Agricultural and Forest Meteorology 259 (2018) 39–47

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Relating foliage and crown projective cover in Australian tree stands

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ARTICLE INFO

Keywords:
Foliage projective cover
Crown projective cover
Crown cover
Canopy Cover
Vertical canopy cover
Canopy gaps

ABSTRACT

Tree cover is quantified using a variety of structural metrics that relate to canopy density, which are often modelled from remotely sensed data. Comparing different metrics, and maps of such metrics, is difficult due to a poor understanding as to how they relate to each other. Two commonly used metrics in Australia are crown projective cover (CPC) and foliage projective cover (FPC). CPC and FPC are the proportion of ground area covered by the vertical projection of tree crowns, and the foliage of tree crowns, respectively. They are dimensionless proportions that vary between zero and one. The relationship between CPC and FPC is a function of the plant area index (PAI), the foliage clumping factor at a zenith angle of zero, the foliage projection function at a zenith angle of zero, tree stand density, mean crown radii, and the proportion of wood to all canopy elements (α). The non-linear relationship was investigated using a dataset of 745 field sites across Australia, for which 1003 coincident CPC and FPC measurements had been made. As measurements of LAI and the other variables were not available, the parameter k was introduced to simplify the equations, which then had only two unknowns: α and k. Best-fit values of α and k were determined using non-linear weighted least-squares regression across all the field sites. Using these values to predict FPC from CPC, and vice versa, achieved low root mean square errors (0.05-0.07) across the field data. The models allow different mapping products to be compared, and also have the potential to facilitate the derivation of FPC from airborne lidar data when field measurements of FPC are not available for calibration. This was demonstrated using a lidar dataset and 12 coincident field sites, across which FPC was derived from a lidar fractional cover metric with an RMSE of 0.08. Further research is required to investigate the stability of this method across different areas and lidar systems.

1. Introduction

Tree cover can be defined using several different structural metrics, such as canopy cover, crown cover, foliage projective cover (FPC) and leaf area index (LAI). Different metrics are measured for different purposes, and although they can follow standard definitions, little systematic research has been conducted into how they relate to each other in real tree stands. Some researchers have attempted to standardise the terminology (Gonsamo et al., 2013), though confusion is still common. A greater understanding of the relationships between metrics is required, to allow data acquired using different methods to be compared, and to ensure that maps based on different metrics are interpreted correctly. Such a comparison should also provide a greater understanding of the inherent structural properties of trees.

Of the commonly used metrics, crown cover is perhaps the simplest to define. It is the proportion of ground area covered by the vertical projection of tree crowns, which are assumed to be opaque and have no overlaps (Gonsamo et al., 2013; Walker and Hopkins et al., 1990). For the purposes of defining all metrics, we define trees as woody vegetation greater than 2 m in height. Crown cover is relatively easy to measure in the field (Walker and Hopkins et al., 1990) and can be mapped from aerial photography (Fensham et al., 2003). It has been referred to by other names, such as canopy closure, canopy cover, or vertical canopy cover, and is commonly used for forest inventories or in definitions of forest (FAO, 2012). In closed forests, crown cover is the inverse of between-crown gaps, which are often the focus for forest ecology and management (Schliemann and Bockheim, 2011). Some definitions of crown cover include the total area of all tree crowns, counting overlap zones twice (Gonsamo et al., 2013). In order to make the definition used in the present paper clear, we propose a new term:

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https://doi.org/10.1016/j.agrformet.2018.04.016
Received 6 August 2017; Received in revised form 17 April 2018; Accepted 18 April 2018
Available online 26 April 2018
0168-1923/

crown projective cover (CPC). By including the word projective, it is clear that CPC only counts overlaps once, as they project onto the same patch of ground.

FPC is the proportion of ground area covered by the vertical projection of tree crown foliage (Specht, 1983; Walker and Hopkins et al., 1990). It was developed in Australia, where it is commonly used to record the canopy foliage density of native tree stands, which mostly do not seasonally drop leaves. It is typically measured in the field using transects (Johansson, 1985), which requires more time than measuring CPC in order to distinguish the foliage and woody canopy elements and the within-crown gaps. FPC is more closely related to LAI and the photosynthetic and evaporative potential of a plant community than CPC, especially in Australian trees and shrubs, which often have low foliage density (Specht, 1983). While CPC treats crowns as opaque objects, the FPC of individual crowns for most Australian woody plants is between 40% and 70% depending on crown architecture (Walker and Hopkins et al., 1990). This also means that FPC has a higher dynamic range than CPC, which usually reaches 0.951.00 for FPC values in the range 0.751.00 (Scarth et al., 2008; Scarth and Phinn, 2000).

LAI is defined as half the total surface area of green leaves per unit of horizontal ground surface area (Chen and Black, 1992). LAI is the main variable used to model canopy photosynthesis and evapotranspiration, as it determines the size of the plant–atmosphere interface and the exchange of energy and mass between the canopy and the atmosphere (Chen et al., 1997; Simioni et al., 2003). Trees may have similar LAI values and very different FPC values due to variation in foliage clumping and leaf orientation angle (Campbell, 1990; Henry et al., 2002). This difference is pronounced in Australian trees and shrubs, whose leaf orientation angle and foliage clumping can be highly variable (Falster and Westoby, 2003; King, 1997). Furthermore, while LAI can be greater than one for dense foliage with overlapping leaves, FPC saturates at a maximum of one. LAI can be determined through direct measurements after destructive sampling or sometimes through leaf litter collection, but is often estimated through indirect means such as measuring light interception or hemispherical photography (Jonckheere et al., 2004). These indirect methods are measuring the proportion of gaps in the canopy (P_{gap}), from which LAI can be modelled, requiring assumptions about the proportion of canopy elements that are wood or foliage.

LAI and FPC are dynamic measures of foliage density, exhibiting changes due to growth, drought, pests, diseases or fires. They are both sensitive to the number of leaves present, and also to the way leaves are distributed and orientated. While LAI will increase through the seasonal vertical growth of foliage shoots, FPC is less sensitive to these changes and is therefore a less dynamic metric (Specht and Specht, 1999). As Australian soils are often low in plant nutrients, foliation and defoliation tends to be synchronous and FPC remains relatively constant throughout the year (Specht, 1983). Furthermore, it has been shown that FPC of mature vegetation in Australia is correlated to the annual water balance of the ecosystem and remains relatively stable over the long-term (Specht, 1983). Even the dynamic nature of LAI is likely to be reduced in Australia, where very few trees are deciduous, even in the seasonal tropics (Bowman and Prior, 2005). CPC is also relatively stable, increasing slowly with tree growth, and decreasing when branches are lost or trees die.

The research presented here was conducted to investigate the relationship between CPC and FPC in native Australian trees, as these two metrics have been used by different organisations to map and monitor vegetation over large areas. For example, Australia's State of the Forests defined forest as vegetation greater than 2 m in height with a minimum CPC of 20% (Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee, 2013). Other organisations have used FPC modelled from satellite imagery or airborne lidar to indicate tree cover (Armston et al., 2009; Danaher et al., 2010; Fisher et al., 2016; Lucas et al., 2006; Queensland Department of Science Information Technology Innovation and the Arts, 2014). Rough methods of converting between the metrics are often used, such as the observation that 20% CPC is approximately equivalent to 12% FPC (Henry et al., 2002). It is also possible that developing a model between CPC and FPC will assist with modelling FPC from airborne lidar data, which generally cannot distinguish wood and foliage canopy elements.

The three main objectives were designed to improve our understanding of how FPC and CPC relate to each other. Firstly, the theoretical model describing canopy foliage light interception and the spatial distribution of crowns developed by Nilson (1999) is presented in the context of relating FPC and CPC. Secondly, an extensive dataset of field measured CPC and FPC was used to examine how the theoretical models can be applied to native Australian vegetation. Thirdly, we demonstrate how a greater understanding of the relationship between FPC and CPC can be used in some examples of mapping applications, with particular emphasis on airborne lidar data. The research builds on a previous investigation conducted by Scarth et al. (2008), who examined the nature of the non-linear relationship between CPC and FPC for native vegetation in Queensland with a smaller, preliminary dataset.

2. Theory

Nilson (1999) developed several models for $P_{gap}(\theta)$, the probability of a beam of light travelling through a gap between the canopy of a stand of trees. The simplest model from earlier work by Nilson (1971) is referred to as the exponential model (Eq. (1)).

$$P_{gap}(\theta) = e^{-\frac{G(\theta)\Omega(\theta)\mathrm{PAI}}{\cos(\theta)}} \tag{1}$$

where θ is the zenith angle of the light, PAI is the plant area index, $\Omega(\theta)$ is the stand foliage clumping factor, and $G(\theta)$ is a function describing the area of foliage projected onto a plane perpendicular to θ, which is dependent on the leaf angle distribution. Eq. (1) uses PAI rather than LAI, to account for the proportion of woody elements to all canopy elements (α), where PAI = LAI/(1 − α) (Chen and Cihlar, 1996).

As FPC is dependent on the distribution of the foliage component viewed at a zero zenith angle, it can be modelled as a function of LAI, according to Eq. (2)(Armston et al., 2012).

$$\mathrm{FPC} = 1 - e^{-G(0)\Omega(0)\mathrm{LAI}} \tag{2}$$

Combining Eqs. (1) and (2), allows FPC to be modelled as a function of P_{gap} and α (Eq. (3)), or α as a function of FPC and P_{gap} (Eq. (4)). It is interesting to note that while LAI is a linear function of PAI and α, the relationship between FPC, P_{gap} and α requires a power function to account for the vertical projection.

$$\mathrm{FPC} = 1 - P_{gap}(0)^{1-\alpha} \tag{3}$$

$$\alpha = 1 - \frac{\log(1-\mathrm{FPC})}{\log(P_{gap}(0))} \tag{4}$$

Nilson (1999) found that the simple exponential model in Eq. (1) underestimated $P_{gap}(\theta)$ when compared to that measured by light interception or hemispherical photography, so more complex models were developed incorporating factors relating to the clumping and overlapping of tree crowns, such as the modified Poisson model (Eqs. (5a), (5b), (5c)).

$$P_{gap}(\theta) = e^{\left(\frac{\ln \mathrm{GI}}{1-\mathrm{GI}} CK \left(1 - e^{\left(\frac{-G(\theta)\Omega(\theta)\mathrm{PAI}}{\cos(\theta) CK}\right)}\right)\right)} \tag{5a}$$

where

$$C = \lambda_c \pi r_c^2 \tag{5b}$$

and

$$K = \sqrt{1 + \left(\frac{h}{2r_c}\right)^2 \tan^2\theta} \tag{5c}$$