GOING UNDERCOVER: MAPPING WOODLAND UNDERSTOREY FROM LEAF-ON AND LEAF-OFF LIDAR DATA

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ABSTRACT:

An understorey model is created for an area of broadleaf, deciduous woodland in eastern England using airborne LiDAR data from winter 2003 (leaf-off conditions) and summer 2005 (leaf-on). The woodland is ancient, semi-natural broadleaf and has a heterogeneous structure, with a mostly closed canopy overstorey and a patchy understorey layer beneath. In places, particularly in the centre of the study area, the top canopy is not mature, but is open and scrubby. The trees of the top canopy (i.e. dominants) together with trees and shrubs that occur in open areas (i.e. sub-dominants) can be sampled directly in leaf-on first return airborne LiDAR data, whereas trees and shrubs that occur hidden as understorey (i.e. suppressed) require a more sophisticated approach to map using airborne LiDAR data. This study makes use of the fact that in temperate deciduous woodland the understorey layer typically leafs out two weeks before the overstorey. Capturing winter (leaf-off) airborne LiDAR data during this time slot maximises the ability to map the understorey layer. Thus, leaf-on first return data were used to define the top canopy for overstorey trees and leaf-off last return data were used to model the understorey layer beneath. Field data from five stands were used to identify crown depth in relation to tree height for the six species of dominant trees in the study area. Thresholds were identified per tree species for crown depth as a percentage of canopy height, and the understorey layer was modelled where leaf-off last return data occurred below the relevant threshold. A minimum height of 1 m was applied to define woody understorey. Critical to this process were a Digital Terrain Model (extracted from the leaf-off last return LiDAR data) to normalise the first and last return LiDAR data to canopy height, and a digital tree species map (derived from the classification of time series airborne multi-spectral data) to guide the application of canopy depth thresholds per species.

1. INTRODUCTION

The vertical structure of woodlands or forest plays an important role in determining microclimatic conditions (including radiation levels at the forest floor), the availability of niche space, habitat quality, the distribution of fuels and subsequent fire behaviour (Brokaw and Lent, 1999, MacArthur and MacArthur, 1961, Pyne et al., 1996). Forests and woodlands can have simple, single-storey canopies or more complicated multi-storey canopies. In forests where there is a heterogeneous vertical structure, dominant trees form the overstorey canopy, whilst sub-dominant trees have free access to light but do not occupy the upper canopy, and suppressed trees have no direct access to light and grow underneath a relatively continuous cover of branches and foliage from adjacent dominant or sub-dominant trees. The understorey can be composed of seedlings and saplings of overstorey trees which persist as suppressed juveniles until a suitable canopy gap opens, and shade tolerant species of trees or shrubs which complete their life-cycles in an environment of lower light intensity and higher humidity than in the overstorey. Information on the understorey layer of woodland can be essential for the accurate modelling of carbon stocks and sequestration (Patenaude et al., 2003) and of bird habitat availability and quality (Broughton et al., 2006).

There are numerous case studies involving the application of airborne LiDAR data for detailed spatial modelling of forest structure (see Lim et al., 2003 for a review) and some techniques have become operational for forest inventory (see Næsset, 2004). At the stand level, measures such as mean tree height and diameter, timber volume, stem number, crown height, biomass, canopy closure, and LAI have been derived using discrete-return small footprint LiDAR data (Magnussen and Boudewyn, 1998, Næsset, 2002, Næsset and Økland 2002). This typically involves regression-based methods in which percentiles of the distribution of canopy height measurements from LiDAR are used to predict forest characteristics within a spatial sampling frame based on empirical relationships. Where the density of laser returns is greater than 5-10 per m^2, then individual tree based approaches have been used (Persson et al., 2002), giving more direct measures of tree height, timber volume and stem number (Maltamo et al., 2004a). These studies tend to be focussed either on single layered forests or on the dominant tree layer if forests are multi-layered, thus deriving variables for dominant trees only (Maltamo et al., 2005). Such measures will not fully characterise the structure of forests with significant vertical heterogeneity. For example, Maltamo et al. (2004b) showed that for a mixed-species woodland of spruce, pine and birch in Finland it was possible to detect over 80% of dominant trees but only 40% of all trees in LiDAR data with approximately 10 hits per m^2. As a result, they found that predictions of timber volume and stem density were underestimated by 24% and 62% respectively, although this could be improved by predicting suppressed trees using theoretical distribution functions (Maltamo et al., 2004a).

The larger footprint, waveform recording LiDAR systems have an obvious advantage for characterising and quantifying forest vertical structure. For example, systems such as SLICER and LVIS have been demonstrated successfully for estimating stand height, mean stem diameter, basal area, and total biomass (Means et al., 1999, Drake et al., 2002, Lefsky et al., 2002), and characterising the canopy height profile (Lefsky et al., 1999, Harding et al., 2001, Parker et al., 2001). However, there have been attempts to characterise forest vertical structure using small footprint discrete return LiDAR data, as it is recognised that the distribution of LiDAR returns over forests and woodland relates to the vertical structure of the tree canopy. Thus, Zimble et al. (2003) characterised woodland as either single or multi-storey by the analysis of LiDAR-derived tree height variance in 30 m grid cells, whilst Riaño et al. (2003) performed cluster analysis of LiDAR tree canopy returns to discriminate overstorey and understorey proportions in 10 m grid cells. Maltamo et al. (2005) developed a histogram thresholding method to designate the distribution of LiDAR canopy height returns as uni- or multi-modal and thus the canopy as single or multi-layered. They constructed regression models for the logarithmic number and Lorey's mean height of understorey trees, using independent variables derived from the LiDAR distributions. However, a common problem reported in these studies is that where the dominant trees form a dense and closed canopy it is not possible to identify understorey by analysing only one return of LiDAR data.

Where the overstorey is deciduous, what is required is LiDAR data from leaf-on and leaf-off conditions; using the leaf-on data to model the overstorey and leaf-off data to identify the understorey. To-date only two papers have touched on this. Hirata et al. (2003) showed, by a visual assessment, that the amount of information on both the ground and the understorey layers was significantly higher in leaf-off LiDAR data for temperate deciduous forests in Japan. Imai et al. (2006) examined LiDAR data from three dates across a growing season, also for temperate deciduous forests in Japan, and produced a canopy height model from leaf-on conditions and a canopy height difference model across all three dates. They then applied height thresholds of 0-1m, 1-5m, 5-10m and > 10m to both models to separate ten classes that distinguished what they called high tree canopy (evergreen and deciduous, with or without a shrub layer), sub-high tree canopy (again separating evergreen and deciduous, with or without a shrub layer), shrub layer (evergreen and deciduous) and ground layer.

The work reported in this paper makes use of dual return LiDAR data acquired in leaf-on and leaf-off conditions for a broadleaf deciduous woodland in the UK. Field data are used to identify the relationship between tree height and crown depth for overstorey tree species and this information is applied to the LiDAR data, using the leaf-on first return data to define the top canopy for overstorey trees, and leaf-off last return data to identify a discontinuous layer of suppressed trees or shrubs below the overstorey canopy. This is based on the identification of thresholds for crown depth as a percentage of canopy height per tree species. Critical to this understorey modelling process therefore, is a tree species map, which here is derived from the classification of time series airborne multi-spectral data.

2. MATERIALS AND METHODS

2.1 Field site

The study area is Monks Wood National Nature Reserve in Cambridgeshire, eastern England (52^o 24' N, 0^o 14' W). This is an ancient woodland of broadleaved deciduous species, which covers 157 hectares. Within this boundary are two cleared areas, totalling 6 ha, which are maintained by grazing. These two fields are not considered to be part of the spatial coverage of Monks Wood in all following descriptions and statistical analyses. However, all other open areas within the boundary of Monks Wood, such as canopy gaps and paths, are included. The total area of Monks Wood is thus considered here to be 151 ha.

Monks Wood is extremely heterogeneous in terms of the woody species making up the tree canopy and understorey, their relative proportions in any area, canopy closure and density, tree height and stem density (Hill and Thomson, 2005). The overstorey tree species of Monks Wood are common ash (*Fraxinus excelsior*), English oak (*Quercus robur*), field maple (*Acer campestre*), silver birch (*Betula pendula*), aspen (*Populus tremula*) and small-leaved elm (*Ulmus carpinifolia*). Ash is the most common and widespread species, occurring mostly as coppice stems but regenerating naturally wherever the canopy is opened (Massey and Welch, 1993). Oak, maple and birch occur less frequently, the latter regenerating from seeds in canopy gaps. Aspen and elm form occasional clusters on the wetter soils, although the elm population declined significantly in the 1970s due to an outbreak of Dutch elm disease. The former elm stands have been left to regenerate naturally and today tend to be rather scrubby in nature. The dominant woody species making up the understorey and fringes of Monks Wood are hawthorn (*Crataegus monogyna*), common hazel (*Corylus avellana*), blackthorn (*Prunus spinosa*), dogwood (*Cornus* sanguinea) and common privet (*Ligustrum vulgare*). Hazel, along with ash, was coppiced until 1995. Hazel now occurs mixed with hawthorn and blackthorn throughout Monks Wood (Massey and Welch 1993). Also to be found in the understorey, especially in more open areas, are elder (*Sambucus nigra*), buckthorn (*Rhamnus catharticus*), grey willow (*Salix cinerea*), goat willow (*S. caprea*), downy birch (*B. pubescens*), crab apple (*Malus sylvestris*) and bramble (*Rubus fruticosus*).

2.2 Field data

The field data used in this study were collected in July 2000. Five contrasting stands were surveyed (see Table 1 in Patenaude et al., 2003). The stands ranged in size between 0.84 ha and 3.69 ha, and covered the range of species composition and structure present within Monks Wood (Tables 1 and 2). Each stand was divided into a grid of 10 equal areas (8 in stand 5), and in each of these grid cells a 20x20m sample plot was located randomly. For each of the 48 plots, the diameter at breast height (DBH) for all woody stems of at least 7cm DBH were recorded, totalling 2191 living stems. Each recorded stem was identified by species and designated as either overstorey or understorey. For the overstorey trees, crown height and crown depth (amongst other measures) were recorded for three randomly selected individuals of each species per plot. This totalled 101 individuals for ash, 62 for oak, 42 for maple, 15 for elm, 9 for aspen and 4 for birch.

	Overstorey		Understorey	
	# stems	Total BA	# stems	Total BA
Stand 1 (2.57 ha)	144	103891	224	18589
Stand 2 (3.35 ha)	248	104830	155	13293
Stand 3 (2.83 ha)	84	47682	325	24087
Stand 4 (3.69 ha)	394	108201	173	12672
Stand 5* (0.84 ha)	229	190687	215	19073

Table 1. Structural composition of the five stands enumerated in Monks Wood. Data per stand are for ten 20x20m plots; Total Basal Area values are in cm^2.
(* values for Stand 5 are weighted to the equivalent of 10 plots)

	Ash	Oak	Maple	Aspen	Elm	Birch
Stand 1	19	60	19	0	0	0
Stand 2	89	3	8	0	0	0
Stand 3	29	6	45	17	0	4
Stand 4	89	8	3	0	0	0
Stand 5	14	5	0	0	80	0

Table 2. Percentage composition of tree species in each stand enumerated from ten 20x20m plots.

The tree crown data were used to examine the relationship between canopy height and crown depth per overstorey tree species across Monks Wood, and to identify thresholds in crown depth as a percentage of canopy height. This information was used to model the understorey layer from the airborne LiDAR data. The field data on understorey stem count and basal area were used to validate the derived understorey model.

In additional to traditional forest mensuration data, a map of the six species of dominant trees which make up the overstorey of Monks Wood was available. This was produced from the supervised classification of a time-series of 2 m spatial resolution Airborne Thematic Mapper (ATM) data, acquired throughout the growing season of 2003. This map has a surveyed overall accuracy of 88% (kappa 0.84) for the identification of ash, aspen, birch, elm, maple and oak tree species in the overstorey canopy (Table 3). Note that for this product, the overstorey is defined as being greater than 8 m tall.

	Composition (%)	Users' Accuracy (%)
Ash	54.9	83.5
Aspen	7.2	71.4
Birch	2.3	90.7
Elm	0.5	84.6
Maple	14.3	84.1
Oak	20.8	97.3

Table 3. Percentage composition of overstorey tree species in Monks Wood based on digital image classification, and the surveyed User's Accuracy for each species.

2.3 Airborne LiDAR data

LiDAR data were acquired with an Optech Inc. Airborne Laser Terrain Mapper (ALTM-3033) on 14 April 2003 and 26 June 2005. These data sets are referred to in this manuscript as leaf-off and leaf-on respectively; however, the acquisition date for the leaf-off data was selected such that whilst the overstorey canopy was still dormant the understorey had already leafed out. For both data sets, the first and last significant return per laser pulse were recorded. The leaf-off data were acquired at an average flying altitude of 980m, with a scan half angle of 15^o generating 1 laser hit per 1 m^2, whilst the leaf-on data were acquired at an average flying altitude of 1125m, with a scan half angle of 20^o generating 1 laser hit per 2 m^2.

The first and last return data of both the leaf-on and leaf-off data sets were each processed into a Digital Surface Model (DSM) via Delaunay Triangulation (Figure 1). The selected spatial resolution was 0.5m, i.e. the approximate horizontal accuracy of data acquisition by the ALTM 3033 at the flying altitude. Comparison of the leaf-off and leaf-on DSMs revealed the need for more precise geo-registration between the two data sets. Thus, 32 ground control points were identified in the first return DSMs of the leaf-on and leaf-off data. These had a predicted accuracy after first order polynomial transformation of 0.48m in x and 0.49m in y (total 0.69m). The same set of ground control points were used to register both the first and last return leaf-on DSMs to the leaf-off DSMs. The total shift after transformation was 0.33m in x and 1.68m in y. Nearest neighbour resampling was used to preserve individual pixel values in the transformed DSMs.

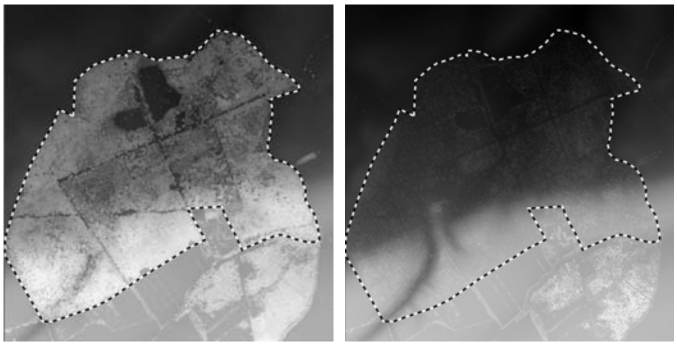

Figure 1. Leaf-on first return DSM (left) and leaf-off last return DSM (right) for Monks Wood, Cambridgeshire, UK. The boundary of the study area is shown by a dashed line.

A Digital Terrain Model (DTM) was generated from the leaf-off last return data, in which 48% of laser returns within the 151 ha Monks Wood were ground hits. This compared with a ground hit rate for the leaf-off first return of 3.1%, and the leaf-on last return (2.7%) and leaf-on first return (1.8%). Ground hits in the leaf-off last return data were identified by a process of adaptive filtering, whereby focal variance in the DSM was calculated over 10x10 and 40x40 pixel windows and thresholds in both were used to determine whether to extract a ground return as a 5x5, 10x10, or 20x20 pixel block minimum for any given area. A DTM was interpolated by applying a thin-plate spline to the extracted local elevation minima. This was carried out as an iterative process, comparing the DTM at each iteration with the leaf-off last return DSM and reducing the minimum filter size from which ground hits were extracted where the two surfaces were within tolerance limits. The accuracy of the resulting DTM was assessed using 244 terrain measurements recorded with an electronic total station (see Gaveau and Hill, 2003). The RMSE was ± 0.27 m (range -0.78 m to +0.59 m).

A Digital Canopy Height Model (DCHM) was then generated for the top canopy of Monks Wood by the per-pixel subtraction of the DTM from the leaf-on first return DSM. In line with the tree species map, the overstorey tree layer was considered as canopy taller than 8 m. The top canopy between 1 m and 8 m was considered to be sub-dominant trees and shrubs. This component of the understorey layer is directly exposed (i.e. not covered by an overstorey layer) and so is readily identifiable from airborne LiDAR data acquired during leaf-on conditions.

Extracting the proportion of the understorey layer that is hidden below the overstorey (i.e. suppressed trees and shrubs) made use of the difference between the leaf-on first return and leaf-off last return LiDAR data. The difference was calculated per-pixel between the leaf-on first return and leaf-off last return DSMs and expressed as a percentage of the leaf-on first return DCHM. The hidden understorey layer was identified as any point where the leaf-off last return occurred below the threshold identified from the field data of crown depth as a percentage of canopy height per tree species. The tree species information came from the co-registered tree species map. A minimum height of 1 m was applied to define woody understorey.

3. RESULTS

For the six species of dominant trees that constitute the overstorey layer in Monks Wood, only in the case of maple was there a strong significant relationship between canopy height and crown depth (R^2 = 0.65, n = 42, p < 0.001). Thus, rather than calculating the likely crown depth for a canopy of any given height for an individual species, an upper threshold was sought per species for percentage crown depth. Histograms of crown depth as a percentage of canopy height for the six overstorey tree species in Monks Wood are shown in Figure 2. The selected thresholds are also shown; these were 60% for ash, birch and elm, 70% for aspen and oak, and 80% for maple. These thresholds were subsequently applied to the leaf-on first return and leaf-off last return airborne LiDAR data to model the hidden understorey layer. The chosen thresholds of maximum crown depth as a percentage of canopy height were deliberately conservative; i.e. were more likely to miss larger trees or shrubs in the understorey where the overstorey canopy was tall but not deep (errors of omission) rather than to incorrectly map the base of deeper overstorey crowns as understorey (errors of commission).

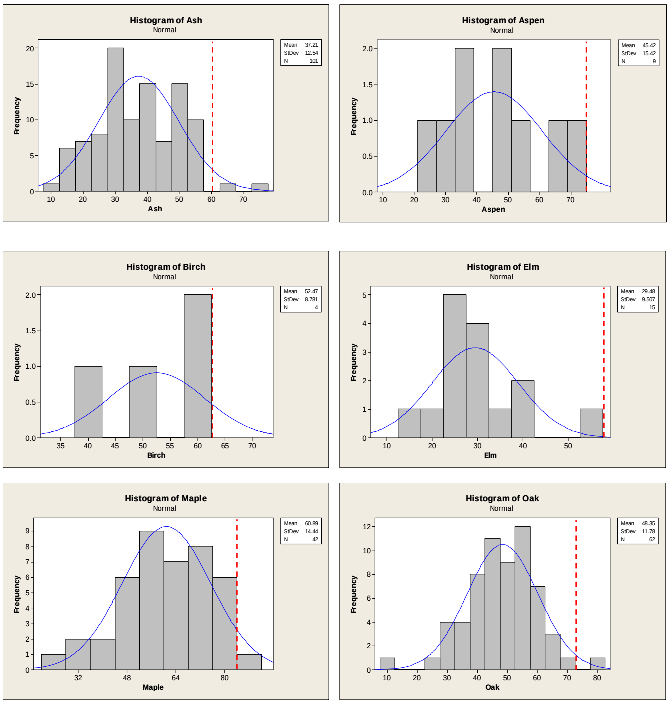

Figure 2. Histograms of crown depth as a percentage of canopy height for the six species of dominant trees that constitute the overstorey layer in Monks Wood. The chosen thresholds are shown by a dashed line.

The DSMs from leaf-on first return and leaf-off last return data clearly relate to two different surfaces, with the leaf-on first return reflecting the predominantly closed nature of the overstorey canopy and the leaf-off last return data supplying information from the understorey layer and ground (Figure 1). Statistics for the two DSMs normalised by the subtraction of terrain elevation are given in Table 4. The leaf-on first return data for Monks Wood had an average canopy height of 13.35 m (standard deviation of 5.10 m), with 83.2% having a canopy height > 8.0 m. This represents the overstorey tree layer, below which there could be a concealed understorey layer. Only 14% of the leaf-on first return data for Monks Wood had a canopy height of between 1 m and 8 m. This is the exposed proportion of the understorey layer (composed of sub-dominant trees and shrubs), and occurs around the woodland margins and in distinct patches in those areas which have been left to regenerate naturally following the loss of elm trees. The exposed portion of the understorey had an average canopy height of 5.46 m (standard deviation 1.87 m). The leaf-off last return data had an average canopy height of 1.38 m (standard deviation 1.61 m), with only 0.3% being > 8 m, and 42.5% returning from canopy between 1 m and 8 m. This could represent either understorey or returns from lower levels within the crowns of overstorey trees.

	Leaf-on first return	Leaf-off last return
Minimum (m)	0.00	0.00
Maximum (m)	25.31	18.95
Mean (m)	13.35	1.38
Standard deviation (m)	5.10	1.61
0 m to 1 m (%)	2.8	57.2
1 m to 8 m (%)	14.0	42.5
> 8 m (%)	83.2	0.3

Table 4. Summary statistics for the normalised leaf-on first return and leaf-off last return LiDAR data for Monks Wood

Figure 3 gives histograms for the difference between the leaf-on first return and leaf-off last return DSMs; expressed in metres and as a percentage of overstorey canopy height. The summary statistics are given in Table 5. The obvious point to note is that there is a high level of penetration between the two LiDAR surfaces, with an average height difference of 11.98 m (standard deviation 5.28 m) and an average penetration rate of 90.2% (standard deviation 12.5%). In fact, just over half (50.5%) of Monks Wood overstorey has a penetration rate in the leaf-off last return data of > 95% of canopy height. This reflects a high level of ground penetration in the leaf-off last return LiDAR data. Note that negative values did occur where tree fall or felling took place between the two dates of LiDAR acquisition. However, these covered only 1% of the land area of Monks Wood and were not considered in the above statistics.

	Difference in metres	Difference as % canopy height
Minimum (m)	-12.97	0.06^*
Maximum (m)	25.09	100.00
Mean (m)	11.98	90.23
Standard deviation (m)	5.28	12.45

Table 5. Summary statistics for the difference between leaf-on first return and leaf-off last return LiDAR data for Monks Wood
(* this value excludes negative height differences).

The concealed component of the understorey layer was modelled based on the difference between the leaf-on first return and leaf-off last return DSMs. This layer of suppressed trees and shrubs covers approximately 30% of the area within the Monks Wood boundary, i.e. some 46.4 hectares. The understorey model covers a range of height values from a chosen minimum of 1.0 m to a maximum of 10.18 m; although 99% has a height range between 1m and 6m. A histogram for the model of concealed understorey is shown in Figure 4. The mean height of the understorey is 2.64 m (standard deviation 1.16m).

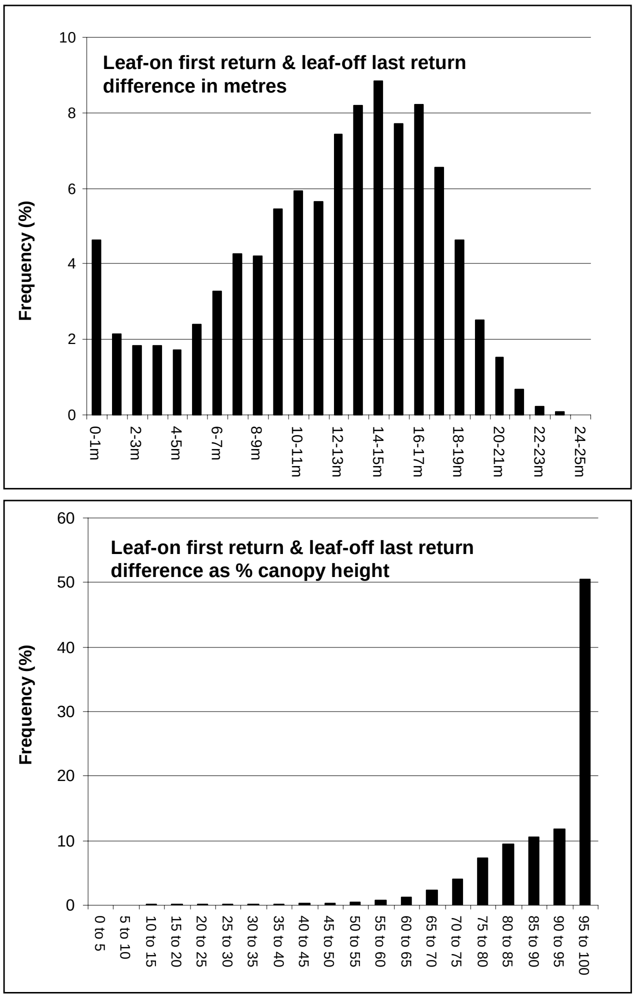

Figure 3. Histograms of the difference between leaf-on first return and leaf-off last return LiDAR data for Monks Wood.

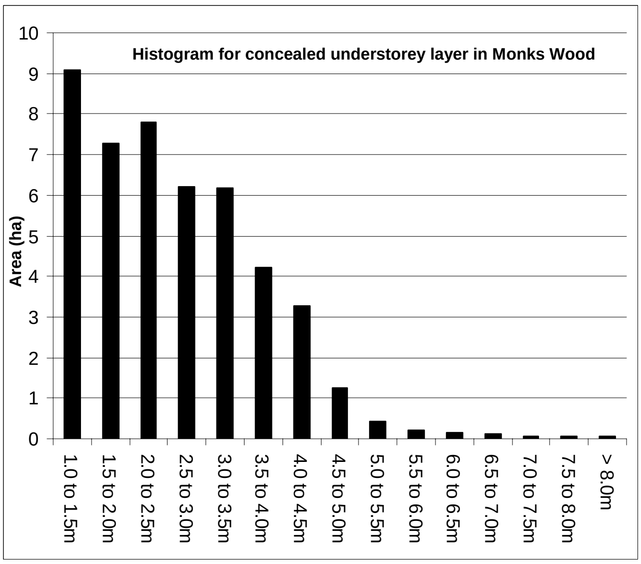

Figure 4. Histogram for the concealed portion of the understorey, as modelled from the leaf-on first return and leaf-off last return LiDAR data.

The total understorey layer of Monks Wood is thus made up of two components, a portion which is shaded below an overstorey and a portion which is exposed. These cover 46.4 ha and 21.2 ha respectively, which represents 30% and 14% of the land area within Monks Wood. The total understorey cover of Monks Wood is thus 67.6 ha, or 44% of the land area. Validation of this combined understorey model was carried out using the field plot measurements of understorey from five stands. For each stand the total Basal Area (in cm^2) of all trees and shrubs designated as understorey was calculated and compared with the percentage cover of understorey modelled from LiDAR. A plot of this for the five stands (with stand 5 weighted by coverage) is shown in Figure 5, with the best fit line from least squares linear regression also plotted. The relationship between the two measures of understorey cover was strong and highly significant ($R^2 = 0.82$, $n = 5$, $p = 0.033$).

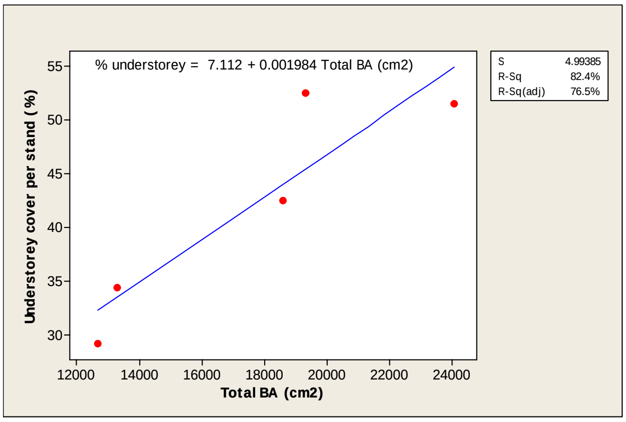

Figure 5. Plot showing the percentage cover of understorey as modelled from airborne LiDAR against field recorded total Basal Area of understorey trees and shrubs in five stands across Monks Wood.

4. DISCUSSION AND CONCLUSIONS

As has been well documented elsewhere, this work has shown that it is possible to map woodland canopy overstorey and scrubby areas along woodland margins and in overstorey canopy gaps from leaf-on first return airborne LiDAR data. Of greater significance is the demonstration of penetration rates of last return LiDAR data during leaf-off conditions. Thus, of the 83% of the study area classed as overstorey based on the leaf-on first return data, some 55.8% of leaf-off last returns came from the ground or ground vegetation layer and virtually all of the remainder came from the understorey. Less than 0.01% of leaf-off last return data came from the overstorey. Therefore, it would be possible to map all non-overstorey trees and shrubs within the study area simply by applying height thresholds of 1 m and 8 m to the leaf-off last return data (66.3 ha, ca 42% of the Monks Wood land area). However, this product would make no distinction between whether the understorey layer was shaded or exposed, which from an ecological perspective is a significant difference. A woodland understorey layer occurring beneath an overstorey is part of a mature and stable vegetation community. The woody species comprising that understorey layer will be shade tolerant. In Monks Wood the most common woody species comprising the shaded understorey are hawthorn, hazel, privet, and dogwood. By contrast, the exposed areas of understorey represent either edge communities or patches of secondary succession. In Monks Wood, blackthorn and hawthorn are the most common edge species, whilst the scrubby successional areas often contain blackthorn, hazel, willow or juveniles of ash, aspen or elm. The shaded and exposed understorey components in Monks Wood, thus have different woody species compositions, associated species assemblages and future trajectories. Distinguishing this is important in terms of both ecological and carbon modelling.

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