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Quantifying woodland structure and habitat quality for birds using airborne laser scanning

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Summary

1. Vegetation height across a 157-ha deciduous woodland was estimated using an airborne remote-sensing technique, airborne laser scanning (ALS), and the data obtained were used to produce a three-dimensional map of the canopy surface of the entire wood.
2. Field-based estimates of a tree canopy density index were compared with mean vegetation height calculated from the ALS data for sample areas of 54×54 m^2 centred on each of 36 nestboxes within the wood. Canopy density index increased with mean vegetation height, such that height explained 86% of the variation in the density index. Thus remote-sensed height could be used as a surrogate for the field-based estimates.
3. Mean chick masses (mass being used as a measure of habitat quality) for Great Tits (*Parus major* L.) and Blue Tits (*P. caeruleus* L.) using the boxes were also examined in relation to the ALS mean vegetation height for the same sample areas.
4. For Blue Tits, mean chick mass at 11 days of age increased with vegetation height around the nestbox, but for Great Tits, the relationship was negative. Possible reasons for this difference are discussed, but the results should be treated with caution because sample sizes were small.
5. The application of ALS in woodland ecology is discussed.

Key-words: Blue Tit, Great Tit, remote-sensing, territory quality, vegetation height

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Introduction

The concept of habitat quality is fundamental to the study of ecology, but quantifying 'quality' in terms meaningful to the organism or population in question is difficult. For woodland birds, these difficulties are compounded by the three-dimensional complexity of the habitat and the height of the vegetation, most of which is out of reach from the ground. Quantifying woodland structure in the field usually involves multiple measurements of features such as stem sizes and densities (James & Shugart 1970; Fuller & Henderson 1992), estimation of plant species composition (Mueller-Dombois & Ellenberg 1974) and measurements of light penetration through the canopy (Chen & Cihlar 1995). Habitat quality has been assessed in terms of food availability, for example by the collection of arthropods or frass (Nour *et al.* 1998; Seki & Takano 1998), but more usually quality is inferred retrospectively from bird breeding success or territory occupancy (Matthysen 1990; Newton 1991; Riddington & Gosler 1995). All these field-based methods are costly in terms of time and labour and can usually be applied only on a small scale.

Remote-sensing has the potential to quantify habitat characteristics at a landscape scale and in three dimensions (Roughgarden, Running & Matson 1991; Hill *et al.* 2002c). Airborne laser scanning (ALS) is a remote-sensing technique that can be used to measure height. In this paper, we describe how ALS was used to measure vegetation height across a woodland and thus provide a three-dimensional (3D) map of the canopy surface of the wood. Remote-sensed vegetation height was compared with field-based estimates of tree canopy structure and the potential uses, and limitations, of ALS data in quantifying habitat quality for woodland birds are discussed. An example, using reproductive performance in Great Tits (*Parus major* L.) and Blue Tits (*Parus caeruleus* L.), of how ALS data might be used to quantify habitat quality is also presented. The operating principles of ALS are described, but technical details can be found elsewhere (e.g. Wehr & Lohr 1999; Lefsky *et al.* 2002), the main focus of this paper being an exploratory examination of the potential value of the technique in ecology.

Materials and methods

STUDY AREA

Monks Wood was declared as a National Nature Reserve in 1953 and comprises 157 ha of deciduous woodland in Cambridgeshire (52°24′ N, 0°14′ W) in eastern England (Massey & Welch 1993). The main tree species in order

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of abundance are Common Ash (*Fraxinus excelsior* L.), English Oak (*Quercus robur* L.) and Field Maple (*Acer campestre* L.). Other species include Small-leaved Elm (*Ulmus minor* Mill.), Silver Birch (*Betula pendula* Roth) and Aspen (*Populus tremula* L.). The main shrub species are Hawthorn (*Crataegus* spp.), Blackthorn (*Prunus spinosa* L.) and Common Hazel (*Corylus avellana* L.) and the field layer is dominated by grasses and sedge (*Carex pendula* Huds.) due to deer grazing (mostly Muntjac *Muntiacus reevesi*). Formal coppicing was suspended in 1995 because of deer damage and in 1999 two compartments of about 8 ha and 14 ha were fenced to exclude deer. Numbers of deer have also been reduced in recent years by culling. In the last two years, some small areas at intersections of certain main rides and on the south side of the wood have been opened up to improve conditions for butterflies. The wood occupies a north facing slope of maximum angle 14·5° and elevational range 6–46 m.

AIRBORNE LASER SCANNING

Airborne laser scanning (ALS) is an 'active' remote-sensing technique operating on a principle of light detection and ranging (LiDAR). It uses a laser range finder and a scanning mechanism to measure the elevation at points within a swath beneath the flight-path of an aircraft. A short-duration pulse of near infrared laser light is transmitted towards the ground by the aircraft-borne laser scanner. The timing and intensity of the return signal (following reflection from a feature on the Earth's surface) are recorded and used to derive a ranging measurement. Control and recording units on board the aircraft regulate the process of on-line data acquisition. To identify the 3D position of each ranged point, the aircraft must have an integrated position and orientation system comprising a differential global positioning system (dGPS) and an inertial measurement unit (IMU). The IMU component records the roll, pitch and heading of the aircraft to determine its orientation, while the dGPS records its precise location (Wehr & Lohr 1999). During post-flight data processing, the position and orientation data are used to geo-reference the ranging measurements. Each incident laser pulse thus supplies accurate (in x, y and z) point-sample elevation data for the ground surface and/or objects on it.

The return signal from an incident laser pulse over woodland contains information about scattering events from surfaces at various distances within the vegetation canopy, the depth of penetration being a function of the incidence angle and canopy density. In general, the first significant 'echo' in the return signal records information at, or near, the canopy surface, while the last significant 'echo' records information from within the canopy or from the ground. When woodland is surveyed in transects with an ALS, most incident laser pulses are returned from within the vegetation canopy, but some are returned from the ground, where it is exposed by gaps in the canopy or by rides, and this dual information enables canopy height to be calculated (Lefsky *et al.* 2002).

There are two distinct ways in which the ALS systems used in terrestrial applications record the information from a return laser pulse. Waveform-recording devices (sometimes referred to as profiling scanners) incorporate a waveform digitizer recording the time-varying intensity of the entire return pulse, while discrete-return devices (sometimes referred to as mapping scanners) record the first and/or last significant 'echo' (determined by an intensity threshold) of the return pulse. The higher spatial resolution and pulse-repetition rates of discrete-return ALS devices (which have a higher density of smaller 'footprints') make them the preferred devices for mapping canopy surface and/or forest floor topography (Lefsky *et al.* 2002).

Data for Monks Wood were acquired by flying a discrete-return ALS device (Optech ALTM 1210, Optech Inc., Toronto, Canada) over the wood on 10 June 2000. The area was covered by a series of parallel flight-lines, which were scanned in overlapping swaths. This resulted in an irregular distribution of laser hits across the study site, but on average one laser hit was recorded every 4·8 m^2 with a footprint size of 0·2–0·3 m. The x- and y-coordinate of each hit was processed into British National Grid Eastings and Northings and the height information into elevation in metres above sea level datum (OSGB36 Datum). The timing and intensity of both the first and last significant return of each laser pulse were recorded, supplying elevation information from near the upper surface and within the canopy, and, in more open areas (e.g. canopy gaps, rides, clearings), from the ground.

A grid, made up of rows and columns of 1-m^2 pixels, was created by fitting an interpolated surface through the ALS point-sample elevation data, using separate grids for the first and last returns. Each of these grids is known as a digital surface model (DSM) as they contain information relating to terrain and the overlying vegetation. The last return DSM had a higher content of ground information and so was used to create a digital terrain model (DTM). This was achieved by a process of adaptive morphological filtering in which local elevation minima were identified using a sampling frame that varied in area in relation to heterogeneity in the DSM. This enabled larger area sampling frames to be used for identifying local minima in areas of the woodland with few gaps or rides (Hill, Gaveau & Spendlove 2002a). A terrain surface was then generated by a thin-plate spline interpolation from the selected local elevation minima. The difference between the elevation of each pixel in the DTM and in the first return DSM then gave canopy height.

A validation exercise for the terrain and canopy height was carried out based on independent field data (collected using a theodolite 'total station' and, for canopy height, a skylift to position the reflector at the canopy upper surface). This demonstrated that the terrain elevation values were derived with a root mean square error of ±0·51 m, and a mean bias of +0·23 m (which in itself caused an average canopy height underestimation of 23 cm). In addition to these errors carried across from the DTM, the canopy height data had a mean bias of −1·09 m for shrubs (n = 43) and −1·95 m for trees (n = 39). The ALS data thus tended to underestimate canopy height, probably because of penetration of laser pulses into the canopy. Shrubs were validated separately because their denser structure was thought likely to have different penetration characteristics (Hill *et al.* 2002a).

HABITAT AND BIRD DATA

Breeding success of Great Tits and Blue Tits using a total of 22 nestboxes in Monks Wood was recorded in 2001 as part of a longer-term study (Hinsley, Rothery & Bellamy 1999). Fourteen additional nestboxes were put up in February 2001 around the Centre for Ecology and Hydrology (CEH) site, boxes being located on the edges of Monks Wood, in vegetation around the buildings and in an area ('The Wilderness') of young trees and scrub. The CEH site boxes were put up initially for other purposes (arising from access problems due to the 2001 outbreak of foot and mouth disease) and were used in this study to increase sample sizes.

In order to locate the nestboxes relative to the ALS data, the positions of the Monks Wood boxes were mapped using a theodolite 'total station'. The positions of the CEH site boxes on the edges of the wood were mapped using a handheld 12-channel GPS receiver (Garmin Etrex Summit; Garmin (Europe) Ltd, Romsey, Hants, UK). The CEH site boxes within 'The Wilderness' were located by measurement using an existing, previously mapped 50-m grid. Mean vegetation height and tree canopy density were recorded for each nestbox for a sample area of 54×54 m^2 (2916 m^2) centred on the box, this area being assumed to be representative of the core of the birds' territory. Mean vegetation height was calculated from the 2916 1-m^2 pixels of the ALS data. For two of the CEH site boxes, parts of buildings lay within the sample area, but the measurements corresponding to these locations were excluded from the calculation of mean height. Tree canopy density was estimated in the field. The proportion of the sample area attributable to each of five density scores (range 0–4, where 0 = absence and 4 = dense, closed canopy) was assessed by eye and an overall index calculated as Σ(score × proportion) (Hinsley *et al*. 1995). The field estimates were made independently by two observers in summer 2001 and the results were expressed as mean values.

For the CEH site boxes in particular, parts of the sample area were occupied by non-woody vegetation and thus it might be argued that the position of the sample area should have been adjusted to maximize the proportion of woodland within the square. However, centring the sample area on the box provided an objective estimate of territory quality in relation to likely foraging distances unbiased by any assumptions of differential habitat use. Also, gaps in the tree canopy were common throughout much of the wood and would have confounded any subjective readjustment of sample areas.

All nestboxes were accessible to both species of tit. Chicks were weighed using a spring balance on day 11 (day of hatching = 0) and mean masses, excluding runts, were calculated. Mean chick mass was used as a measure of breeding success likely to reflect territory quality (Przybylo, Wiggins & Merilä 2001) because it combines the effects of food abundance with the adults' abilities to find it (foraging efficiency) and to deliver it to the nest (travel costs). Previous work had also found chick mass to vary with wood size, and hence probably with territory quality (Hinsley *et al.* 1999). Both species of tit feed their young chiefly on tree-dwelling caterpillars and thus canopy height was thought likely to influence habitat quality. Timing of breeding was recorded using first egg dates.

Although the ALS data were collected in 2000, chick masses from 2001 were used to investigate the relationships between mean vegetation height and foraging habitat quality for the following reasons. Vegetation changes related to height were thought unlikely to have been significant between summer 2000 and spring 2001; major tree falls were not recorded near any boxes in this time period. For the CEH site boxes, data were only available for 2001. In 2000, only four of the Monks Wood boxes were used by Blue Tits (Blue Tits can be out-competed for boxes by Great Tits), but eight were used in 2001. For Great Tits, nine Monks Wood boxes were used in 2000 and 11 in 2001. Thus the main analysis used the (2001) bird data, but results from 2000 for Great Tits are also mentioned in the discussion because they are relevant to the problem of quantifying habitat quality. It is recognized that these sample sizes are very small, but the results are presented as a demonstration of potential, rather than as definitive relationships.

Results

The vegetation height map of Monks Wood, and the nestbox locations, are shown in Fig. 1. Two areas of mown/grazed grass can be seen in the north side of the wood and the wider rides, maintained by mowing, are visible as straight lines. Much of the wood was felled for timber around the 1920s and the effects of past timber removal can be seen in the pattern of tree heights, with much of the central area of the wood lacking tall trees. Of the 157 ha, only 49 ha reach heights in excess of 15 m. The CEH site is located within the south edge of the wood and comprises a network of mostly single story buildings interspersed with grass and a few trees plus a series of field plots separated by experimental hedgerows. The effects of different management techniques (e.g. laying, coppicing, uncut) can be seen in

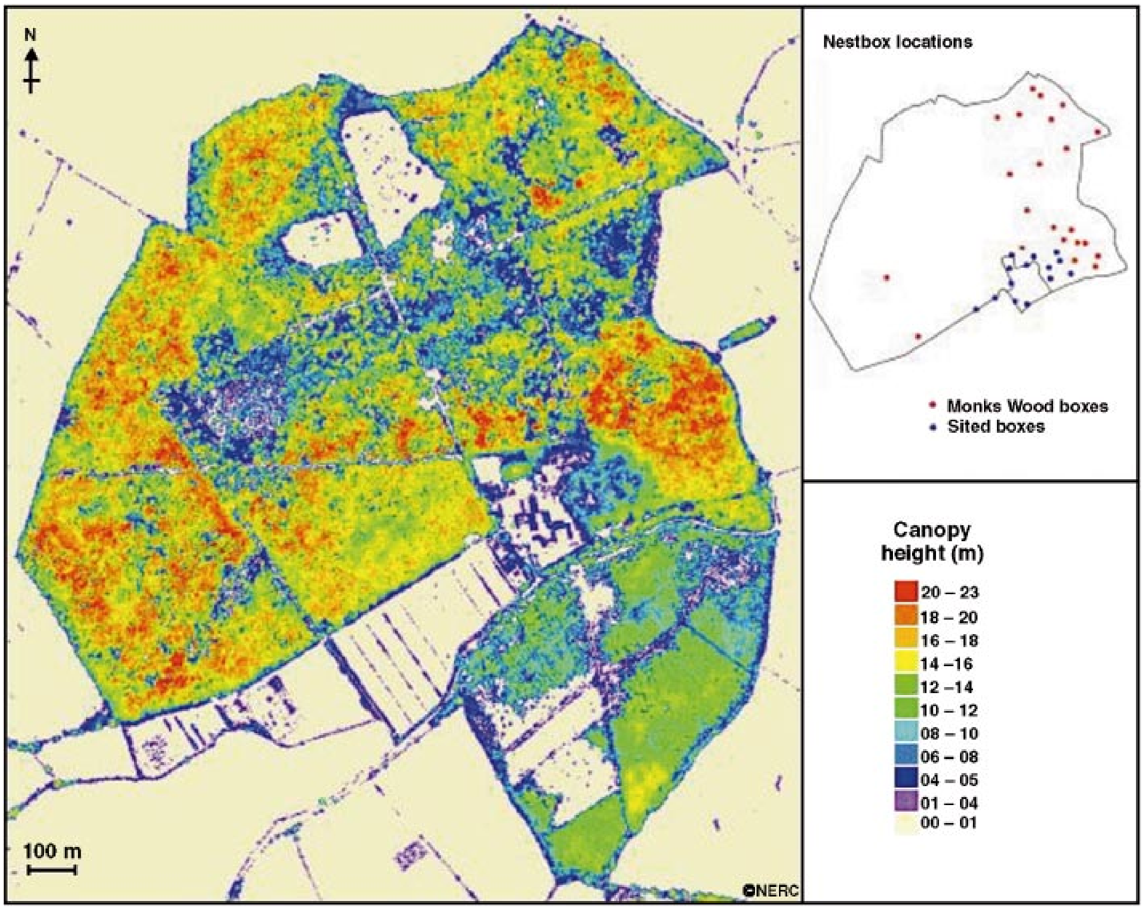

Fig. 1. Vegetation height map of Monks Wood derived from the ALS data. Locations of the nestboxes are shown in the insert, the Monks Wood boxes in red and the CEH site boxes in blue. Map reproduced with permission of NERC.

these hedgerows. The south side of the wood is adjoined across a minor road by a 37-ha plantation of conifers, mostly spruce (*Picea* spp.) and pine (*Pinus* spp.), plus some Common Beech (*Fagus silvatica* L.).

There was a significant linear relationship between the two independent estimates of tree canopy density index for the sample areas around the nestboxes ($r^2 = 0{\cdot}77$, $P < 0{\cdot}001$, $n = 36$) and the mean values were used in all subsequent analyses. For both the Monks Wood boxes and the CEH site boxes, the canopy density index for the sample area was linearly related to the ALS measurement of mean vegetation height (Fig. 2). The overall relationship for both sets of boxes combined was also significantly related to the ALS height measurements (Fig. 2).

For Blue Tits, mean chick mass at 11 days of age increased with mean vegetation height around the nestbox for both the Monks Wood boxes and the CEH site boxes (Fig. 3a). Mean mass also tended to increase with canopy density for both sets of boxes, but the relationships were not significant. Mean (± SE) chick mass in Blue Tits for all the CEH site boxes combined was $10{\cdot}5 \pm 0{\cdot}22$ g ($n = 5$), the same as the overall mean for the Monks Wood boxes ($10{\cdot}5 \pm 0{\cdot}12$ g, $n = 8$).

For Great Tits, mean chick mass declined with both mean vegetation height (Fig. 3b) and canopy density for both the Monks Wood and the CEH site boxes

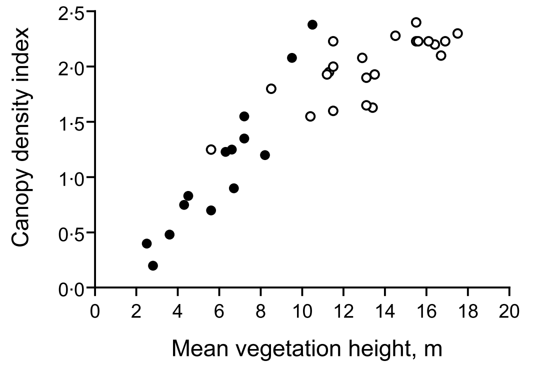

Fig. 2. Relationships between field measurement of tree canopy density and ALS measurement of mean vegetation height for sample areas centred on each nestbox for the Monks Wood (○) and CEH site boxes (●). Monks Wood boxes: canopy density = 0·943 (0·19) + 0·0785 (0·014) height, $r^2 = 0{\cdot}58$, $P < 0{\cdot}001$, $n = 22$. CEH site boxes: canopy density = −0·408 (0·16) + 0·246 (0·025) height, $r^2 = 0{\cdot}88$, $P < 0{\cdot}001$, $n = 14$. For all boxes combined: canopy density = −0·826 (0·172) + 2·54 (0·172) $\log_{10}$ height, $r^2 = 0{\cdot}86$, $P < 0{\cdot}001$, $n = 36$. Standard errors of regression coefficients are given in parentheses.

(Monks Wood boxes: mass = 23·7 (0·55) – 2·80 (0·27) canopy density, $r^2 = 0{\cdot}91$, $P < 0{\cdot}001$, $n = 11$. CEH site boxes: mass = 18·1 (0·98) – 1·65 (0·68) canopy density, $r^2 = 0{\cdot}45$, $P = 0{\cdot}06$, $n = 7$). Mean (± SE) chick mass in Great Tits for all CEH site boxes combined was

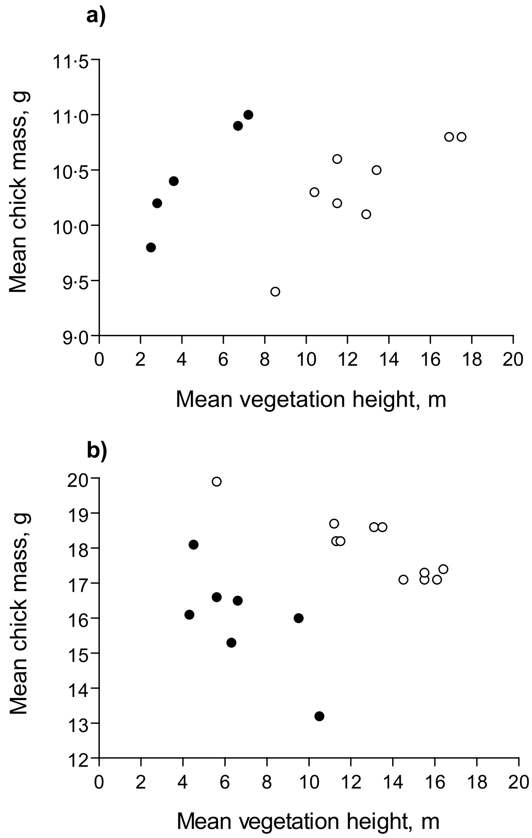

Fig. 3. Blue Tit (a) and Great Tit (b) mean chick masses in relation to ALS mean vegetation height around the nestbox for Monks Wood boxes (○) and CEH site boxes (●) in 2001. Blue Tit, Monks Wood boxes: mass = 8·78 (0·46) + 0·121 (0·035) height, $r^2 = 0{\cdot}61$, $P = 0{\cdot}014$, $n = 8$. CEH site boxes: mass = 9·49 (0·19) + 0·213 (0·038) height, $r^2 = 0{\cdot}88$, $P = 0{\cdot}01$, $n = 5$. Great Tits, Monks Wood boxes: mass = 21·4 (0·54) − 0·260 (0·04) height, $r^2 = 0{\cdot}80$, $P < 0{\cdot}001$, $n = 11$. CEH site boxes: mass = 19·1 (1·34) − 0·468 (0·19) height, $r^2 = 0{\cdot}46$, $P = 0{\cdot}05$, $n = 7$.

16·0 ± 0·56 g ($n = 7$), significantly less than the overall mean for the Monks Wood boxes of 18·1 ± 0·27 g ($n = 11$) ($t = 3{\cdot}27$, df = 8, $P = 0{\cdot}01$).

There was no overall relationship between chick mass and mean vegetation height for the Monks Wood and CEH site boxes combined for either species. There was also no relationship between chick masses and timing of breeding for either species in the Monks Wood boxes or for Blue Tits in the CEH site boxes. For Great Tits in the CEH site boxes, mass increased with laying date, but the relationship was not significant ($P = 0{\cdot}062$).

Discussion

The relationship between the field-based estimates of tree canopy density and the ALS mean vegetation height probably arose because, in general, taller and hence usually older, trees have a greater spread and depth of canopy and both these features were used in the field estimation of canopy density index. For the predominantly ash/oak/field maple combination of tree species in Monks Wood, remote-sensed mean vegetation height could be used as a surrogate for tree canopy density. However, it would be of interest to know how the relationship between the two methods would perform for other combinations and relative abundances of tree species, and for other structures, such as coppiced woodland. The difference between the Monks Wood and the CEH site boxes in the slope of the relationship (Fig. 2) was probably due to the greater proportion of low values included in the calculation of mean vegetation height for the CEH site boxes.

The selection of the 54×54 m^2 sample area around each box was largely arbitrary, but also unavoidable in the absence of any information about the birds' foraging behaviour within their territories. However, with remote-sensed data for an entire wood, any number, shape and size of sample areas could be used, the only constraint being the spatial resolution at which data were collected. It would also be possible to define territories in terms of bird usage, for example, by radio tracking to locate actual foraging destinations. The ecological example used here concerned breeding success, but remote-sensed data could also have an important application in identifying habitat types (e.g. tree-fall gaps, Fuller 2000) used by certain species and hence in the determination and prediction of species likely occurrences and distributions in woodland and other habitats (Fuller & Henderson 1992; Donald *et al.* 1998). ALS could be particularly appropriate for quantifying structure in habitats such as scrub and young plantation restocks where tall cover is often sparse and access on the ground can be difficult due to the density of the vegetation (e.g. Rango *et al.* 2000). Repeat surveys would offer the opportunity to track habitat changes and concomitant effects on bird populations.

The primary purpose of the ALS data collected here was to measure height, but it can also be used to estimate other parameters including crown diameter, tree density, biomass and timber volume, canopy closure and canopy roughness (Lefsky *et al.* 1999; Means *et al.* 2000; Næsset 2002). As a remote-sensing system operating in near infrared wavelengths, ALS has only limited power to penetrate the tree canopy, but such penetration characteristics themselves may be useful in assessing vegetation density (Hill, Hinsley & Gaveau 2002b). Furthermore, for deciduous woodland, ALS data collected in winter may be able to provide additional information about the interior structure including ground cover. On its own, ALS can only quantify certain aspects of structure, but in conjunction with other remote-sensing techniques such as SAR (synthetic aperture radar, e.g. Askne *et al.* 1997; Balzter 2001) and airborne hyperspectral (Treitz & Howarth 1999), it should have considerable application in woodland ecology.

For Blue Tits, that chick mass should increase with increasing vegetation height around the nestbox made sense in that greater mean height implied older trees with a well-developed canopy and greater supply of invertebrates. However, the results for Great Tits were counterintuitive in that the relationships between chick mass and both height and canopy density were negative. One possible explanation for this difference may be related to the two species' body masses and foraging behaviour. Blue Tits (9–11 g) concentrate their foraging in the outer parts of the tree canopy (Lack 1971), while Great Tits (17–20 g) tend to feed lower down, foraging more on larger branches and on the ground (Perrins 1979). Thus the structure provided by a tall, closed canopy, with most leaf growth concentrated in the canopy itself, may be more suitable for the smaller and more agile Blue Tit, whereas a more varied height profile may offer the larger Great Tit greater access to a sturdier vegetation structure and to the ground. Competition between the two species might also be a factor; several studies have found that nestling mass in Great Tits is negatively correlated with Blue Tit population density (Minot 1981; Török & Tóth 1999).

Great Tits using the CEH site boxes reared lighter young than those in the Monks Wood boxes. In previous work (Hinsley *et al.* 1999), Great Tits, but not Blue Tits, were also found to rear lighter young in small woods. This suggested that Great Tits might be more sensitive to habitat quality and/or edge effects than Blue Tits. The lack of an overall relationship between mass and height for the Monks Wood and CEH site boxes combined (Fig. 3) implied some fundamental difference in habitat quality, but might have also been due, at least in part, to the greater proportion of low values used in the calculation of mean height for the CEH site boxes.

Studies of reproductive success in tits, and other bird species, typically show strong year effects in relation to environmental variables (e.g. Slagsvold 1976; Perrins 1979; Nager & van Noordwijk 1995). In 2001, the breeding season was relatively late and, in general, late seasons are associated with poorer breeding performance (Hinsley *et al.* 1999). Under poor conditions for breeding, differences between both territory quality and parental performance might be expected to be most detectable in terms of their impact on chick condition and survival. Therefore, assessment of territory quality may vary between years and such variation might account for the strong relationships between chick masses and vegetation height apparent for both Great Tits and Blue Tits in 2001 (Fig. 3). Such relationships may be harder to detect when conditions for breeding are good. For example, for Great Tits in Monks Wood in 2000 (an average season in terms of timing and bird performance), chick mass again declined with both increasing mean vegetation height and canopy density, but the former relationship was not significant and the latter only at the 10% level ($r^2 = 26\%$, $P = 0{\cdot}094$, $n = 8$). Therefore, the response of tits to vegetation height needs to be investigated more thoroughly with larger samples sizes across a range of breeding conditions.

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