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Evaluating the performance of the MODIS Leaf Area Index (LAI) product over a Mediterranean dryland planted forest

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The launch of the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites improved the ability to evaluate several surface biophysical parameters, including Leaf Area Index (LAI), which is provided as an operational MODIS product, available at 1-km spatial resolution and at 8-day intervals. However, for heterogeneous and sparse planted forests that are common to the semi-arid eastern Mediterranean region, the data at low spatial resolution may be significantly biased by the contribution of different background elements to the total surface reflectance received by the sensor and cannot therefore correctly reflect the real forest phenology. In the current paper the performance of the MODIS LAI product was examined over a dryland Mediterranean forest in southern Israel. The study found a significant discrepancy between ground-based and MODIS LAI datasets. In general, MODIS LAI values were *c*.51% of the ground-based LAI measurements. In addition ground based LAI peaked in the summer due to the natural growth cycle of the pine trees, while MODIS values peaked in the winter. The MODIS seasonal course could be explained by the development of annuals and crypto- and micro-phytes in the understorey and the clearing areas during the mid winter months that are included in the MODIS LAI product but not in the ground based measurements. However, for that period MODIS estimates should have exceeded ground-based estimates while in fact they were still lower. The relationship between MOD12C1 Land Cover Type 3 and MOD15A2 products is discussed.

1. Introduction

Leaf Area Index (LAI) is one of the main factors driving eco-physiological processes responsible for forest growth, and is used as an input to various ecosystem models. Ground-based methods of LAI estimation are widely used; however, they yield accurate information only for the close vicinity of the measured point. Consequently, satellite remote sensing systems have been proposed as a solution for extensive spatial LAI assessment (e.g. Andersen *et al.* 2002, Colombo *et al.* 2003). Currently, LAI is globally and routinely provided by NASA as an operational Moderate Resolution Imaging Spectroradiometer (MODIS) product at 1-km spatial resolution and at 8-day intervals. However, such low spatial resolution data, for which each pixel may be made up of several land cover types, might be of limited

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utility for semi-arid forested areas that are mostly sparse and heterogeneous (Sprintsin *et al.* 2007), therefore requiring detailed and careful validation by region- or site-specific measurements. LAI is a key parameter in land process models, terrestrial carbon modelling, dynamic vegetation models, large-scale carbon budgets and large scale climate models (Prince *et al*. 2001, Picard *et al.* 2005). Due to its central role in the dissipation of radiant energy input its erroneous assessment will affect the results of the models implemented. It is therefore important to assess the accuracy of the estimates supplied by the MODIS team, particularly in areas in which water limits plant development and in areas with heterogeneous cover.

Generally, the performance of the MODIS LAI product (MOD15A2) has been addressed in various studies that show reasonable LAI estimation from low spatial resolution imagery as compared to field data collection or high spatial resolution data (Privette *at al.* 2002, Morisette *et al.* 2003) over the network of EOS land validation core sites that was established in order to provide ground-based data for validation of MODLAND products (Morisette *et al.* 2002). Unfortunately, the distribution of these sites is very uneven, failing to cover a large fraction of the Earth's surface land. In particular, the Mediterranean region has never been systematically validated by ground measurements. However, during the past 40 years considerable areas in the eastern Mediterranean have been extensively afforested. In Israel alone, over 100 000 hectares were planted during this period. Thus the assessment of LAI on a high spatial scale at high temporal resolution can assist in studies at the ecosystem level related to climate change. The objective of this study was to investigate the performance of the MODIS LAI product for a dryland planted forest that can be deemed as being typical of large tracts of afforested lands of the eastern Mediterranean region.

2.   Study area

The study was conducted in the Yatir forest (31°21′ N and 35°02′ E, 630 m AMSL; ~3000 hectare area) located in a transitional area between arid and semi-arid climatic zones. The long-term average annual precipitation is 280 mm and the average total annual potential evapotranspiration is 1600 mm per year. The forest is predominantly planted with *Pinus halepensis Mill*. trees, mostly planted during 1964–1974. Average tree density is ~320 ± 75 trees ha^{-1}, mean tree height (H) ~9 ± 2 m, diameter at breast height (DBH) ~17 ± 4 cm, and canopy cover (CC) ~ 53 ± 15%. The trees grow on shallow Rendsina and lithosols soils (0.2–1.5 m depth) and overlay chalks and limestone. The understorey vegetation develops during the rainy season and disappears shortly thereafter (Grunzweig *et al.* 2003).

3.   Materials and methods

3.1   *Ground measurements of canopy structure*

LAI measurements were conducted monthly during a two-year period (September 2004–August 2006) with the Tracing Radiation and Architecture of Canopies (TRAC) photo-sensor device (Chen and Cihlar 1995, Leblanc *et al.* 2002). Measurements were made below the tree canopy, but above any understorey growth. Three plots of ~1000 m^2 each (approximately 31.6 × 31.6 m) were selected in the central, most mature (≈ 34–39 year old) section of the forest. Each plot was divided into 11 parallel east–west oriented sub-plots and transects were measured along the length of each sub-plot, giving a total sampling length exceeding 300 m per plot.

Table 1. A comparison of sampling plots characteristics to the entire forest averages. Numbers in parenthesis are the standard deviation of measurements.

Plot	Trees (ha^{-1})	Diameter at breast height (cm)	Tree height (m)	Canopy cover (%)
1	380	15 (3)	12 (5)	61
2	330	16 (4)	9 (2)	46
3	300	16 (5)	9 (2)	45
Entire forest	320 (75)	17 (4)	9 (2)	53 (15)

A detailed comparison of plots' characteristics on tree and plot levels to the overall forest averages provided by the Israeli Forest Service revealed small and acceptable deviation between both sets (table 1), and these were deemed to be representative of the entire forest.

To avoid the influence of non-random distribution of leaf inclination on transmitted solar radiation transects were measured three times a day for different solar zenith angles (SZA) with an average daily SZA of approximately 57° for each plot. Data analysis was conducted with the TRACWin program (Leblanc *et al.* 2002) and the average LAI of the three plots was assumed to be representative of that part of the Yatir forest. TRAC data were calibrated against allometric equations acquired distractively (Grünzweig *et al.* 2003). Those comparisons show ~ 7% difference between TRAC measured LAI (1.3 m^2 m^{-2}) and LAI estimated allometrically (1.21 m^2 m^{-2}), as a result of which TRAC data was accepted as the true overall LAI.

3.2 *Image data retrieval and processing*

The 1-km, 16-day composite, global data LAI product (MOD15A2; Collection 4) (Knyazikhin *et al.* 1999) was obtained through the Earth Resources Observation System (EROS) Data Active Archive Center (DAAC) over the entire studied period. A total of 96 images were processed and the area of interest (AOI) was extracted from the entire image. Mean and standard deviation (STD) were calculated over each studied AOI to describe the two-year dynamic of MODIS LAI. The statistics were then averaged for monthly values to fit the TRAC-measured dataset.

3.3 *Comparability of studied datasets*

The problem of upscaling and comparability between ground-based observations and low-resolution satellite imagery for the specific study area was the main issue of our previous paper (Sprintsin *et al.* 2007). Since (a) the results and intercomparisons between three datasets (i.e. TRAC and high- and low-resolution imagery) were found to be sufficient, and (b) the plots for ground measurements were carefully tested and found to be representative for the entire forest (in terms of tree and plot parameters; table 1) we feel justified in comparing directly between TRAC measurements (i.e. sub-pixel level) and MODIS operational product (i.e.

whole pixel level) while extending previous results and studying the ability of MODIS to capture the annual cycle of LAI.

4. Results

The seasonal evolution of TRAC-measured and MODIS-evaluated LAI is presented in figure 1. The overstorey LAI phenology as measured by the TRAC instrument is characterized by an increase from low values ($\sim$1.57) during the wet (November–March) to high values ($\sim$1.76) during the dry (March–August) season. In contrast, the MODIS LAI, which related to the entire mixed degree of a pixel including unvegetated areas and over and understorey, strongly diverges from the ground measurements. It peaks in the winter (1.4, as attained during the winter of 2004–2005 and 0.9 during the winter of 2005–2006 (December to March)), while reaching its lowest level (*c*.0.54) during the summer months (from June to September). This LAI distribution is in phase with the rainfall distribution.

The ground-based measurements show that overall average LAI increased towards the end of the first year (1.83 compared to 1.74), remained more or less constant until January 2006 and decreased to its lowest at March. A sudden increase was observed between March and April 2006 and a declining trend is observed thereafter, presumably in response to lower precipitation rates during the 2005–2006 hydrological year (373.5 mm for 2004–2005 as compared with 224 mm for 2005–2006; figure 1). This decline is also observed in MODIS LAI that was lower for the second as compared to the first year.
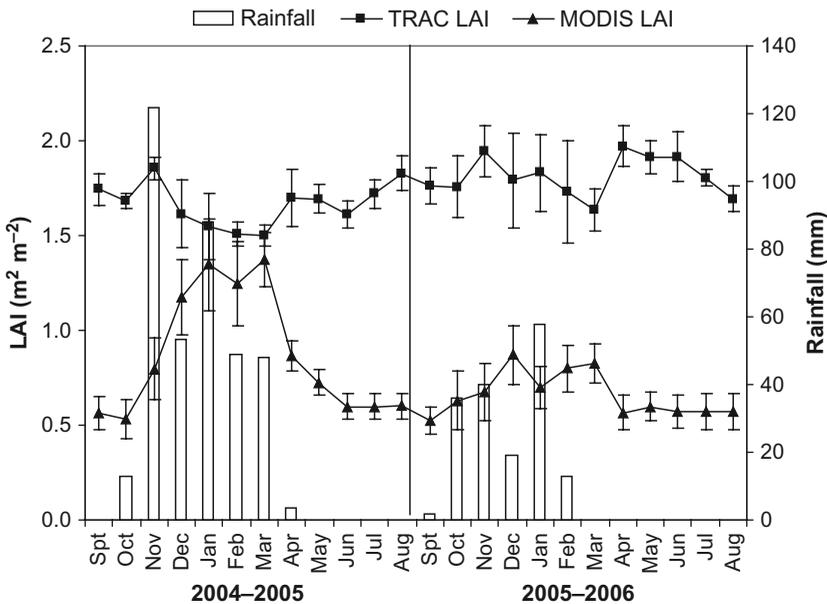

Figure 1. Annual dynamics of LAI measured by TRAC and acquired by MODIS for the two years of measurements, along with the corresponding monthly rainfall. Vertical bars represent standard error of measurements, calculated as $SE = \frac{STD}{\sqrt{n-1}}$ with *n* for the number of measurements or pixels.

5. Discussion

The provenance of Mediterranean pines is from a more humid climate, and despite some adaptation to local conditions, they also share many characteristics with temperate pine species (Liphschitz and Lev-Yadun 1986), amongst them needle flushing in spring and summer growth (Maseyk 2006). These features correspond to an increase in LAI. The results presented in figure 1 for two years of TRAC measurements support this expectation and show a similar trend for both years of the experiment.

As stated previously, the Yatir forest is sparse (average canopy cover was ~53% during the studied period) and also contains several plots covered by agricultural crops (figure 2). Such high landscape heterogeneity is combined with the clumpiness of the studied forest (Sprintsin *et al.* 2007). Clumpy vegetation can result in increased transmittance that causes underestimates of LAI in the inversion algorithms (e.g. Lang 1986, Welles and Cohen 1996). At low resolution, the unforested areas (clearings, large gaps or agricultural fields) are completely undetectable. They are integrated and mostly dissolved in the mixed 1 km^2 pixels of the MOD15A2 product (so it is likely that the MODIS measurements cannot determine this clumpiness). Furthermore, by mixing with the surrounding vegetation these areas contribute to a total reflectance measured by the overpassing satellite lowering the LAI to unreasonable levels (Sprintsin *et al.* 2007).
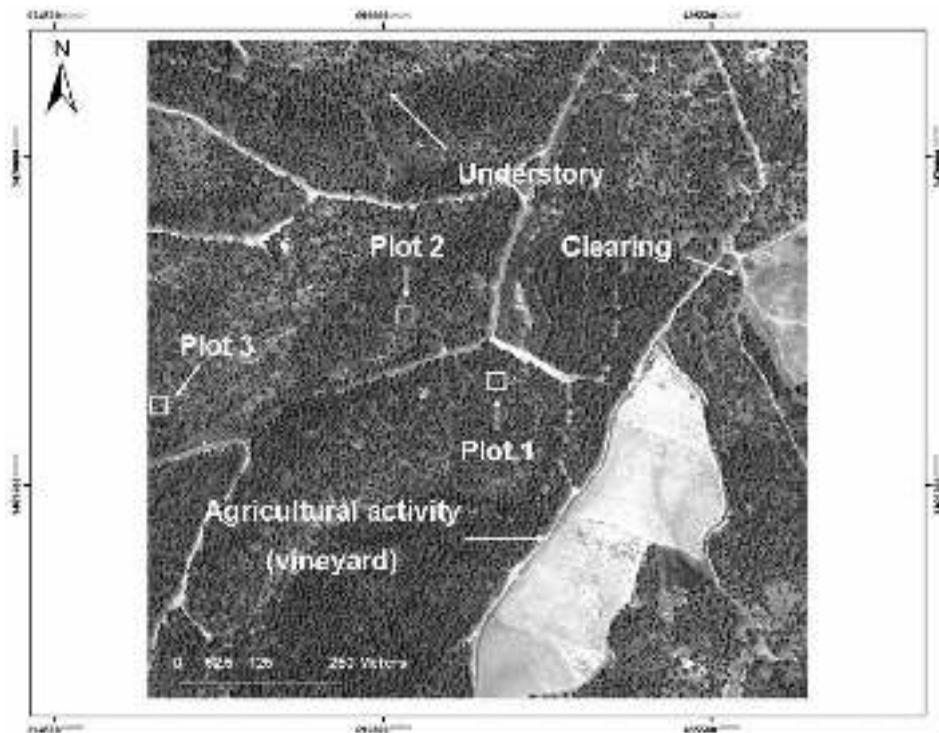

Figure 2. A representative area within the Yatir forest equals to one MODIS LAI/FPAR product pixel (1 km^2) with a location of training plots within it (white quadrates). The figure is a false colour composite IKONOS image (4 × 4 m spatial resolution) acquired at the end of the wet season (March 2004). Note the annual vegetation presented in red within forest stands.

It should be noted that any type of unmixing could certainly help to solve a problem of discrepancies between ground- and satellite-based observations. Unmixing, however, can be performed only on original (i.e. reflectance) datasets (which were out of the scope of the present study), while the operational products studied here should not require any additional processing, being straightforwardly applicable. We assume further that the contribution of unforested areas to a total surface reflectance is exaggerated during the winter, when ephemeral understorey annual plants and hemi-cryptophytes increase the total leaf coverage, compensate the phenological decrease of *Pinus halepensis* LAI (Maseyk *et al.* 2008) and cause the LAI in the MODIS product to increase. An additional factor that has to be taken into account is the microphytes (especially mosses) that turn green after the first rains of the season, before the germination of the annuals. The microphytes are widely spread in the clearing areas as well as inbetween the trees, producing relatively high reflectance values especially in the early winter (Karnieli *et al.* 1996, 1999).

Although the annual phenology generally increases the total LAI during winter as determined by both (the main and the backup) MODIS LAI algorithms, it was found to be always significantly underestimated, as compared to that measured by TRAC (average LAI values for both datasets are 1.74 ± 0.13 for TRAC compared to 0.76 ± 0.27 for MODIS) and its magnitude remained significantly lower than the ground based measurements of the overstorey. Following the explanations provided above we expected that during the summer, when the understorey is negligible, the MODIS LAI would be approximately equal to the ground-based measurements. Nonetheless, the results show the unreasonable decrease in LAI during the summertime, leading us to assume that it may be another reason for the discrepancies between both datasets.

As a result, we found that the area covered by forest is mistakenly associated with the larger territory classified by MODIS land cover classification product (MOD12C1 Land Cover Type 3 (LAI/FPAR biomes)) as shrubland. This general ignorance of the area covered by needleleaf forest that is big enough to be missed by land cover classification (approximately three MOD12C1 pixels) would not be expected by a MOD15A2 product user. Moreover, an overlapping between the MOD15A2 product and the map of afforested areas all over the state of Israel clearly indicates serious classification errors in spotting forests around the country (figure 3).

Figure 3 clearly indicates that more than a half of the country's territory is classified as shrubland. It also shows that most of the afforested areas fall into this category. The rest is unclassified (Negev desert area) or classified as broadleaf crops (e.g. coastal areas, southward of Haifa). As almost 100 000 ha of Israeli territory are afforested (I. Moshe, personal communication) this classification is not acceptable and is generally unclear, leading to a discrepancy between ground-based and satellite-based observations of forest canopy dynamics. Although all Israeli forests indeed belong to a Mediterranean forests, woodlands and shrublands biome (WWF 2007), this biome is by definition a mosaic landscape (Mooney *et al.* 2001), thus we certainly would anticipate more careful interpretation of measured surface reflectance by isolating the Mediterranean forests, woodlands and shrublands ecoregion as an additional biome within MOD12C1 Land Cover Type 3 product and consequently by treating each pixel separately.

In any event, it is clear that the magnitude of the MODIS LAI product is significantly out of phase with the overstorey phenology.
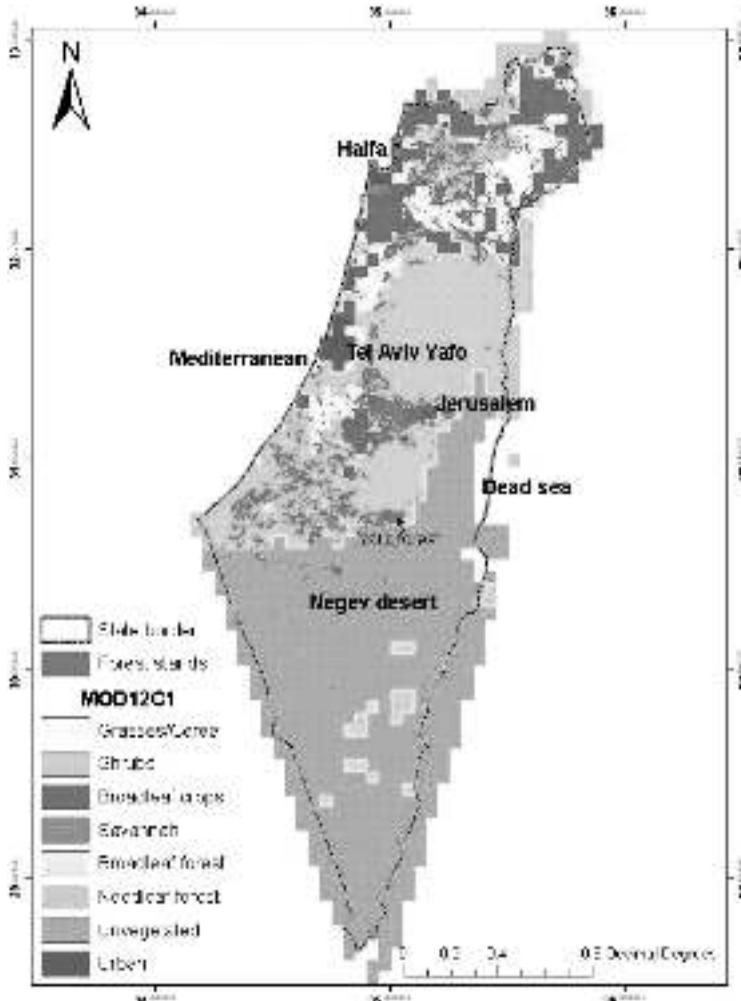
Figure 3. An overlap between land cover classification product (MOD12C1 Land Cover Type 3 (LAI/FPAR biomes) and the map of afforested areas all over the state of Israel. Note a discrepancy between actual land cover type distribution and MODIS-based land cover classification.

6. Conclusions

We studied the applicability of the MODIS LAI product (MOD15A2) to a dryland forest in the eastern Mediterranean region. We found that the area covered by the studied forest was misinterpreted by MOD12C1 Land Cover Type 3 (LAI/FPAR biomes) classification, being wrongly dissolved within a general shrubland land cover class, which also distorts the MOD15A2 product. As a result, we consider that the network of EOS land validation core sites should be extended to include territories thus far not covered, in order to increase the accuracy of standard MODLAND products while matching it also for overstorey studies.

In addition, it should be noted that the validity of low-resolution satellite imagery for forestry applications is strongly constrained by the inability to distinguish between different surface elements and land use as well as by the seasonality in annual emergence. The latter depends solely on soil water availability and has a strong effect on the total surface reflectance as measured by the satellite sensor, primarily during the wet season. The needle phenology of *Pinus Halepensis*, however, involves summer growth, occurring when the water availability is low. Consequently, a significant discrepancy between the annual course of TRAC-measured and MODIS evaluated LAI was found. This discrepancy restricts the MODIS LAI applicability for studying the overstorey processes, at least for semi-arid regions characterized by sparse and heterogeneous vegetation cover. However, a future work on ground-based quantitative estimates of the understorey vegetation LAI is required in order to validate the magnitude of the MODIS-derived LAI.

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