

LONG-TERM COMPARISON OF *IN SITU* AND REMOTELY-SENSED LEAF AREA INDEX IN TEMPERATE AND MEDITERRANEAN BROADLEAVED FORESTS

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ABSTRACT:

Monitoring vegetation structure and functioning is critical for modelling terrestrial ecosystems and energy cycles. Leaf area index (LAI) is an important structural property of vegetation used in many land-surface, climate, and forest monitoring applications. Remote sensing provides a unique way to obtain estimates of leaf area index at spatially extensive areas. However, the analysis and extraction of quantitative information from remotely-sensed data require accurate cross-calibration with *in situ* forest measurements, which are generally spatially- and temporally-limited, thereby limiting the ability to compare the seasonal dynamic patterns between field and remotely-sensed time series. This is particularly relevant in temperate broadleaved forests, which are characterized by high level of complexity, which can complicate the retrieval of vegetation attributes from remotely-sensed data.

In this study, we performed a long-term comparison of MODIS LAI products with continuous *in situ* leaf area index measurements collected monthly in temperate and Mediterranean forests from 2000 to 2016. Results indicated that LAI showed a good correlation between satellite and ground data for most of the stands, and the pattern in seasonal changes were highly overlapping between the time-series. We conclude that MODIS LAI data are suitable for phenological application and for up-scaling LAI from the stand level to larger scales.

1. INTRODUCTION

Monitoring forest structure and functioning is critical for understanding changes in forest coverage and health in response to management and climate, and for modelling terrestrial carbon and energy cycles. Remote sensing provides a unique way to obtain estimates of forest attributes at spatially extensive areas, from local to the global scale. In addition, the availability of standardized information over time allows to make projections under different forest management and climate change scenarios (Ciolli et al., 2012; Ferretti et al., 2018; Ciolli et al., 2018).

Among the measured variable, leaf area index (LAI), defined as half the total green leaf area per unit ground surface area (Chen and Black, 1992), is an important structural property of vegetation used in many land-surface, climate, and monitoring programs. LAI directly influences the radiative transfer of sunlight in vegetation, determining the amount of radiation measured by optical (passive) remotely-sensed sensors in the visible and infrared portions of the electromagnetic spectrum (Asnar et al., 1984; Zhen and Moskal, 2009).

Optical remote sensing of leaf area index requires accurate calibration with *in situ* measurements (Boer et al. 2008; Prosspatin and Panferov, 2013; Xu et al., 2018). This is particularly relevant in temperate and Mediterranean forests, which are characterized by high level of complexity, which can complicate the retrieval of vegetation attributes from optical remotely-sensed sensors (Angelini et al. 2015; Leroux et al., 2018; Munier et al., 2018; Puletti et al., 2018). However, *in situ* datasets are mainly available in boreal forests (e.g., Kuusk et al., 2009) and austral forests (e.g., Woodgate et al., 2015), while such datasets in temperate and Mediterranean forests are scarce. In addition, the majorities of previous studies build relationships exploiting *in situ* measurements performed in a single period (typically a single field campaign), since the availability of long-term ground-truth data series has been limited by the cost and time required by field sampling. The operational Moderate Resolution

Imaging Spectroradiometer (MODIS) sensors have provided an opportunity for opening a new horizon of satellite LAI products (Myneni et al., 2015). The latest version (Collection 6, C6) provides continuous LAI data since 2000. To date, no previous studies have performed a comprehensive temporal investigation of LAI time series, since the preliminary evaluations were temporally limited (Xu et al., 2018).

In this study, we performed a long-term comparison between MODIS LAI products with continuous *in situ* leaf area index measurements collected in temperate and Mediterranean forests from 2000 to 2016. Our specific objectives were:

- Evaluate the temporal consistency of (latest) MODIS LAI product along its operational range;
- Checking the ability of MODIS to detect trend, intra-annual variations, seasonal cycle of LAI as compared with *in situ* measurements in Mediterranean and temperate forests
- Evaluate the applicability of MODIS LAI products at the forest stand scale.

2. MATERIAL AND METHODS

2.1 Study area

The data have been collected within the framework of a wider project (LIFE 14 ENV/IT/000514 “FutureForCoppiceS”; www.futureforcoppices.eu) aimed to demonstrate the effect of different management options on sustainable forest management criteria and indicators in temperate and Mediterranean coppice forests. In the project, 45 stands were surveyed in seven forest districts located in two Italian regions (Sardinia and Tuscany) the area sampled was on average about 2800 m² (800-10000 m²). Thirteen stands located in Tuscany were amongst selected to be included in this study due to their larger temporal availability of leaf area index data and extent comparable with MODIS resolution. The stands are located in large homogeneous forest stand areas and are representative of two European Forest Types (EFT; Barbati et al., 2014): thermophilus deciduous forests

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dominated by Turkey oak (*Quercus cerris* L.) (EFT 8.2) and mountainous beech (*Fagus sylvatica* L.) forests (EFT 7.3). The data are available from an open repository (Chianucci et al., 2018). Table 1 lists the characteristics of the studied stands.

Forest district	EFT	Stand density n ha ⁻¹	Basal area m ² ha ⁻¹
Alpe di Catenaiia	7.3	412	29.77
Alpe di Catenaiia	7.3	2046	48.15
Alpe di Catenaiia	7.3	419	39.45
Alpe di Catenaiia	7.3	108	19.9
Alto Tevere	8.2	436	20.21
Alto Tevere	8.2	1222	33.26
Colline Metallifere	8.2	4509	30.17
Colline Metallifere	8.2	54	1.37
Colline Metallifere	8.2	682	16.31
Foresta di Caselli	8.2	2667	38.89
Foresta di Caselli	8.2	2167	44.11
Foresta di Caselli	8.2	3417	41.66
Foresta di Caselli	8.2	2922	42.67

Table 1. Main characteristics of the studied stands

2.2 In situ leaf area index

LAI measurements were performed monthly every year, from 1999 to 2016, in the studied stands, just after dawn or close to sunset and under uniform sky conditions using the LAI-2000. Plant Canopy Analyzer (LI-COR, Lincoln, NE, USA). The optics of LAI-2000 consists of a fisheye lens divided into five concentric rings. Each ring simultaneously integrates incoming radiation in the 320 - 490 nm wavelength (blue light) range. During each sampling session, one above-canopy reference measurement was recorded in clearings near each stand. Nine to 15 below-canopy measurements were then collected for each stand. The fisheye lens of the instrument was covered by a 90° view cap to avoid the influence of surrounding trees on the reference measurements. Gap fraction was estimated as the fraction of below- to above-canopy readings. Leaf area index corrected for apparent clumping (Ryu et al., 2010) was then calculated using the Miller's (1967) theorem.

2.3 Remotely sensed leaf area index

Remotely sensed LAI measurements for the studied stands were obtained from the MODIS sensor (Moderate Resolution Imaging Spectroradiometer) available on Terra and Aqua satellites, formerly known as EOS AM-1 and EOS PM-1.

MODIS Land Products Subset MOD15A2 was chosen because it provided readily available 8-day composite LAI measurements starting from the year 2000 to present. Data were downloaded from the Distributed Active Archive Center (ORL DAAC, 2018). Data were downloaded for a window of 7x7 km centered on the forest district average coordinates with a resolution of 1km (Myneni, et al., 2015).

2.4 Statistical analyses

Data were processed in R environment (R Core Team 2015). First, the time-series alignment between field and remote sensed data was performed using the 'eXtensible' package (Ryan and Ulrich 2017) and interpolation for missing data. The data were then checked for cross-correlation using the 'CCF' function of the 'nlme' package (Pinheiro and Bates, 2017). CCF was run also on the difference between LAI value at time t and the previous value at time $t-1$ to account for the correlation about the direction of change rather than considering the absolute values. A paired T test was then performed to assess the difference in the two time-

series for both absolute values and differences between subsequent times, using a significant threshold of $p < 0.01$.

3. RESULTS

The studied stands were characterized by relatively-high canopy density, as indicated by the high LAI values observed in summer (vegetation-peak period). Field measurements yielded LAI values ranging between 0.75 and 6.73 in beech stands (average \pm standard deviation: 4.4 ± 1.6) and between 0.33 to 7.97 in thermophilous oak stands (3.5 ± 1.1) considering all the seasonal data series. MODIS LAI values ranged between 0.10 and 5.66 in beech stands (4.3 ± 1.2) and ranged between 0.10 to 6.37 in thermophilous oak stands (4.01 ± 1.3).

The analysis was performed for separate districts where the starting year of sampling and the number of field LAI measurements was (brackets): Alpe di Catenaiia (1999, 298), Alto Tevere (1999, 178), Colline Metallifere (1999, 259) and Foresta di Caselli (1999, 255). Results showed a significant agreement in trend between field and remotely sensed data considering either the aligned data series (Figure 1) and the data averaged on monthly basis (Figure 2) in the considered forest district ($p < 0.01$), with the exception of Foresta di Caselli ($p = 0.089$, thermophilous oak forests) and Alpe di Catenaiia ($p = 0.14$, mountainous beech forests) districts, where the alignment was not significant.

The CCF analysis showed a significant agreement between field and remotely-sensed LAI values (T test) meaning that the LAI changed in the same direction in both types of measurements.

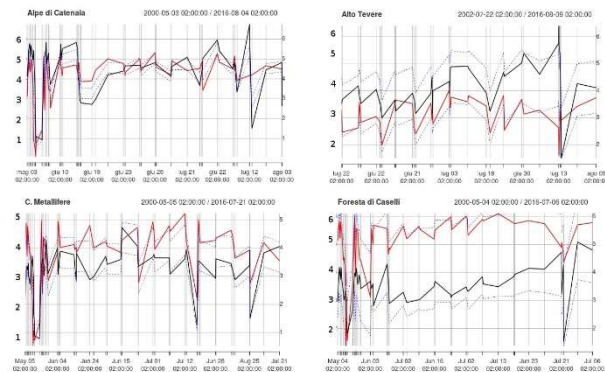


Figure 1 Aligned time series for field (black) and remotely sensed (red) LAI measurements with 95% confidence intervals (blue dashed lines) in the following districts: a) Alpe di Catenaiia, b) Alto Tevere, c) Colline Metallifere and d), Foresta di Caselli, Italy.

4. DISCUSSION AND CONCLUSIONS

The main results imbue confidence in the consistency of long-term MODIS LAI time series. The advantage of MODIS products is its large temporal and spatial resolution, which has often been used for large scale studies on LAI across biomes (Weiss et al., 2007). Our results also indicated that MODIS LAI products can be used for medium spatial scale (forest stand level) applications, based on the agreement between satellite and field measurements. The repeated seasonal field measurements also allowed to verify that MODIS LAI can capture the seasonality pattern of LAI at the stand scale, as the speed and sign of change are comparable between field and satellite time-series data.

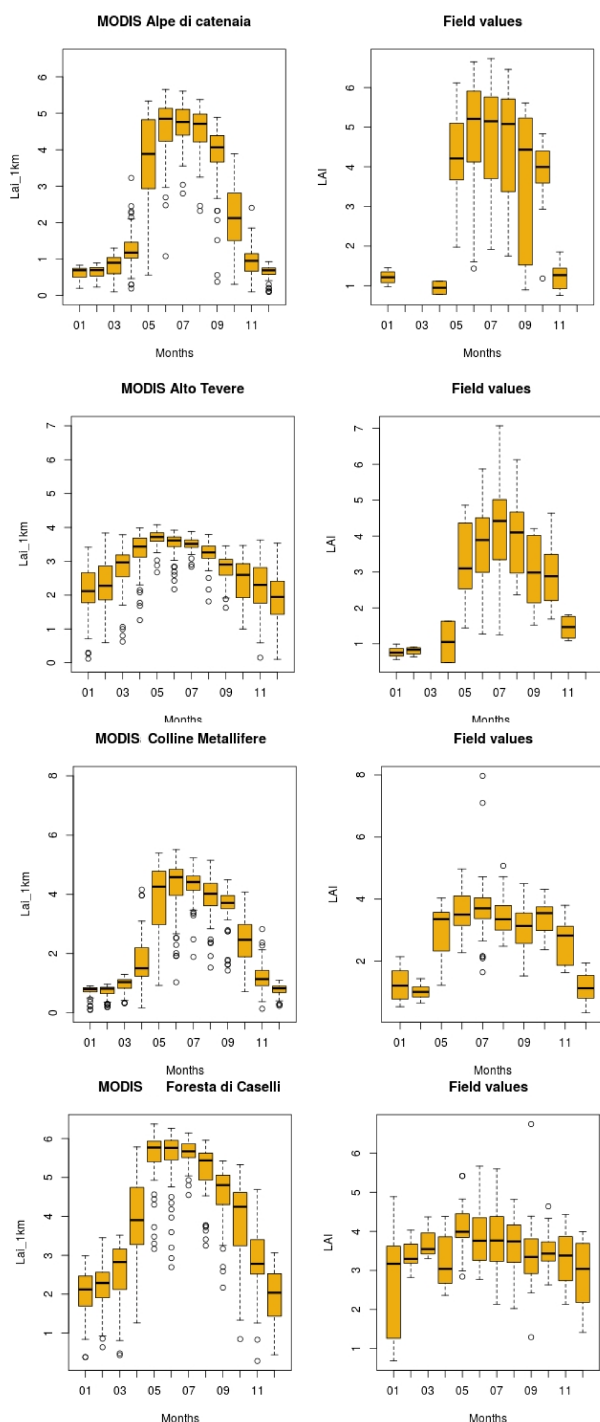


Figure 2 Average monthly values (2000-2016) of LAI measured from MODIS (left) and LAI measured on site (right) for each district, from top to bottom: Alpe di Catenaiia, Alto Tevere, Colline Metallifere and Foresta di Caselli, Italy.

While consistent with another study performed in an open canopy stand (Ryu et al., 2012), the results extend the applicability of MODIS LAI in temperate and Mediterranean forests, which are often characterized by very high canopy density ($LAI > 5 \text{ m}^2 \text{ m}^{-2}$, Alivernini et al., 2018; Cinnirella et al., 2002; Thimonier et al., 2010; this study) which can limit the retrieval of optical information from satellite data. Indeed, optical measures often saturate at leaf area index values of about 5 (Thenkabail et al., 2000), while vegetation indices using near-infrared bands may saturate at lower values (Davi et al., 2006; Turner et al., 1999).

In addition, Mediterranean forests exhibits different phenological patterns according to forest categories and types, and therefore accurate temporal resolution data are strongly required for discriminating different forest types in these environments. Taken together, results indicated that temporal MODIS LAI are suitable for modelling and up-scaling LAI from the stands to larger areas. The discrepancy in the average of LAI measurements from the two sources, which can be observed in some points of the series, can be explained by the different spatial resolution of the data (Rocchini 2007, Geri et al., 2011, Xu et al., 2018). MODIS LAI has the resolution of 1 km, and despite the field measurements were taken in stands that are representative of the surroundings, the above-mentioned limits in measures taken in temperate forest is compatible with the observed pattern. We conclude that the availability of long time-series satellite products with quick revisiting time enabled a reliable investigation of seasonal patterns dynamics, which can support finer application on forests ecology and management and phenological monitoring.

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