

Satellite Remote Sensing for Spatio-Temporal Estimation of Leaf Area Index in Heterogeneous Forests

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Abstract-Biophysical parameter values such as LAI have proved useful in a number of environmental applications. An approach is presented for producing the spatio-temporal estimation of leaf area index (LAI) of a heterogeneous forest using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images. This is performed by decomposing MODIS LAI for a heterogeneous forest using the Linear Mixture Model (LMM) and the information about the class fraction from an aerial image. Results showed that the decomposed MODIS LAI values were estimated well with maximum and minimum RMSE of 0.37, and 0.17, respectively. We concluded that our approach can be used to decompose MODIS LAI successfully for any heterogeneous forest.

Keywords- Leaf Area Index (LAI); Mixed Pixels; Moderate Resolution Imaging Spectroradiometer (MODIS) Satellite Imagery

I. INTRODUCTION

Global changes are driving alterations in climate, water resources, and ecological systems. Monitoring these changes, and thereby especially the spatial and temporal variability of vegetation properties, is one of the foremost fields of research within remote sensing. The knowledge of these variables is crucial to understanding terrestrial biosphere processes and can be used for the parameterization of various physical models, quantifying the exchange of energy and matter between the land surface and the atmosphere. Due to the role of green leaves in controlling biological and physical processes in plant canopies, the Leaf Area Index (LAI) is a key element of vegetation structure and an important input parameter to hydrological models. It is defined as half the total leaf surface area per unit ground surface area projected on a local horizontal datum [1]. The LAI can be estimated in the field either by direct (e.g., destructive sampling and litterfall) or by indirect (e.g. measurements of light transmission through canopies) procedures. Although their extensive usage, these methods demand considerable amounts of labour and time especially for a large spatial and temporal variability [2]. Therefore, satellite remote sensing systems have been proposed as a good solution for measurement of forest parameters as providing extensive spatial information for different forest phenomena [3]. For instance, the Moderate Resolution Imaging Spectroradiometer (MODIS) on-board Earth Observing System (EOS) Terra/Aqua platforms, provides LAI as a standard product (MOD15) at a 1 km support, every eight days [3]. The low spatial support of the MODIS LAI product, however, limits the utility at local scales especially in the heterogeneous forest that are mostly planted, as in this study. Mustafa et al. [4] have estimated MODIS LAI at 250 m spatial support using MODIS normalized difference vegetation index (NDVI) product. Even with this finer support, the high landscape heterogeneity can be completely dissolved in 250 m pixels. Consequently, it could be concluded that such areas are not well represented in readily available global data and require more detailed surface representation by high spatial resolution satellite images such as IKONOS. The high spatial resolution images, however, are often not available during the year, due to atmospheric characteristics such as the presence of clouds and aerosols, and those images are expensive. Thus, for effective monitoring of terrestrial ecosystems for a long period of time it is more convenient to use lower cost high temporal resolution data.

The aim of this study is to estimate LAI in heterogeneous forests that show variation in space and time using MODIS data. This is performed by decomposing MODIS LAI, thus produce separate data for individual species. The study is applied to a heterogeneous forest, called the Speulderbos, in The Netherlands.

II. MATERIALS AND METHODS

A. Study Area

The Speulderbos forest is located between 51° 96' 06" to 52° 38' 00" N and 05° 61' 69" to 06° 08' 90" E (Fig. 1), it was planted in 1962. The tree height in 2006 was approximately 32 m with a density of 785 trees ha⁻¹. The forest cover consists of five tree species, i.e., Beech (*Fagus sylvatica*), Douglas fir (*Pseudotsuga menziesii*), Hemlock (*Tsuga spp*), Japanese larch (*Larix kaempferi*) and Scotch pine (*Pinus sylvestris*) [5]. A 46 m high tower with a climate station is situated at 52° 15' 08" N, 05° 41' 25" E, near the village of Garderen. An area of 4 km² has been considered in this study, Fig. 1.

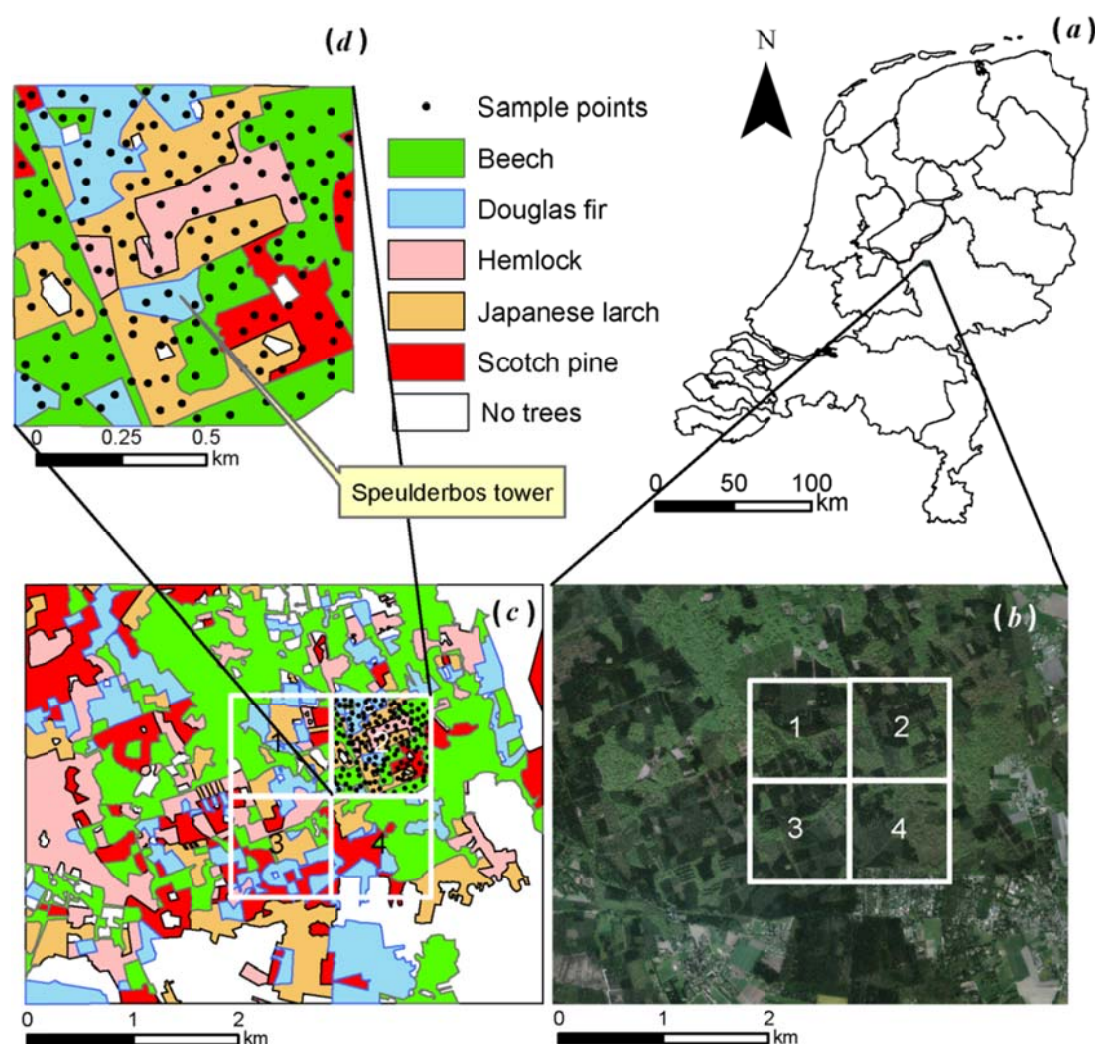


Fig. 1 Map (a) region of The Netherlands, (b) high resolution aerial image (c) classification of forest tree species using manual segmentation, and (d) sampling design of the 1×1 km

B. LAI Ground Data

1) Spatial Sampling:

Prior to the field work, a natural colour aerial image with a 0.25 m spatial support acquired during the summer of 2011 was used. A visual interpretation allowed us to determine forest cover species that verified in the field. Subsequently, the aerial image was manually segmented into five segments, one for each tree species and used as a reference polygon (Fig. 1(c)). Thereafter, the sample points were distributed over each segment following a stratified random sampling, Fig. 1(d). The number of sample points assigned to each tree segment was based on the proportion to the area covered by that segment. In total 155 sample points were distributed over the study area (Fig. 1(d)). The location of each sample point was mapped in a field campaign using two handheld GPS devices (Garmin eTrx and MobileMapper™ 6) with ± 3 m accuracy. These locations were labelled by marking the trees to allow taking consecutive LAI measurements (five times within every 16 days) at the same locations, from the end of April to the end of June 2011.

2) Methods and Measurements:

The Digital Hemispherical Photographs (DHPs) technique is used for LAI measurements. We used a Canon EOS 5D camera (21 megapixel) with a 15 mm F2.8 EX fisheye lens and a 180° field-of-view (15 mm, f/2.8). The camera with fisheye lens was held at 1.3 m above the ground and mounted on the tripod and pointed at 90° in the vertical direction (Fig. 2). At each sample point three photos with a distance of 5 m were taken and processed with the Gap Light Analyzer (GLA) software [6]. All measurements were made under diffuse light conditions to avoid introducing errors due to the presence of sunlit foliage. The LAI field data (LAI_{FD}) are obtained for all tree species of area number 2 as shown in Fig. 1 (c), and from April 23rd, 2011 to June 26th, 2011, and used as a validation data.



Fig. 2 Hemispherical camera and tripod set up in the discontinuous forest site

C. Satellite Data

For the sake of simplicity, we assume that pixels have a square footprint, that the ground sampling distance (GSD) equals the size of the footprint, and we ignore the effect of the point spread function (PSF). LAI estimation values can be provided by a spaceborne product, in particular MODIS every 8-days at 1 km spatial support [7]. The MODIS data sets for this study were:

- MOD03: Geolocation Fields Daily Level 1A (L1A) swath 1 km (originally 926.6 m) data, containing geodetic coordinates, ground elevation, solar and satellite zenith, and azimuth angles for each MODIS 1 km sample. These data are provided as a 'companion' data set to the Level 1B (L1B) calibrated radiance [8].
- MOD13Q: The VI product is gridded maps depicting spatial and temporal variations in vegetation activity for monitoring of the Earth's terrestrial vegetation. The bands of interest in this study are day of the year (DOY), the NDVI, and pixel reliability. NDVI data are available on a 16 day basis at a 250 m spatial support, whereas the original product is of 231.7 m support that is used in this study. The pixel reliability band in the NDVI product describes if pixels were generated using the historical filling criteria [9].
- MOD15A: MODIS LAI/ Fraction of Absorbed Photosynthetically Active radiation (FPAR) product. It is composed every 8 days at a 1 km spatial support on a Sinusoidal (SIN) 10-degree grid [7]. In this study the original product support of 926.6 m is used. The globe is tiled into 36 tiles along the east-west axis, and 18 tiles along the north-south axis, each covering $1200 \times 1200 \text{ km}^2$ [8]. The composite 8 day product is produced by using maximum FPAR.

In [4], we derived LAI from the MODIS NDVI product at a nominal 231.7 m spatial support and composited over 16 days. This is used in this study to produce LAI at finer support and we referred to it as a modified MODIS LAI (LAI_M) to distinguish it from the MODIS LAI product provided by NASA.

D. MODIS LAI Decomposition

1) Determination of Subpixel Area Proportion:

The LAI_M is derived from the composited MODIS NDVI product of 231.7 m every 16 days. A filter based on the MODIS VI algorithm including quality, cloud, and viewing geometry resulted in a composite VI image containing pixels from different days of the year. The DOY used in the composite product is linked to the L1B footprint of that day, identified using the information from the composite DOY band.

The Level 4 MODIS global LAI/FPAR product is assumed to have a fixed grid all the time with the spatial support of 926.6 m [7, 8] and labelled as a reference footprint. Four reference footprints are selected that fit to the size of the study of interest. These reference footprints are numbered as 1, 2, 3, 4 (Fig. 1 (b), and (c)) and gridded into 16 cells of spatial support of 231.7 m to match with the MODIS NDVI product. In order to identify the correct geolocation of each pixel in the MODIS VI products, we used MODIS MOD03 geolocation data of the day available from the compositing VI images. The MOD03 images with a spatial support of 926.6 m are also gridded into 16 cells of 231.7 m. MOD03 gridded cells of the identified DOY are intersected with the gridded cells of reference footprint and a shortest distance between centers of a grid cell of the MOD03 footprint and the grid cell of the reference footprint is selected (Fig. 3 (a)). The selected grid cell of MOD03 footprint considered to be the corresponded ground cell. Subsequent, the area proportion is determined by intersecting reference polygons of each tree species with the grid cell of MOD03 footprint of 231.7 m support. Fig. 3 (b) illustrates the procedure of determining the area proportion of each species within the MODIS grid cell that corresponds to the ground cell. This procedure was applied to all composite MODIS NDVI images (5 images) over the study time of two months.

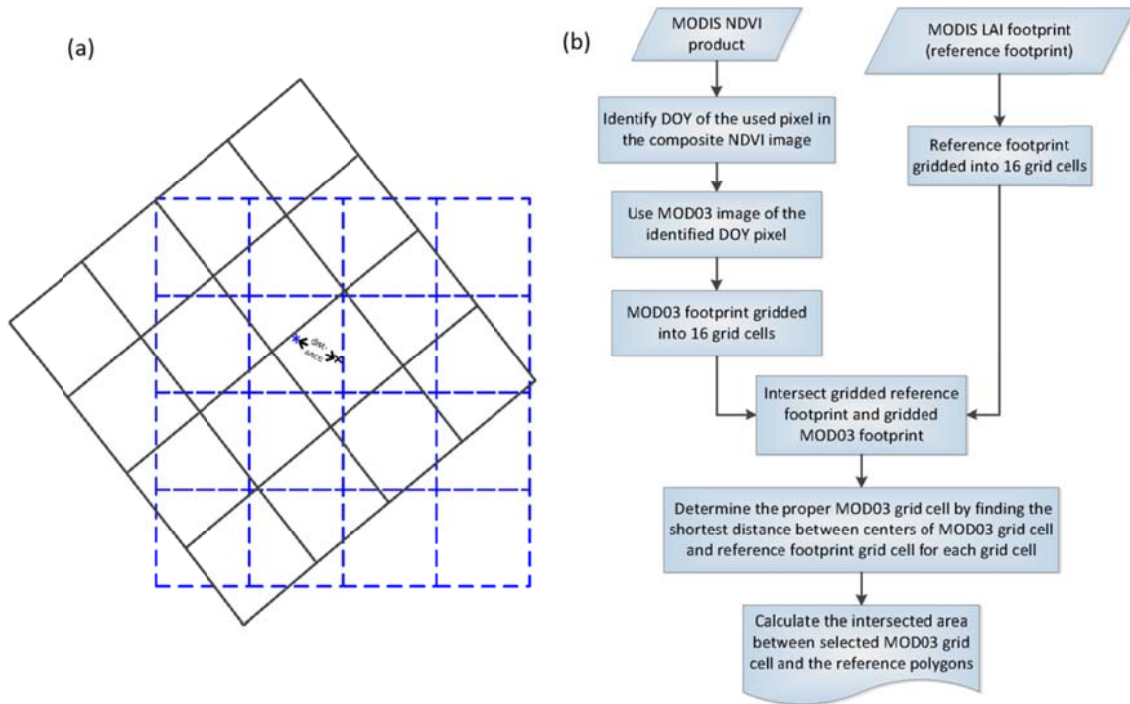


Fig. 3 (a) An example of determining a proper grid cell of MOD03 by selecting a shortest distance between the centre of a grid cell (x) of the MOD03 footprint and the centre of a grid cell (*) of the reference footprint (dashed line)

(b) Flowchart process of determining area proportion of each species within the MODIS grid cell

2) Decomposition:

We used the Linear Mixture model (LMM) to decompose the LAI_M value. The LMM assumes that the spectrum measured by a sensor is a linear combination of the spectra of all components within the pixel [10]. According to its definition, the LAI over a specific area can be interpreted as a linear composition of LAI s in subareas. This is achieved by considering the LAI_M pixel as a linear combination of LAI values of all species present in the modified MODIS pixel, and we assumed one LAI value of a certain species in the entire study area by ignoring the spatial variation of the species. The LMM is thus expressed as:

$$x_k^i = \sum_j A_{k,j}^i y_j^i + \epsilon_k^i \quad (1)$$

where i ($i = 1, \dots, 5$) refers to the image number, x_k^i is the LAI_M for pixel k at image i , A^i is a matrix of the area proportion values of species j ($j = 1, \dots, 5$) in pixel k at image i , y_j^i is the LAI of tree species j at image i , and ϵ_k^i is the residual for pixel k at image i . $A_{k,j}^i$ values are varying over images i based on the size of the polygon of each species j occupies in the footprint of grid cell of MOD03. Therefore, the explanatory variables in Expression (1) are the x^i (LAI_M) of each pixel and the A^i in the grid cells of MOD03. Hence, solving (1) using least squares leads to retrieving LAI values of each species in the MODIS image that is referred as the decomposed MODIS LAI (LAI_{SAT}). The resulting residual values by LMM for each species were used to assess the fit of the model. We applied this procedure to the set of MODIS images that were collected between April 23rd, 2011 to June 26th, 2011, by assuming that there is no major change in the forest composition as labeled by the reference polygons of each species.

III. RESULTS

Fig. 4 shows the resulted LAI_{SAT} values by decomposing the LAI_M values. We noticed unexpected decomposed MODIS LAI values at June 10th, 2011. This was due to MODIS orbit observations being far from nadir at all 16 days for the composite MODIS NDVI. This made the footprint resolution of a grid cell more than 1.2 km. Consequently, the area proportion resulting from intersecting the reference polygons with a grid cell footprint influences the calculation of the LAI values for all species. The unexpected decomposed MODIS LAI value of all species is replaced with the precedent values (Fig. 5). The spatio-temporal distribution for area number 2 (Fig. 1 (c)) of the LAI_{SAT} at the spatial support 231.7 m of mixed species is shown in Fig. 6. This is performed after considering the proportion of each species in the composition of each pixel. The accuracy of the decomposed LAI was tested using the Root Mean Square Error ($RMSE_{SAT}$) and the Relative Error (RE_{SAT}) rate with respect to the LAI field data. We found that the outcome of the decomposition approach was satisfactory with $RMSE_{SAT}$ of 0.31, 0.26, 0.37, 0.17, and 0.23 for Beech, Douglas fir, Hemlock, Japanese larch, and Scotch pine, respectively (Table I). Moreover, the RE_{SAT} of all of Beech, Douglas fir, Hemlock, Japanese larch, and Scotch pine were 7.31%, 6.43%, 8.68%, 3.47%, and 4.47%, respectively (Table I).

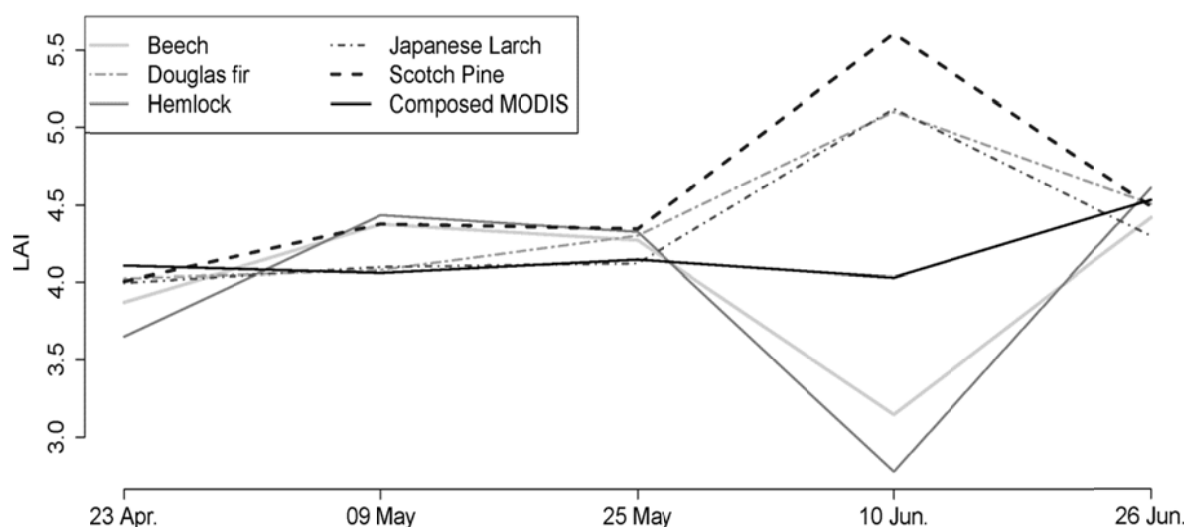


Fig. 4 Decomposed MODIS LAI into five LAI values of five species, Beech, Douglas fir, Hemlock, Japanese larch, and Scotch pine

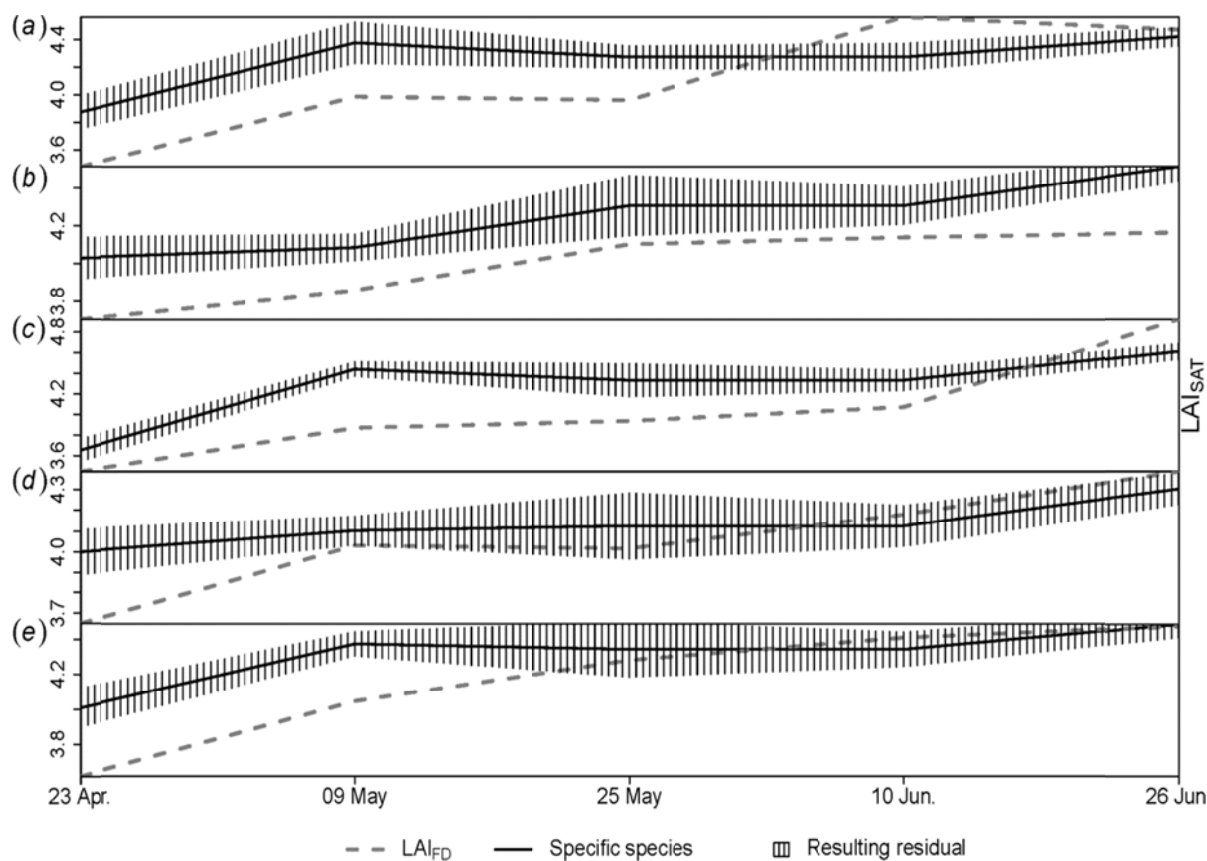


Fig. 5 Decomposed MODIS LAI into five LAI values of five species after replacing the unexpected LAI values with the precedent LAI values. (a) Beech, (b) Douglas fir, (c) Hemlock, (d) Japanese larch, and (e) Scotch pine

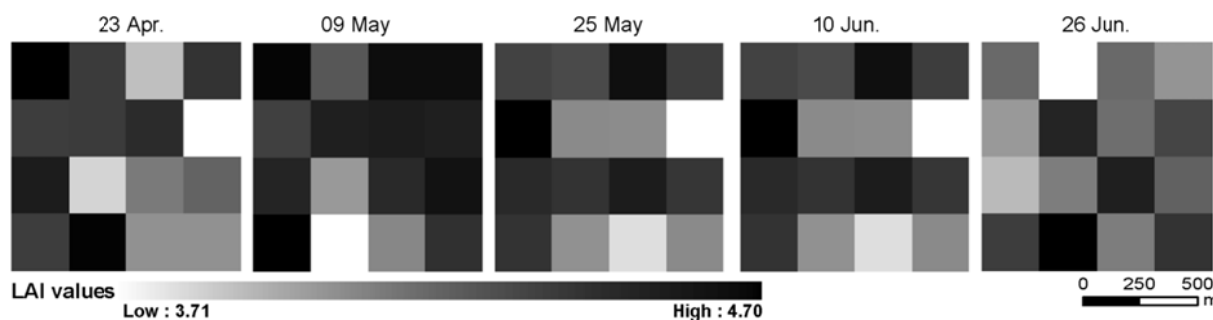


Fig. 6 The spatio-temporal distribution of the mixture LAI values considering the area proportion of each species from end of April 2011 till end of June 2011

TABLE I THE MEAN VALUES (μ), THE STANDARD DEVIATION (σ), ROOT MEAN SQUARE ERRORS ($RMSE_{SAT}$) AND RELATIVE ERRORS (RE_{SAT}) FOR THE DECOMPOSED LAI (LAI_{SAT}), AND THE LAI FIELD DATA (LAI_{FD}) OF FIVE TREE SPECIES DURING STUDY TIME

	Source	μ	σ	$RMSE_{SAT}$	RE_{SAT}
Beech	LAI_{SAT}	4.24	0.22	0.31	7.31%
	LAI_{FD}	4.09	0.43		
Douglas fir	LAI_{SAT}	4.24	0.20	0.26	6.43%
	LAI_{FD}	4.00	0.20		
Hemlock	LAI_{SAT}	4.27	0.36	0.37	8.68%
	LAI_{FD}	4.04	0.54		
Japanese larch	LAI_{SAT}	4.13	0.11	0.17	3.47%
	LAI_{FD}	4.05	0.26		
Scotch pine	LAI_{SAT}	4.31	0.18	0.23	4.47%
	LAI_{FD}	4.16	0.35		
Composed LAI	LAI_{SAT}	4.17	0.20	1.45	25.25%
	LAI_{FD}	5.60	0.43		

IV. DISCUSSION

The LAI value for a heterogeneous forest that shows variation in space and time is estimated using MODIS data. It is achieved by using LMM and information of the area proportion of each species within pixels of MODIS images. Our results showed that the decomposed MODIS LAI is estimated with significant values. The deviation between decomposed MODIS LAI and LAI field data are lower than the deviation between the composed MODIS LAI and LAI field data.

The strength of this approach is that the spatial LAI values can be estimated for a heterogeneous forest by classifying satellite images into the forest cover species. It requires dealing with the original raw data of satellite images and the use of the Linear Mixture Model. This study showed the applicability of the method with several tree species by treating each species individually and combines them taking in the consideration the area proportion of each species. Hence, a reliable and accurate LAI values can be estimated for mixture pixels.

We realize that the decomposition of MODIS LAI and identifying area proportions of each tree species directly using the nominal 250 m support of the VI product is not a suitable procedure. This is because the VI product is not a realistic representation of the actual ground area (i.e., instantaneous field of view (IFOV)) measured by the MODIS sensor. The composite VI images are derived by compositing image data from multiple images acquired from different orbit paths over a 16-day period, which has a different footprint every time. This was a reason of determining area proportion using MOD03 footprints. Two assumptions were proposed to implement the decomposition approach. First, no major change in the forest composition in terms of area proportion in the reference polygons of each species occurred during the study period. Second, one LAI value assumed for a specific species by ignoring a spatial variation of the species and considered as an average value. The latter assumption rarely holds in practice, but it allows a simple unmixing. This is, however, limiting the approach and a more dedicated model is required to do this species unmixing more reliably. These assumptions as sources of uncertainty might influence the accuracy of the LAI_{SAT} .

Some issues require further work. Extension of the time period and increased of the spatial scale may show a better explanation of seasonal changes in the LAI. Also, ground measurements should be collected for the study area at the same spatio-temporal support of the satellite images might improve validation of our approach.

Spatial data of the forest are becoming increasingly important for forest vegetation management, decision making and for climate change issues. The reliable and accurate estimations of the biophysical variables as LAI are useful and have served as inputs to functional models of ecosystem biogeochemistry. It provides a better understanding of the forest, description of the spatial pattern of forest structure, and which ultimately can serve as an informative factor in climate change.

V. CONCLUSIONS

In this study the LAI estimation for individual species with MODIS pixels is achieved by delineating the area proportion of each species followed by LMM. We conclude that the decomposed MODIS LAI of individual species is estimated successfully, such that the deviation between the decomposed LAI and the LAI filed data is 74.48% lower than the deviation between composed MODIS LAI and the LAI field data. Lastly, given the presented method and results in this study, our approach can be applied successfully to estimate LAI values for any heterogeneous forest.

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