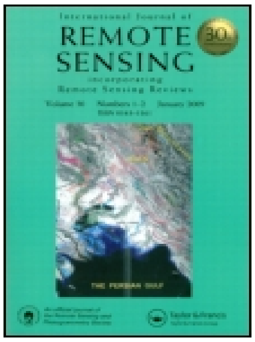

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Quantifying the spatial properties of forest canopy gaps using LiDAR imagery and GIS

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Abstract. The spatial properties of gaps have an important influence upon the regeneration dynamics and species composition of forests. However, such properties can be difficult to quantify over large spatial areas using field measurements. This research considers how we conceptualize and define forest canopy gaps from a remote sensing point of view and highlights the inadequacies of passive optical remotely sensed data for delineating gaps. The study employs the analytical functions of a geographical information system to extract gap spatial characteristics from imagery acquired by an active remote sensing device, an airborne light detection and ranging instrument (LiDAR). These techniques were applied to an area of semi-natural broadleaved deciduous forest, in order to map gap size, shape complexity, vegetation height diversity and gap connectivity. A vegetation cover map derived from imagery from an airborne multispectral scanner was used in combination with the LiDAR data to characterize the dominant vegetation types within gaps. Although the quantification of these gap characteristics alone is insufficient to provide conclusive evidence on specific processes, the paper demonstrates how such information can be indicative of the general status of a forest and can provide new perspectives and possibilities or further ecological research and forest monitoring activities.

1. Introduction

The influence of canopy openings on ecological processes has been recognized and researched for a considerable period. In 1770 Finnish botanist Pehr Kalm, in his book *Travels in North America*, was probably the first researcher to describe the general occurrence and important ecological role of tree-fall disturbance in primeval temperate forests (Kuuluvainen 1994). However, the first formal investigation of the subject was that of Sernander (1936) who recognized the importance of storm gaps in forest ecology in Fiby Urskog, a 'virgin' stand of Norway spruce, Scots pine and aspen on the southern margins of the boreal forest

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near Uppsala, Sweden. This was followed by the work of Watt (1947) who recognized that regeneration was largely confined to gaps and that the composition and timing of regeneration depended on gap size, the condition of the canopy and the coincidence between gap formation and mast years. In tropical and temperate ecosystems the importance of gap openings in forest ecology has now been widely studied (see two special features on the subject in 1989–90 in *Canadian Journal of Forest Research*, **20**, 619–667 and *Ecology*, **70**(3), 535–576). Issues which have received particular attention include the relationships between forest species composition and the size and frequency of gaps (e.g. Runkle 1982, Brokaw 1987, Qinghong and Hytterborn 1991), the influence of gap creating species (e.g. Woods 1984) and the importance of environmental heterogeneity within gaps (Putz 1983). These studies have contributed to an emerging recognition that gap disturbance contributes significantly to the formation and change of forest ecological characteristics, such as structural heterogeneity, tree population dynamics, tree species composition, variation in ground micro-topography and understorey vegetation, and overall species diversity (Beatty 1984, Brokaw 1985a, b, Denslow 1985, Barik *et al*. 1992).

This growing body of evidence has emphasized the importance of quantifying gap characteristics for both ecological studies and forestry purposes and has led to the development of techniques using high spatial resolution optical remotely sensed imagery to provide spatially comprehensive descriptions of forest gaps (Blackburn 1993, Blackburn and Milton 1996, 1997, Jackson *et al*. 2000). Recent developments in light detection and ranging instruments (LiDAR) have significantly advanced the ability to derive accurate measurements of the topography of Earth surface features and hold promise for quantifying the geometrical properties of forest gaps. The aim of this study is to investigate the utility of LiDAR data for extracting gap characteristics. The specific objectives are: (i) to develop a conceptual and practical definition of gaps as ecosystem entities that can be measured from remotely sensed data in order to guide the subsequent research; (ii) to extract gap spatial features: size, boundaries, centres, shape complexity, height diversity and connectivity from LiDAR imagery; (iii) to combine LiDAR and Airborne Thematic Mapper (a passive optical scanner) imagery to derive information on gap vegetation type; and (iv) to provide a methodological framework based on a set of rules for gap extraction to enable future comparisons and monitoring capabilities.

2. Conceptualizing gaps as remotely sensed ecological features

One important factor which provides a link between the concepts of a gap as an ecological feature and that of a remotely sensed object is radiation. The creation of a gap drastically changes the light regime within the forest canopy and at the forest floor and this in turn leads to biotic responses. This implies that the creation of a gap will have a major effect on the radiation reflected from the forest in that locality. This provides a theoretical basis for using passive optical remotely sensed imagery, which records reflected radiation, for monitoring such features. However, a series of difficulties limits the applicability of this approach.

Within an image obtained using a passive optical remote sensing instrument, gap features are represented by a complex combination of the reflectance properties of a large number of scene elements, including illuminated tree canopy, shaded canopy, illuminated understorey, and shaded understorey. Moreover, the gap as a spectral feature is transient and varies on a number of timescales. Throughout the day, the varying solar illumination angle causes the shaded and illuminated components of canopy and gaps to constantly change. Throughout the year, particularly with deciduous forests, the spectral reflectance characteristics of the tree canopy change dramatically (see Blackburn and Milton 1995) which leads to variations in the spectral quality of the shadows cast by the canopy within the gaps. Furthermore, as the understorey develops, ages and dies, the spectral reflectance properties of the contents of a gap can vary widely from a litter/soil dominated response to that of a vigorous vegetation canopy. In the case of dense understorey species, such as bracken (*Pteridium aquilinum*), the spectral reflectance properties can be very similar to those of a mature tree canopy (especially for open or damaged tree crowns) (see Koukoulas and Blackburn 2001). Several workers (e.g. Barden 1989, Lieberman *et al.* 1989, Porma *et al.* 1989) have suggested that the radiance response of a gap depends on many factors such as the tree density, the overlapping of the neighbouring tree canopies, the understorey vegetation, the micro-topography, the dominant tree species and the solar angle defining the gap light regime.

For these reasons, it is not sensible to consider a gap as simply a hole in the tree canopy which is represented in a remotely sensed image by low value pixels surrounded by those of higher value. Nevertheless, this can be the case in some circumstances, as is demonstrated in the section of the aerial photograph in figure 1. Here the three-dimensional surface profile of pixel values in the green band depicts the gap as a well-defined depression. Even in this case it is clear that the gap cannot be described as a cylinder with the same perimeter and area at the top as at the bottom, but rather like a cone with the perimeter decreasing from the top to bottom. However, this is still a simplification of the vertical structure of the gap and a visit to the site reveals much more complexity. Furthermore, the aerial photograph (and its negative image) shown in figure 2, which covers an area of semi-natural broadleaved deciduous forest, aptly demonstrates the inadequacies of the notion that a gap can be described as a canopy hole. Here the scene is dominated by understorey vegetation (grass and bracken) with sparse trees that form the 'objects' in the matrix.

The effects of canopy shading on the radiation response of gaps is illustrated in the portion of the infrared aerial photograph shown in figure 3. In the surface

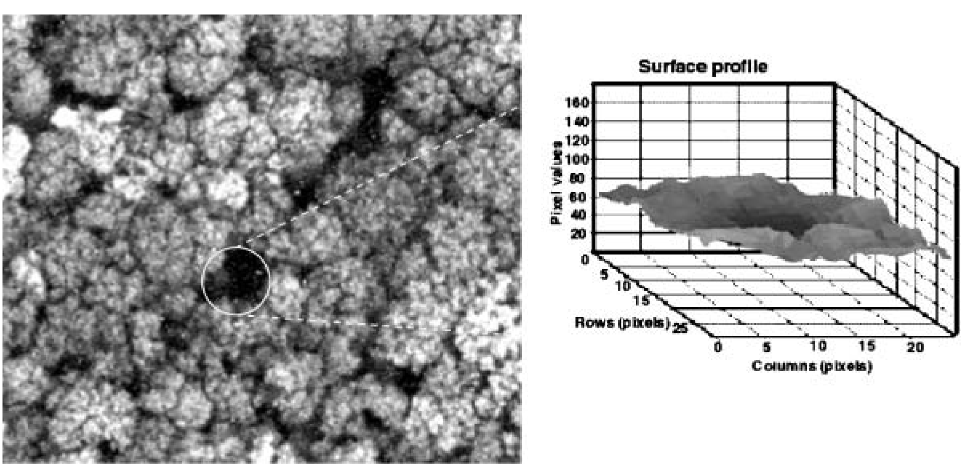
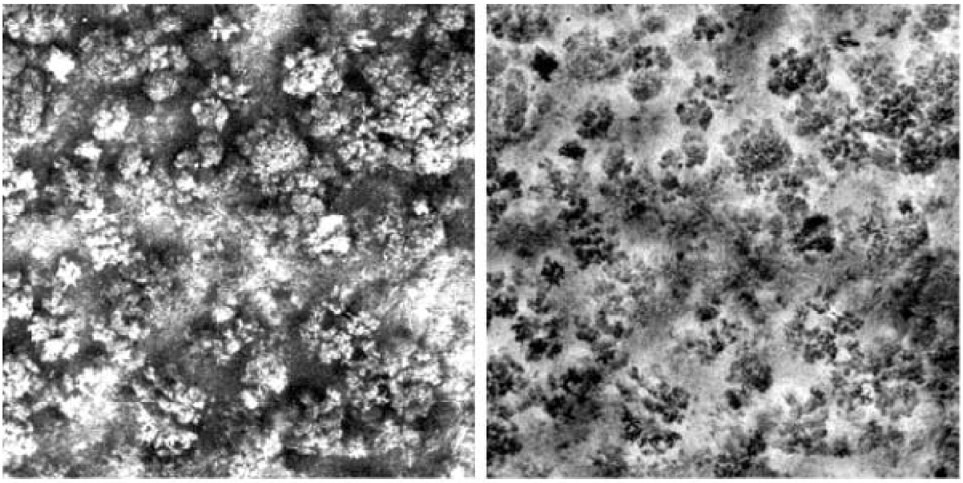


Figure 1. Aerial photograph of a dense broadleaved deciduous tree canopy showing a canopy opening (circled) and its spectral surface profile (green band).



(a) (b)

Figure 2. Aerial photograph of open broadleaved deciduous forest and its negative image.

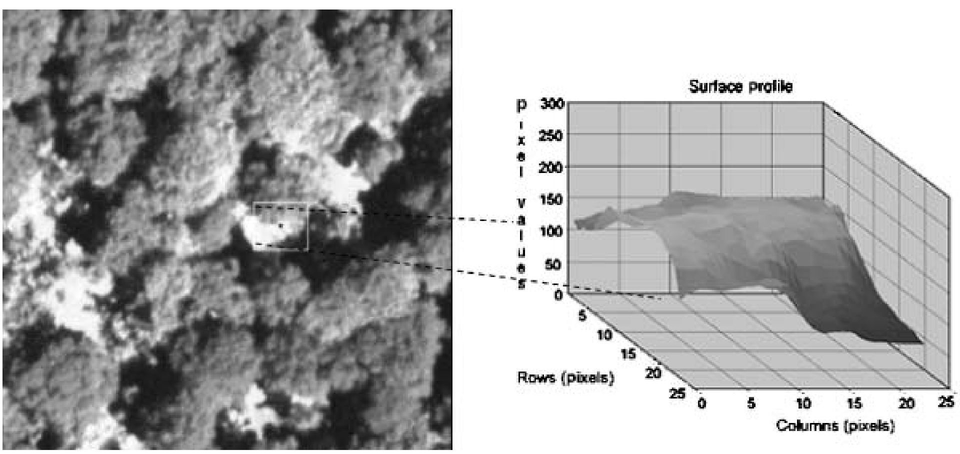


Figure 3. The problem of shadows in gap areas.

profile of pixel values of the small test area, the upper left corner is covered by a tree crown, and the rest of the area contains understorey vegetation. While the non-tree area has the same surface type (bracken) throughout, the spectral response varies widely as the lower right corner is shaded by a neighbouring tree crown, while the lower left corner is illuminated. This demonstrates why it is difficult to apply, for example, multispectral classification techniques to delineate the true gap area, because of the spatial variation in spectral response within a gap. However, Jackson *et al*. (2000) took advantage of these uncertainties to infer the internal structure and contents of gaps using multispectral remotely sensed imagery.

LiDAR systems offer the opportunity of overcoming many of the problems associated with passive optical remote sensing of canopy gaps by making high spatial resolution direct measurements of canopy height. These active imaging systems, using their own source of electromagnetic radiation, produce imagery which is independent of the solar angle and unaffected by variations in spectral reflectance (the mode of operation of the LiDAR used in this study is explained in the 'Data' section of this paper). Nevertheless, before we can investigate the utility of LiDAR data for mapping gaps and in order that we can compare results of different studies or undertake monitoring using a time series of images, it is important to identify a sound definition for canopy gaps.

While many studies of gaps are reported in the literature, few provide a clear definition, often simply referring to 'canopy openings' or 'holes in the foliage' (e.g. Bazzaz 1984, Whitmore 1984, Barden 1989, Spies and Franklin 1989), 'openings created by disturbances' (Peterken 1996) or 'patches created by the removal of canopy' (Connell 1989). Brokaw (1982) provided a more precise definition: ''A 'hole' in the forest extending through all levels down to an average of 2 m above the ground. The sides of forest openings are irregular in profile, but for a workable definition, the side at a particular place on the perimeter is located at the innermost point reached by foliage, at any level at that place on the perimeter.'' Brokaw (1982, 1985a, b, 1987) used this definition for estimating the degree of canopy destruction resulting from natural disturbances and to delimit the area in which the early stages of regeneration of plant populations, especially pioneers, are affected as a result of the canopy opening and the associated changes in the microclimate. However, Porma *et al.* (1989) argued that the vertical projection of the canopy opening underestimates the area affected by the opening.

Barden (1989) describes the different results he had to those of another researcher (J. R. Runkle) while both of them worked in the same area, the same time periods and years but independently. The differences were partly caused by differences in definitions and methods they used. Both Barden and Runkle agreed on a general definition of a gap as 'an opening in the canopy stratum formed by death of a single tree, part of tree, or a few trees in a group'. However, they differed in their definitions of the 'height of entry into the canopy stratum': for Runkle, gap closure occurred when replacement trees fill the opening to a height of 10–20 m but for Barden this was 18–30 m. Their definitions also differed in the specification of the minimum diameter of the trunk of a tree that can form a gap when it dies; for Runkle this was 25 cm while for Barden it was 50 cm. This example demonstrates how two studies of gaps, within the same study site, cannot be compared because of differing gap definitions. This highlights the need to adopt a robust definition which can be applied in both *in situ* and remote sensing contexts.

Therefore, in the present research, we define gaps as areas of low level vegetation caused initially by single or multiple tree-falls. The extent of each gap is defined at a certain height which is dependent on the height of the surrounding tree crowns. Specifically, the gap boundary is determined at the line where the tree crowns are still dense and the slope of the surface of the tree crowns' vertical shape becomes steeper (where tree crowns are conceived approximately as vertical ellipsoid objects). The threshold values used to formalize this descriptive definition into a numerical delineation depend upon the particular forest type or environment under investigation. The exact procedure that was followed in this study in order to identify forest gaps is described in the methodology section.

3. Study site

The study site was located in the New Forest in southern England which is recognized as being of international importance to nature conservation. It is mostly Crown property and managed by the Forestry Commission. The unenclosed forests are permanently open to grazing by the ponies and cattle of the Commoners. Its history and ecology have been described by Tubbs (1986). The area used for this research was Frame Wood, which contains several types of semi-natural and plantation broadleaved deciduous forests. This array of forest types, within close proximity to each other, presents a wide range in all of the canopy and gap variables of interest. Frame Wood has been the subject of a number of previous ecological remote sensing studies (Milton *et al.* 1994, Blackburn and Milton 1996, 1997, Koukoulas and Blackburn 1997, 1998, Koukoulas 2001). The site is dominated by oaks (*Quercus robur* and *Quercus petrea*) with an age profile starting in 'A2' generation (2.5–4.0 m girth, established in the seventeenth century) and beech (*Fagus sylvatica*) present from the 'B' generation (1–2 m girth, established in gaps of fallen trees older than the A2 generation) (Flower 1977). There was selective felling during the eighteenth and the nineteenth centuries, with a gradual removal of trees older than A2 generation, hence the site is best described as semi-natural.

4. Data

4.1. *Light detection and ranging (LiDAR) system*

Light amplification by stimulated emission of radiation (LASER) scanning systems with high pulse repetition have been available on the market over the last two decades but have only recently come into more widespread use due to improvements in their accuracy and reliability, reductions in cost and improvements in global positioning systems (GPS). Such systems are also known as laser radars and the acronyms used are LADAR (laser detection and ranging) and, more commonly, LiDAR (light detection and ranging) (Bachman 1979, Jelalian 1992). Useful overviews of airborne laser scanning can be found in Wehr and Lohr (1999) and Baltsavias (1999a, b).

The LiDAR data for this research were acquired by the UK Environment Agency (EA) in July 1997. The LiDAR instrument used was an Optech Airborne Laser Terrain Mapping (ALTM) 1020. This system uses a scanning laser to measure the distance between the aircraft and the ground, allowing the acquisition of accurate digital surface models. Operating specifications permit flying speeds of 200–250 km h^{-1} (55–70 m s^{-1}), flying heights of 300–3000 m, scan angles up to 20° and laser pulse rates of 2000–25 000 pulses/s. The LiDAR is installed in a light aircraft and flown over the area of interest. The position of the aircraft whilst in the air is recorded using a differential GPS, with exact location being determined using a differential signal from base-stations set up at known positions. The orientations (roll, pitch and bearing) of the aircraft are also recorded (EA 2000). Uncertainty in the geographical coordinates of the output ALTM imagery does not exceed 0.1% of the flight height.

For the purposes of this study the altitude of the aircraft was 730 m (2400 ft) above the ground level and a swath width of approximately 600 m was surveyed along each flightline. The laser, which produces near-infrared radiation at 1047 nm wavelength, scans across the aircraft flight line at 5000 light pulses/s, sweeping left and right in a zigzag movement over the ground. Individual measurements were made at approximately 2 m intervals. The travel times of the laser pulses, from the aircraft to the ground and back, are measured with a precise interval timer. This instrument recorded the time of the first returned pulse. The time intervals are then converted into range measurements using the velocity of light. In this way the surface height is calculated to an accuracy of within 15 cm.

4.2. *Airborne Thematic Mapper (ATM) imagery*

Image data were also acquired using the Daedalus Airborne Thematic Mapper (ATM, type 1268) instrument onboard the Natural Environment Research Council (NERC) Airborne Remote Sensing Facility. The aircraft altitude was 670 m (2200 ft), producing imagery with a nominal spatial resolution of 1 m. The ATM has 11 individual detectors, covering the visible and near-infrared (bands 1–8), short-wave infrared (bands 9 and 10) and thermal infrared (band 11) (table 1). An additional output band (12) uses the same thermal infrared detector as band 11, but is recorded at half the gain in order to increase the sensitivity for high radiance targets (A. Wilson, personal communication, 1999). During the image pre-processing undertaken by the NERC facility, the raw, 'sensor format' data at original resolution (level 0) are reformatted into image files with ancillary files appended (level 1a). Image calibration follows, where radiometric calibration algorithms are applied to produce radiance or irradiance. Location and navigational information is then appended (level 1b). At this point NERC data processing ends and data are distributed in CD-ROMs together with software for further (user) processing (Wilson 1995). Therefore the data provided for this research were at processing level 1b (levels are named according to National Aeronautics and Space Administration (NASA) standard product definition).

5. Methodology

The data analysis was performed using ArcView GIS (v.3.1) software (Environmental Systems Research Institute, Inc.).

5.1. *Gap identification using LiDAR imagery*

To map vegetation height accurately the effect of the topography of the area (i.e. elevation of the land surface) had to be eliminated from the raw LiDAR data. For this, a canopy height model (CHM) was created where each grid cell (pixel) represented vegetation height above ground level. It is possible to conceptualize the CHM as the horizontal and vertical distribution of tree canopies on a plane surface. A digital terrain model (DTM) for the Frame Wood area was generated by using points in the LiDAR image that represent bare ground or very low (grass lawn) vegetation. These points were identified with the help of a classified ATM image (Koukoulas and Blackburn 2001) and a knowledge of the site from field visits. The

Table 1. The ATM bandset.

Bands	Lower limit (nm)	Centre (nm)	Upper limit (nm)
1	424	436	448
2	469	493	518
3	522	561	601
4	594	614	635
5	627	660	694
6	691	726	761
7	754	839	924
8	897	962	1027
9	1600	1692	1785
10	2097	2244	2391
11	8400	9950	11 500
12	8400	9950	11 500

ground points were spread randomly throughout the study site in rides, footpaths and canopy gaps, and a total of 245 points were sampled with 185 used for interpolation and the rest for the accuracy assessment of the resultant DTM. In order to obtain the most accurate representation of the topography of the area three interpolation methods were applied to the ground points: ordinary Kriging using the semi-variogram (Gaussian model) to calculate the weights, spline interpolation and Delaunay triangulation. The DTMs created using these methods were then compared and assessed for accuracy. In order to create a CHM, the most accurate of the DTMs produced (in this case using the spline method) was subtracted from the original LiDAR image. The utility of LiDAR as a source for generation of accurate DTMs has been demonstrated in recent studies (Huising and Gomes Pereira 1998, Baltsavias 1999c, Gomes Pereira and Janssen 1999). In the present study this method had two main advantages. Firstly, the DTM was generated from recently acquired, highly accurate data and, secondly, the coordinates of the derived surface corresponded exactly with the LiDAR image so there was no error as a result of mis-registration.

From field visits, it was determined that the height below which areas would be identified as gaps should be between 3 and 5 m. In order to specify the threshold height exactly, slope values were calculated for the CHM. The idea was that where tree canopy and gap areas meet, the slope should be the steepest, and the height where most of these high slope values occur would be the appropriate height to distinguish canopy from gaps. By examining the slope image it was determined that slope values of less than 60° occurred within the perimeter of broadleaved deciduous tree crowns and steeper slopes were present at the edges of crowns. Therefore, grid cells with height less than or equal to 5 m and values of slope higher than 60° were selected. These grid cells were found to have a mean height of 3.8 m and modal value of 4 m. The height of 4 m was therefore selected as the threshold for distinguishing canopy from gap areas. From the CHM all the grid cells with a height value less than or equal to 4 m were assigned as gap areas. A terminology is used throughout this paper for specific components of canopy openings which were identified during the analysis described in the following sections. Therefore, areas defined by the 4 m height threshold are denoted as *Gaps A*.

5.2. *Extraction of gap boundaries and centres*

The layer in raster format (grid format in ArcView) that represented *Gaps A* was resampled to a 1 m cell size to facilitate the application of grid morphological functions. According to the definition of gaps, as given above, only openings created from tree-falls (i.e. the loss of at least one whole crown) needed to be identified. Therefore, morphological functions were applied in order to distinguish gaps as individual objects. Shrinking was found to be the most suitable function for isolating individual gaps from the interconnected grid cells of height 4 m or less, some of which were gaps and some of which were openings in between trees (i.e. features smaller than that created by the loss of at least one whole crown). The shrinking function identified the external boundaries of clumped grid cells and reduces their size, by removing strips of cells, the number of which is defined by the analyst. After some experimentation it was apparent that this function could not be applied universally to the whole extent of the grid. Shrinking by one grid cell isolated (disconnected) small clumps from each other but the larger clumps remained connected by a thinner ‘corridor’ of grid cells. Shrinking by three grid cells isolated large clumps of grid cells but eliminated some small clumps. Therefore, in order to overcome this problem, two parallel sub-procedures were developed.

The first routine (sub-procedure 1 in figure 4) began by shrinking *Gaps A* by three grid cells. The resulting grid was converted to a polygon format (*Gaps* B_1). Despite the shrinking process, some of these polygons still represented canopy openings between trees (*Gaps* C_1), which had a distinct elongated shape and were too thin to be created by the loss of whole tree crowns from the canopy. The most suitable criterion for identifying such polygons was the area/perimeter (A/P) ratio which quantifies shape and has the same value for polygons which were different in size but similar in shape. For this study site, a sample of polygons were selected manually and this indicated that *Gaps* C_1 could be identified on the basis of the A/P ratio, having a value of equal to or less than 0.67. The *Gaps* C_1 polygons were subsequently eliminated from the *Gaps* B_1 layer and the resultant polygons (*Gaps* D_1) represented canopy openings created only from tree-falls. However, these polygons were derived from shrunken clumps of grid cells and therefore did not represent the full extent of gaps (only the inner core). To rectify this problem, 3 m buffer polygons were generated around *Gaps* D_1 to estimate the actual area covered

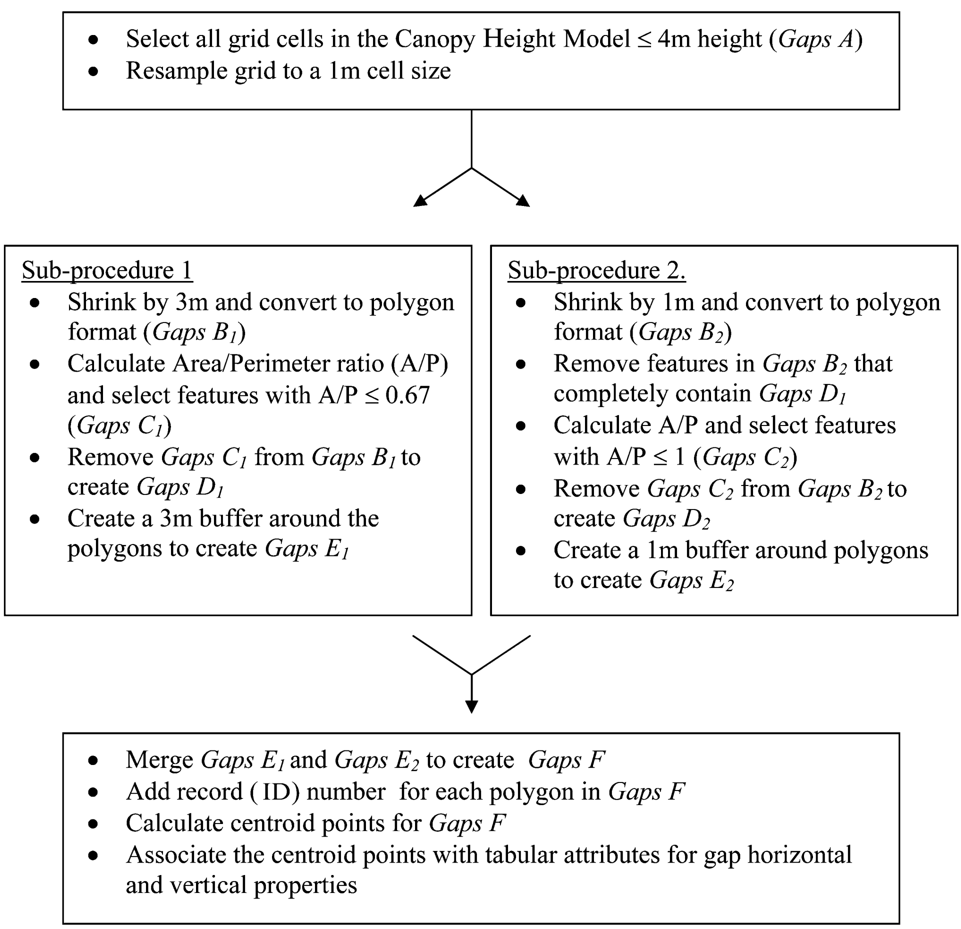


Figure 4. Summary procedure for the extraction of gap boundaries, centres and shapes.

by each gap. Although the resulting polygon boundaries (*Gaps* E_1) were generalized, they were more representative of the actual gap coverage than the squared corners of the grid clumps (*Gaps A*), which were an artefact of the original raster format of the CHM.

Sub-procedure 2 (see figure 4) began by shrinking *Gaps A* by one grid cell and converting the output to polygon format. The resulting layer (*Gaps* B_2) included features that were also identified in sub-procedure 1 (since shrinking by one cell also incorporates spatial features that also remained when the layer was shrunk by three cells). These features were eliminated at this stage to avoid duplication of polygons in the final layer by removing *Gaps* D_1 from *Gaps* B_2. Again it was necessary to remove polygons which represented canopy openings between trees (*Gaps* C_2) as opposed to gaps created by the loss of whole trees. *Gaps* C_2 were identified on the basis of an A/P value of less than or equal to 1 and were removed from the polygon layer in order to create *Gaps* D_2. A 1 m buffer polygon was then generated around *Gaps* D_2 and the resulting layer (*Gaps* E_2) so as to reconstruct the actual area covered by each gap.

The final stage involved the merging of the gap layers (*Gaps* E_1 and E_2) resulting from the two sub-procedures to create a final map of gaps for the study area (*Gaps F*). Record (ID) numbers were attached to each polygon in *Gaps F* and the centroid point of each gap was calculated using Montgomery's script from www.esri.com/arcscripts. The centroid points were then associated with tabular attributes for gap horizontal and vertical properties (described below), to enable subsequent analysis.

5.3. *Estimation of gap horizontal and vertical properties*

5.3.1. *Gap size*

The importance of gap size and its influence on species has been the subject of study of many researchers. Brokaw (1987) found that there was a positive relationship between total species abundance and gap size. Whitmore (1989) suggested that differences in sizes of gaps result in differences in species composition. Poulson and Platt (1989) demonstrated that the gap size controls the light regime within a forest, which in turn interacts with sapling architecture to influence the diversity of species that reach the canopy. Kuuluvainen (1994) emphasized the increasing evidence of the role of small-scale gaps in regeneration dynamics. Kupfer and Runkle (1996) found that gaps exhibited increased dissimilarity over the first decade of succession and attributed this divergence to the different seed inputs from the edge individuals and the heterogeneity of light caused by different gap sizes. Myers *et al.* (2000) found a highly significant relationship between Brazil nut sapling density and gap size. Kennedy and Swaine (1992) found that there was no relationship between gap size and the number of seeds germinated, but they suggested that gap size had a clear influence on the performance of the established colonists. They also found that the chance of a tree growing in a gap is related to gap area and the abundance of the species in the forest. On this issue, Kuuluvainen (1994) suggested that in a gap the survival, growth, and recruitment of tree seedlings is determined by gap size and the long-term below- and above-ground interference between tree seedlings, understorey vegetation and adjacent large trees. Gap size can be measured using the area and/or gap perimeter. In the present research, gap size was quantified using the area in square metres.

5.3.2. *Gap shape*

The shape of forest stands and gaps is particularly important for wildlife, because habitat conditions and shape are often closely interrelated (Patton 1975, Covich 1976, Marcot and Meretsky 1983). Gap spatial complexity together with the gap size controls the light regime and therefore it is important in controlling regeneration. Gap shape complexity is also important for the fauna of a forest, if we consider gaps as patches in a canopy matrix (see Blackburn and Milton 1996). Forman and Godron (1986 p. 107) suggested that 'patch shape is undoubtedly important in the dispersal and foraging of organisms'. A simple description of gap shape is the A/P relationship. In this research, this relationship was quantified using a gap shape complexity index (GSCI), calculated using Patton's diversity or edge index (Patton 1975, Blackburn and Milton 1996):

$$\mathrm{GSCI} = \frac{\text{Gap perimeter}}{2\sqrt{\text{Gap Area} \times \pi}} \tag{1}$$

5.3.3. *Gap vegetation height diversity*

The height diversity of gap vegetation is a measure of internal heterogeneity within gaps and, together with the shape complexity, controls distribution of light and movement of foraging organisms. Gap vegetation height diversity, as a measure of gap heterogeneity, has not been studied widely mainly because of the difficulty and the intensity of the task. In this study, the use of LiDAR airborne imagery made possible the study of vegetation surface topography within gaps. Height diversity within gaps was quantified with the Shannon formula (Shannon and Weaver 1962, Kuuluvainen *et al.* 1996, Zenner and Hibbs 2000):

$$\mathrm{GHD} = -\sum_{i=1}^{N} p_i \ln p_i \tag{2}$$

where p_i is the proportion of gap grid cells in the ith height class. A script in Avenue$^{\mathrm{TM}}$ was developed for this purpose and is available from the authors on request.

5.4. *Gap vegetation type*

Two important vegetation types occurring in gaps in the semi-natural stands of the New Forest are bracken and grass. The identification of gaps with extensive bracken coverage was important as rapid expansion of bracken can severely hinder the re-establishment of a woody cover (Rodwell 1991 p. 265, Dolling 1999). Repeated heavy grazing from large herbivores (horses, deer, cattle) often maintains a dense ground cover of gramineous species within gaps. This can prevent or delay regeneration of tree species and such gaps can be considered to be 'chronic disturbance patches' (Forman and Godron 1986). Therefore, characterization of gap vegetation can provide important information to contribute to an understanding of forest regeneration dynamics. Furthermore, the main vegetation type contained with a gap area is indicative of local micro-environmental and habitat conditions and this is a useful characteristic to identify for any further ecological analysis.

To identify the main vegetation type within gaps the following procedure was followed. The ATM imagery was co-registered with the LiDAR data and a multispectral classification was applied to the ATM data to create an accurate vegetation cover map. The classification procedure and accuracy assessment was discussed by Koukoulas and Blackburn (2001). The vegetation cover map was then converted to the grid format of ArcView to enable further spatial analysis. The gap boundaries derived from the LiDAR data (*Gaps F*) were used to extract areas from the vegetation cover map that were within gaps. The result was converted to vector format and spatially intersected with the gap boundaries layer in order to join the tabular information from the layers. Subsequent work was carried out with the tabular information of the resultant layer. Fields in the table included information for the area, perimeter, record number of gaps (as inherited from the gap boundaries layer) and information about the area, perimeter and code number of each vegetation type within the gap boundaries. In order to avoid confusion the 'Area' field for gaps was renamed 'Gap-area', the 'Perimeter' field 'Gap-perimeter', and the record number the 'Gap-id' field. Therefore, the new layer contained information on the coverage of vegetation types within the gap boundaries. As a result the initial gap polygons were divided into vegetation class polygons. The area and the perimeter were subsequently calculated for the vegetation classes, and the proportion of each vegetation type within each gap was calculated. The vegetation class that covered the majority of the area of each gap was taken to be the main vegetation type.

The results showed that this procedure could be applied successfully to large gaps (with area greater than $250\,m^2$), but had lower success in small gaps (less than $250\,m^2$) where parts of the gap area were shaded (in the ATM imagery) and other parts were covered by lower branches of surrounding trees. In these cases the main vegetation type was determined based on those portions of the gap which were not affected by shading or low tree branches.

5.5. *Gap connectivity*

The isolation and/or connectivity of gaps, has an important control upon the movement of faunal species, propagation of floral species and spread of physical and biological disturbances in forests. In relation to the latter, in semi-natural or natural forests, it is possible to speculate on the mechanisms of formation of gaps based on their size, shape and relative connectivity, or isolation. For example, Blackburn and Milton (1996) studied gap spatial properties in the New Forest and their results indicated that large gaps have been created by progressive disturbance and enlargement of smaller gaps rather than by catastrophic events such as large-scale wind-throw.

In the present study gap connectivity was quantified based on the identification of continuous canopy openings (corridors) that connected two or more gaps. In order to extract the network of gap connections, the canopy surface model was used and cells with a height value of 4 m or less (*Gaps A*) were extracted and saved in a grid layer. A thinning morphological function known as skeletonizing (see Gonzalez and Wintz 1987 pp. 398–402) was applied to extract the spatial skeleton of the above grid layer. The values of the resulting 'skeleton' grid layer were reclassified (1 for the 'skeleton' and 0 for the background) and then converted to vector format. The resultant layer contained all areas less than or equal to 4 m in height, representing both gaps (*Gaps F*) and corridors (mostly *Gaps* C_1 and C_2). In order to extract the corridors only the gap layer (*Gaps F*) was used and a buffer of 2.5 m was created around the gap polygons. This buffer layer was then used to erase the linear features in the skeleton layer that were within the boundaries of *Gaps F* polygons and within a distance of 2.5 m of the gap boundaries. The 2.5 m threshold was chosen after experimentation to remove linear areas that appeared between the trees that surround gaps and did not lead to any other gap area. Those gaps that were within a slightly increased distance (2.6 m) from corridors were selected and assigned a connectivity value of one and the rest connectivity value zero.

The above procedure to assign connectivity status to each gap is based on the existence of corridors between gaps. It is, however, possible for two gaps to be very close to each other (within 5 m) without any apparent corridor between them. These gaps could be connected but if there are corridors between them may have been eliminated by the 2.5 m threshold distance (2.5 m from two neighbouring polygons equates to a 5 m elimination zone). To rectify this problem the gaps layer was split into two layers based on their connectivity value (0 or 1). Those polygons in the layer with connectivity zero that were within a distance of 5 m (2.5 m plus 2.5 m from each polygon) of the polygons of the other layer with connectivity equal to one were selected. The selected polygons were reassigned a connectivity value of one. These new connectivity values were copied back to the gap layer to produce the corrected and final connectivity values. During this procedure aerial photographs were displayed in the background in order to help with decisions on the threshold values and connectivity of gaps. It must be noted, however, that interpretation of aerial photographs was used only as a guidance for specific parts of the procedure and was not the driving force for the whole procedure.

6. Results and discussion

Gap areas resulting from tree-falls have been extracted from LiDAR data for the study area of Frame Wood in the New Forest and the results (*Gaps F*) are shown in figure 5. The extraction of gap areas as applied in this research is a deterministic process based on decisions made and rules applied as described in the methodology section. Therefore, this approach is as effective and objective as the rules on which the methodology was based. It is difficult to apply a statistical test of the effectiveness of the methodology, since the exact 'true' area of gaps is not known and there is no universal definition of gaps. Any field measurements would have to be applied at different horizontal and vertical scales, making the two measurements non-comparable. It is, however, possible to examine the individual steps of the extraction process and evaluate the outcome by visual interpretation of aerial photographs from the same area. While aerial photographs were used (in combination with a knowledge of the site from field visits) to provide some assistance with developing the gap extraction procedures it was felt to be inappropriate to undertake a formal accuracy evaluation based on a comparison with manually interpreted aerial photographs because of the problems associated with passive optical remote sensing of gaps discussed earlier.

The gap extraction process is summarized in figure 6. On the background is the *Gaps A* layer that resulted by selecting cells in the canopy surface model with height less or equal to 4 m. The results of the gap shrinkage by both 3 m (*Gaps* B_1) and 1 m (*Gaps* B_2) are shown. Figure 6 demonstrates that most single grid cells along with any elongated group of cells (*Gaps* C_1 and C_2) have been eliminated from the final gap layer (*Gaps F*). Both these categories represent small canopy openings either within a tree crown or between trees and have been correctly eliminated according to the definition of gap, specified earlier. However, after a closer examination some cell 'clumps', which were of equal size with some of the gap polygons in the final gap layer, were found to be erroneously excluded (shown by the arrows in figure 6).

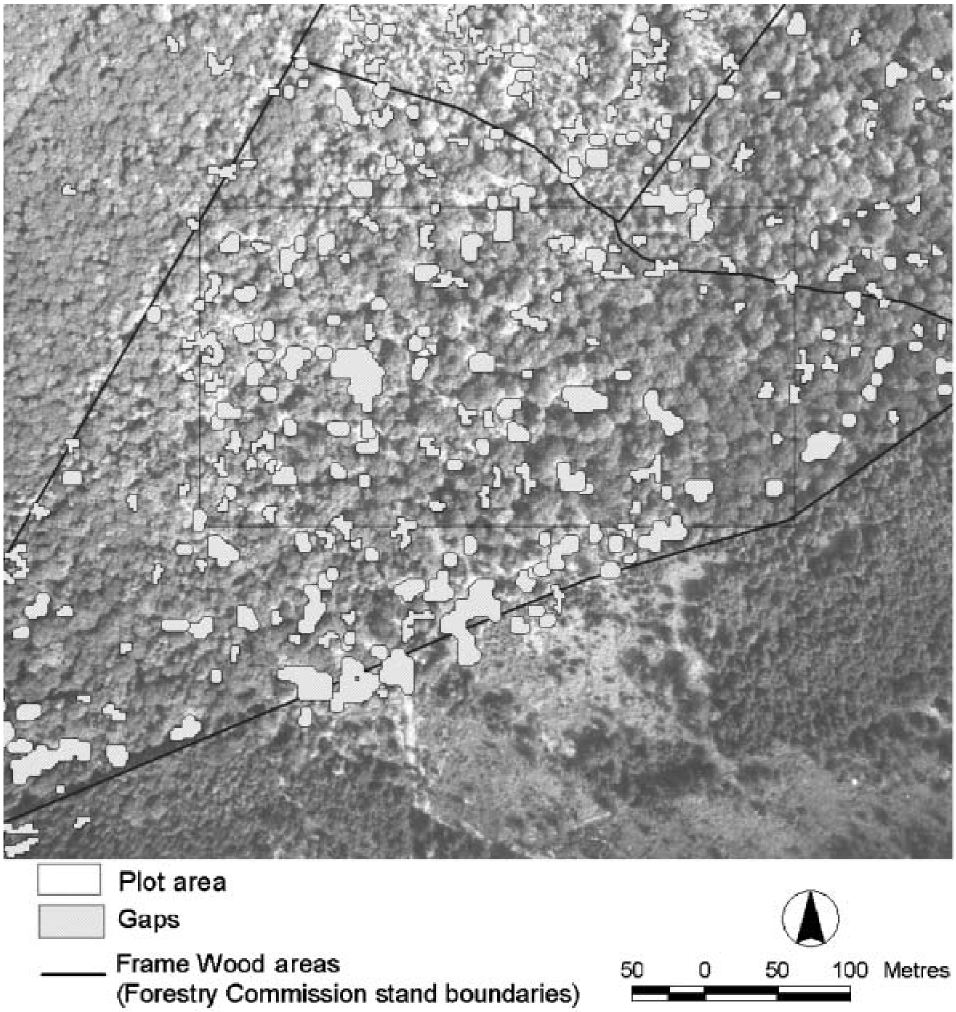


Figure 5. Gaps in Frame Wood.

An examination of aerial photographs from the same area revealed that these were indeed canopy openings, and in fact were linked to the nearest identified gaps. These areas were omitted in the selection of those 'shrunken by one' polygons (*Gaps* B_2) that did not contain the 'shrunken by three' polygons (*Gaps* D_1) (see figure 4). However, these areas were only a small percentage of the total number of gaps (6 out of 98) and it is not likely to have an important effect in further statistical analysis of gap distribution.

6.1. *Distribution of gap size*

In the present study gaps covered 15% of the plot area and 91 gaps were extracted in an area of 9 ha. The results for gap sizes (figure 7(*a*)) were differed from previous research in the same area by Blackburn and Milton (1996) who found that gap area frequency distribution had an exponential form. Despite the fact that the data and the extraction procedure used were different, the differences occur mainly

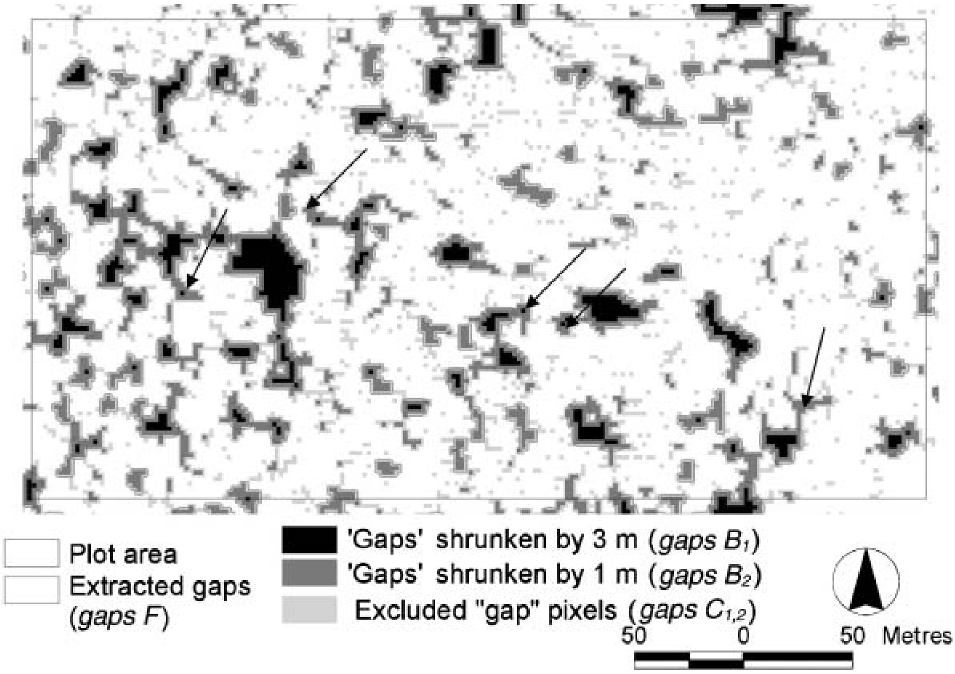


Figure 6. Gap extraction. '*Gaps A*' are all the gap pixels in the image.

due to the differing definitions of gaps used. The major difference between the two histograms (figure 7(*a*) in this paper and figure 4 in Blackburn and Milton 1996) is the classes of gap areas less than 30 m^2 that were not included in the results of this research. According to the definition of gaps in this research, 'single' grid cells and elongated cell clumps are not gaps resulting from a tree-fall and therefore were left out in the extraction process. The above comparison of the gap area frequency distributions highlights the different outcomes of two different definitions and it is not referring to the spatial accuracy of the two methodologies.

The results (figures 5 and 7(*a*)) indicated that most gaps are of small size or equal to the size of one mature tree crown (less than 250 m^2). Figure 8(*a*) demonstrates that, overall, there was a strong positive linear correlation between area and perimeter, which indicates that the gaps in the study area had a similar shape (i.e. a consistent area to perimeter ratio). However, it can also be seen that larger gaps tend to have a greater range of shapes while this variability was considerably reduced for smaller gaps. This level of consistency in the shape of smaller gaps, with little divergence from a circular form, indicates that they were created by single tree falls. Implications of gap shape variations are discussed further in the following section.

6.2. *Distribution of gap shape complexity*

Figure 9 shows gaps at the study site classified on the basis of their shape complexity index using the 'natural breaks' method (see also the GSCI frequency distribution shown in figure 7(*b*)). This method identifies breakpoints between classes using a statistical formula that minimizes the sum of the variance within each of the classes (Jenk's optimization) and finds groupings and patterns inherent

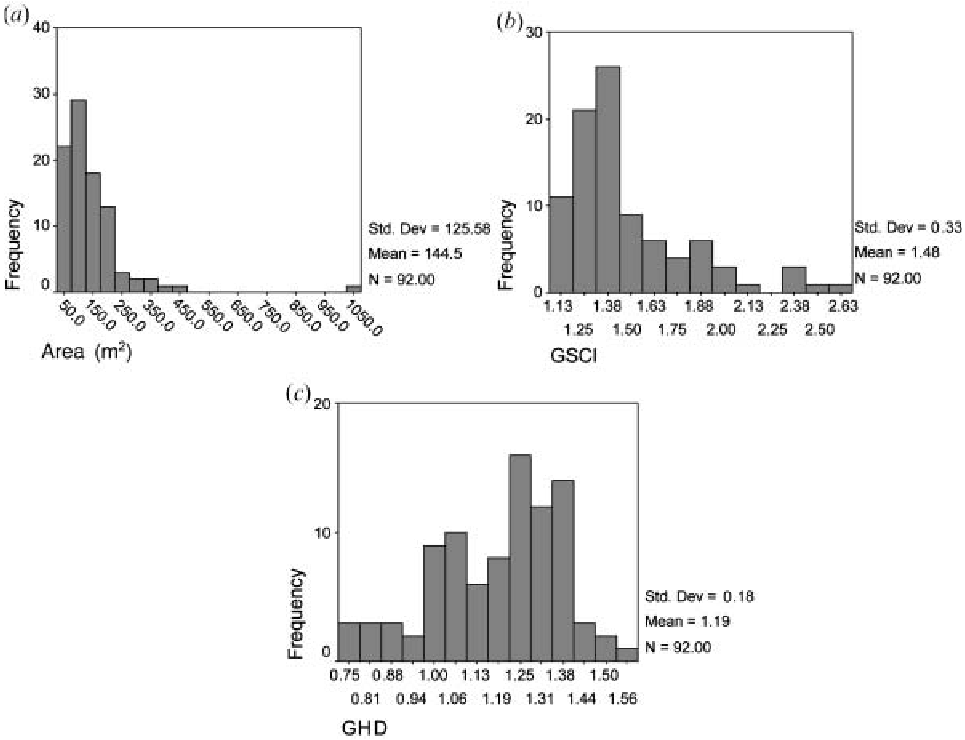


Figure 7. Gap area, GSCI and GHD frequency distributions.

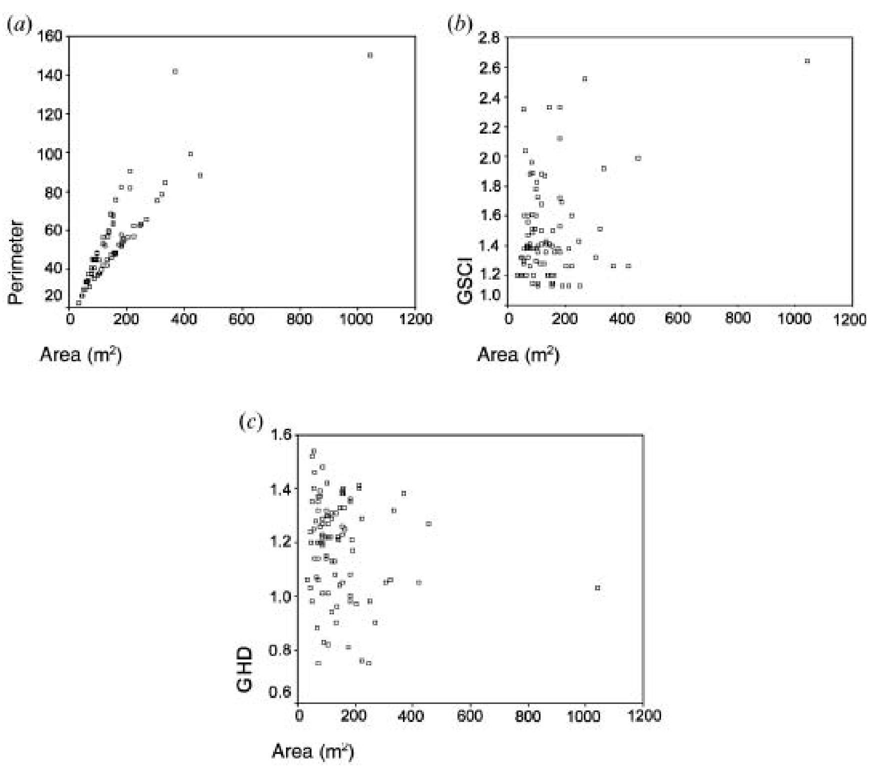


Figure 8. Scatter plots of gap area (m^2), perimeter (m), GSCI and GHD.

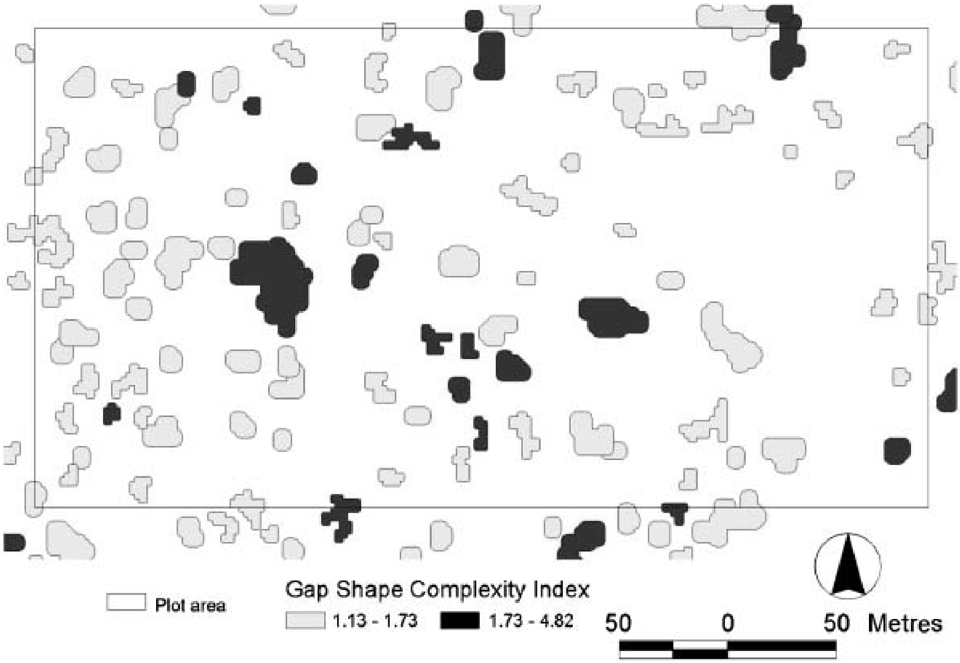


Figure 9. Gap shape complexity distribution.

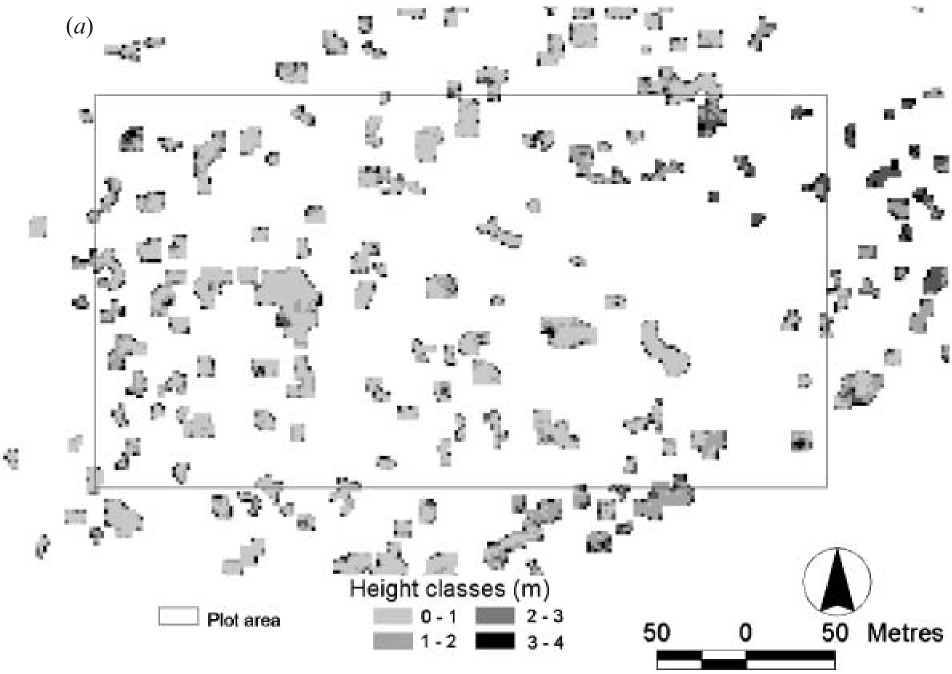
in the data. Figure 9 demonstrates that there is no relationship between the gap shape complexity and size. Indeed, it was found that gap size and complexity had a very low Spearman's correlation coefficient of 0.18 (see also figure 8(*b*)). In absolute terms, gaps were generally complex in shape. A circle would have a shape complexity index of 1 and a square 1.13 (or 13% complexity). Taking into account that gap polygons have been generalized to avoid the square corners of the raster format and that the mean complexity value was 1.48 (or 48% complexity), then the average gap is nearly 4 (48 : 13) times more complex than a square shape. The most complex gap (GSCI = 2.64; 164% complexity) in the plot area is 12.6 times more complex than a square.

The frequency distribution of gap shape complexity index (figure 7(*b*)) exhibited neither normality nor exponential distribution (based on a Kolomogrov–Smirnov test). In a single tree-fall the gap created should have a relatively low shape complexity index if a degree of uniformity is assumed for the tree crown. Big catastrophic events such as fire or strong windstorms also leave uniform patches in a forested area (Franklin *et al.* 1987) and therefore relatively simple in shape. Based on the above assumptions gaps with high shape complexity which exist in Frame Wood are likely to have been created by gradual enlargement through a series of individual tree falls over time (see also figure 8(*a*) and (*b*) and figure 9).

6.3. *Distribution of gap vegetation height diversity*

The distribution of gap vegetation height in Frame Wood is shown in figure 10(*a*), with height represented using four classes (zero height was included to the '0–1' class for illustration purposes). The height diversity index (Shannon index) for each gap is mapped in figure 10(*b*). To provide some context for these results, the maximum diversity (GHDmax), which would have been achieved if all height

(a)



(b)

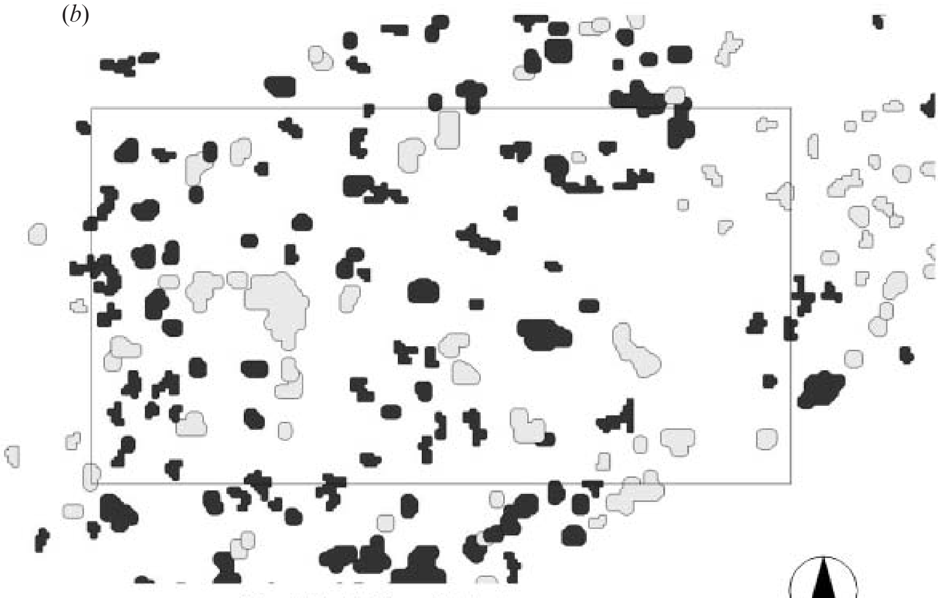


Figure 10. Distribution of gap vegetation height in Frame Wood: (*a*) height variation within gaps; (*b*) distribution of gap height diversity.

classes were equally represented, is equal to GHDmax = ln(Hc) = 1.61, where Hc = number of height classes = 5. In this respect, larger values of the height diversity index represent more vertically heterogeneous gap vegetation. Taylor (1978) pointed out that if Shannon diversity indices were calculated for a number of samples then the resulting values would be normally distributed. In the present study, a Kolmogorov–Smirnov test confirmed that the gap vegetation height diversity index (GHD) followed a normal distribution (see figure 7(*c*)), which meant that the majority of gaps were close to the mean height diversity index of 1.19. In order to interpret these results, the ratio of the mean GHD to the maximum GHD value was calculated. This ratio, according to Pielou (1969), is a representation of evenness and takes values between 0 and 1, with 1 representing equal abundance of all height classes. In the present case Pielou's evenness index is equal to (1.19/1.61 =) 0.74, which demonstrates the vertical heterogeneity in the gap vegetation in the study area. However, observing figure 10(*a*) a sense of flatness is apparent in the internal areas of the gaps. Vertical heterogeneity occurs mainly in the gap edges which could be attributed to low tree branches (from surrounding trees) or the existence of edge species colonization. For the study site, gap height heterogeneity and gap size were found to be unrelated (see figure 8(*c*)).

6.4. *Distribution of vegetation in gaps*

The dominant vegetation types found in gaps were bracken and grass and their distribution is shown in figure 11. Gaps covered by bracken appeared to be clustered while gaps containing predominantly grass were randomly distributed. This was demonstrated statistically by Koukoulas (2001) in a study on gap and tree

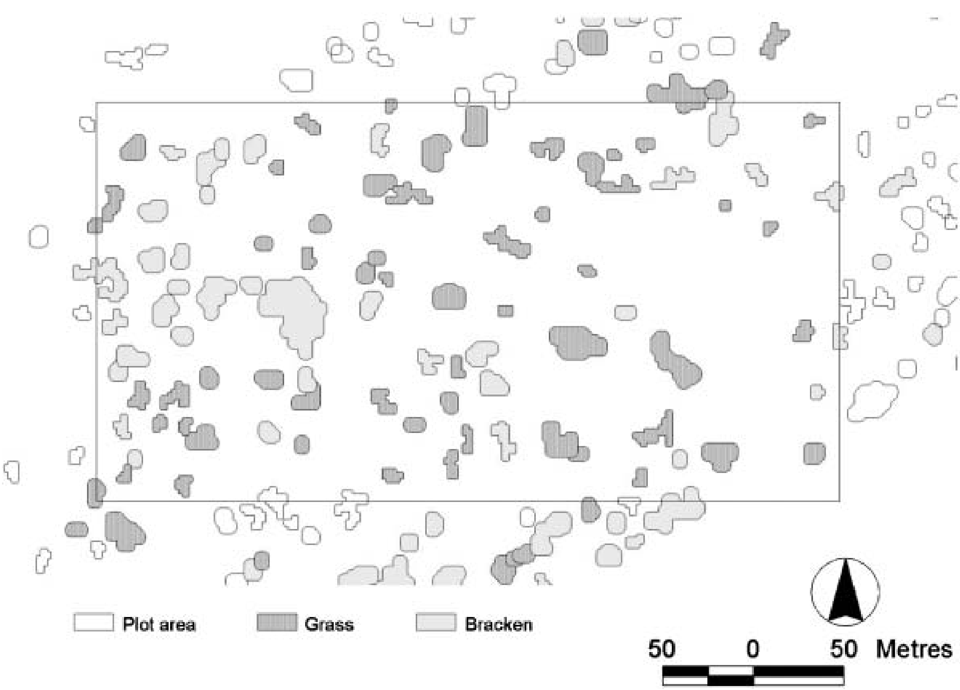


Figure 11. Main vegetation in gaps.

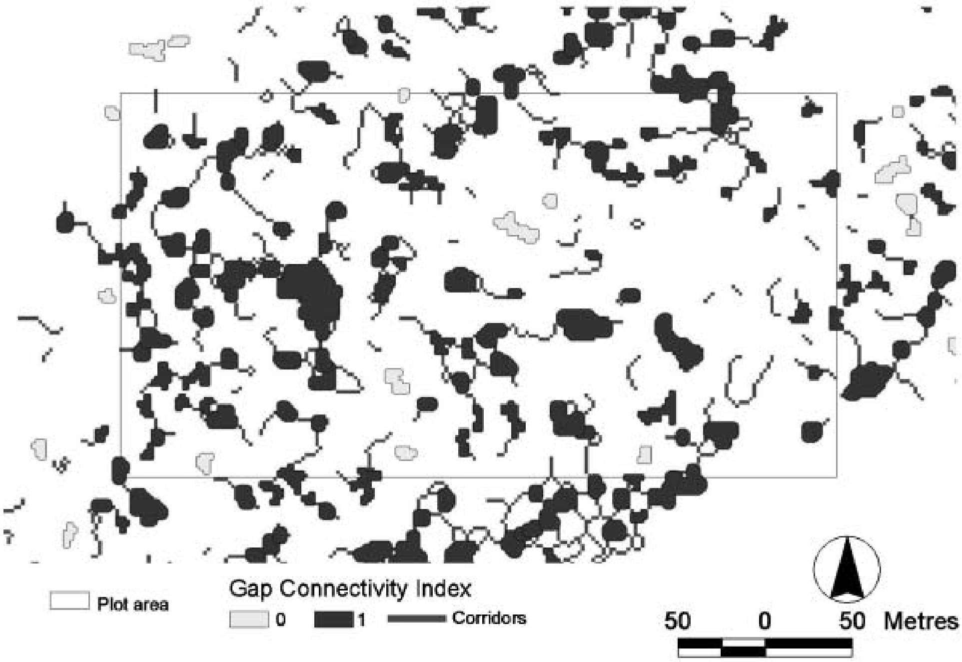


Figure 12. Gap connectivity.

distribution in this area. This can be explained by the invasive nature of bracken, which infests contiguous areas of ground by vegetative reproduction through underground rhizomes. This effective means of propagation and aggressive growth characteristics means that bracken often completely out-competes most other understorey species and entirely dominates the gap vegetation (Pakeman and Marrs 1992).

6.5. *Gap connectivity*

Figure 12 illustrates that gaps in the study area were highly interconnected and only a small percentage (7.6%) were isolated (no connecting corridors were found). This high degree of connectivity reinforces the theory (Blackburn 1993) that gaps are progressively enlarged and join each other to create large gaps within this study site. The high density of gaps, 10 per ha, combined with high connectivity and low regeneration (see Tubbs 1986) has important implications for the future development of the forest. One can hypothesize that a process of continuous gap enlargement could lead to high canopy fragmentation and in view of the failing regeneration, due to intense grazing and bracken invasion, this could lead to severe degradation of the upper forest canopy. In such a development, a different ecosystem would emerge. This hypothesis could not be tested in the present research since remotely sensed data were available only for one period of time. However, the above hypothesis and the implications of the current results could be tested using multi-temporal remotely sensed data together with the methodology for the quantification of gap features described in this paper.

7. Conclusions

LiDAR imagery and GIS functions were found to be highly effective for gap feature extraction. Problems that occur with passive optical remote sensing such as shadows and spectral reflectance and irradiance variations were avoided using LiDAR data. The gap definition proposed in this research proved to be robust and functional. It is anticipated that the methodological framework developed here will be easily applicable to other forest sites as it uses commonly available functions found within geographical information systems. The threshold values required for the accurate extraction of gap and corridor features from LiDAR data can be determined using a basic knowledge of the canopy characteristics of a site and visual inspection of the results for a sample area. When implemented for an extensive forest area the remotely sensed approach developed in this study provides an efficient and robust alternative to time-consuming and often subjective field-based measurements of gap characteristics. The digital outputs of the gap extraction procedure are directly amenable to manipulation using spatial analytical algorithms. While it is beyond the scope of this paper to employ the data on gap properties in a formal statistical or simulation model, the results do illustrate how such data is of value in inferring information on important regeneration or ecological processes. Such information may be difficult to obtain for whole forest stands by any other means.

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