Forest Ecology and Management 335 (2015) 255–260

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Ground based LiDAR demonstrates the legacy of management history to canopy structure and composition across a fragmented temperate woodland

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ARTICLE INFO

Article history:
Received 25 May 2014
Received in revised form 27 August 2014
Accepted 29 August 2014

Keywords:
Canopy structure
LiDAR
Forest fragments
Land-use history
Secondary forest
Wytham Woods

ABSTRACT

The structure of forest canopies correlates with stand maturity and biomass, and develops consistently over time. Remote-sensing technologies such as Light Detection and Ranging (LiDAR) have become prominent tools for measuring structural characteristics of forests.

We walked a portable canopy LiDAR (PCL), an up-facing rangefinder that detects vegetation through the canopy at two kilohertz, along multiple transects at ten different forest stands in the area of Wytham Woods, Oxfordshire, UK. The stands had different species composition, were situated at forest edges and in forest core, were in fragments of different sizes and had different land-use histories. With these data we tested structural differences in vegetation across these stand types.

Although none of the stands have been managed in the last 70 years, they have not converged structurally. Vertical canopy structure differed between stands that regrew naturally from open field and those with a history of coppice management. Forest stands that have developed following major fellings or through spread on to former grazing land showed some structural similarities to classic natural succession from large disturbances. Stands that were actively managed as coppice over preceding centuries, showed a similar structural pattern to mature forest, but without the tall overstorey that can develop into old growth communities.

This structural divergence indicates two distinct pathways for secondary forests: with implications for the future biomass, stand structure, and species composition. The legacy of management practices can determine canopy structure decades after the forest is removed from active management, but can also be difficult to discern with remote sensing data. We recommend that "ground-truthing" remote sensing data go beyond traditional checks of height and topography, as the history and composition of secondary forests can have an important influence on the pace and compositional structure of recovery from management.

Published by Elsevier B.V.

1. Introduction

Tree canopies exert strong influences on the structure and function of forest ecosystems (Lowman and Rinker, 2004; Shugart et al., 2010). Spatio-temporal variation in the density of a forest canopy can determine understorey light levels (Parker et al., 2004), local climate and microclimate (Shuttleworth et al., 1989; Clinton, 2003), tree regeneration (Barbeito et al., 2009; Bebber et al., 2002), plant and animal community composition (Frelich et al., 2003; Richards and Windsor, 2007), and carbon storage (Penne et al., 2010). Quantifying canopy structure and dynamics can therefore address critical questions in forest ecology (Lowman and Rinker, 2004; Wilson, 2011). We carried out a quantified analysis of canopy

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http://dx.doi.org/10.1016/j.foreco.2014.08.039
0378-1127/Published by Elsevier B.V.

structure as it related to land use history and recovery from active management, which could add to current models of structural regeneration and thus guiding predictions about the pace and direction of forest recovery from anthropogenic disturbance.

Forest canopies are highly dynamic, responding to disturbances across spatial and temporal scales. Although forest successional dynamics cover a continuum of disturbance intensity and frequency, natural mechanisms tend to lead to a limited number of trajectories of canopy development observed across many types of temperate broadleaf forests. Gap-phase dynamics are most commonly associated with low-intensity, high-frequency disturbances, such as canopy openings caused by the deaths of individual trees (Brokaw, 1985). The resulting small light gaps are filled rapidly by advanced regeneration (i.e., juvenile trees that avoid the gap generating disturbance) and ingrowth from neighboring trees (Hubbell and Foster, 1986; Brokaw, 1985). Infrequent but high-intensity disturbances (e.g., wind throw, fire, liana-connected tree-fall gaps) remove the canopy of large areas of forest, releasing tree seedlings and saplings from competition for light, allowing incoming seeds to colonize, thus initiating successional trajectories that are often predictable in terms of canopy structure and vertical stratification and which play out across many decades or centuries (Franklin et al., 2002; Ishii et al., 2004; Oliver and Larson, 1996).

Most temperate forests, however, are exposed to or recovering from anthropogenic, rather than natural, disturbances, particularly from land-use change and timber management. Furthermore the response to these disturbances may be different where forest cover is highly fragmented as opposed to largely continuous cover. For example in the UK, forests have existed only as small isolated patches for centuries due to human activities (FAO, 2010; Rackham, 2001; Whitney, 1996).

The recent availability of remote-sensing technologies offers the potential to make accurate measurements of canopy structure, which allow us to explore different types and intensities of anthropogenic disturbance on canopy structure.

LiDAR technology is a common approach to measuring forest structure (Wulder et al., 2012). LiDAR systems use a range-finder to send and record the return of many pulses of light per second, giving precise estimates of the distance of objects from the source. LiDAR systems on aircraft or satellites can now provide information on forest structure over landscapes and regional scales (Asner et al., 2012; Wulder et al., 2012). Airborne systems, however, are expensive to build, maintain, and schedule for specific studies. An alternative is to use a ground-based system, known as Portable Canopy LiDAR (PCL) (Parker et al., 2004). This system is carried from a front-facing platform at waist height and fires 2000 pulses per second up through the canopy rather than down on to it. This system captures 'slices' of the canopy instead of 3-dimensional profiles, but it offers a precise, objective, and easily

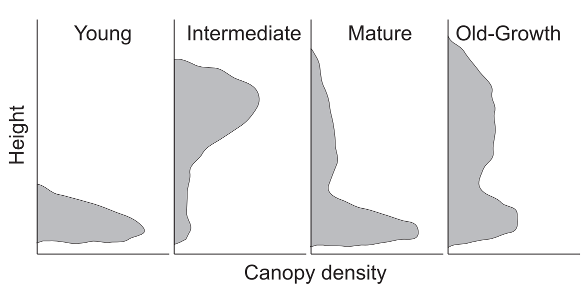

Fig. 1. Abstracted Canopy Height Profiles (CHPs) for Young, Intermediate, Mature and Old-Growth forest stands in the Eastern USA (adapted from Parker and Russ (2004)). Although initial stand formation shows dense, uniform canopy with little understorey, as the forest matures, treefall gaps allow a mix of over and understorey vegetation. Stand maturity in this successional pathway also leads to higher outer canopy.

deployed approach to measuring forest structure that is readily translatable to the similar class of technologies used in airborne and satellite systems.

Here, we use a PCL system in forest fragments in the UK to determine if fragment size, edge to core ratio, management history, and composition produce structural patterns similar to those found in the forest successional stages (Fig. 1). Specifically, we use PCL to test whether (1) woodland core differs in canopy structure from edge, and across fragments of varying sizes and shapes; (2) stand edges influences canopy structure; (3) forests that have been actively managed in the past follow successional recovery in the same way that forests that have grown up on open grazing land.

2. Materials and methods

2.1. Site

Field work was conducted at Wytham Woods, and the surrounding fragments, in Oxfordshire, UK (1°20'W 51°47′N) in July and August 2009. Wytham Woods is a relatively large (ca. 400 ha) fragment of mixed woodland, surrounded by numerous other woodland fragments in an agricultural landscape matrix (Fig. 2), typifying the range of woodland sizes and management-histories found in the UK (Kirby and Gibson, 2010 and Supplement A). The wood is situated on a small hill rising to 165 m a.s.l. from the surrounding plain at 60 m a.s.l.

The Woods and fragments show a mixture of origins and management histories (Kirby and Gibson, 2010; Morecroft et al., 2008): ancient semi-natural woodland formerly treated as coppice; other semi-natural woodland regenerated naturally within former wood-pasture or on open grazings, and plantations of both broadleaves and conifers, some of were established on open ground and some within the ancient woodland. The semi-natural woodlands are mainly of National Vegetation Classification (Rodwell, 1991) type W8 (*Fraxinus excelsior – Acer Campestre – Mercurialis perennis*).

2.1.1. Permanent sample plots

Permanent sample plots were established in Wytham Woods and surrounding fragments in 2008 and 2009 (Table 1 and Fig. 2) (Supplement A). All stems above 1 cm diameter at 1.3 m height were tagged, mapped, identified to species, and diameter-measured in the 18 ha Wytham core plot (Butt et al., 2009; Butt et al., 2014). In the seven 'satellite' plots, the lower diameter at breast height (DBH) limit was 5 cm. The satellite plots comprised two forest edge plots, and five plots in forest fragments of differing sizes. In addition, five 100 m transects were established in the northern and southern edges of Wytham Wood (Fig. 2).

Each plot was sampled by a series of transects (details in Table 1), totaling 4.5 km. All transects were perpendicular to forest edges except the Southern Edge Fragment, which is long and thin and had only one transect run lengthwise through it (Table 1). The edge plots were sampled perpendicular to the forest boundary for ca. 100 m, beginning 0–2 m from the boundary depending on whether dense, impenetrable vegetation was present which could not be sampled (explained in Section 3).

2.2. Portable Canopy LiDAR (PCL)

Canopy structure data were collected from the plots along the transects using a portable canopy LiDAR system (PCL). The PCL included an up-facing Riegl LD90-3100VHS-FLP range-finder (Riegl USA, Orlando, Florida) attached with battery and small note-book computer to a front-facing platform worn by the surveyor with a harness system. The surveyor walked in a straight line at a consistent pace along the transects, measuring the transects in