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Long term and seasonal courses of leaf area index in a semi-arid forest plantation

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ABSTRACT

Effective leaf area index (LAI_e) in the semi-arid *Pinus halepensis* plantation, located between arid and semi-arid climatic zones at the edge of the Negev and Judean deserts, was measured bi-annually during four years (2001–2004) and more intensively (monthly) during the following two years (2004–2006) by a number of non-contact optical devices. The measurements showed a gradual increase in LAI_e from ~ 1 (± 0.25) to ~ 1.8 (± 0.11) during these years. All instruments, when used properly, gave similar results that were also comparable with actual leaf area index measured by litter collection and destructive sampling and allometric estimates. Because of the constraint of clear sky conditions, which limited the use of the fisheye type sensors to times of twilight, the fisheye techniques were less useful. The tracing radiation and architecture of canopies system, which includes specific treatment of two levels of clumpiness of the sparse forest stand, was used successfully for the intensive monitoring. The mean clumpiness index, 0.61, is considered representative for the specific environment. Finally, the LAI_e measurements at the start of each season were used to constrain phenology-based estimates of annual LAI_e development, resulting in a continuous course of LAI_e in the forest over the five-year period. Intra-seasonal LAI_e variation in the order of 10% of total LAI_e predicted by the model was also observed in the intensive TRAC measurements, giving confidence in the TRAC system and indicating its sensitivity and applicability in woodlands even with low LAI_e values. The results can be important for forest management decision support as well as for use in evaluation of remote sensing techniques for forests at the lowest range of LAI_e values.

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1. Introduction

Leaf area index (LAI) is a central parameter in characterizing plant systems. It strongly influences the timing and magnitude of many ecosystem processes, such as rain interception, evapotranspiration, photosynthesis, respiration, soil organic matter input, and is a basic canopy structural parameter of process-based canopy ecophysiology and land-surface models. In forests, which can cover vast areas, correct estimates of LAI are essential for evaluating ecosystem impacts on climate, biogeochemical cycling and energy balance. It is therefore necessary to obtain detailed information on LAI behavior, including the magnitude and drivers of temporal LAI variations, in different environments. Considering the anticipated

expansion of dryland and drought affected regions in the future (Pineal et al., 1998), studies of LAI dynamics in dryland forest environments are necessary, but remain limited (López-Serrano et al., 2000; Law et al., 2001a,b; Sprintsin et al., 2007, 2009a,b). Furthermore, correct characterization of the different, but often indirect, methods of measuring LAI is essential for reliable estimates of LAI.

Several semi-direct (i.e., by allometry) and indirect (i.e., non-contact optical) methods for LAI measurement have been developed and tested (e.g., Hutchinson et al., 1986; Gower et al., 1999; Brown et al., 2000; Andersen et al., 2002; Jonckheere et al., 2004; Wang et al., 2004). Although the former have been shown to be comparable with theoretically more accurate destructive sampling measurements, they can have a number of limitations due to using site-specific equations and variable sensitivity to stand age, density, and climatic conditions (Le Dantec et al., 2000). Therefore, for regular ground-based monitoring of forests, a practical option is non-contact gap fraction inversion (GFI), in which measurements of total, direct or diffuse radiation transmittance through the canopy to the forest floor is used to estimate LAI (Breda, 2003). A potential problem with indirect techniques is the discontinuous

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nature of most tree canopies and forest stands. This problem, however, is usually overcome using a fitting parameter that accounts for non-random leaf arrangement (Nilson, 1971; Chen and Black, 1992; Welles and Cohen, 1996). Plantation forestry was originally established to provide industrial timber, initially for local use in countries, which had small natural forest estates. Today, plantation forests comprise around 135 million hectares globally, with annual afforestation and reforestation rates nearing 10% of total forest area and are extended functionally to non-industrial use such as greening and recreation (FAO, 2006) and geographically to arid and semi-arid environments (Ffolliott et al., 1995). Even though the latter comprise a significant part of the Earth's terrestrial surface and have experienced extensive afforestation efforts since the early 1960s, there is a lack of scientific attention paid to LAI of dryland forests. In particular, lack of foliage structural parameterization has limited the implementation of non-destructive techniques, as these forests can present a considerable challenge to GFI methods due to being highly clumped and unevenly structured in the spatial domain (Sprintsin et al., 2007). Some forest processes, which depend on LAI, are mainly influenced by the first few canopy layers, where the largest part of the solar radiation is absorbed and which are most active. This implies that in forests with low LAI (as expected for water-limited environments) small changes in LAI can have a large impact on environmental and canopy processes and therefore accurate measurement is essential. Therefore, reliable characterization of LAI is important for optimum management of ecosystem services and sustainability.

Here we investigated the measurements of LAI of a semi-arid planted Aleppo pine forest characterized by low stand density (≈ 300 trees ha^{-1} ; Sprintsin et al., 2009a,b) and an incomplete canopy cover ($\approx 57\%$; Sprintsin et al., 2007). Individual tree crowns are sparsely leafed and the sky is clearly visible even when standing below a large tree. Precipitation (~ 280 mm year^{-1}) varies greatly from year to year (Volcani et al., 2005) with about 70% of the effective rainfall (e.g., events > 2 mm) being lost via transpiration (Schiller and Cohen, 1998; Raz-Yaseef et al., 2010), and it is not clear to what extent variations in rainfall influence LAI or what the temporal dynamics of that influence is. Furthermore, it is unclear if in these conditions forest LAI reaches a steady state and if so, at what age?

The objectives of this study were two-fold. First, to summarize multi-year LAI measurements in a dryland forest plantation and second, to report the annual dynamics of LAI based on intensive monitoring of the seasonal course measured with one selected GFI method, given that the published data regarding the specific environment and species is sufficiently rare (López-Serrano et al., 2000). The measured seasonal course was also compared to model estimates based on phenology (needle elongation and senescence) dynamics (Maseyk et al., 2008).

This paper focuses on three particular questions:

1. To what extent do inversion methods give accurate and reliable estimates of LAI in sparse semi-arid forests?
2. How well can inter- and intra-yearly changes in LAI be monitored with inversion techniques?
3. Is LAI of the Yatir forest, which can be considered typical of large tracts of afforested lands of the eastern Mediterranean region, stable during the year and over a longer period of time?

2. Theory

2.1. Indirect methods for LAI assessment

In this study LAI was defined as horizontally projected leaf area, i.e., the area of 'shadow' that would be cast by each leaf in the

canopy with a light source at infinite distance and perpendicular to it, summed up for all leaves in the canopy (Ross, 1981; Asner et al., 2003, definition 3). Determination of a leaf surface area index from this information requires knowledge of the ratio of surface area to projected area.

Indirect 'gap fraction' methods of LAI estimation are based on the measurement of light transmission through canopies and a statistical approach to foliar element distribution (Lang, 1986; Lang and Xiang, 1986; Welles and Cohen, 1996; Cohen et al., 2000; Breda, 2003). These methods apply the Beer-Lambert's law where transmittance of direct radiation by the canopy depends on incident direct irradiance, canopy structure and optical properties such that:

$$P(\theta) = e^{-G(\theta)LAI_e / \cos \theta} \quad (1)$$

where $P(\theta)$ is gap fraction, LAI_e is the effective LAI, which includes leaves and non-leafy materials (Leblanc et al., 2005a,b). θ is solar zenith angle; and $G(\theta)$ is the foliage projection coefficient corresponding to the fractional relative projection of the foliage on the plane normal to the zenith direction. $G(\theta)$, which depends on the foliage angular distribution, can be determined from gap fraction measurements made at a range of θ s (Norman and Campbell, 1989a,b). Another alternative is to measure gap fraction at $\theta \sim 57^\circ$, where $G(\theta)$ is similar for most leaf angle distributions (Lang, 1987).

The Poisson model, i.e., Eq. (1), describes canopies with randomly distributed canopy elements (i.e., leaves or shoots). In the case of non-random, clumpy leaf arrangement, straightforward inversion leads to significant errors caused by increased transmittance of solar radiation through the canopy and subsequent underestimation of LAI (e.g., Welles and Cohen, 1996; Gower et al., 1999). Non-random distributions of canopy elements can be dealt with by introducing a clumping index ($\Omega(\theta)$) into the right-hand side of Eq. (1), with $\Omega(\theta)$ for regular leaf arrangement (Nilson, 1971).

In coniferous stands, three major scales of clumpiness can be identified: within-shoot clumping of needles, within-canopy clumping of shoots and branches and inter-tree or within-stand clumping. The basic foliage unit of conifer trees, however, is the shoot, whose size was approximated by Chen and Cihlar (1995) as the average projected shoot width. This is because small (between-needles) gaps disappear in the shadow in a short distance as a result of the penumbra effect (Chen and Black, 1992). Consequently, the amount of needle area within the shoots can be hardly estimated by optical gap fraction instruments (Leblanc et al., 2002) and the $\Omega(\theta)$ value has to be presented as the ratio between the element clumping index that includes the effect of foliage clumping at scales larger than a shoot ($\Omega_E(\theta)$) and the needle-to-shoot area ratio that quantifies the effect of foliage clumping within the shoot (γ_e). Values of γ_e for several species are available in the literature (e.g., Chen et al., 1997; Gower et al., 1997) while the $\Omega_E(\theta)$ can be found for different θ following Kucharik et al. (1999) as:

$$\Omega_E(\theta) = \frac{\Omega_{E,max}}{1 + b \exp(k\theta^p)} \quad (2)$$

where θ is in radians, p and k are species specific constants and b can be found by solving Eq. (3) with one measurement of $\Omega_E(\theta)$. The maximum value of clumping index ($\Omega_{E,max}$) is proportional to stem density as:

$$\Omega_{E,max} = \left(\frac{N \cdot CW}{\sqrt{A}} \right)^{0.7} \quad (3)$$

where CW is an average crown width (m) and N is the number of stems per area, A .

Generally, it should be remembered that optical methods estimate LAI_e (a.k.a. plant area index) rather than true leaf area index (LAI). The latter could be calculated from leaf litter, allometry and/or by destructive sampling. So just as the calculation of leaf

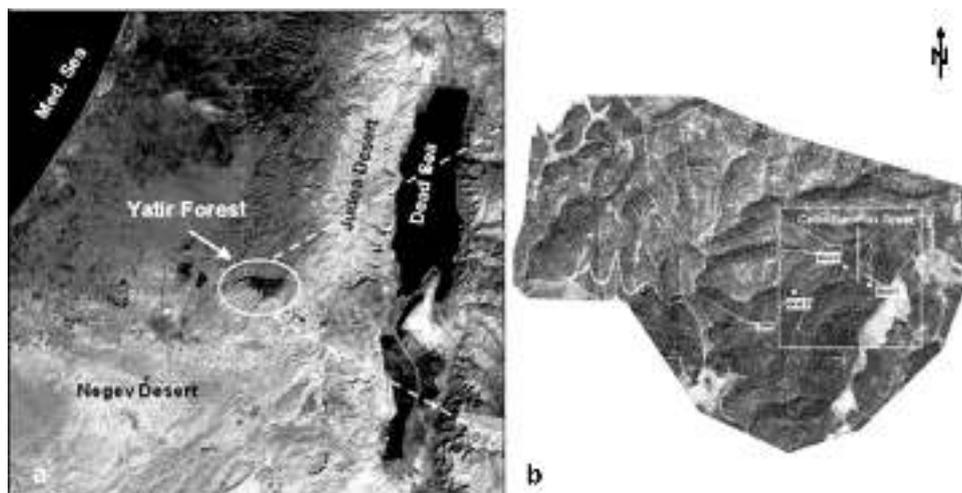


Fig. 1. (a) Landsat-TM image of Central Israel. Note the location of the Yatir forest on the desert fringe, visible as the sharp contrast between bright tones (arid zone) and dark tones (semi-arid zone). (b) Sampling plots are indicated by white dots within the FluxNet site footprint area of approximately 1 km² (white rectangle) described by Grünzweig et al. (2003).

surface area index requires a priori information on the shape of the leaf cross section, the determination of the projected area of woody material must be quantified for the specific species and habitat independently of the gap fraction inversion measurements, e.g., as the woody-to-total area ratio. Since not all the techniques used in this study include this parameter, care has been taken to differentiate between LAI_c and LAI.

2.2. Foliage orientation

The contact number $K_N(\theta)$ expresses the average number of contacts that a direct beam would make when traversing the canopy at given θ , i.e.:

$$K_N(\theta) = \ln(P(\theta)) \cos \theta \quad (4)$$

Lang (1986) showed that the slope of the relationship between K_N and θ can be used to determine the mean leaf area and a mean value of G and determined a polynomial equation to express that relationship. Campbell (1986) expressed the leaf angle distribution in terms of the relative angular distribution of area on the surface of an ellipsoid. Norman and Campbell (1989a,b) developed a numerical method to determine the value of the ratio between the vertical and horizontal axis of the normalized ellipsoid from the relationship between K and θ . Their numerical routine was used in the current study for determining the mean leaf angle of the foliage when using the TRAC and Sunlink devices, while the other instruments include built in processing with similar algorithms.

All of the optical instruments used for these measurements cannot resolve the contribution of stems to the leaf angle distribution. In our case and elsewhere, we should keep this in mind. The woody-to-total area ratio for pines similar in morphology to ours is approximately 0.1, and since we did not measure this ratio we took that as constant. For our case we assume that the contribution of woody stems to the leaf angle distribution is minimal.

3. Materials and methods

3.1. Study area

The study was conducted in Yatir forest (31°21'N and 35°02'E, 630 m AMSL; ~3000 ha area) located between arid and semi-arid climatic zones at the edge of the Negev and Judean deserts (Fig. 1a).

The mean annual precipitation (~280 mm) usually occurs during ~30 days year⁻¹ between November and March and is characterized by large annual fluctuations and an uneven distribution of the rainfall events within the rainy season. The average total annual potential evapotranspiration (PET) is 1600 mm year⁻¹, yielding a long-term aridity index (PET/precipitation) of ~5.6–5.9, associated with arid regions (UNEP, 1992). Management practices, primarily including heavy thinning, aim to maintain forest vitality under limited available water. As a result, the area is heterogeneous and the forest currently consists of individual canopies rather than tree rows.

The hottest month in the Yatir region is July and the coldest is January. The average yearly maximum and minimum temperatures are 32.3°C and 6.9°C, respectively (Schiller and Cohen, 1998). Most of the forest was planted during 1964–1969, so it is almost even-aged, and is close to a monoculture dominated by Aleppo pine (*Pinus halepensis* Mill.). The trees grow on shallow Rendzina soil and lithosols (0.2–1 m deep) overlay chinks and limestone. The ground water table is deep (~300 m) and sparse understory vegetation develops during the rainy season and disappears shortly thereafter (Grünzweig et al., 2003). Due to its unique location the Yatir forest is a focal point for extensive dryland research. Since 2000 the Weizmann Institute of Science has maintained a flux tower in the forest as part of the CarboEuroFlux program (<http://www.carboeurope.org>).

3.2. Sampling design

The forest plantation was originally planted in a regular pattern, but over the years thinning and natural causes have led to an irregular distribution of trees in the forest. The measurements were made with regular grid sampling, since the trees were not planted in rows (Weiss et al., 2004). Three plots of ~1100 m² (approximately 33 m × 33 m) each were chosen within the flux tower footprint area (ca 1 km²) in the central, most mature (~34–39 year old in the year 2001) section of the forest (Fig. 1b). The location of the plots was chosen to be as convenient as possible for repeating measurements at daily and yearly time-scales. Each plot was divided into eleven parallel east–west oriented sub-plots. Wooden pegs were hammered into the soil at 3 m intervals along the length of the sub-plots crossing tree crowns and inter-tree crowns spaces and guiding operators of gap fraction equipment when making measurement series (e.g., for the Sunlink) or long scans (with TRAC).

With TRAC, operator speed could thus also be gauged according to the time taken to traverse each 3 m interval.

3.3. Gap fraction inversion methods

Canopy structure measurements were made with a variety of 'gap fraction inversion' instruments. These instruments included two 'fisheye' type devices and four devices that measure a series of radiation measurements along a transect. The fisheye devices were the LAI2000 (Licor, Lincoln, NE) canopy analyzer and a digital camera (Nikon Coolpix 950) with a fisheye lens and WinSCANOPY software (Regent Instruments Inc., Ottawa, Canada). The radiation series instruments were three linear photo-sensor array probes, the Sunlink, the LP-80 (both of Decagon devices, Pullman, WA), the Sunscan (Delta-T, Cambridge, UK) and a three-sensor probe, TRAC (Tracing Radiation and Architecture of Canopies, Third Wave Engineering, Winnipeg, Canada). Measurements with these devices were made in campaigns during the spring and fall between March 2001 and March 2004. In all cases at least two devices were deployed in order to compare results. After this series of campaigns, more frequent routine measurements were carried out with the TRAC device during the years 2004–2006.

3.4. LAI2000

The LAI2000 measurements were made during a short period of about a half hour when the sun was at or below the horizon at dusk and no sunlit leaves were visible at the top of the canopy. In one case simultaneous reference measurements were made with a second LAI2000 on the top of the flux-net tower above the canopy. These were merged with the below-canopy measurements in post-processing. In the rest of the cases reference and below canopy measurements were made with the same instrument. Reference measurements were made every 15–20 min in a large clearing outside of the plot and the values were interpolated according to time. A 90° view-limiting cap covered the LAI2000 lens, with the opening away from the operator. A series of 5 measurements (one per each sub-plot) were made along the outer edge of the plot looking inward. During the short time period available for measurement (see above) the two plots closest to the flux tower were measured. Processing of the data used the standard LAI2000 algorithms.

3.5. Fisheye camera measurements

Fisheye-lens photographs were taken from below the canopy at the center of each plot. A fisheye converter, FC-E8, was mounted on a Nikon Coolpix 950 camera fixed on a tripod 1.3 m above the ground, leveled and aligned with the magnetic North. As with LAI2000 measurements, fisheye-lens photographs were taken during dusk. Since this period is very short and fish-eye equipment is not easily operated, each plot was covered on different days (total of three days of measurements). Images were analyzed for canopy openness and LAI_e with the WinSCANOPY 2006a program (Regent Instruments Inc.) using their recommended algorithm.

3.6. Linear photosensor array (LPA) probes: Sunlink, LP-80 and Sunscan

These three LPA probes were used in the same manner. The Sunlink was wired to a CR10X datalogger (Campbell Scientific, Logan, UT) with an extended memory and the 80 individual sensor measurements were stored for post processing. With the LP-80 and Sunscan, processing of the array of measurements (80 for the LP-80 and 64 for the Sunscan) is internal, each using its own algorithm, although these give similar results.

Measurements with these probes were above the pegs along the transects in each sub-plot, so that approximately 121 points were measured, giving, for the LP-80 and Sunscan, a total of 9680 points, and for the Sunscan 7744 points measured per plot and time. Since sensors are 1 cm apart, these correspond to measurement lengths of approximately 97 and 77 m, respectively, in each of the three plots. With the Sunlink, linear averaged transmittance of direct photosynthetically active radiation (PAR, 400–700 nm) was computed for each measurement of the 80 sensors and averaging between measurement positions was logarithmic. For complete details of data processing with the Sunlink see Cohen et al. (1997).

Measurements in the three sub-plots were made at three times during the day, corresponding to a range of solar zenith angles. Processing of the log averaged transmittance allowed computation of LAI_e as well as mean leaf angle and the ratio of vertical to horizontal leaf area based on the ellipsoidal leaf area distribution function (Campbell, 1986; Norman and Campbell, 1989a,b).

3.7. TRAC

TRAC design and operation are described elsewhere (e.g., Chen and Cihlar, 1995; Chen et al., 1997; Leblanc et al., 2002, 2005a,b; Eriksson et al., 2005). It records PAR measured with three Quantum sensors (Licor LI190) at a frequency of 32 Hz. TRAC uses canopy gap fraction to estimate LAI_e and also calculates the canopy gap size distribution (the physical dimensions of a gap), which is used to estimate the element clumping index and to convert LAI_e into LAI (Leblanc et al., 2005a,b). Generally, the instrument was designed to overcome the bias resulting from the clumpy nature of discontinuous canopies (and particularly coniferous forests).

Monthly measurements were made with TRAC from September to August (which is one rain-year) during a two-year period (2004–2006). Plot size, noted above, conformed to the recommended transect size for use of the TRAC instrument for measuring (i.e., 100–400 m; Leblanc et al., 2002). Transects were measured along the length of each of the eleven sub-plots, totalling approximately 350 m in length (11 mm × 33 mm; see above description of sub-plot layout), and mean LAI_e was calculated for each plot. The operator walked at a rate of 1 m s⁻¹ giving a total of >11,000 measured points per plot. East–west orientation (see Section 3.2) has been chosen in accordance with earth–sun geometry in order to prevent possible sensor shading by the operator as suggested by Leblanc et al. (2002). Transects were repeated three times a day for different solar zenith angles (SZA), ranging from about 48° to about 64° with an average per day SZA equal to about 57° for every plot. This arrangement limited the influence of leaf angle distribution on the estimates of LAI_e. Data was analyzed with the TRACWin program (Leblanc et al., 2002) and the average value for the three plots was considered to be representative of Yatir forest LAI_e. Mean element width was taken as 100 mm, an estimate of average needle length. Needle-to-shoot ratio (γ_e), and woody-to-total ratio (α) were taken as 1.7 and 0.1, respectively, based on literature values for morphologically similar pine species (Gower et al., 1999; see above).

Two independent tests for the reliability and consistency of TRAC measurements were performed: (1) we compared between two values of LAI_e measured at the same SZA, one at sunrise and another at sunset hours, and (2) a second LAI_e measurement of all plots was made immediately at one time point. The differences between LAI_es were 0.01 for the first and 0.02 for the second case.

3.8. Allometric LAI determination

Allometric equations developed at the site were used to calculate canopy leaf dry mass (g m⁻²) for each plot from measured diameter at breast height (DBH) and tree height (see

Table 1

Description of the training plots. TPP stands for the number of trees per plot, DBH for diameter at breast height, CW for crown width and CC for canopy cover.

Plot name	TPP	DBH [cm]	CW [m]	Height [m]	CC %
1	35	16	8	8	67
2	30	15	4	8	51
3	25	16	4	8	37

Bar Massada et al., 2006; Grünzweig et al., 2007). Dry mass was converted to leaf area by the average specific leaf area (SLA = $0.0044 \pm 0.0009 \text{ m}^{-2} \text{ g}^{-1}$), which was determined from three age cohorts from lower and upper crown sections on ten trees per plot. Leaf area was determined in the lab on fresh leaves.

3.9. LAI estimation from leaf litter

Leaf litter was collected between 2001 and 2004 in 25 litter traps of 0.5 m^2 each and removed from the traps every 1–2 months (Maseyk et al., 2008). It was assumed that leaf litter dry mass equals live leaf dry mass, i.e., leaves did not lose dry weight during the process of senescence. The fraction of leaf mass falling from the tree in one season was estimated from the average number of age cohorts present in the SLA samples. The mean lifespan of 2.3 years (turnover of 43% each year) across all plots was used to estimate canopy leaf mass from leaf litter. Leaf mass was multiplied by SLA to yield LAI.

3.10. Plot structure: direct measurements

In addition to LAI_e (or LAI), standard tree biometrics including DBH, crown width (CW), and tree height (H) were measured using a caliper, a measuring tape, and a clinometer, respectively, during a special field campaign in April–May 2004. The tree canopy was assumed to be circular, thus CW was converted to crown area (CA), which was summarized per plot. Plot canopy cover (CC) was calculated as the ratio of the sum of crown area of all trees within a plot-to-plot area. Stem density was defined as the number of trees per plot (TPP). Table 1 gives field measured parameters and a comparison of the studied plots.

4. Results

The study of LAI_e began with a measurement program over the course of four years to get an idea of the spatial and temporal variability of LAI_e at the site. Measurements on each date were made with more than one instrument, sometimes with different operators. Since the Sunlink was systematically used on each date of measurements and the values of logarithmically averaged transmittance of direct radiation, as calculated by this device, conforms to the expected approximately linear relationship between transmittance and solar zenith angle (SZA) for the range of zenith angles measured (Fig. 2), its results served as the reference values.

LAI determined by allometric techniques (Table 2a) increased steadily over the entire period covered by the study from 1.4 to

Table 2a

LAI_e/LAI ($\text{m}^2 \text{ m}^{-2}$) values measured with gap fraction inversion, allometric and leaf litter methods: (a) comparison of annual average LAI_e measured by the Sunlink or by TRAC (*) and LAI estimated from leaf litter and DBH and tree height. Note that the allometric and litter data are annually integrated values.

Season	Sunlink or TRAC* LAI _e	Allometric LAI	Leaf litter LAI
2000–2001		1.4	
2001–2002	1.2 ± 0.1	1.5	1.4 ± 0.2
2002–2003	1.2 ± 0.14	1.5	1.3 ± 0.1
2003–2004	1.3 ± 0.1	1.6	1.5 ± 0.2
2004–2005	$1.7^* \pm 0.16$	1.7	1.5 ± 0.2
2005–2006	$1.9^* \pm 0.19$	1.8	

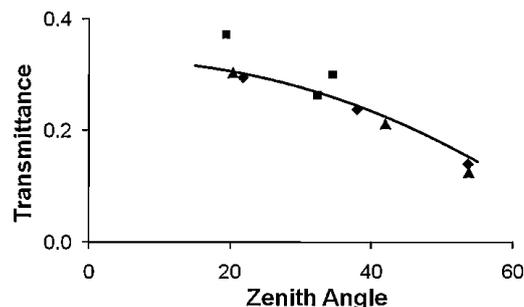


Fig. 2. Logarithmically averaged transmittance of direct PAR plotted as a function of solar zenith angle. Each point is an average of approximately 121 measurements with the Sunlink in August 2002. The three shapes indicate the three plots and the solid line was computed for the average PAI determined from these measurements, 2.2, and a random angular distribution of leaf area.

$1.8 \text{ m}^2 \text{ m}^{-2}$, with an average value of $1.62 \pm 0.13 \text{ m}^2 \text{ m}^{-2}$. Average LAI_e measured by Sunlink during the years 2001–2004 ($1.23 \pm 0.06 \text{ m}^2 \text{ m}^{-2}$) was ca 20% lower than allometric estimates ($1.53 \pm 0.06 \text{ m}^2 \text{ m}^{-2}$) also showing a small but steady increase over the measurement period. The monthly LAI_e measurements with TRAC in 2004–2006 ranged between 1.5 and 2, giving annual averages that were similar to the allometric estimates of actual LAI (1.7 and 1.9 for the first and second years, respectively). The similarity between TRAC and allometric measurements could be explained by the ability of TRAC to account for within-canopy and within-stand clumping that does not influence allometric estimates but may lead to errors when using other optical devices. As such, TRAC is the most effective GFI method for patchy landscapes and was chosen for more intensive monitoring of LAI_e seasonal dynamics.

Clumpiness may have caused the differences between the allometric estimates and the Sunlink measurements during 2001–2004. Another reason may be the large changes in LAI (approximately 20%) that occur during the year, and are discussed below. LAI_e measured by the gap fraction instruments (Table 2b) varied from 0.94 ± 0.1 in March 2001 to 1.79 ± 0.13 in March 2004. Fig. 3 summarizes Table 2b and presents the multi-year dynamic of LAI_e as measured by optical devices for the whole study period. In the table all values are LAI_e except those calculated destructively, from leaf litter and by means of allometric equation. TRAC assumed that 10% of LAI_e is woody (see Section 3). This difference should have led to lower values for TRAC, but in fact the difference between TRAC and the other methods was not significant. Anyway, the inclusion of TRAC cannot explain the gradual increase in LAI_e/LAI with time during the whole period of measurement.

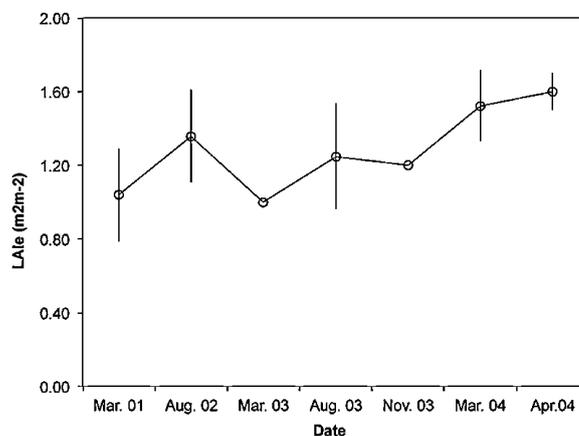


Fig. 3. Multi-annual dynamic of PAI as measured by optical devices for the whole study period.

Table 2b

Non-contact measurements of LAI_e and LAI (*) measured with different instrumentation. ± indicates standard deviation of the plots where more than one plot was measured and number in parentheses indicates how many plots were measured.

Date	Sunlink	TRAC*	LAI 2000	Fisheye	LP-80	Sunscan	Destructive*	Allometry*	Litterfall*	Final LAI
March 01	0.94 ± 0.1 (2)		0.83					1.4	0.98	1.04 ± 0.25
August 02	1.43 ± 0.1(3)			0.92 ± 0.11(3)		1.54 ± 0.29(3)		1.5	1.4	1.36 ± 0.25
March 03	1.0 ± 0.18(3)									1.00
August 03	0.76 ± 0.12(3)	1.3 ± 0.15(3)	1.38 ± 0.15(2)					1.5	1.3	1.25 ± 0.28
November 03							1.2 ± 0.83			1.20
March 04	1.79 ± 0.13(3)	1.33 ± 0.01(3)	1.49 ± 0.12(2)	1.25	1.69 ± 0.2(3)			1.6	1.5	1.52 ± 0.19
April 04		1.6 ± 0.24(3)						1.7	1.5	1.6 ± 0.1
Avg	1.18 ± 0.42	1.32 ± 0.02	1.23 ± 0.35					1.46 ± 0.11	1.30 ± 0.23	

This increase demonstrates the growth of the forest that although mature, has not reached a steady state.

4.1. Two-year monthly TRAC measurements

The two-year (2004–2006) monthly courses of TRAC-measured LAI_e and inventory-based DBH accompanied by the mean and standard deviation (SD) are shown in Fig. 4a. The significant differences between March and November (1.5 ± 0.06 vs. 1.85 ± 0.14 and 1.64 ± 0.17 vs. 1.94 ± 0.06 for first and second years, respectively) demonstrate high season-to-season variability in canopy dynamics. LAI_e decreased in the wet season (November–March) and increased in the spring, remaining relatively high during the

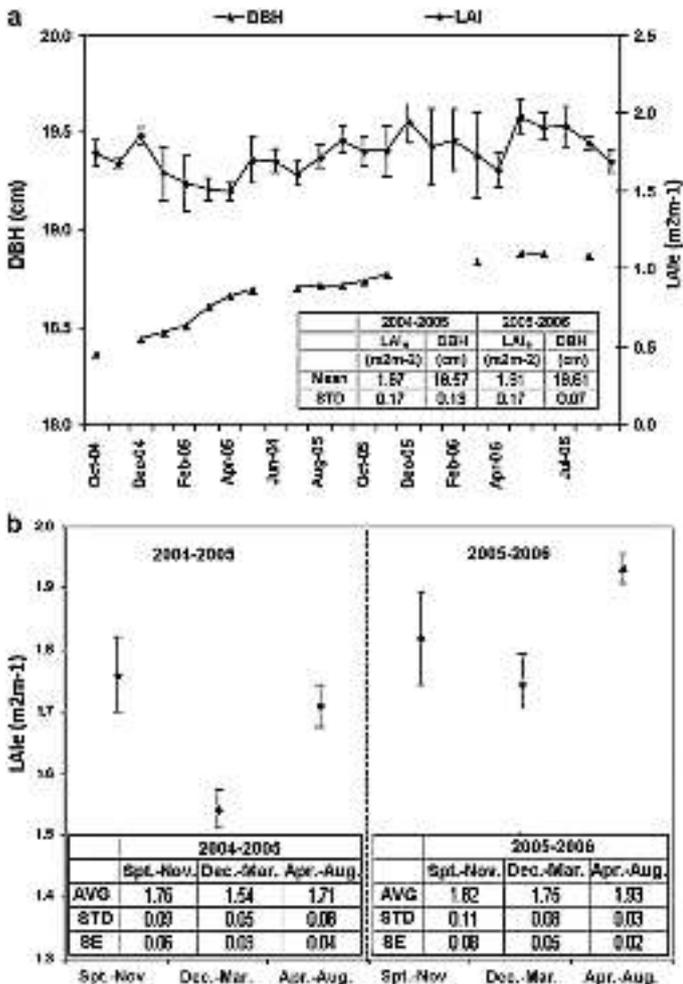


Fig. 4. (a) Two-year trend of LAI_e and diameter at breast height (DBH). (b) LAI_e averaged for wet and dry periods. Vertical bars represent ± one standard error of the measurements. Dashed vertical line separates between seasons.

dry-season (March–November) and average values for these two periods were significantly different (Fig. 4b; *t*-test *p* < 0.01).

LAI_e values were further averaged for three periods: (a) September–November (autumn); (b) December–March (winter) and (c) April–August (summer) (Fig. 4b). In the first year autumn and summer periods were not significantly different while winter LAI_e was significantly lower. A similar trend is apparent in the second year, but the trend was not significant due to large inter-plot variations.

Annual average LAI_e increased during the two years from 1.67 ± 0.03 to 1.81 ± 0.03. The increase is in agreement with the site DBH and flux measurements (not shown) that indicate an overall increase in forest biomass with time.

Table 3 gives the monthly LAI_e for the two years of the experiment, and the significance of differences between the two years and the different seasons.

4.2. Foliage orientation and arrangement

Leaf angle distribution (LAD) and shape factor *G*(*θ*) were determined by analysis of the measurements made with TRAC at two or more solar zenith angles. The two-year course of *G*(*θ*) shows that it was almost constant and more stable during the second year (Fig. 5), as reflected by STD, which was higher during the first year (0.05 and 0.03, respectively). Average *G*(*θ*) was 0.48, which did not significantly differ from that for a random LAD, 0.5.

Table 3

Monthly averages of LAI_e measured during the two-years of monthly measurement. Superscripts “a”, “w” and “s” indicate autumn, winter and spring periods, respectively, while “1” and “2” separate the results into two seasons according to significance of the differences between the mean value for the group of months.

Month	2004–2005	2005–2006	Avg
September	1.74 ^{a,1}	1.76 ^{a,1}	1.75 ^{a,1}
October	1.68 ^{a,1}	1.76 ^{a,1}	1.72 ^{a,1}
November	1.85 ^{a,1}	1.94 ^{a,1}	1.9 ^{a,1}
December	1.61 ^{w,2}	1.79 ^{w,1}	1.7 ^{w,1}
January	1.55 ^{w,2}	1.83 ^{w,1}	1.69 ^{w,2}
February	1.51 ^{w,2}	1.73 ^{w,1}	1.62 ^{w,2}
March	1.50 ^{w,2}	1.64 ^{w,1}	1.57 ^{w,2}
April	1.70 ^{s,2}	1.97 ^{s,2}	1.84 ^{s,1}
May	1.69 ^{s,2}	1.91 ^{s,2}	1.8 ^{s,1}
June	1.61 ^{s,2}	1.91 ^{s,2}	1.76 ^{s,1}
July	1.72 ^{s,2}	1.81 ^{s,2}	1.76 ^{s,1}
August	1.83 ^{s,2}	1.69 ^{s,2}	1.76 ^{s,1}
Avg	1.67	1.81	1.74
STD	0.11	0.11	0.09
SE	0.03	0.03	0.03
Sign.	<i>p</i> < 0.05		
Sign. a–w	<i>p</i> < 0.05	NS	<i>p</i> < 0.05
Sign. w–s	NS	<i>p</i> < 0.05	<i>p</i> < 0.05
Sign. a–s	<i>p</i> < 0.05	<i>p</i> < 0.05	NS
Sign. 1–2	<i>p</i> < 0.05	<i>p</i> < 0.05	<i>p</i> < 0.05

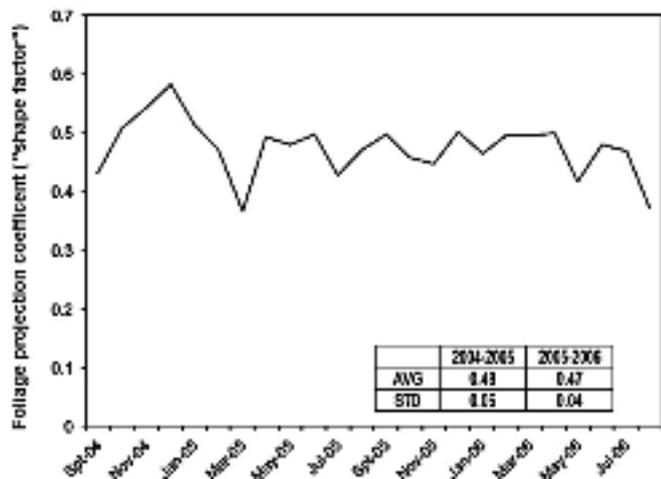


Fig. 5. Two-year course of foliage projection coefficient (i.e., shape factor) for the two-year period of measurements.

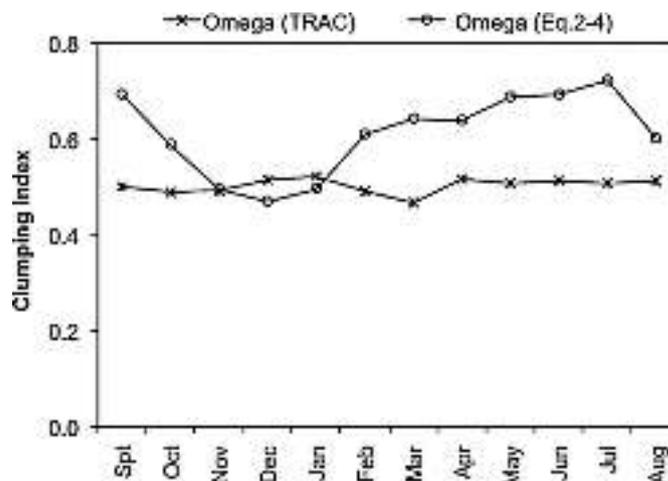


Fig. 6. Annual course of clumping index in the Yatir forest.

4.3. Clumpiness

Average values of clumping index calculated using (a) gap size distributions and TRAC software and (b) the procedure described by Eqs. (2) and (3) was 0.5 ± 0.02 and 0.61 ± 0.09 , respectively. Temporal variation for the first method was much smaller, as indicated by the standard deviations.

5. Discussion

In most forests tree density and LAI_e exceed that in Yatir, and at some point during the season the canopy is likely to close. In particular, LAI_e of less than 2 for a 35–40 year old forest is unusual. Asner et al. (2003) built a database of LAI_e measurements from around the world. Average values for all biomes except desert exceeded 2. Values for temperate and boreal evergreen needle leaf forests were 6.7 and 3.5, respectively. The dryland forest studied here is an intensively managed afforestation ecosystem. Tree density is low and the canopy is never closed. This case presents a challenge to GFI measurement techniques, which are based on inversion of theory that describes radiation transfer in turbid media, which is more appropriate to canopies with full or close to full closure. Although those methods have already been tested for crops (López-Lozano et al., 2009), in calibrations of GFI techniques little attention is usually given to the low values that occupy the lower left hand side of the figures (e.g., Arias et al., 2007; Breda, 2003). Even so, studies like the current one show that GFI techniques are robust and can give good results in these cases. Use of appropriate sampling size and advanced techniques to either minimize the influence of clumpiness or estimate its parameters enable accurate measurement.

In the current study, care was taken to select three relatively uniform plots and large grids for measurement. In each plot the linear photo-sensor array techniques sampled PAR at 1 cm intervals and averaged up to 80 cm per linear average, and log averaged in each plot with a total measured length of approximately 100 m. The TRAC instrument measured PAR every 3 cm and averaged over a length of more than 300 m. The LAI2000 sensor measured from 12 or 16 points at each plot, but its use was limited because it was only used when the sun was below the horizon. The precautions described above (Table 1) may explain why all the measurement techniques gave similar values. The implication of these results is that if a GFI is appropriately applied considering the local conditions, its results will be accurate for both continuous and discontinuous canopies as well. None of the techniques used gave outlying data so none could be considered inadequate for the job.

Besides the effect of clumping, the differences between the allometric estimates and Sunlink results during 2002–2004 (Table 2a) may be explained by the fact that the allometric-LAI is a function of biometric parameters (DBH and height) and is therefore insensitive to inter-annual variations in the growth/litterfall ratio. This ratio, however, is sensitive to specific climatic conditions during the current and the preceding years (i.e., precipitation rates and consequent level of the residual soil water content), and total litterfall was seen to vary between years. Therefore, as a result, litterfall may exceed needle growth in dry years, resulting in a reduction in LAI, while even a minor increase in DBH will result in an increase in the estimated LAI. Thus, optical methods are required to capture such inter-annual variability in LAI in environments with sensitive growth/litterfall ratios.

The only real problem was with the LAI2000 and fisheye photography techniques, which could be used only during a short twilight period after sundown. Measurements made when the sun was higher in the sky in our predominantly clear sky conditions gave significantly lower results because the upper sunlit leaves were brighter than the background sky. The short duration of twilight precluded measurements at the third, more distant grid. Thus, we concluded that the LAI2000 and fisheye photography techniques were inferior in our conditions.

For the specific case of dryland forests, the clumping of foliage was expected (i.e., $\Omega(\theta) < 1$), since stem density of such a forest is never homogeneous on a spatial scale, and this dictates the structure and spatial arrangement of the forest overstory. The results were in the range previously reported for conifer stands (Chen, 1996; Kucharik et al., 1999; Law et al., 2001a,b; Chen et al., 2005; Leblanc et al., 2005a,b; Pisek et al., 2010).

In general, the multi-year average clumping index derived from TRAC was lower than that estimated from stand structural parameters (Fig. 6; 0.5 compared to 0.61) presenting very smooth and stable annual behavior as compared to a sharp annual oscillations shown by Ω estimated with regard to stand structure. The reason for this small but significant difference is that the TRAC measurements were limited to a small range of sun angles (see Section 3), which caused them to avoid the effects of irregularity in canopy arrangement on LAI_e evaluation combined with the heterogeneity and structural irregularity of the landscape (Sprintsin et al., 2007).

On the other hand, the model described by Eqs. (2) and (3) gave more reasonable values since it reflects the current structural heterogeneity of the landscape, which reflects the intensive management practices and specific objectives of the Israeli Forest Service (e.g., greening the landscape and recreation), which aspire

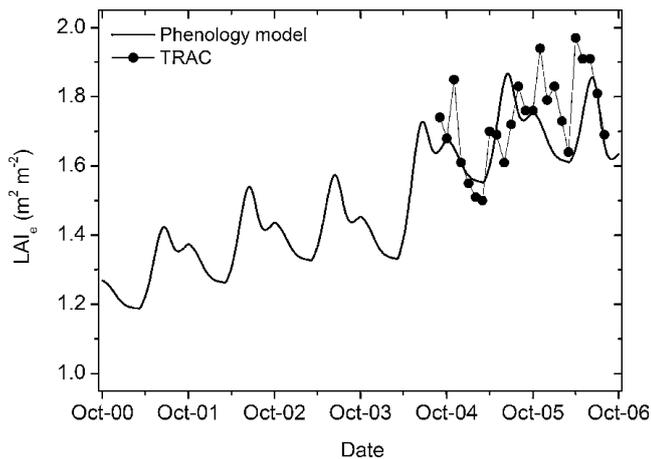


Fig. 7. Temporal course of LAI_e calculated from the phenological model, constrained to the results of the six LAI measurement campaigns during the first period of the study (2001–2004) and including the monthly TRAC measurements from 2004 to 2006.

to increase shading. That policy leads to estimated values of Ω that are close to those typical for a perfectly random canopy arrangement and we therefore take $\Omega = 0.61 \pm 0.09$ to be correct for Yatir forest. A deviation of the clumping index from that typical for a perfectly random canopy arrangement means that even for high LAI_e values the Yatir forest never reaches full canopy cover, and remains clumpy during all phenological stages.

Although it has been traditionally assumed that clumping remains constant over seasons (Baldocchi et al., 2002; Sampson et al., 2006), evidence in recent literature (Ryu et al., 2010) indicates that it could have very strong annual oscillations driven by site/species phenology. The annual dynamics of the clumping index in Yatir forest presented by Fig. 6 follows needle phenology and concurrency of needle growth and litterfall. The latter occurs in two phases as described by Maseyk et al. (2008). The majority of litterfall occurs during the summer needle growth period, compensating for the influence of higher SZAs on clumping estimation and making the canopy more uniform in the horizontal plane and closer to a random leaf arrangement ($0.7 < \Omega < 0.8$). The remaining part falls during the winter decreasing leaf area and increasing clumping that is reflected in a lower clumping index ($0.6 < \Omega < 0.7$).

The seasonal variation in LAI_e of this forest has been described using information from seasonal litterfall and needle growth measurements (Maseyk et al., 2008), from which relative seasonal growth and litterfall functions were established. The seasonal LAI_e pattern of a given year was estimated by scaling the relative phenological functions by the measured LAI_e at the start and end of the year (i.e., 1st October). While this method does not account for the slight difference in timing of needle and branch growth, it provides an estimate of LAI_e development over the season based on average leaf phenology characteristics of the forest, which were found to be quite conserved between the years in which these measurements were made (2001–2004).

These phenology-based estimates indicate that LAI_e declines slightly during winter (from November through February), followed by an increase in spring and early summer when rapid needle growth exceeds senescence rates and then another, sharper, decrease in late summer when litterfall peaks. There was good agreement in the main features of the seasonal LAI_e dynamics between the phenology and optically derived estimates over the two years of intensive TRAC measurements (Fig. 7 and Table 3). This agreement between the independent approaches suggests these seasonal variations are real and on the order of $\pm 10\%$ about the annual mean.

Relative to the seasonal variation in ecosystem processes, such as canopy photosynthesis, the variation in LAI_e is small. However, the $\sim 30\%$ increase over the study period will have proportional impact on annual budgets. For example, this increase in LAI_e has been a significant component of the general increase in gross photosynthesis (GPP) observed over the same period (Maseyk et al., 2008), offsetting the general decline in soil water content (SWC) over the same period. LAI_e was more strongly correlated with the inter-annual variations in GPP than average soil water content, and this relationship was particularly strong ($R^2 = 0.85$) in the years with annual rainfall in the range of $+30\%$ to -20% of the annual average, i.e., excluding the dry year of 2005–2006 (30% less than average rainfall). Furthermore, a metric of $SWC \times LAI_e$ was strongly correlated with GPP across all years ($R^2 = 0.78$), indicating that LAI_e dynamics are an important component of inter-annual and decadal scale variation fluxes in these environments.

Interestingly, due to the summer needle growth behavior of pines, seasonal maximal LAI_e values were seen in the middle of the dry season, before the majority of litterfall has occurred and when CO_2 assimilation rates are low and evaporative demand is high. However, it is not known to what extent senesced needles remain on the tree before falling, and a high LAI_e with inactive needles in the dry season could be beneficial in reducing soil evaporation (Raz-Yaseef et al., 2010). These seasonal variations in LAI_e may also explain some of the inter-annual variability obtained in LAI_e measurements from measurements made at different times of the year.

In addition, the TRAC measurements also revealed variations that were not observed in the model and may be related to responses to specific climate variations. For example, in 2005 the growth in LAI occurred in two stages, the first during March and the second in July and August. However in 2006, in which rainfall of the preceding winter was well below average, all LAI increase was in March and April. This difference indicates that a possible drought related shift in the needle growth/senescence ratio occurred early in the season. Clearly, there is more to be learned about dryland forest canopy LAI dynamics, and these results demonstrate how combining appropriate measurements and models can serve to improve understanding of foliage processes.

The long-term increase in LAI_e in the forest (Fig. 7) would eventually lead to forest closure if the amount of water available is adequate. Otherwise, as is the case in these forests, growth is constrained by minimum water requirements of a given leaf area and the forest hydrological balance (e.g., Schiller et al., 2003). For this reason the forest is periodically thinned. Applying the course of LAI to a transpiration model for these trees and comparison with available water might improve the planning of thinning dates.

The results obtained in this study are appropriate for use to improve remote sensing measurements of canopy structural properties as presented in Sprintsin et al. (2007, 2009a,b) who used some of these results to investigate the influence of spatial resolution on estimates of LAI_e made by satellite measurements and to evaluate the performance of the moderate resolution imaging spectroradiometer's operational LAI product in dryland.

6. Conclusions

LAI_e in the semi-arid Yatir forest was measured bi-annually during three years and more intensively monthly during the following two years. The measurements, which were carried out with a number of instruments, showed a 30–40% increase in LAI_e and LAI during those years, and that all instruments, when used properly, gave similar values. Because of the constraint of clear sky conditions, which limited the use of the fisheye type sensors to times of twilight, the fisheye techniques were less useful. The TRAC sys-

tem, which includes specific treatment of two levels of clumpiness of the sparse forest stand, was used successfully for the intensive monitoring. The LAI_e/LAI measurements were used to constrain a model of leaf phenology, which resulted in an estimated continuous course of LAI_e in the forest during the five-year period. Although the absolute accuracy of the LAI_e determination by indirect optical methods may be around 20% (Pekin and Macfarlane, 2009), the proper established sampling infrastructure (e.g., repeating measurements over the fixed large grid size) increases their resolution as indicated by the standard error of our measurements. So although the absolute values may not be more than 20% accurate, relative (e.g., seasonal) changes are highly significant (Fig. 4b) and are of importance for forest management decision support as well as for use in evaluation of remote sensing techniques for forests at the lowest range of LAI_e and LAI values.

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