Available online at www.sciencedirect.com

SCIENCE DIRECT®

Agricultural and Forest Meteorology 132 (2005) 96–114

AGRICULTURAL AND FOREST METEOROLOGY

www.elsevier.com/locate/agrformet

# Assessment of automatic gap fraction estimation of forests from digital hemispherical photography

Inge Jonckheere [a,*], Kris Nackaerts [b], Bart Muys [a], Pol Coppin [a]

[a] Katholieke Universiteit Leuven, Laboratory for Forest, Nature and Landscape Research, Vital Decosterstraat 102, 3000 Leuven, Belgium

[b] Intergraph Mapping and Geospatial Solutions, Intergraph Benelux (Belgium) B.V. (NASDAQ: INGR), Tennessee House, Riverside Business Park, Internationalelaan/Bld International, 55 B5, 1070 Brussels, Belgium

Received 7 December 2004; accepted 6 June 2005

**Abstract**

Thresholding is a central part of the analysis of hemispherical images in terms of gap fraction and leaf area index (LAI), and the selection of optimal thresholds has remained a challenge over decades. The need for an objective, automatic, operator-independent thresholding method has long been of interest to scientists using hemispherical photography. This manuscript deals with the comparison of a wide variety of different well-known automatic thresholding techniques against the subjective manual method, using high-dynamic range digital hemispherical photographs. The performance of the different thresholding methods was evaluated based on: (1) visual inspection by means of a multi-criteria decision system and (2) quantitative analysis of the methods' sensitivity to an overall performance criterium. The automatic Ridler clustering method proved to be the most robust thresholding method for various canopy structure conditions. This automatic method might be the best solution for a fast, reliable and objective use of hemispherical photographs for gap fraction and LAI estimation in forest stands, given that the threshold setting is no longer manually performed. The fine-tuning potential of local thresholding methods to better address particular photographic limitations (e.g. over-exposure in a certain image region) is also presented.


*Keywords:* Gap fraction; Hemispherical photography; LAI; Thresholding

## 1. Introduction

### 1.1. Hemispherical photography

In ecological, hydrological, geo-morphological and biophysical process modelling, the forest canopy is generally characterized by leaf area index (LAI), defined as the total leaf area per unit ground surface area (Watson, 1947). LAI is the most common and,

* Corresponding author. Tel.: +32 16 329770; fax: +32 16 329760.
*E-mail address:* Inge.Jonckheere@biw.kuleuven.be (I. Jonckheere).

0168-1923/$ – see front matter 
doi:10.1016/j.agrformet.2005.06.003

**Nomenclature**

| | |
|---|---|
| $L_e$ | effective LAI |
| $m_b$ | sample mean of gray values associated with background (sky) pixels |
| $m_f$ | sample mean of gray values associated with foreground (vegetation) pixels |
| $P$ | zenith angle in the hemispherical object region |
| $P'$ | distance from the centre of the image |
| $P_s$ | number of image pixels classified as sky |
| $P_{ns}$ | number of image pixels classified as vegetation |
| $r$ | radial distance |
| $R$ | radius of hemispherical photograph |
| $T$ | threshold value |
| $T(\theta, \alpha)$ | gap fraction for a range of zenith angles with mean angle $\theta$ and angular resolution $\alpha$ |
| $\alpha$ | angular resolution |
| $\theta$ | zenith angle |

arguably, most useful comparative measure of vegetation structure in forest canopies. This is especially critical when considering that the forest canopy is the functional interface between 90% of Earth's terrestrial biomass and the atmosphere (Ozanne et al., 2003). Rapid, reliable and accurate measurements of forest LAI are of fundamental importance to estimate the exchange of carbon, water, nutrients and light in numerous studies on the Earth's ecosystems.

The usefulness of indirect LAI determination in forest monitoring by means of hemispherical photography has already been demonstrated (see review of indirect methods in Jonckheere et al., 2004). Digital hemispherical photography analysis provides a valuable alternative for the accurate quantification of canopy structure, since canopy structure parameters (such as canopy cover and gap fraction) can be extracted from the photograph. LAI subsequently can be determined from gap fraction measurements by inverting a light interception model. However, the first step in such an analysis is the segmentation of hemispherical photographs in order to identify the gap fraction (or the complementary canopy cover). Consistent extraction of gap fraction (GF) from color hemispherical photographs is still one of the main technical challenges in the processing of data from this optical imagery. Accurate segmentation is of the utmost importance, given that the outcome of this step will have significant influence on all subsequent processing.

Hemispherical canopy photography traditionally has relied upon analog black and white or color films, and CCD-scanners to produce digital images for analysis (Fraser, 1997). The use of traditional analog hemispherical photography for GF and LAI determination not only leads to time-consuming analysis, but its limited 6-bit dynamic range (i.e. maximum 64 discrete brightness levels) also cause problems (Hinz et al., 2001). This low dynamic range causes difficulties in distinguishing sunlit leaves from relatively small, under-exposed gaps in the canopy. A leaf illuminated by direct sunlight might, for example, is not distinguishable from the surrounding sky, since the brightness difference is too small to be detected by the imaging system. Camera exposure settings therefore have a major impact on the GF and LAI measurements and are a major cause of measurement errors as demonstrated by Chen et al. (1991).

Commercial consumer-priced digital cameras offer a dynamic range of 8 bits (256 levels, e.g. Nikon Coolpix 950, Nikon, Japan), with a spatial resolution close to that of film emulsions (Hale and Edwards, 2002). These characteristics provide forest scientists with a practical alternative to traditional film photography (Frazer et al., 2001). The dynamic range of professional digital sensors nowadays ranges between 12 and 16 bits (4096–65,536 levels, e.g. Kodak DCS series, Eastman Kodak, USA). The resolution of camera sensors, equipped with high-resolution detector arrays (six million pixels and more) is fast becoming comparable to traditional 35 mm and larger film cameras (Russ, 2002). Consequently, modern digital image enhancement technologies offer remarkable opportunities to improve hemispherical canopy image quality and contrast.

Jonckheere et al. (2004) presents a detailed discussion related to analog and digital hemispherical photography, and the practical and technical advantages of digital hemispherical photography.

The quality of the fisheye optics is a constraint in the cases of both digital hemispherical and analogue photography. In essence, hemispherical photographs produce a hemisphere of directions on a plane (Rich,