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Efficient assessment of topographic solar radiation to improve plant distribution models

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ABSTRACT

Plant ecologists have recognised the importance of solar radiation for decades but have difficulty measuring it on plots. Proxies recorded on the ground or geographical information system (GIS) indices processed with a digital elevation model (DEM) have generally been used. Here we compare the efficiency of different methods of estimating spatially distributed topographic solar radiation, from the simplest ones (proxies based on slope, and sine or cosine transformed values of aspect) to more elaborate ones using a GIS program suited to calculations of monthly clear sky and overcast solar radiation. We used a 50-m DEM to estimate solar radiation with these different methods for the whole of France (550,000 km^2). Radiation indices were compared with ground measurements from meteorological stations and used to model the distribution of silver fir (*Abies alba*), sycamore (*Acer pseudoplatanus*), and downy oak (*Quercus pubescens*), forest species known to be sensitive to light. Results show that sine and cosine of aspect, combined or not with slope, are inefficient at simulating solar radiation over large areas. Solar radiation, calculated for clear sky and especially including cloud cover, is more relevant, leading respectively to an R^2 of 0.46 and 0.78 between measured and predicted annual radiation. Calculation with cloud cover appears to be the most efficient index for improving distribution models for the three species studied. Slope and aspect transformations are less efficient than the GIS calculations, but the difference between these proxies decreased on a local scale. Using both with GIS solar radiation, cosine of aspect, with or without interaction with slope, slightly improves distribution models on a local scale, but this effect attenuates with increase in area studied. We conclude that the effect of proxies studied is scale-dependent, but GIS-based calculation including cloudiness variability is more appropriate than topographic proxies or clear sky models in estimating solar radiation and improving the efficiency of plant distribution models.

1. Introduction

Vegetation studies require accurate data over extensive areas in order to model species distribution on the scale of their distribution area (Guisan and Thuiller, 2005). This is made possible by the development of large databases (Brisse et al., 1995; Gégout et al., 2005), improvements in sampling methods (Elith et al., 2006) and computing capacity. Solar radiation plays an important role in the distribution, composition, and productivity of ecosystems through photosynthetic activity

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(Gates, 1980; Satterlund and Means, 1978) and contributes to several parameters of the water balance (including air and soil heating, evapotranspiration, wind, snow and ice melt) (Lebourgeois and Piedallu, 2005; Pierce et al., 2005). Many authors have sought to link solar radiation and the distribution or the productivity of plant species or communities (Dirnbock et al., 2003; Franklin, 1998; Meentemeyer et al., 2001; Tappeiner et al., 1998; Zimmermann and Kienast, 1999).

Modelling plant distribution commonly requires information on both the presence and absence of species, recorded on the ground, and values of ecological factors in the same plots. These explanatory factors can be recorded in the field or obtained by combination with GIS data layers. Measuring long-term solar radiation directly on plots is unrealistic over large areas, due to the number of plots necessary to establish relevant distribution models (Coudun and Gegout, 2006). Few ground meteorological stations record these data, which are among the climatological values least frequently measured (Pierce et al., 2005; Yang et al., 2006).

Researchers have therefore used other methods to estimate radiation on plots. The simplest is to use proxies based on slope or aspect, which are based on local differences in radiation. These variables are often used because they are easy to measure or calculate (Carroll et al., 1999; Clark et al., 1999). Aspect being a circular variable, ecologists use a sine or cosine transformation to obtain a continuous gradient, stressing the north–south or east–west gradient (northness or eastness). The sine or cosine-transformed aspect values can be recorded on the ground or determined by GIS indices processed with a DEM (Austin et al., 1990; Pierce et al., 2005). Development of GIS technology since the early 1990s has enabled researchers to elaborate more sophisticated models of solar radiation (Kang et al., 2002; Wilson and Gallant, 2000). These provide geographical information for any point of the study site, using different more or less simplified methods of calculation. They are recognised to be in general cost-efficient and well suited to topographically complex areas (Hofierka and Suri, 2002; Rich et al., 1995), and are commonly used in ecological studies (Guisan et al., 1998; Zimmermann and Kienast, 1999).

The efficiency of these methods of radiation estimation has received little attention, although they have been used in many ecological studies, and important differences have already been noted between different data sources (Aber and Freuder, 2000). Slope and aspect transformations represent an indirect gradient related to distribution of vegetation, and their effect is principally presumed to be linked to solar radiation (Austin, 2002). These proxies do not include effect of latitude and cloud on sunshine duration, and the same radiation value could arise from different combinations of slope and aspect when large areas are considered. However, they are considered interesting because they are generated without much loss of precision compared with biophysical indices (Guisan and Zimmermann, 2000). Solar radiation calculated with GIS models represents direct gradients having physiological effects on plants and is preferable to indirect gradients, the source of correlation with vegetation having been identified (Austin, 2002). However, different programs are used for solar radiation calculations, with variable success (Kang et al., 2002), making comparisons difficult. Many of them do not consider large-scale modulators like variations in cloud cover, and the effect of this simplification for predictive modelling has been little studied. The predictive ability of these different indices in modelling plant distribution is incompletely defined and previous studies have encountered difficulties in establishing the best explanatory variable to predict vegetation patterns, from slope or aspect transformed indices or potential solar radiation (Franklin et al., 2000; Miller and Franklin, 2002). Some authors also argue that solar radiation is not enough to describe vegetation/environment correlations and that microclimate represented by aspect and slope must be considered (Austin, 2005).

The aim of this study was to compare different methods of solar radiation estimation, to evaluate their contribution to measurements and their efficiency in plant distribution models. Five methods of calculation were used: (i) sine transformation of aspect, (ii) cosine transformation of aspect, (iii) interaction between slope and cosine of aspect, (iv) cloud-free solar radiation model, and (v) solar calculation modelled using cloud cover values. We used the Helios program (Piedallu and Gégout, 2007) to model solar radiation. We chose this program because it takes into account both local topographical (slope, aspect, shadowing) and global parameters (latitude, cloud cover), and requires few, easy-to-obtain input parameters: only DEM and cloud cover values from meteorological ground stations are needed. We compared these different methods in order to estimate (i) if solar radiation calculated with GIS models performs better than slope–aspect transformations, (ii) for the GIS models, if the method of calculation or the period considered have an influence on the results, (iii) if the predictive ability of the different proxies is scale-dependent, and (iv) if the use of slope–aspect transformations enhances the species distribution models that include GIS processed solar radiation.

The five different solar radiation indices were implemented for France (550,000 km^2) at the finest available resolution covering the whole country (50×50 m grid resolution). To assess their quality, modelled radiation data were compared with a dataset of measured values collected from meteorological stations. Their ability to predict species distribution was then evaluated by modelling on different scales the distribution of three plant species known to be sensitive to light: silver fir (*Abies alba*), sycamore (*Acer pseudoplatanus*), and downy oak (*Quercus pubescens*).

2. Methods

2.1. Estimation of solar radiation

Slope and aspect were derived from the French National Geographic Institute (IGN) Digital Elevation Model at 50 m resolution with ArcGIS 9.0 software. Aspect was converted to linear measures of eastness and northness by sine and cosine transformation. Cosine of aspect was then multiplied by slope to include inclination variability in the proxy.

Helios, a GIS program (Piedallu and Gégout, 2007), was used to estimate clear sky (Helios) and overcast solar radiation (Helios-c). This program computes hourly shortwave radiation by adding direct, diffuse, and terrain-reflected components (Dubayah and Rich, 1995; Duguay, 1993). The calculation is