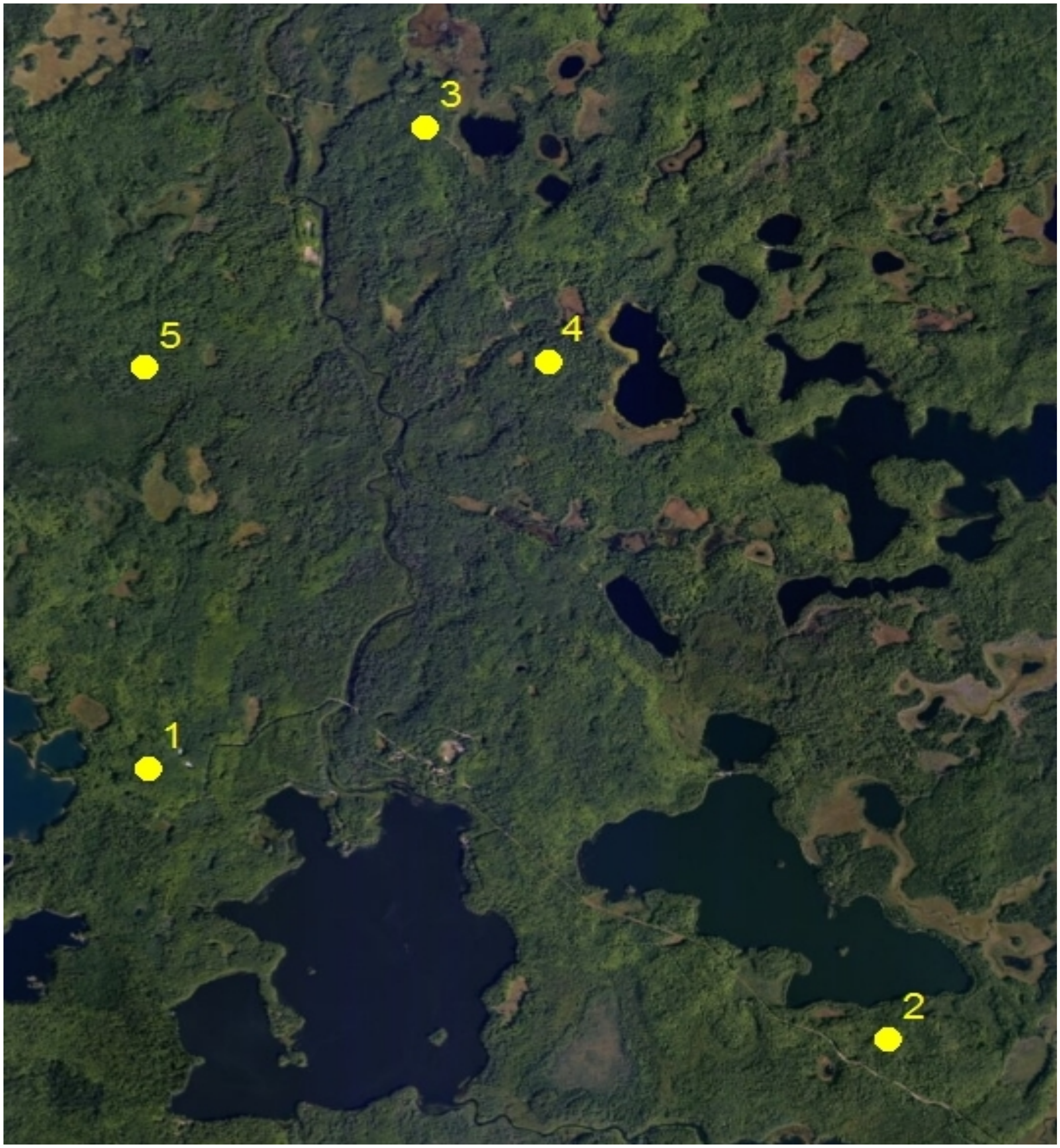


Figure 2 High-resolution image of study site at UNDERC in the Upper Peninsula of Michigan (46’13’N, 89’32’W)

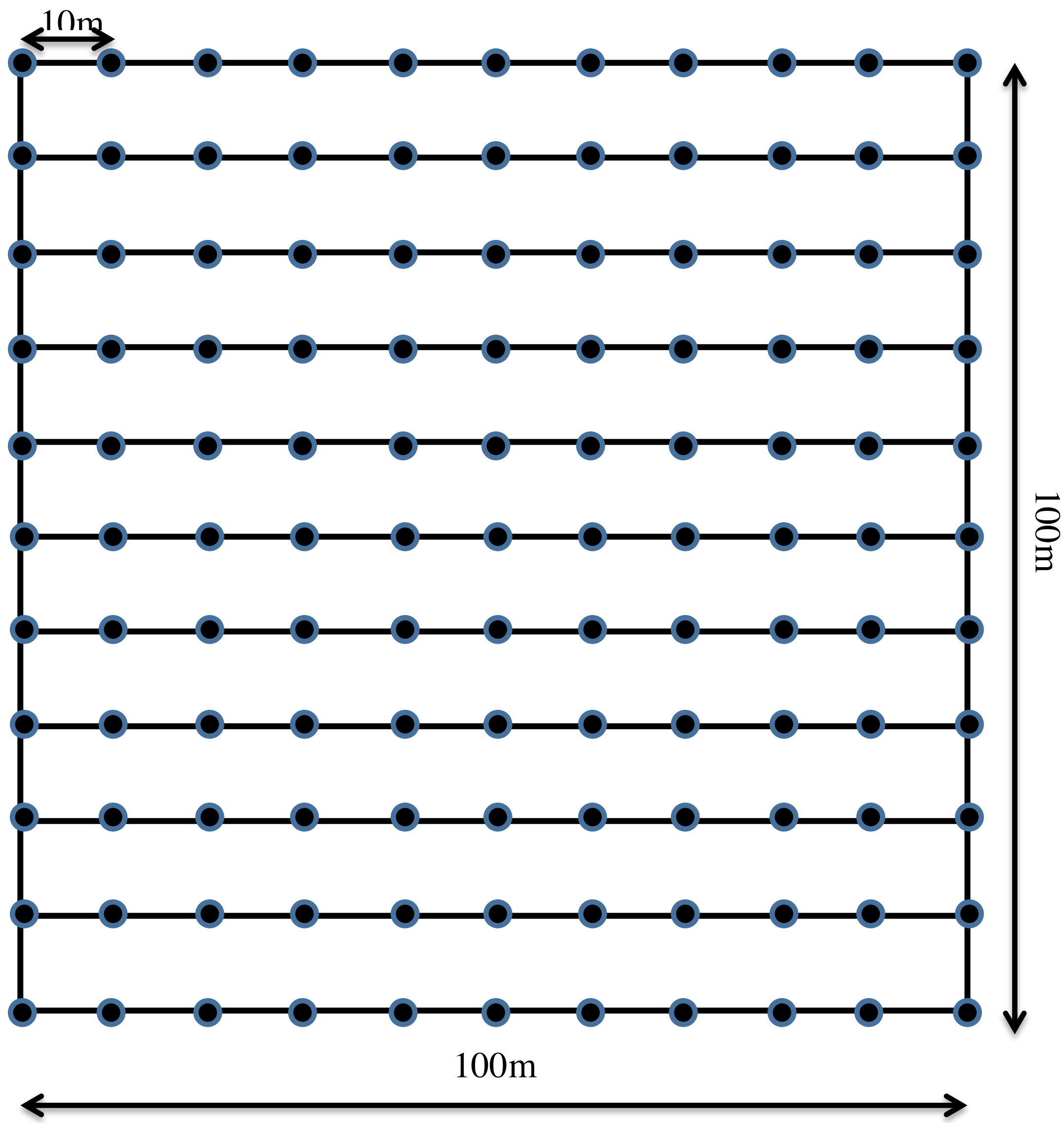


Figure 3 Layout of ground measurement sampling grid and transects. Each point represents a sampling location

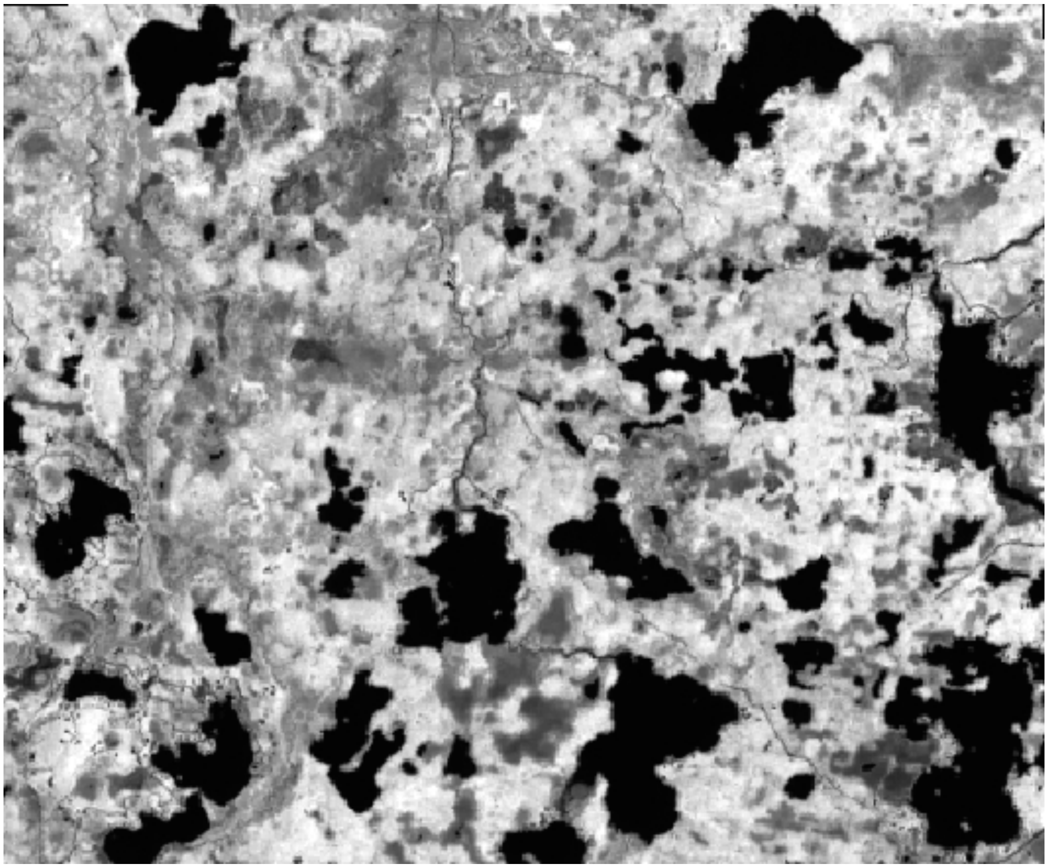


Figure 4 An RSR image derived from Landsat 8's OLI sensor using equation (4)

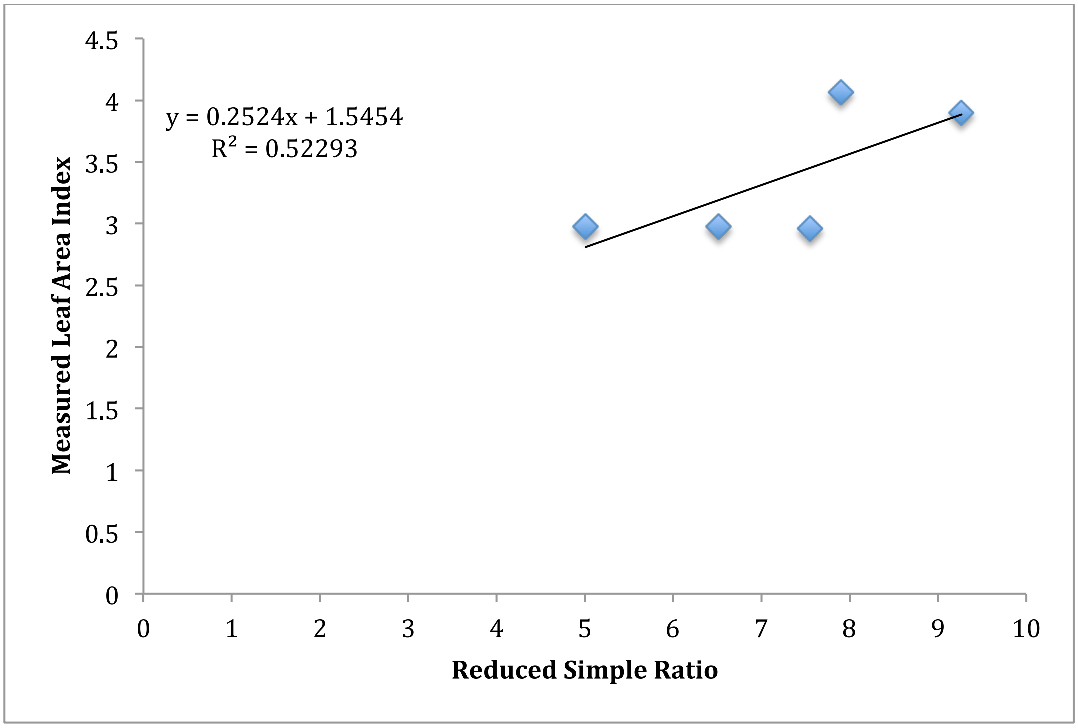


Figure 5 Correlation between RSR and measured LAI

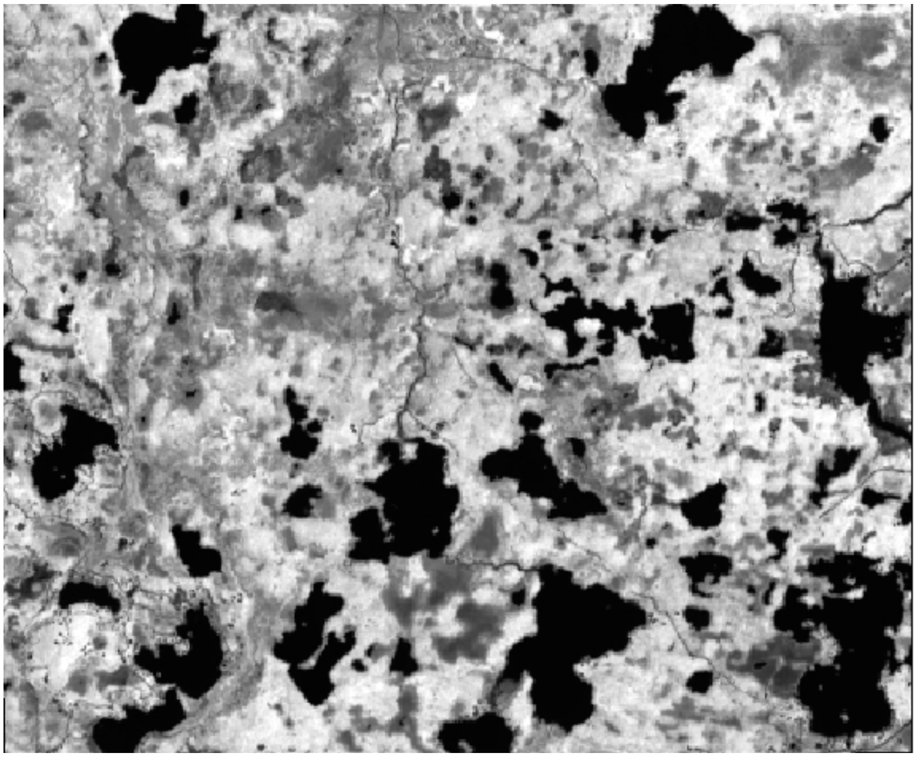
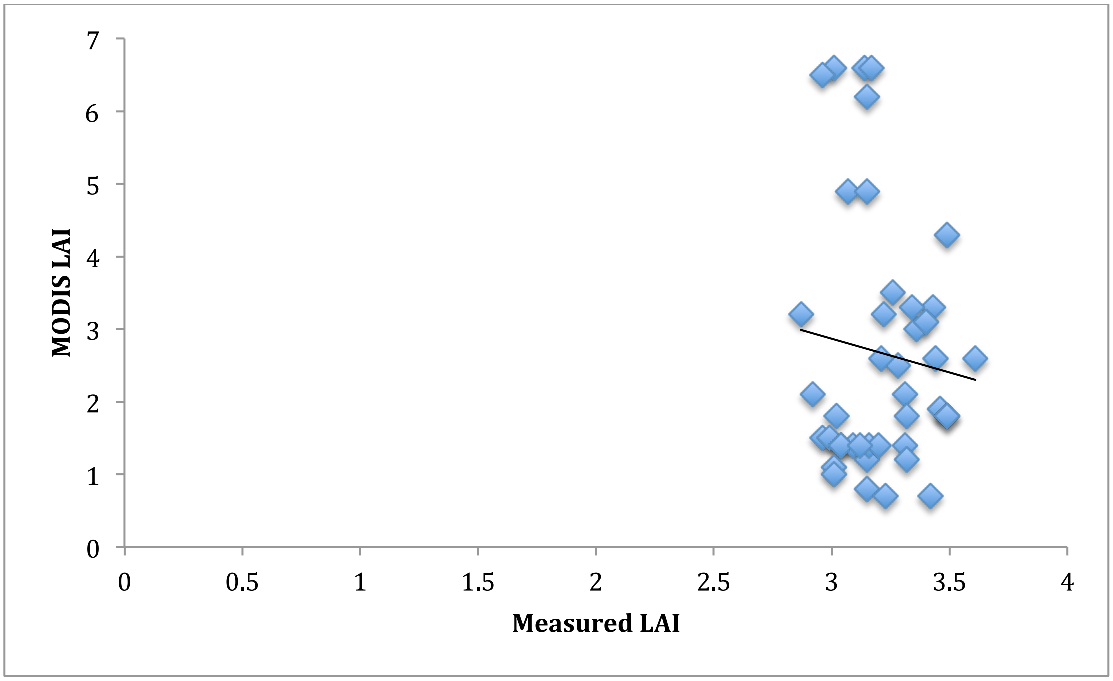
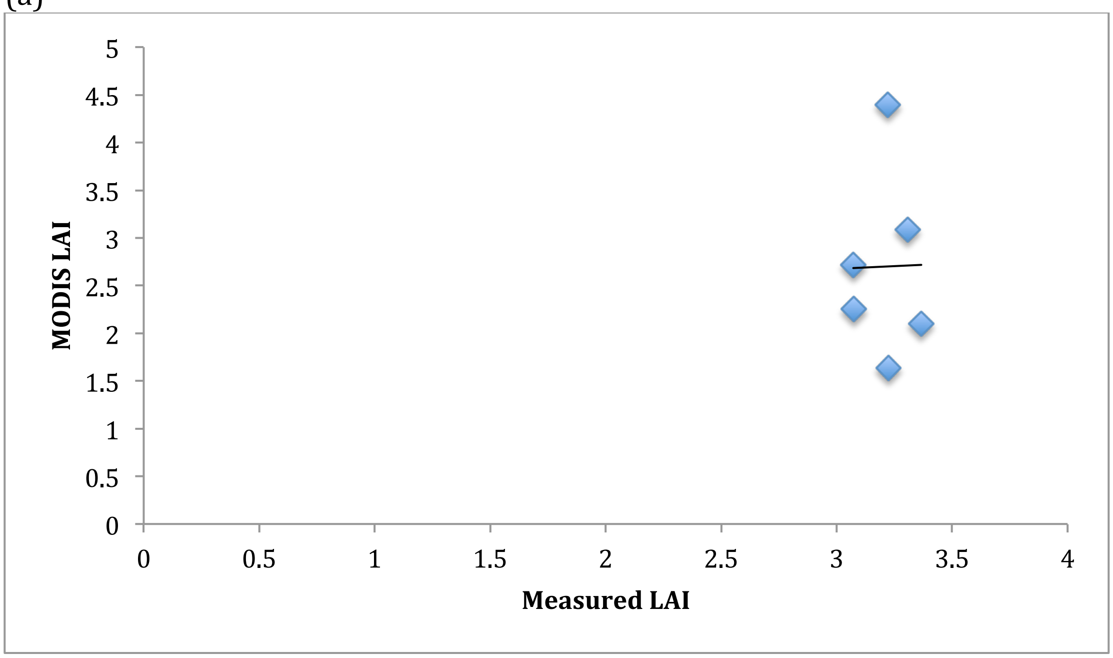


Figure 6 Fine-resolution LAI map derived from the RSR map in Fig (4) using equation (5)



(a)



(b)

Figure 7 Correlation between aggregated OLI derived LAI and MODIS LAI on (a) pixel-by-pixel scale and (b) patch-by-patch scale

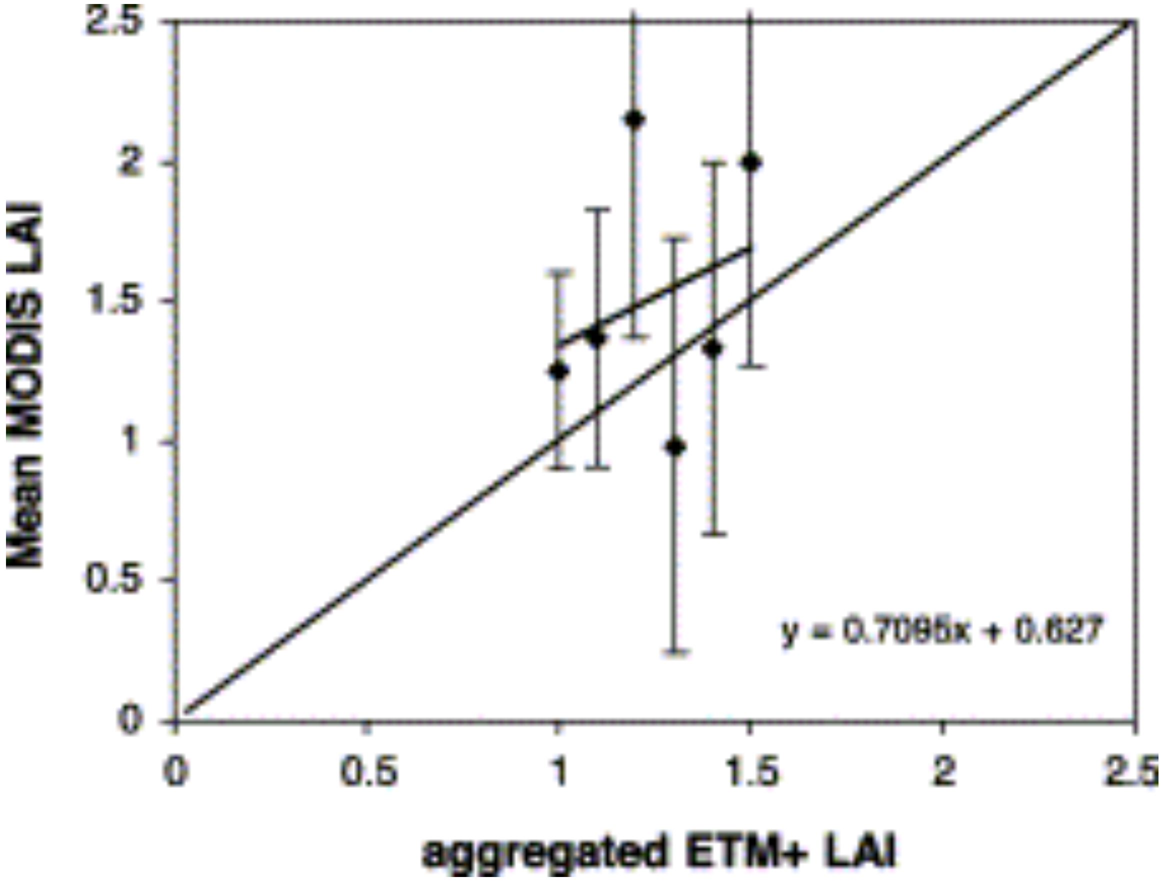


Figure 8 Patch-by-patch relationship between MODIS LAI and aggregated LAI from Wang *et al.* (2004)

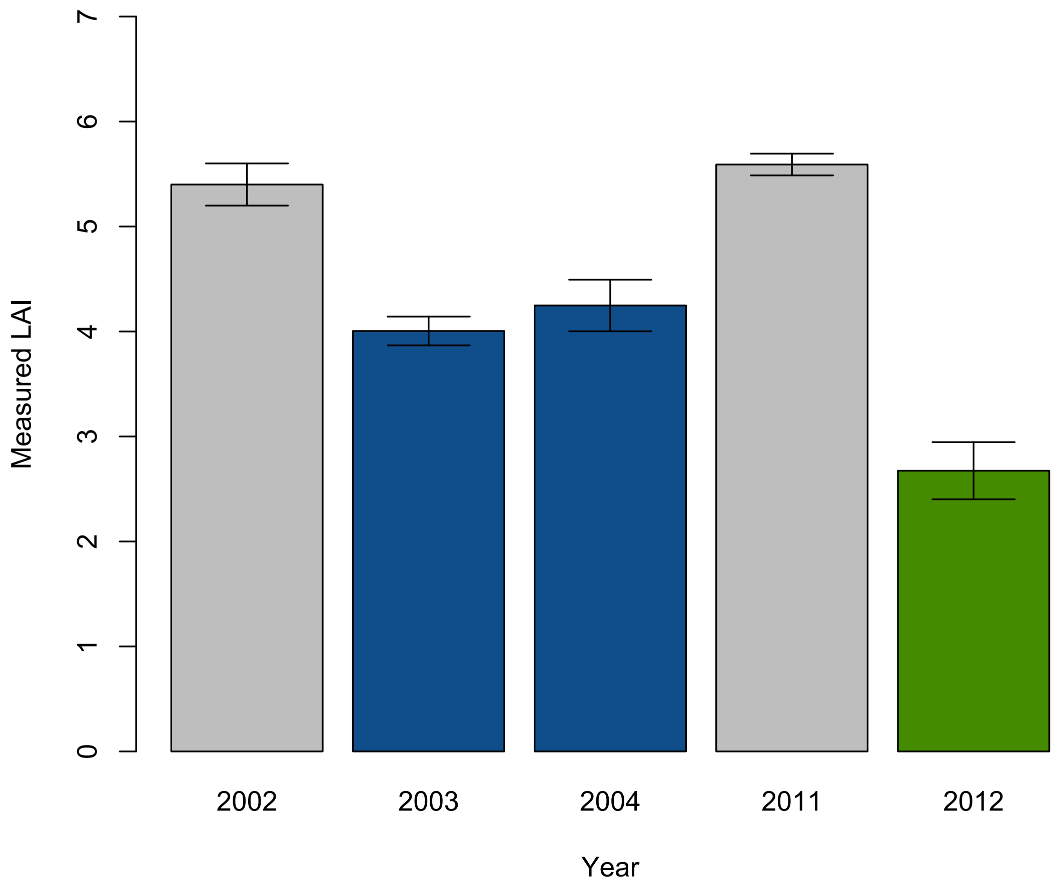


Figure 9 Inter-comparison MODIS LAI values of different years for the Northwest part of UNDERC. Difference in color indicates significant difference LAI values. df=4