Object-based approach for mapping complex forest structure phases using LiDAR data

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ABSTRACT:

Managed forests are important components of the landscape comprising different stand structural phases (stand initiation, stem exclusion and understorey re-initiation) and delivering important ecosystem functions such as timber production and biodiversity. This paper focuses on the development of a classification method for determining structural phases for conifers and broadleaves using LiDAR data and object-based image analysis (OBIA) approach over a large study area (110 km^2). Firstly, using OBIA, homogenous stands were segmented with minimum area of 100m^2. Tree tops were detected from a canopy height model and gap area between trees determined. Secondly, stand parameters such as tree density and tree height statistics (mean, standard deviation and percentiles) were calculated. The final classification was based on the analysis of stands with known structural phases where the best classifiers were 60th and 80th tree height percentile, tree density and area of gaps between trees. In the study area more than 13,000 stands were allocated and 9,616 of them classified into the three phases, the area proportions being: stem exclusion 68%, understorey re-initiation 28% and stand initiation 4%. The range of stand sizes varied from 100 to 80,476 m^2 across all phases. Our approach shows that it is feasible to classify forest stands into structural phases on a large scale that would have value in forest management planning.

1. INTRODUCTION

Forests are dynamic assemblages of stands at different structural phases interspersed with open ground and other habitats. In the twentieth century there was a major expansion of forestry, with the planting of non-native conifers, and creation of even-aged plantations managed on a patch clear fell system (W. L. Mason 2007). There is now increasing interest in transforming the structure of even-aged plantations through continuous cover forestry (B. Mason & Kerr 2004) with the development of irregular stand structures. Structural phases previously defined by (Oliver & Larson 1996) have been adopted as a framework for the development of continuous cover forestry in the UK. These phases are: stand initiation, stem exclusion, understorey re-initiation and old-growth. One aspect of sustainable forest management, is to attempt to organise and manage the structural phases so that ecosystem services like timber production, recreation and biodiversity are maintained and enhanced (Kohm & Franklin 1997). In terms of biodiversity conservation, it is recognised that functional connectivity between the structural phase components needs to be retained at the landscape scale. Functional connectivity, relates to attributes of the landscape which allow dispersal of species between habitat patches and therefore has both spatial and temporal components (Watts et al. 2005). Sustainable forest management objectives are delivered through the a design planning process which uses planning applications such as; the assessment of wind risk and ecological spatial modelling to define woodland habitat networks in fragmented landscapes (Watts et al. 2007). Thus there is a need to determine the structural phases at the forest landscape scale.

The differentiation between four stand structure phases is a complex process involving both field-based methods (Emborg et al. 2000) and analysis of data from other sources, especially remote sensing (Ewijk et al. 2009; Falkowski et al. 2009). (Emborg et al. 2000) defined structural phases for broadleaved trees based on knowledge of the ecological requirements of the main tree species, vertical tree structure and size of tree gaps. Identification of the best predictors to classify forest stand structure phases from Light Detection and Ranging (LiDAR) data was tested by (Pascual et al. 2008; Falkowski et al. 2009) and the results showed that mean tree height and canopy cover were the most important variables. (Ewijk et al. 2009) described stand phases from raw point LIDAR data using tree height bins and abundance of LiDAR returns within a height bin. Thus suitable predictors for the classification of stands into the vertical structural phases appear to relate mostly to tree height and information about gap dynamics.

Correct delineation of stands is an important aspect of a proper classification into forest stand structure phases as they are the keystones for forest management (Pascual et al. 2008). The classification of structural phases has been done at the stand level with a consideration of the minimum mapping unit (MMU). (Emborg et al. 2000) defined MMU as an area of 100m^2; larger MMUs were found to be too coarse as they possibly covered more than one phase. Traditionally stands are delineated from aerial photos using visual interpretation. This method is time consuming, subjective and expensive and thus new fast methods incorporating segmentation of stands from remote sensing data such as aerial photography and LiDAR data have shown to be cost effective and consistent (Leckie et al. 2003).

Technological advances of LiDAR measuring at three-dimensions give us a capability to better analyse and classify forest into various structural phases then a traditional optical imagery (Ewijk et al. 2009). Furthermore, a combination of passive and active remote sensing data in the forest structure classification was previously found beneficial (Hill & Thomson 2005) conversely to use of only one of them.

In this paper we describe an approach of employing LiDAR data to identify forest structural phases and high resolution aerial photography with 25cm spatial resolution for its validation. Object-based image analysis was considered as a promising method that could help classify various forest structural phases across large areas (Falkowski et al. 2009) and faster when compared to the traditional visual method. An OBIA approach was used to identify and locate various forest structural phases for conifers and broadleaves within woodlands in Loch Lomond and the Trossachs National Park on the southern edge of the Scottish Highlands.

2. DATA AND METHOD

2.1 Study area

The study site is located within the Trossachs National Park (1.865 km^2) in Scotland, UK covering an area of 110 km^2. The area was outlined by the extent of the available LiDAR dataset. Ancillary data defining woodland boundary and information about tree species was obtained from the Sub-compartment database (SCDB) covering land owned by Forestry Commission, UK. This database provides detailed information about each woodland compartment such as planting year, tree species composition and spacing between trees. Conifers comprise over 85% of the wooded portion of the study area (Table 1), with the dominant species being non-native Sitka spruce, Norway spruce and native Scots pine.

Table 1 Proportion of woodland categories in the study area

	Area [km^2]	Area [%]
Broadleaves	12.08	14.28
Conifers	72.50	85.72

LiDAR data were gathered in spring 2008 across the study area (Table 2). Raw data were interpolated by Infoterra to 1m spatial resolution to Digital Terrain Model (DTM) and Digital Elevation Model (DEM). A Canopy height model (CHM) was calculated as a subtraction of DEM from DTM. Pixels with height below 1m were automatically classified as ground or non-vegetation.

Table 2 Description of LiDAR dataset

Date of flight	Resolution	Coverage	Footprint	Scanning angle
12/3/08	1-3 hits/m^2	200 km^2	10 cm	20°

2.2 Description of stand structural phases

The stand initiation phase is described as a site where new individuals and species colonise for several years after a disturbance (Oliver & Larson 1996). Where this disturbance results from clear-felling, new vegetation can become established through natural regeneration or planting (Ewijk et al. 2009). Trees are small (up to 3 meters in height) and with high density of growing plants. The stem exclusion phase is characterised by the presence of competition between trees (Ewijk et al. 2009); new trees do not appear and some start to die off. Furthermore, the surviving trees grow even larger and become dominant in the stand (Oliver & Larson 1996). Occupation of open space reaches its limits and no new individuals are established. This phase is often divided into two subgroups, early and late stage, that are mainly differentiated by a number of gaps between trees (closed canopy) and size of trees defined by diameter at breast height (Emborg et al. 2000). The understorey re-initiation phase is characterised by the process of new tree regeneration or colonization where spaces are created through the death of large trees and light conditions become more suitable (Ewijk et al. 2009). There is slow development of the forest floor in the understorey with growth mainly of shrubs and herbs (Oliver & Larson 1996). Additionally, this phase can also be defined as a composition of mature trees without any crown competition thus allowing understorey re-initiation in gaps between trees.

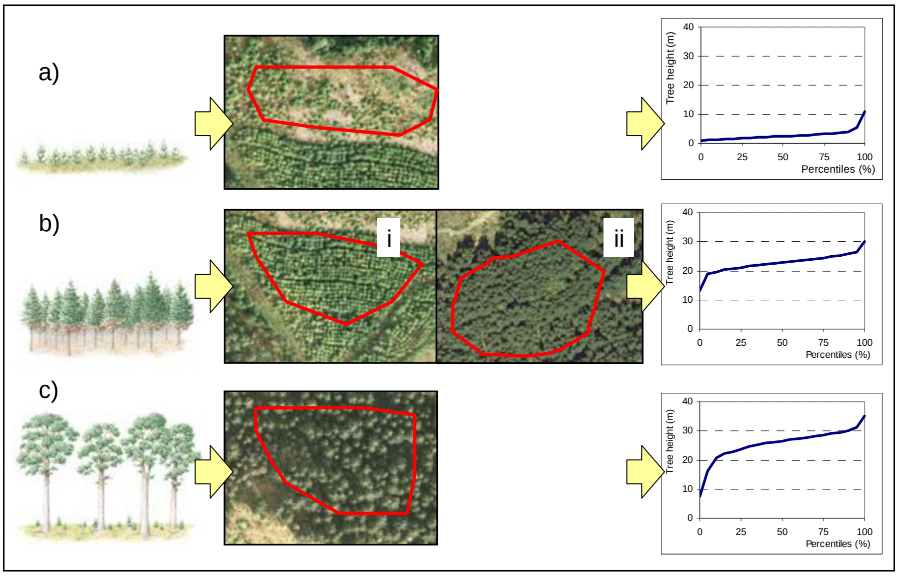

Figure 1 Pictorial illustrations, representative aerial photography and tree height percentile curves for a) stand initiation ; b) stem exclusion: early (i) and late stage (ii); and c) understorey re-initiation phases within the Loch Lomond and Trossachs NP study area

2.3 Methodology

The proposed method employs a 'bottom-up principle' which, 1) determines individual trees as primary objects with a tree-detection algorithm, 2) merges trees into clusters representing larger forest stand units, and 3) classifies forest units into homogeneous structural phases defined by percentile proportions of individual objects (trees), their parameters and proportion of tree gaps within a stand.

The main analysing and processing steps are shown in Figure 2. First, trees were detected from the CHM which determined height of the vegetation and trees. Secondly areas without forest were omitted by cross-referencing to data held within the SCDB. Description statistics such as tree height percentiles and tree density (per ha) were calculated for each stand summarizing information about individual trees. Information on gap area was obtained from OBIA as described in section 2.3.1. Finally decision rules for the classification of stand structural phases were developed and then applied employing attribute information obtained for each stand from OBIA analysis.

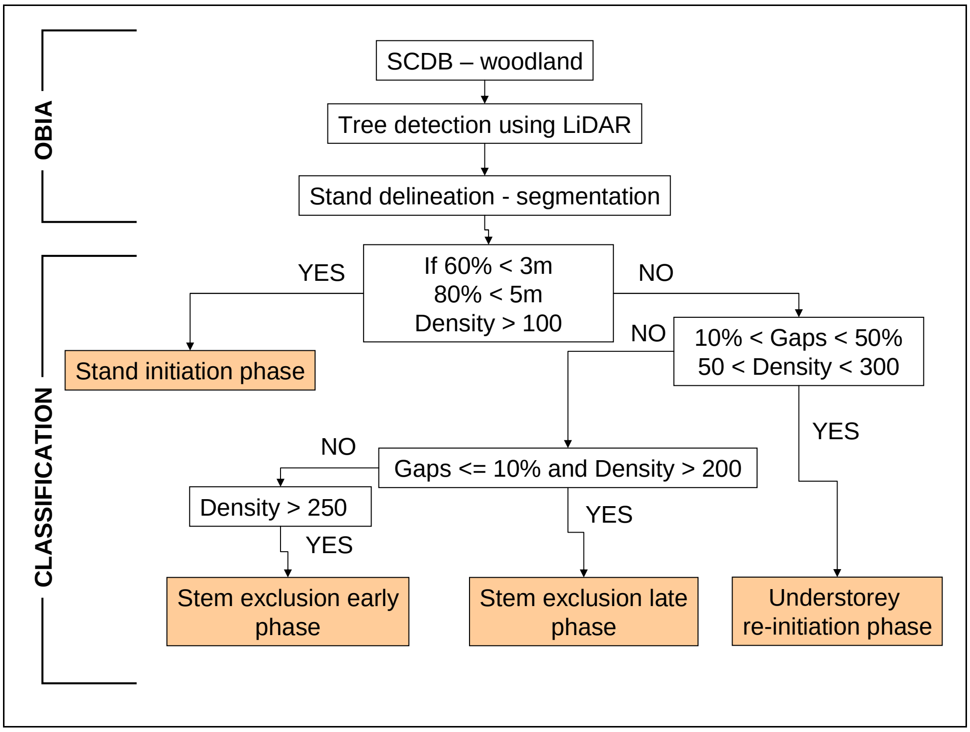

Figure 2 Processing flowchart of proposed method for the classification of stands into the forest structural phases (tree height percentiles within a stand = 60% and 80%; Density = tree density per hectare; Gaps = area of ground (%))

2.3.1 Object-based image analysis

The Object-based image analysis approach was based on the 'bottom-up principle' (Figure 3). This approach allows the classification of forest stands into structural phases using information previously gathered about trees, such as tree height and gaps between trees. In Definiens Developer 8 (Definiens 2009) trees or tree tops were detected from the CHM employing local maxima algorithm. Additionally, above the current object level a super-level was created to delineate stands using a multi-resolution segmentation algorithm with emphasize on CHM values and homogeneity of objects (compactness set to: 0.9). This took into account the nature of stand shape and boundaries derived from the SCDB for conifers and broadleaves. Gap area was directly calculated in Definiens Developer 8 with Relative area function. Attributes derived from segmented objects are shown in Table 3 .

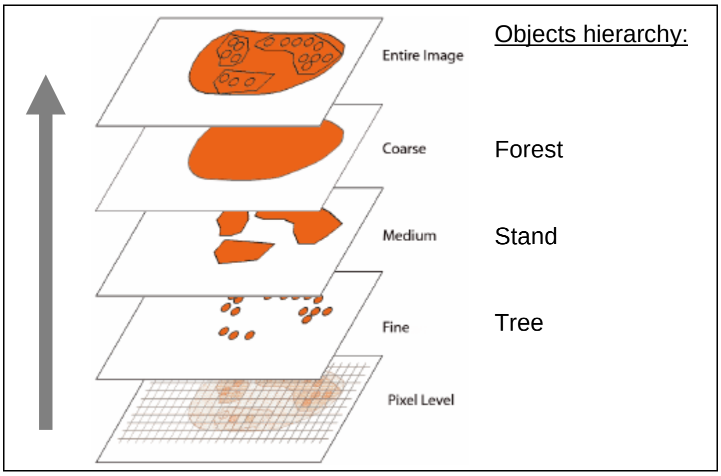

Figure 3 Principle of bottom up approach (modified figure from source: (Definiens 2008))

Table 3 Attributes derived for segmented objects using OBIA approach

Segmented Objects	Area [m^2]	Classified as Conifers or Broadleaves	Number of trees	Area of ground [%]	Tree height [m]
Stands	x	x	x	x	
Tree tops					x

2.3.2 Stand phases classification

To classify previously segmented stands into structural phases selected variables were tested in data analysis. Previous studies (Hill & Thomson 2005; Pascual et al. 2008; Ewijk et al. 2009; Falkowski et al. 2009) used variables such as mean tree height, tree density and proportion of tree height bins for stand classification. In our approach we firstly calculated descriptive statistics (minimum, maximum, mean, standard deviation and percentiles (0,5,10,...,90,95,100)) within a stand for tree tops using R (R Development Core Team 2009). Then these variables were examined and analyzed across test sites in the study area where structural phases had already been defined by local experts. This lead to a final selection of variables: density of trees (per ha), tree height percentiles, and the relative area of gaps represented by ground between trees (in the range 0 – 100%) obtained from OBIA in Definiens Developer 8. Tree height percentiles were used mainly to differentiate between stand initiation phase and other two phases (see example of percentiles Figure 1). Tree density enabled us to eliminate stands with small trees at low density, classify understorey re-initiation phase and distinguish between early and late stages of stem exclusion. Gap area was an important classification variable especially for understorey re-initiation phase where the presence of open canopy or canopy gaps potentially allows new regeneration.

3. RESULTS

In our study area 13,136 segmented stands were identified with a minimum mapping unit of 100m^2 and 9,616 classified into three stand structural phases; 3,520 segments did not fall into any of the three phases characteristics. Overall statistics are presented in Table 4. The majority of stands were classified into stem exclusion phase (68%) with 28% and 4% classified as understorey re-initiation and stand initiation respectively. In terms of the area proportion of individual phases across the study area the dominant was stem exclusion counting for 73% of all woodland area followed by understorey re-initiation (21%) and stand initiation (6%). The stand sizes varied between classes from 100 to 80,476 m^2 with a mean in range of 2,270 to 5,302 m^2. The mean tree density was lowest in the understorey re-initiation class (180 trees/ha) and highest (351 trees/ha) in the stem exclusion phase (early stage). Gaps between trees varied considerably with a minimum average of 1.87% for stem exclusion (late stage) and up to 77.18% for stand initiation phase.

Table 4 Summary statistics for segmented and classified stands

	Stem exclusion - early			Stem exclusion - late			Stand initiation			Understorey re-initiation		
	D[3]	G[4]	A[5]	D[3]	G[4]	A[5]	D[3]	G[4]	A[5]	D[3]	G[4]	A[5]
Min	250.39	10.01	100	200.03	0.00	102	100.72	27.47	112	50.15	10.01	105
Max	862.07	81.11	80,476	1243.78	9.97	39,576	633.02	98.58	43,254	299.92	49.94	30,305
Mean	351.57	29.53	5,302	320.11	1.87	3,104	218.84	77.18	4,510	180.49	25.95	2,270
St.dev	59.54	17.30	7,225	75.52	2.52	3,019	95.79	14.41	5,556	65.92	11.28	2,461
Number[1]		7.12			60.51			4.43			27.93	
T. area[2]		12.22			60.79			6.47			20.52	

[1] number of stands (%), [2] total area (%), [3] D - tree density (trees/ha), [4] G - area of gaps within a stand (%), [5] A - area of stand (m^2)

Densities of trees from all stands are presented in Figure 4 (a) showing overall higher values for stem exclusion phase compared to the other two phases. We also observed a steep peak towards higher densities in all phases except understorey re-initiation. Differences in the relative gap area are evident especially for stand initiation phase reaching a gap area of 50% only in 10% of data. Similar patterns were evident for the understorey re-initiation and stem exclusion early stage. The stem exclusion late stage had a very low relative gap area with values reaching only to 10% (Figure 4 (b)).

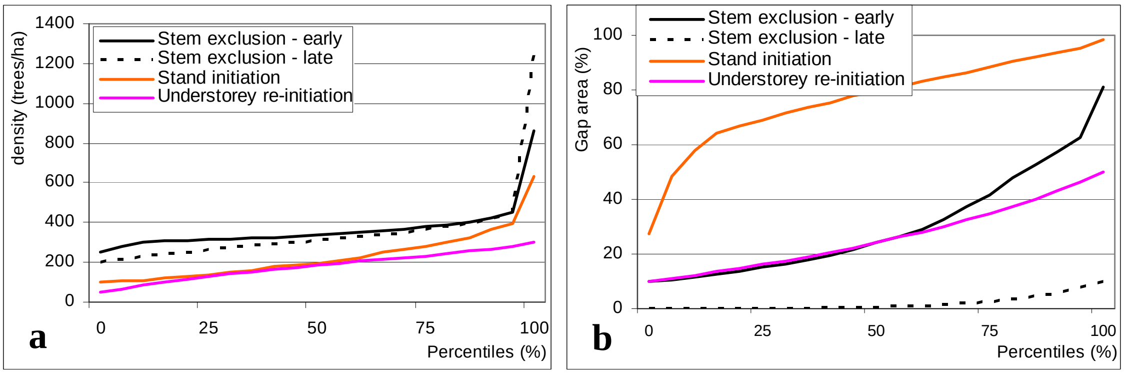

Figure 4 Summary for all stands: tree densities (a) and relative area of gaps within a stand (b)

The validation process was based purely on a visual interpretation of aerial photography as field data were missing. In addition, as a consequence of the large study area and the impracticality of validating all stands, only sample sites were randomly selected with an emphasize on an equal distribution of structural phases. Only several stands were used to examine the accuracy of our classification with an overall results showing reasonably good classification for stem exclusion and stand initiation. The level of accuracy for understorey re-initiation was lower compared to other phases thus the classification needs to be modified and improved.

4. DISCUSSION AND CONCLUSION

New technologies, techniques and datasets are improving rapidly, enabling us to identify forest stand parameters quickly and accurately. Optical remote sensing imagery linked with LiDAR data is proving to be very useful for many studies trying to classify forest stand structural phases (Hill & Thomson 2005; Pascual et al. 2008; Ewijk et al. 2009; Falkowski et al. 2009). The advantage of an OBIA approach in forest stand delineation lies in its capability to use various types of datasets such as vector and raster. This study presented the benefits of current vector (SCDB) and raster (LiDAR) datasets in the analysis and classification of forest stands into structural phases.

Our analysis consisted of two steps. Firstly, segmentation of stands and trees detection employing OBIA and secondly classification into three structural phases using classification variables obtained from statistical and CHM analysis. The process of stand boundary detection is a difficult task as several studies have highlighted (Leckie et al. 2003; Pascual et al. 2008). The minimum mapping unit played an important role as stands less than 100m^2 were considered too small. Information gathered from tree top detection process provided enough information at the stand level. The second part of the analysis focused on the selection of appropriate classifiers. The key variables for the delineation of stand initiation were tree height percentiles (60 and 80%) (Figure 1) that describe accurately the low vegetation and high tree density. In our study this phase was easier to identify compared to other phases as noted in other studies (Falkowski et al. 2009). The other two phases (stem exclusion and understorey re-initiation) were more similar in terms of tree height values and hence the additional variable, relative area of tree gaps, was used to distinguish between the phases. In other studies additional variables such as DBH (Ewijk et al. 2009), canopy cover and mean tree height (Falkowski et al. 2009) have been used to distinguish between stem exclusion and understorey re-initiation phases. Our approach combined tree density and relative area of gaps (as the converse of canopy over) as the best predictors of more developed stand structural phases. The results showed reasonably good classification for stem exclusion, although less reliably for understorey re-initiation due to increased frequency of gaps near the edges of woodland which were taken into account by the classification process. Similar findings of lower accuracy for understorey re-initiation phase were presented in (Maltamo et al. 2005; Falkowski et al. 2009) as a result of the occurrence of dense canopy and difficulty in detecting understorey vegetation with LiDAR. In our stand phases classification we tried to pick up the inter-stand variation in order to correctly classify segmented stands following (Ewijk et al. 2009). This process is very complex and needs further analysis and research. However, the proportions of individual phases within the forest presented in Table 4 were similar to findings in (Emborg et al. 2000) even though they studied purely broadleaves trees.

In some cases when bushes were wrongly classified as small trees from LiDAR data this lead to a misclassification into stand initiation phase. In addition, the number of trees in stand initiation phase was probably underestimated due to the coarseness of the pixel size of the dataset (1m) and the type of detection algorithm used. Thus new methods or higher quality data should be used to address this issue and improve overall accuracy.

In conclusion, stand structural phases are very complex units that are hard to precisely identify and locate even in the field so the results of this work are satisfying. Large scale mapping and classification of forest stand structural phases is achievable with available methods and datasets and can be applied to other sites as the methodology is not specifically dependent on site conditions. Output of the project will be used for Forest Strategy planning within the Trossachs NP.

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