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Terrestrial laser scanning to estimate plot-level forest canopy fuel properties

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ABSTRACT

This paper evaluates the potential of a terrestrial laser scanner (TLS) to characterize forest canopy fuel characteristics at plot level. Several canopy properties, namely canopy height, canopy cover, canopy base height and fuel strata gap were estimated. Different approaches were tested to avoid the effect of canopy shadowing on canopy height estimation caused by deployment of the TLS below the canopy. Estimation of canopy height using a grid approach provided a coefficient of determination of $R^2 = 0.81$ and an RMSE of 2.47 m. A similar RMSE was obtained using the 99th percentile of the height distribution of the highest points, representing the 1% of the data, although the coefficient of determination was lower ($R^2 = 0.70$). Canopy cover (CC) was estimated as a function of the occupied cells of a grid superimposed upon the TLS point clouds. It was found that CC estimates were dependent on the cell size selected, with 3 cm being the optimum resolution for this study. The effect of the zenith view angle on CC estimates was also analyzed. A simple method was developed to estimate canopy base height from the vegetation vertical profiles derived from an occupied/non-occupied voxels approach. Canopy base height was estimated with an RMSE of 3.09 m and an $R^2 = 0.86$. Terrestrial laser scanning also provides a unique opportunity to estimate the fuel strata gap (FSG), which has not been previously derived from remotely sensed data. The FSG was also derived from the vegetation vertical profile with an RMSE of 1.53 m and an $R^2 = 0.87$.

1. Introduction

An accurate, spatially explicit, description of fuels is critical to prevent fire ignition and propagation, to model fire behaviour and to reduce fire effects since, amongst the *fire fundamentals triangle* vertices, fuels are the only component that humans can modify, through thinning or prescribed fires, to reduce fire hazard (Koutsias and Karteris, 2003; Salas and Chuvieco, 1994). In order to assess crown fire hazard as well as to design appropriate silvicultural treatments and prioritize treatment areas to reduce crown fire potential (Keane et al., 2005), an accurate description of canopy fuel characteristics is necessary.

Several canopy characteristics have been found to be related either directly or indirectly to the occurrence and behaviour of crown fires, and form the input for a number of fire behaviour and effects models such as NEXUS (Scott, 1999), FARSITE (Finney, 1998) and FLAMMAP (Stratton, 2006). Canopy height (CH) is an important canopy property since it indirectly influences crown fire occurrence through its effect on wind speed reduction and fuel moisture content (Reinhardt et al., 2006) as well as lofting of embers from a flaming tree (Albini, 1979a). Several definitions of canopy height can be found in the literature. Scott and Reinhardt (2005) defined it as the average height of the tallest five trees in the plot; Reinhardt et al. (2006) proposed to compute it as the highest point at which the CBD exceeds a given threshold, and Reeves et al. (2009) defined CH as the basal area-weighted mean height of the dominant and co-dominant trees within each 30-m grid cell used in the LANDFIRE project. Canopy cover (CC) represents the proportion of the forest floor that is covered by the vertical projection of the tree crowns. This variable characterizes the horizontal continuity of canopy fuels, affecting the potential development and propagation of crown fires, and it is used together with CH in fire modelling to estimate the wind reduction factor and fine fuel moisture content (Albini and Baughman, 1979b; Rothermel et al., 1986). Canopy base height (CBH) is an important parameter in modelling the transition of surface to crown fires since it determines the distance between the canopy and the ground. Several definitions of CBH can be found in the literature. Finney (1998) defined CBH as the vertical distance from the ground to the base of live crowns, whereas Ottmar et al. (1998) defined it as the height of the lowest continuous live or dead

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branch material of the tree canopy. Within the context of assessing the risk of crown fires, CBH has been defined as the lowest height above the ground at which there is sufficient canopy fuel to allow vertical propagation of fire through the canopy (Scott and Reinhardt, 2001). This minimum amount of fuel, which is represented by the minimum canopy bulk density (CBD) value required to propagate the fire to the crown, has been established somewhat arbitrarily using a wide range of values, for example, 0.011 kg/m^3 (Keane et al., 2006), 0.04 kg/m^3 (Mitsopoulos and Dimitrakopoulos, 2007) and 0.037 kg/m^3 (Sando and Wick, 1972). Despite the fact that this latter definition can be considered appropriate for fire risk assessment, it cannot be directly determined in the field.

In the literature it is often the case that the terms crown and canopy are used indistinctly to describe canopy fuel characteristics; however, it should be remarked that the term crown refers to individual tree characteristics whereas the term canopy makes reference to stand characteristics.

Estimation of canopy fuel properties has relied mainly on field measurements using direct or indirect methods. Direct methods require destructive sampling of trees to determine biomass by component (live or dead fuels) and size class (Küçük et al., 2008; Mitsopoulos and Dimitrakopoulos, 2007; Reinhardt et al., 2006; Scott and Reinhardt, 2005) allowing for the generation of allometric equations to derive these properties from inventory data. Direct methods are generally difficult to implement in an operational way and so non-destructive indirect methods, based on optical data or measurements readily available to forest managers (Reinhardt et al., 2006), have been developed.

In the last decade airborne LiDAR systems both, discrete return and full waveform have been proved useful to estimate canopy fuel properties. For example, Andersen et al. (2005) established an empirical model relating LiDAR metrics to field-based canopy height, which was defined as the highest height at which the canopy fuel density was greater than 0.011 kg/m^3. Skowronski et al. (2007) also found that mean canopy height could be accurately approximated using the 80th percentile of all LiDAR returns. A voxel-based approach was proposed by Popescu and Zhao (2008) to estimate the CBH of individual trees, by fitting a fourth degree polynomial to the vertical profile of individual trees and finding the first inflection point after the maximum of that polynomial. Riaño et al. (2003, 2004) defined the CBH as the height at which the 1st percentage of canopy hits occurred. Similarly, Holmgren and Persson (2004) computed CBH as the height of the highest 0.5 m height interval containing less than 1% of the total number of non-ground laser returns within a crown area. CBD has been effectively estimated from LiDAR data by deriving regression models (Andersen et al., 2005; Hall et al., 2005) and by relating foliage biomass to canopy volume (Riaño et al., 2003, 2004). CC can be derived from LiDAR data as the proportion of canopy returns to all returns, or by the ratio of the intensity of canopy returns to the intensity of all returns within a plot (García et al., 2010; Morsdorf et al., 2006). More recently, the capability of ground-based or terrestrial LiDAR systems (TLS) to estimate vegetation properties such as diameter at breast height (DBH), tree height, or timber volume, has been shown (Henning and Radtke, 2006; Hopkinson et al., 2004; Watt and Donoghue, 2005). Parameters such as leaf area index (LAI) (Hosoi and Omasa, 2006; Lovell et al., 2003) and gap fraction (Danson et al., 2007) have also been successfully estimated using TLS systems. Loudermilk et al. (2009) investigated the capability of TLS to characterize surface fuels at individual plant and plot scales. They found that fuel volume estimated using point-intercept fuel sampling was significantly larger than the volume derived from TLS data at an individual scale but not at a plot scale. They also found that surface fuel height distribution could be measured more reliably using TLS data than point-intercept measurements. Given the capacity of TLS to provide very high-density three-dimensional point data, they represent an opportunity to obtain information on vegetation structure that is difficult to gather from either destructive or any other field-based measurement.

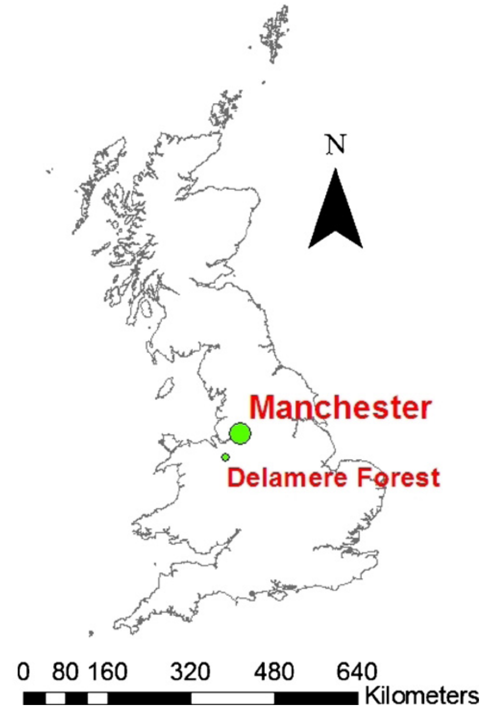

Fig. 1. Location of the study area.

The main objective of this work was to evaluate the potential of TLS data to characterize forest canopy fuel properties at plot level. Specifically, canopy height and canopy cover were estimated. In addition, an automatic procedure was developed to derive the canopy base height from a voxel-based vegetation vertical profile (VVP). Finally, the fuel strata gap (FSG), which represents the distance between the surface and the canopy fuel strata, was also estimated.

2. Methods

2.1. Study area

The study was carried out in Delamere Forest (53.22597 N; 2.6429 W), which is managed by the U.K. Forestry Commission and is located around 40 km south-west of Manchester, within the county of Cheshire, covering 972 ha (Fig. 1). The study area is mainly composed of homogeneous stands of Scots pine and larch, as well as mixed stands of oak and birch. Eight circular plots with a radius of 10 m were selected and located in several deciduous and coniferous stands within the study site, representing different species and development stages. The deciduous stands, plots D1, D2 and D3 were composed of birch (*Betula spp.*), oak (*Querkus spp.*) and Sweet chestnut (*Castanea sativa*) and were more than 100 years old. The plot density as expressed by basal area ranged between 23.3 and 44 m^2 ha^{-1}. The coniferous stands, plots C1 and C2 were composed of Scots pine (*Pinus sylvestris*) and Corsican pine (*Pinus nigra var maritima*) aged 65 years, with a plot density of 36.9 and 40.6 m^2 ha^{-1}, respectively; plot C3 was composed of Corsican pine (*Pinus nigra var maritima*) and Weymouth pine (*Pinus strobus*) aged 40 years, with a density of 39.1 m^2 ha^{-1}; and finally plots L1 and L2 were composed of younger Japanese larch (*Larix kaempferi*) aged 30 years and a plot density of 25.1 and 44.8 m^2 ha^{-1}, respectively.