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

Michael Sprintsin [a,*], S. Cohen [b], K. Maseyk [c,1], E. Rotenberg [c], J. Grünzweig [d], A. Karnieli [a], P. Berliner [a], D. Yakir [c]

[a] *Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, SedeBoqer Campus 84990, Israel*
[b] *Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization, The Volcani Center, Bet Dagan 50250, Israel*
[c] *Department of Environmental Sciences and Energy Research, Weizmann Institute of Science, Rehovot 76100, Israel*
[d] *Robert H. Smith Institute of Plant Sciences and Genetics in Agriculture, Faculty of Agricultural, Food and Environmental Quality Sciences, The Hebrew University of Jerusalem, Rehovot 76100, Israel*

ARTICLE INFO

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.

© 2011 Elsevier B.V. All rights reserved.

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

* Corresponding author at: Institute of Agricultural Engineering, Agricultural Research Organization, The Volcani Centre, P.O. Box 6, Bet Dagan 50250, Israel. Tel.: +972 3 9683523.

E-mail address: misprin@gmail.com (M. Sprintsin).
[1] Currently at UMR 7618 Bioemco, Université Pierre et Marie Curie, Paris, France.

nature of most tree canopies and forest stands. This problem, how-ever, 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, planta-tion 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 spa-tial domain (Sprintsin et al., 2007). Some forest processes, which depend on LAI, are mainly influenced by the first few canopy lay-ers, 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, reli-able 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 ($\approx$300 trees ha^{-1}; Sprintsin et al., 2009a,b) and an incomplete canopy cover ($\approx$57%; Sprintsin et al., 2007). Individual tree crowns are sparsely leafed and the sky is clearly visible even when standing below a large tree. Precipitation ($\sim$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 summa-rize multi-year LAI measurements in a dryland forest plantation and second, to report the annual dynamics of LAI based on inten-sive 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 statis-tical 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 trans-mittance of direct radiation by the canopy depends on incident direct irradiance, canopy structure and optical properties such that:

$$P(\theta) = e^{-G(\theta)\text{LAI}_e / \cos \theta} \tag{1}$$

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 cor-responding 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 frac-tion measurements made at a range of θs (Norman and Campbell, 1989a,b). Another alternative is to measure gap fraction at $\theta \sim 57°$, where $G(\theta)$ is similar for most leaf angle distributions (Lang, 1987).

The Poisson model, i.e., Eq. (1), describes canopies with ran-domly 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 trans-mittance 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). Val-ues 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:

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

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 ($\Omega_{E,\text{max}}$) is proportional to stem density as:

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

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 esti-mate 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