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Modeling and predicting solar radiation transmittance in mixed forests at a within-stand scale from tree species basal area

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ABSTRACT

Light under tree canopy cover is essential for the study and understanding of plant diversity, regeneration, plant growth and many other forest ecosystem processes; however, quantifying light is difficult and requires specialized equipment. That is why proxies or models predicting light availability can help scientists to obtain estimates of transmittance and forest managers to better assess and adjust silvicultural practices at a reasonable cost. The main objective of our research was to develop a model to predict local solar radiation transmittance from species basal area in mono-specific and mixed stands of sessile oak (*Quercus petraea*) and Scots pine (*Pinus sylvestris*). Models based on the Beer-Lambert law were fitted and compared using 163 measures of solar radiation transmittance obtained from hemispherical photographs and light sensors. In mono-specific stands, local transmittance was predicted by local basal area considered on a radius equaling approximately tree height. In mixed stands, the same model broken down into its mono-specific components (local basal area of each species multiplied by their own extinction coefficients) predicted transmittance well. The extinction coefficients we obtained were very close to those previously established for these species and did not differ between mono-specific and mixed stands. Our model explained 77% of the variation in transmittance when random effects were included and 64% of the variance without taking into account these random effects. The predictive value of the model was good with high accuracy (mean signed deviation not significantly different from zero) and a fairly high precision (relative mean absolute error = 20%). The fact that tree canopy transmittance in mixed stands can be predicted by extinction coefficients obtained from mono-specific stands indicates that modifications in crown structure and leaf distribution are only slight, or even non-existent, when the two species grow in a mixture.

1. Introduction

Solar radiation is a key resource in most ecosystems, and it takes on a particular importance in the forest understorey where it determines the growth and survival of plant species as well as community diversity (e.g. Begon et al., 2006; Plue et al., 2013; Jagodzinski et al., 2016). However, light measurements under forest canopy are difficult to acquire and are too expensive and time-consuming for forest managers (Lieffers et al., 1999). That is why many studies have aimed to develop relationships and models between light and certain stand or tree characteristics in order to provide indirect estimates of light under forest cover (Ligot et al., 2014).

Among the different approaches, the one based on the Beer-Lambert light attenuation law in turbid media has found particular favor due to its simplicity. Tree leaves are considered as sufficiently small elements so that solar radiation may be computed according to leaf density, if certain assumptions about leaf distribution and clumping are made (Ligot et al., 2014). For decades leaf area index (LAI) has often been taken as a proxy for leaf density in the crowns. However, since LAI is still difficult to routinely measure, dendrometric characteristics, such as tree basal area, which are related to leaf area or LAI have typically been used in these calculations instead of direct LAI (Perry et al., 1969; Waring et al., 1982; Albrektson, 1984; Hale et al., 2009; Reich et al., 2012; Majasalmi et al., 2013; Goudie et al., 2016). To improve these models, additional variables such as stand age were added to account for the non-linearity between basal area and LAI, or time since last thinning and thinning intensity to account for disturbance effects (Sonohat et al., 2004). The resulting models based on the

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Beer-Lambert law and fitted at the stand scale are a good trade-off between typical empirical models and typical process-based models.

Such models have mainly been used for mono-specific stands (e.g. Sonohat et al., 2004; Balandier et al., 2006; Ligot et al., 2014) while much more complex models have usually been used for mixed and heterogeneous stands, for example predicting light interception for each single tree and unit of ground area (Cannell and Grace, 1993; Brown and Parker, 1994; Brunner, 1998; Da Silva et al., 2012; Forrester, 2014; Ligot et al., 2016). Foresters' interest in mixed and heterogeneous stands is growing though.

Developing easy-to-use generic models for stands other than even-aged mono-specific stands is therefore an important issue. The Beer-Lambert law can also be applied to mixed stands but this requires accounting for the distribution of foliage for the different tree species composing the vegetation layers (Cannell and Grace, 1993). Mixtures often increase the heterogeneity of leaf distribution within and among species and modeling such a situation would require a higher level of description than for mono-specific stands (Barillot et al., 2011). Plant morphogenesis also depends on light quality (Smith, 2000); it has been shown that the quality of light under forest cover depends on the tree species composition of the canopy (Lieffers et al., 1999) and is generally well related to the amount of transmitted light (Balandier et al., 2006). It can therefore be assumed that tree architecture and the light-related characteristics of crowns, branches and leaves can be changed when a tree species grows in mixed stands because of the interactions with other tree species (Pretzsch, 2014). The question is whether tree species interactions significantly affect the quantity and quality of the transmitted light (Ligot et al., 2016).

Models based on the Beer-Lambert law have generally been used to estimate transmittance at a coarse scale (stand level) to better suit the assumption of leaf homogeneity (Ligot et al., 2014). However, to reflect regeneration growth or plant species distribution within a stand, predicting transmittance at a smaller scale can be useful (Brunner, 1998). Whether this is possible or not to develop models based on the Beer-Lambert law at a more local scale (within-stand level) remains to be seen and was one of the questions asked in this study. In particular, it will be necessary to determine the minimum area around a given point within which trees must be considered to meet the assumption of homogeneity.

The main objectives of our study were:

(1) To model and predict transmittance based on the Beer-Lambert law and basal area in mono-specific stands of sessile oak (*Quercus petraea*) and Scots pine (*Pinus sylvestris*) and to compare the extinction coefficients with those of existing models. We hypothesize that basal area would be a good predictor of transmittance in mono-specific stands as demonstrated in previous studies.

(2) To model and predict transmittance in oak – pine mixed stands based on the Beer-Lambert law and the basal area of each species. We hypothesize that a model based on the Beer-Lambert law could be used in mixed stands and that the extinction coefficients of tree species would be modified in mixed stands due to interactions between species.

(3) To determine whether transmittance could be predicted at a more local scale (within-stand level), i.e. to determine the area around a given point required to compute basal area used in the model based on the Beer-Lambert law. We hypothesize that there would be an optimal radial distance from the reference point to compute stand density in order to predict local transmittance.

2. Materials and methods

2.1. Forest sites and sampling design

All the measurements were performed in the Orleans National Forest (France, 47°49′N, 2°29′E) on 0.5 ha plots in the OPTMix experimental area (www.optmix.irstea.fr, Korboulewsky et al., 2015). The stands in this experimental network have three types of composition: mono-specific even-aged stands of sessile oak, mono-specific even-aged stands of Scots pine, and oak-pine mixed stands. For each stand composition type, three management units, several kilometers apart from each other were sampled in the south-eastern part of the Orleans forest. Each of these management units contains two levels of stand density: two plots (three plots in mixed stands) have a low stand density, corresponding to a dynamic management strategy; and one plot has a medium stand density, corresponding to a conservative management strategy (Table 1). In each management unit, three 0.5-ha plots (2 low and 1 medium density) were sampled in mono-specific stands and four (3 low and 1 medium density) in mixed stands. Each plot was surrounded by a 20-meter-wide buffer zone with the same stand characteristics as the measurement plot.

2.2. The forest plot characteristics

Sampled stands were between 70 and 80 years old with a dominant height between 18 and 22 m for oaks and between 20 and 24 m for pines. For each of the 30 plots (Table 1), an inventory of all trees with a diameter above 7.5 cm DBH (diameter at breast height - 130 cm above the ground) was completed in winter 2013–2014. In the OPTMix experimental area, all understorey trees taller than 2 m but shorter than the main tree canopy have been removed so that the tree canopy is made up of a single tree layer. Tree locations (precision ± 0.1 m) were recorded with a total station (Trimble M3 Mechanical Total Station, Sunnyvale California, USA). Plot basal area was between 13 and 22 m^2/ha for mono-specific oak stands (Fig. 1a), between 18 and 31 m^2/ha for mono-specific pine stands (Fig. 1b) and between 16 and 30 m^2/ha in mixed stands (Fig. 1c).

2.3. Solar radiation transmittance estimates

Solar radiation transmittance was estimated by hemispherical photographs and light sensors. The equipment was a digital single-lens reflex camera body (EOS 5D, Canon, Tokyo, Japan) with a circular fisheye lens (8 mm F3.5 EX DG circular fisheye, Sigma, Kawasaki, Japan) with a 180° angle of view. The photographs were taken two meters above the ground (i.e. above the herbaceous understorey vegetation) before sunrise or after sunset.

For each 0.5 ha plot, five photographs were taken. The plot was divided into five parts of equal area and one point was randomly chosen in each part. In some plots, one or two additional photographs were taken for the needs of another study. A total of 163 photographs spread over 30 plots and nine management units were obtained (Table 1).

The color pictures obtained were then transformed into black (vegetation) and white (sky) pictures with the PiafPhotem software (Adam et al., 2006). Thresholding is a subjective method depending on the expertise of the operator. To overcome this problem, our general methodology was to adjust the photograph threshold relative to actual light measurement based on light sensor devices. This method is close to the one proposed by Zhao and He (2016) using a measure of above canopy light to correct photograph threshold biased by different sky illuminations. In our case, the black and white threshold used to classify the pixels on