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An improved theoretical model of canopy gap probability for Leaf Area Index estimation in woody ecosystems

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ABSTRACT

This study presents an improved theoretical formulation of the gap probability (*Pgap*) model, typically applied to indirectly estimate LAI in woody ecosystems. Specifically, we present the woody element projection function (G_W), which characterises the angular contribution of non-leaf facets in woody ecosystems, and explain how it may be used to improve the accuracy of indirect LAI retrieval via the application of the *Pgap* model. G_W enables separate treatment of the leaf and wood projection functions in the theoretical model, important in the typical case when *Pgap* includes the influence of both leaf and wood canopy elements. This study then validates the improved theoretical model using experimental data. Here, *Pgap* was calculated from a 3D scattering model, parameterised with highly-detailed 3D explicit tree models reconstructed from empirical data of a sampled forest stand. The experimental data was then used to quantify additional effects of view zenith angle (*VZA*), leaf angle distribution (LAD), and the influence of woody components on the indirect estimation of LAI and within-crown clumping via application of the *Pgap* model. Additionally, we quantify within-crown clumping of reconstructed tree models for leaf and woody elements both together and separately for the first time. LAI errors up to 25% at zenith were found when ignoring G_W and were shown to be a function of *VZA*. Conversely, at the approximate 57.3° (1 radian) *VZA*, results show that there was no effect of G_W due to the wood projection function converging with leaf projection functions. Within-crown clumping factors for the modelled dataset were as low as 0.35. Consequently, making a common assumption of a random distribution of canopy elements at the crown scale would lead to an LAI error of up to 65% for the 3D forest stand. We also conclude that when estimating LAI via the *Pgap* model, separate treatment of canopy material projection '*G*' functions are required at *VZA's* other than 1 radian. The findings of this study and the extended physical formulation presented here impact upon indirect *Pgap* LAI retrieval methods from sensors of all platforms in clumped canopy environments or canopies with woody (non-leaf) elements contributing to the extinction of light.

1. Introduction

Leaf Area Index (LAI) is an essential climate variable (ECV) functionally related to the energy and mass exchange of water, carbon, and light fluxes through plant canopies (GCOS, 2011; Law et al., 2001; Spanner et al., 1990). It is usually defined as the total one-sided area of leaf tissue per unit of ground area (Chen and Black, 1992). LAI is a key parameter used in plant growth and radiative transfer models, coupling vegetation to the climate system. Given its importance, LAI is a common product derived from a number of active and passive remote sensing (satellite, airborne, and ground based) instruments.

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There is an increasing need for more accurate and traceable measurements in support of calibration and validation of Earth Observation (EO) products. The Global Climate Observing System (GCOS), whose goal is to provide comprehensive information on the total climate system, has specified LAI product values to match to within 20% of independently derived estimates, with the requirement to increase that to within 5% for future applications (Fernandes et al., 2014). These accuracy targets leave a small margin for uncertainty, requiring higher order accuracies to be achieved by methods used to benchmark LAI products. This poses a challenge for commonly utilised indirect techniques to meet accuracy targets for benchmarking, which typically suffer from a greater level of uncertainty than direct methods (Jonckheere et al., 2004). On the other hand, indirect methods are preferred over direct methods due to their scalability and non-destructive nature for large area attribution of plant communities.

A frequently employed indirect LAI estimation method involves the application of the *Pgap* model. The theoretical model relates structural attributes to the proportion and spatial distribution of canopy gaps, usually characterised by the so-called gap probability '*Pgap*'. *Pgap* is defined as the probability of a ray of light passing unobstructed through the canopy e.g. Nilson (1971). It is a function of several structural attributes that affect the extinction of light within plant canopies and consequently the remote sensing signal, namely the; (i) proportion and density of leaf and non-leaf components (these attributes combine to give the metric Plant Area Index 'PAI'), (ii) canopy element angle distribution, and (iii) degree of canopy element clumping. Each of these structural attributes can vary substantially with viewing angle, scale, and environment, even amongst stands of the same species (Table 1). In addition, the structural attributes are linearly related to LAI in the theoretical model, and thus have a significant impact on the final LAI estimate (Eq. (5)). In order to accurately calculate LAI using the theoretical formulation, all model-input structural attributes are required to be estimated or assumed with an acceptable level of uncertainty. However, current practises do not typically consider uncertainty in the input structural attributes among other limitations of the application of the *Pgap* model, further explained below.

Pgap estimates for LAI calculation are ubiquitous and are derived from instruments across all platforms, thus enabling LAI estimation from the local to global scale; see reviews by Bréda (2003), Weiss et al. (2004), and Zheng and Moskal (2009). For example, Digital Hemispherical Photography (DHP), LAI-2000/2200, and TRAC instruments utilise the *Pgap* model to estimate LAI, and are commonly used to validate global LAI products (Camacho et al., 2013; Garrigues et al., 2008; Sea et al., 2011). Although the primary function of these instruments is to measure *Pgap*, it is commonplace for the final LAI estimates of these methods to assume a value for any one or more of the input structural factors comprising its formulation (Weiss et al., 2004), in addition to ignoring uncertainty of these inputs. Such a practise is limiting when some of these structural factors can be highly variable with scale or view angle (Table 1), especially when aiming to quantify LAI to an accuracy threshold off less than 5% as requested by GCOS.

The formulation of the *Pgap* model was extended by Chen (1996) to attempt to account for plant communities with a significant woody-to-total plant area 'α' value (Section 2.2). In forested landscapes, α typically ranges between 0.1 and 0.4 (Gower et al., 1999) and has been reported to be as high as 0.7 in *Pinus banksiana* stands (Deblonde et al., 1994). It also reaches a value of 1 in deciduous forests during leaf-off conditions. Although the combined contribution of branches and stems can intercept a significant amount of radiation, the intercepted proportion is a function of individual plant structure, viewing angle, and instrument location (e.g. below the canopy, mid-canopy or above). Therefore, the intercepting woody components are likely to affect angular *Pgap* measurements, yet are not explicitly accounted for in the same manner as foliage in the current formulation of the *Pgap* model (Section 2.3). In other words, the leaf angle distribution parameter is typically applied incorrectly applied to all non-leaf or woody elements within the instrument field-of-view. This current limitation of the *Pgap* model is further explained in the typical context of applying α to convert an estimate of PAI into LAI in the next paragraph.

The majority of *Pgap* estimation methods do not or have been unable to separate the contribution of leaf from non-leaf elements. Of the few studies that have separated leaf from non-leaf elements in their *Pgap* estimates, the unknown degree of mutual shading or occlusion of wood and leaf components is likely have introduced errors into the method (Kucharik et al., 1998). Generally, two methods have been employed which attempt to account for non-leaf elements. The first is to ignore them and thus obtain an estimate of PAI rather than LAI from the *Pgap* model; e.g. Morsdorf et al. (2006), Pueschel et al. (2012), and Tang et al. (2014). The second is to apply α to PAI estimates through $\text{LAI} = \text{PAI} \cdot (1 - \alpha)$; where $\alpha \neq 0$ Chen (1996). Employing the *Pgap* model to estimate PAI or LAI in the typical circumstance of only applying a LAD value assumes the woody elements have the same angular distribution as leaf elements (i.e. the Leaf Angle Distribution = Wood Angle Distribution 'WAD'); e.g. Chen (1996), Kucharik et al. (1998) and Sea et al. (2011). However, few studies elucidate this assumption and no studies, to the authors knowledge, have attempted to quantify the WAD or the LAI error introduced when this assumption does not hold.

Nilson (1971) recognised a divergence in theoretical understanding in the application of *Pgap* and extinction of radiation formulae, citing models presented in Monsi and Saeki (1965) and Monteith (1965) amongst others. The extinction coefficient '*k*', a widely incorporated parameter characterising the rate of light extinction through a canopy, has been inconsistently utilised in studies of forest environments. For example, Hopkinson et al. (2013) and Zhao et al. (2011) defined '*k*' as only varying with leaf angle distribution 'LAD' and considered clumping separately, whereas Ryu et al. (2012) and Verger et al. (2011) also defined '*k*' as varying with only LAD, and did not consider clumping effects. Ryu et al. (2012) reasoned that within-crown clumping was negligible and therefore was excluded when calculating Plant Area Index 'PAI' from the *Pgap* model. Additionally, Hu et al. (2014) presented a clumping retrieval method based on path length distri-

Table 1
Structural attributes of the LAI formulation from *Pgap* measurements and their typical range in forests and woodlands. The structural attributes sensitivity to scale and view angle are presented for a typical sampling scale of an undisturbed natural forest stand.

Structural attribute	Scale variant	View angle variant	Typical range	Reference
Clumping (Ω)	High	Med	0.4–1	Zhao et al. (2012), Leblanc et al. (2005), Chen et al. (2005)
Wood-to-total plant area (α)	Low	N/A	0.1–0.4	Kucharik et al. (1998), Gower et al. (1999)
Leaf angle distribution (LAD)	Med	High	0.4–0.8[a]	Wang et al. (2007), Pisek et al. (2013)
Wood angle distribution (WAD)	Med	High	0.2–0.6[a]	This study
Leaf Area Index (LAI)	Med	N/A	0.5–6	Gower et al. (1999), Asner et al. (2003)

[a] Represents the typical projection function (G) range. Clumping levels are presented at the stand scale.