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Estimating leaf area index of mature temperate forests using regressions on site and vegetation data

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ABSTRACT

Canopy gap fraction and leaf area index (LAI) were measured using hemispherical photography in 91 mature forests across Switzerland, including coniferous, broadleaved and mixed stands. The gap fraction and LAI derived from five photographs per site could be reproduced with a high coefficient of determination ($R^2 > 0.7$) by regression against simple stand parameters obtained from vegetation surveys: coverages of the tree, shrub and herb layers, and tree height. The method appeared to be robust across the different types of forests. Applied to 981 sites across Switzerland, the regression model produced LAI values ranging from 1.4 to 6.7. These predictions were compared with site variables not included in the regression. LAI appeared limited by the altitude, with maximal values decreasing by one third from 400 to 2000 m above see level. Water availability was also clearly a limitation at sites with a negative water balance, i.e. where the yearly potential evapotranspiration exceeded the precipitation. High or low values of a humidity index based on the ground vegetation also corresponded to a limitation of the LAI, with shorter trees at dry sites and more open canopies at wet sites. Compared to optical measurements (including hemispherical photography), our regression method is fast and inexpensive. Such an approach appears very promising for obtaining reliable estimates of LAI for many sites with low costs. These estimates can then be fed into process models at the stand level.

1. Introduction

Leaf area index (LAI), defined as one half the total leaf area per unit ground surface area (Chen and Black, 1991), is an essential canopy characteristic that controls the energy, water and carbon fluxes between the terrestrial ecosystems and the atmosphere (Bonan, 1993). Most ecosystem process models that simulate carbon and water cycles on a stand or regional scale thus require LAI as an input variable (e.g. Running and Coughlan, 1988; Running and Gower, 1991). LAI can be directly obtained by sampling vegetation destructively, determining the dry mass of the whole foliage and, on a subsample of the harvested foliage, the specific leaf area (SLA, the ratio of fresh leaf area to dry foliage mass). In forests, destructive harvesting is commonly associated with the development of allometric relationships between LAI and variables such as tree stem diameter or sapwood cross-sectional area (e.g. Long and Smith, 1988; Gower et al., 1997). Such allometric equations are species and site-specific. Applying these equations to other sites may result in substantial errors (Grier et al., 1984), since several factors influence allometric coefficients, in particular nutrient availability, water regime and tree age.

As an alternative to destructively harvesting foliage, the LAI of broadleaved stands can be determined semi-directly from litterfall sampling during leaf fall. LAI is then calculated by multiplying the collected mass of leaves by the specific leaf area, which must be determined for each tree species separately. The SLA should also be determined specifically for the studied site, since it can vary with site fertility, within and between years, or with the duration of the collection interval (Bréda, 2003).

Because both the direct and the semi-direct methods for determining LAI are labour intensive and time consuming for forest canopies, a number of techniques relying on the radiative transfer theory (Anderson, 1971; Ross, 1981) have been developed to derive LAI from measurements of the transmission of radiation through the canopy. The most widely applied indirect techniques infer LAI from the distribution of the gap fraction (i.e. the fraction of the view in some direction from beneath the canopy that is not blocked by foliage). In these techniques, LAI is obtained by the inversion of the model describing the attenuation of radiation through the canopy, using gap fraction data measured over a range of zenith angles. Several instruments and methods, which include the hemispherical photography technique, are available to measure the distribution of the gap fraction (see review by Bréda, 2003).

The hemispherical photography technique derives gap fraction data from photographs of the canopy taken upward with an extreme wide-angle lens (typically 180° viewing angle). This tech-

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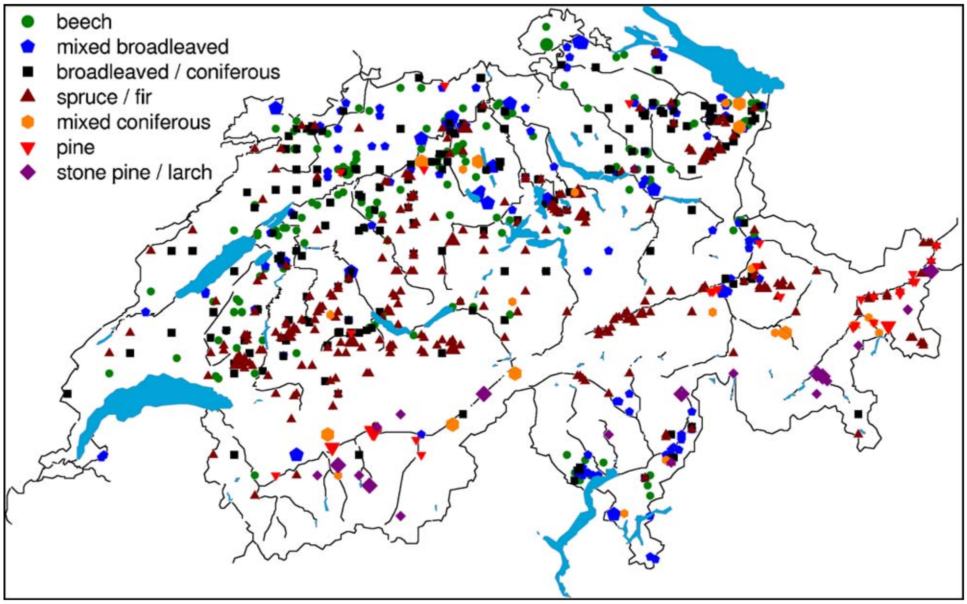

Fig. 1. Map of Switzerland showing the location of the 91 sites where the gap fraction and LAI were assessed with hemispherical photography (large symbols) and the 981 sites to which the regressions obtained were applied (small symbols). See Table 1 for the definition of the forest types.

nique requires great care at several steps of the data acquisition, in particular when selecting the exposure settings in the field, or when choosing the threshold to distinguish the canopy from the sky during image analysis (Thimonier et al., 2010). However, compared with sensors that measure light transmission, it has the major asset that it permanently archives the canopy structure. Moreover, using the information available from the photographs, the effects of a ground slope or of canopy clumping on LAI estimation can be directly corrected for. Hemispherical photography, like all methods based on the measurement of light transmission and gap fraction, is affected by the ambient light conditions, especially by the presence of the sun and of clouds. This considerably limits their use across sites in large-scale studies.

Methods of estimating LAI by remote sensing have been developed which rely on the different reflectance properties of vegetation and soil (Weiss and Baret, 1999). In the case of forests, deriving LAI from satellite imaging faces several challenges, among them the difficulty of separating the tree canopy from the ground vegetation, the need to account for canopy clumping, and the effect of ground slopes. Until recently, the forest LAI datasets obtained from remote sensing were, therefore, not satisfactory and limited in their range (e.g. Rautiainen, 2005; Garrigues et al., 2008). In recent years, there has been significant progress, especially using multi-angular sensors. Analysing the reflectance at different angles relative to the nadir and to the sun indeed provides information on the 3-dimensional structure of forest canopies (Hasegawa et al., 2010; Pisek et al., 2010). Corresponding datasets are being developed but their resolution is still limited to the kilometre scale and they need to be validated more broadly by comparison with ground-based measurements.

In this study, we estimated the LAI of mature forest stands using digital hemispherical photography at some 100 sites distributed across the whole of Switzerland. Our aim was to evaluate whether LAI could be alternatively derived from vegetation surveys, which are commonly carried out on forest sites. Our final objective was to obtain the LAI values needed as input data to run a water balance model (CoupModel; Jansson and Karlberg, 2004) on over a thousand forest sites across Switzerland for which vegetation data are available along with geophysical and soil data. We also wanted, at the same time, to examine how LAI relates to environmental factors.

2. Materials and methods

2.1. Field campaign

Hemispherical photographs of the canopy were taken in the summers 2004–2008 at 114 forest sites distributed across all the main regions of Switzerland (Jura, Plateau, Northern Pre-Alps, Alps, and Southern Alps; Fig. 1). These sites have also been used in other studies conducted by researchers at our institute (WSL, Birmensdorf). Vegetation surveys were carried out at these sites. All plant species occurring in a square 200-m^2 plot in the herb, shrub and tree layers were recorded using the Braun-Blanquet cover abundance scale (Braun-Blanquet, 1964; Mueller-Dombois and Ellenberg, 1974). This method is fast and generally recognised as sufficiently accurate to assess the prevailing environmental conditions and how they change (Wikum and Shanholtzer, 1978). It has been widely used in many countries on all five continents with, for example, more than 6000 forested sites assessed in Switzerland (Wohlgemuth, 1992) and in France (Gégout et al., 2005). As part of the vegetation survey, the coverage of the tree, the shrub and the herb layers were estimated visually as the proportion of their vertically projected area. Tree height was measured with a Vertex III ultrasonic instrument (Haglöf, Långsele, Sweden) on at least two of the tallest trees. The height of the shrub layer was estimated by the observers.

At each site, five hemispherical photographs of the canopy were taken, one at the centre of the vegetation plot and four in the corners. An exception was the data set stemming from the seven LWF (Long term Forest Ecosystem Research) sites. At the LWF sites, photographs were taken at 16 locations systematically distributed over a 43 m × 43 m area (Thimonier et al., 2010). Photographs were taken 1.5 m above ground using a digital camera (Coolpix 4500, Nikon, Tokyo, Japan) with a 183° fish-eye lens (Nikon FC-E8) fitted to a plate with a bubble level and compass, and mounted on a tripod. From each of the five points per plot, four photographs were taken with different exposures. The first was in automatic mode. The exposure of the second was set manually, with the aperture fixed at F/5.3, and the shutter speed set according to the reading of a spot-meter (Asahi Pentax V, Asahi, Tokyo) pointed towards a canopy gap near the zenith. The third and fourth photographs were then taken with the exposure increased