Forest stand delineation through remote sensing and Object-Based Image Analysis

José Antonio Ortega García
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Supervisor: Dr. Julia Åhlén
Examiner: Professor Bin Jiang
Assistant examiner: Mr. Ding Ma
Abstract

Forest stand delineation is an essential task of forest management planning which can be time consuming and exposed to subjectivity. The increasing availability of LiDAR data and multispectral imagery offers an opportunity to improve stand delineation by means of remotely-sensed data. Under these premises, ASTER imagery and low-density LiDAR data have been used to automatically delineate forest stands in several forests of Navarra (Spain) through Object-Based Image Analysis (OBIA). Canopy cover, mean height and the canopy model have been extracted from LiDAR data and, along with VNIR ASTER bands, introduced in OBIA for forest segmentation. The outcome of segmentation has been contrasted, on the one hand, assessing segments’ inner heterogeneity. On the other, OBIA’s segments and existing stand delineations have been compared with a new method of geometrical fitting which has been ad hoc designed for this study. Results suggest that low-density LiDAR and multispectral data, along with OBIA, are a powerful tool for stand delineation. Multispectral images have a limited predicting utility for species differentiation and, in practical terms, they help to discriminate between broad-leaved, conifer and mixed stands. The performance of ASTER data, though, could be improved with higher spatial resolution VNIR imagery, specifically sub-metric VNIR orthophotos. LiDAR data, in contrast, offers a great potential for forest structure depiction. This perspective is connected with the increasingly higher resolution datasets which are to be provided by public institutions and the rapid development of drone technology. Complexity of OBIA may limit the use of this technique for small consulting firms but it is an advisable instrument for companies and institutions involved in major forestry projects.

Key words: forest stand, stand delineation, LiDAR, ASTER, OBIA, segmentation, canopy height model
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List of abbreviations

BA: Basal area
CC: Canopy Cover
CM: Canopy Model
DBH: Diameter at breast height
DEM: Digital Elevation Model
DSM: Digital Surface Model
FMP: Forest Management Plan
Hm: Mean height
IGN: Instituto Groográfico Nacional
LiDAR: Light Detection and Ranging
NDVI: Normalised Difference Vegetation Index
NIR: Near-Infrared
OBIA: Object-Based Image Analysis
PNOA: Plan Nacional de Ortofotografía Aérea
VNIR: Visible and Near-Infrared
1 Introduction

Forests have been an important matter in most of societies for different and changing reasons. In a European context, this importance is nowadays represented by the EU Forest Strategy, which was adopted in 2013 by the European Commission to promote forests and forest management, stressing forest’s multifunctional aspect. Multi-functionality is actually one of the main ideas of contemporary forestry in comparison with previous approaches to this science. It implies that forests simultaneously provide a series of goods and services to societies, including production of natural resources, environmental and social benefits. Issues such as landscape preservation, recreation, carbon fixation, amongst others, are of growing concern perceived by society and directly related to forest conservation. The multifunctional dimension of forests is particularly high in Spain, due to the diversity of forest types, as well as geographical and social conditions (Gonzalez-Molina et al., 2006). The correct management of forests is achieved by forest management plans (from now, FMP). Forest management planning is a discipline aiming at organizing forest’s natural resources in space and time, to achieve a sustainable use of such resources. Its importance is frequently stated in laws and regulations, which may also define their structure and content. The Spanish Forest Act (Ley 43/2003, de 21 de noviembre, de Montes), in particular, determines that public administrations must promote the creation of FMP and fix in which situations this plans are compulsory.

Even though forest science started in Germany during the 18th century, it is in the 19th century when the importance of FMP take shape (Gonzalez-Molina et al., 2006). Since then, the structure of FMPs has evolved and different modalities have appeared over time, although a set of basic points are common for most of them. Typically, a FMP contains a number of objectives, a description of the forest and a series of recommendations and scheduled actions. The description section normally includes the legal and socio-economic contexts, a study of its ecology and natural values and the analysis of the natural resources which, in most of cases, relate to the dendrometric characteristics of the forest. Cartography-wise, FMPs include the division of the forestland in units and subunits aiming to spatially organize the management of the forest (stands, working circles, compartments, etc.), what is known as forest stand delineation.

After the outbreak of the economic crisis in Spain, in 2008, public budgets have decreased dramatically in some sectors. The drafting of FMP specifically experienced important monetary cuts since they greatly depend on public budgets. Consequently, the amount of such projects have been reduced for the past years and forestry consulting firms have been forced to implement cost cuttings in order to maintain their competitiveness. Reducing costs in some steps of FMP drafting, such as forest stand delineation, seems to be an imperative under these circumstances. Thus, one of the most important motivations for this work is precisely contribute to the viability of such firms and the quality of their FMPs. The interest of this thesis is also based on the benefiting from freely available data
such as ASTER imagery and, especially, LiDAR data derived from Spain’s Aerial Orthophoto National Plan (PNOA). Therefore, there is potential prospection for firms and institutions, as many geomatic products are nowadays freely available for internet download at no cost, in contrast with recent years.

1.1 Problem statement

Forest delineation is generally done by photo-interpretation followed by field inspection. The main identified drawbacks in such procedure are three: a) some relevant characteristics of the forest for stand delineation may go unnoticed in the photo-interpretation process, b) it is time consuming and, therefore, costly, and c) a degree of subjectivity is implicit in the process.

Some differences in stand features can be easily grasped by photo-interpretation. This possibility depends on the nature of the feature and the degree of variation. A stand of conifers is normally differentiated from a stand of broadleaved trees and even some species within those groups can also be easily segregated (e.g. Pinus pinea and Pinus radiata; Quercus ilex and Quercus robur, etc.). Density, canopy cover or mean height are also susceptible of easy recognition if differences are relevant. However, some differences in certain parameters may be important enough to produce a separation of two contiguous stands but not to be clearly discerned through photo-interpretation. For example, differences in basal area or volume of two adjacent forest stands are far more difficult to determine. As a result, in many cases, forest stands cannot be separated from the adjacent ones, only based on how they look like in an orthophoto, even using the infrared band (when available). This lack of certainty about some parameters results in advanced error management on the field and additional delineation has to be done in situ, normally with the help of GNSS (Global Navigation Satellite System) devices.

The second identified shortcoming of the described method is that it is time consuming and a rather tedious (Dechesne et al., 2016; Dechesne et al., 2017; Diedershagen et al., 2004). A thorough examination of an orthophoto requires time, especially when this activity is combined with the inspection of other sources of information such as DEM-derived data, orthophotos from previous years, LiDAR 3D representations, etc. This extra time spent in such tasks is of vital importance for firms and institutions dealing with FMP and reduces either the viability or the quality of the overall work.

The third problem found in this practice is related to the degree of subjectivity and the different visual criteria that different experts may have over the same spot. Unlike the first problem, this issue is not attached to what it is indiscernible in an orthophoto but rather to what it is discernible and yet it varies depending on the discretionary decision of an interpreter (González et al., 2004.). For a given forest with a gradual variation of canopy cover, for instance, some interpreters may have a tendency to divide it in many stands whereas some others may opt to set less divisions, based on what they believe is meaningful in forestry terms. In relation with this point, there is a further difficulty
consisting in solving the question of the continuum. In some cases, ecosystems may show a progression towards other ecosystems, where there is no distinguishable limit between them. In such circumstances, delineation becomes more difficult and exposed to the photo-interpreter subjectivity.

The use of LiDAR and multispectral images has been proved in many studies as a feasible way to delineate forest stands (Eysn et al., 2012). However, the fact is that forest firms have not been using such techniques on a regular basis. Some factors influencing this situation are the cost of implementing remote sensing in stand delineation and the technical complexity of the issue itself. On the one hand, the mentioned cost refers to high resolution data, which are not free of charge but are the best option to extract accurate results. On the other hand, the proposed solutions for implementing LiDAR for FMP involve the setting of forest inventory plots to correlate ground truth with LiDAR metrics. If a FMP is budgeted as to be executed only or mostly through stand estimations, the extra-cost of setting forest inventory plots may probably be unaffordable. This problem becomes more obvious when dealing with small properties due to the effect of economies of scale.

Figure 1. Stand delineation at the forest of Junta Bidasoa-Berroarán (Navarra, Spain).

Note: representation of the main tree species for every stand (source: Forest management plan of the forest of Junta Bidasoa-Berroarán, unpublished. Courtesy of Basartea S.L.).

The technical complexity of using LiDAR for stand delineation is fostered by the high
heterogeneity over the Spanish forests, particularly in the North East. Northeastern Spain comprises a wide spectrum of forest ecosystems, ranging from semi-arid sites, where *Pinus halepensis* or *Quercus ilex* prevail, to Atlantic communities of *Fagus sylvatica* or *Quercus robur*, subalpine communities of *Pinus uncinata* and plantations of allochthonous species such as *Pinus radiata*, *Pseudotsuga menziesii*, etc. In this context of high biodiversity, some forests may contain a large number of tree species in a reduced extent. The forest of Junta Bidasoa-Berroarán (F11), with over 600 hectares, exemplifies this situation with 20 inventoried main tree species (Figure 1). A high degree of biodiversity and heterogeneity not only complicates photo-interpretation but also impacts on the applicability of any alternative to manually delineate forest stands. Technical complexity has to do not only with the forests but with the firms themselves. Most of forestry consulting firms in the region are small and lack the knowledge to face complex geo-spatial solutions. Therefore, any proposed alternative for forest stand delineation should take into account this aspect.

1.2 Aim of the thesis

In the context of stand forest management planning in North East Spain, the aim of this thesis is finding an operational way to delineate forest stands, based on freely-available multispectral and LiDAR data, through Object-Based Image Analysis (OBIA). More specifically, this aim entails the use of low-density LiDAR data provided by the *Plan Nacional de Ortofotografía Aérea* and the ASTER imagery available in the internet. The automatic delineation of forest stands, by means of remotely sensed data, will be executed with the different algorithms of OBIA, avoiding human bias and delivering a result exclusively based on the physical reality of both the terrain and the vegetation. The outcome should improve the overall quality of forest stand delineation where current procedures reveal some limitations. It should also reduce the time expenditure and complexity involved in this process in comparison with the workflows which most of Spanish forestry firms are using.

The associated objective of this thesis is to assess viability of forest stands delineation using the above-mentioned approach, in order to achieve an improvement in efficiency and quality in forest stand delineation. The study of forests which have been already delineated in the context of a forest management plan, will serve to compare both procedures and extract appropriate conclusions. Having both delineations (on the one hand, manually set and, on the other, automatically produced) will be an essential element for the discussion and the final conclusions derived in this thesis.

1.3 Structure of the thesis

This report is structured in four main parts and a conclusion. The first part comprises an introductory section where the topic of this thesis is put into context and some specificities of forest delineation are explained, in order to draw a general frame of understanding. Then, the problemsatics of manual forest stand delineation is addressed, as well as the
potential problems of an automatic solution, which is the stated objective in this thesis. A second section is devoted to introduce the theoretical background on the thesis’s topic. In particular, this part deals with the use of OBIA, multispectral imagery and, especially, LiDAR to predict forest structure, as well as the use of these data sources in forest stand delineation. Some previous, relevant research on these topics is reviewed and its content is commented in line with the purpose of this thesis. The third part of this document deals with the data, the software and method used in this research work. A description of data acquisition, manipulation and analysis, as well as accuracy assessment procedures, is given. The fourth part of this report shows the results of the NDVI analysis, several automatic delineations and their accuracy assessment. In the last part of the report the results are discussed and compared with the existing FMP delineations. This section includes the conclusions, where some future implications are pointed out.
2 Theoretical background

This section reviews relevant considerations on forest stand delineation, made by scholars and researchers, and the main techniques used so far. The first part deepens into the concept of forest stand itself, how historically it has evolved and what the current techniques for stand delineation consist of. The second subheading states the basics of remote sensing techniques apply to the study of forests. Relevant forestry-related research work is pointed out in the field of remote sensing, with special emphasis in LiDAR experiences. The last of the theoretical background section explains the foundations of OBIA and how it has been used to differentiate trees and forest stands in several cases.

2.1 Forest stand delineation

The analysis of natural resources is an essential part of any FMP and it generally refers to the study of forest parameters such as tree species composition, tree density, age and diameter distribution, tree height, basal area, timber volume, etc. This analysis is commonly done in two possible ways: through forest inventories or through stand estimation. Both methods have in common a general site description but differ in the accuracy and the spatial scope of estimating forest parameters. Stand estimations record structural parameters for the entire stand without high accuracy and are normally undertaken in all stands. Forest inventories, in contrast, present a higher accuracy and are restricted to inventory plots of 5-15 m radius, where all trees’ diameters are measured and tree heights are sampled. Due to the high cost of this second method, many FMPs regard forest inventories only for specific areas of especial interest.

The current trend in many parts of Europe is to adopt methods of FMP based on spatial units called stands or forest stands. Stand-based FMPs were conceived by Johann F. Judeich towards the end of 19th century as a solution to overcome the excessive rigidity of existing methodologies at that time (Gonzalez-Molina et al., 2006). The definition of forest stand varies amongst different authors. Leppänen et al. (2008) state that stands are timber inventory units, forestry data and containers and operation units in timberland management. They note though, that stands may be set either on operational or on biological basis. Gonzalez-Molina et al. (2006) define them as spatial units for dasocratic management, forest inventories and forest felling. Mustonen et al. (2008) regard them in a simpler way, as areas of forestland presenting homogeneous characteristics. Finally, Ford-Robertson (1971) in Sullivan et al (2009), gives a complete and comprehensive definition, matching the purpose of this study: ‘a community, particularly of trees, possessing sufficient uniformity as regards to composition, age, spatial arrangement, or condition, to be distinguishable from adjacent communities, so forming a silvicultural or management entity’. The spatial definition of such forest stands is a crucial step within the planning and subsequent execution of tasks. Some strategic decisions, such as where, when or how to implement silvicultural actions (e.g. tree cuttings) are taken at stand level (Dechesne et al., 2016). Therefore, its correct delineation becomes a critic point at which
the planner has to deal with the complexity of a list of variables as well as the complexity of the forestland itself.

Forest stand delineation or stratification has been traditionally held by interpretation of aerial photographs (Mauro et al., n.d.; Leppänen et al., 2008). Nowadays, the generalized availability of orthophotos at relatively large spatial resolution in Spain (normally, 50 cm or 25 cm) has made this product the main tool for forest stand delineation at a preliminary stage (Varo-Martinez et al., 2017). Gonzalez-Molina et al. (2006) suggest a standard delineation procedure, consisting in combining aerial imagery, topographical maps and the stand limits from previous plans, when they are available. Overlay of additional information, regarding the legal status of the land, management considerations, ecological features, etc., might also be used, in order to participate in the stratification. These authors point out, though, that this should be considered as an initial approach and that final delineation is always to be obtained after a detailed field inspection. This procedure has actually been followed by most of Spanish FMP, for the past twenty years. In this context, field inspection has served at different purposes: on the one hand, it has been the way of correcting wrongly interpreted stand limits and adding unnoticed ones during the photo-interpretation stage. On the other hand, these inspections have been simultaneously used for describing forest stands and recording timber resources through stand estimations.

2.2 The remote sensing approach

Remotely-sensed data have been used to describe forests in different manners for long-time, as it has in forest delineation (Eysn et al., 2012). Several studies have been undertaken in relation with forest stand delineation through remote sensing techniques, either only using LiDAR data (Næsset, 2002), or combining it with multispectral or hyperspectral data (Schardt et al., 2015). It is not usual to find examples of multispectral data as the only source to address stand delineation, as forest structure is crucial to explain delineation. Dechesne et al. (2016) conclude that the combined use of LiDAR and multispectral data for forest delineation is recommended due to their complementarity. Chen et al. (2012) contributes to this view stating that optical data can improve biomass estimates if combined with LiDAR.

Satellite sensors’ visible and NIR bands have been widely used for differentiating vegetation types for decades, especially since the appearance of Landsat satellite. Vegetation’s reflectance for red and NIR spectral segments are very different from most of other surfaces (being relatively high for NIR and relatively low for the red section of the spectrum, in vegetated areas). This behaviour allows the use of the Normalised Difference Vegetation Index (NDVI), which is expressed as (NIR-R)/(NIR+R), to satisfactorily discriminate vegetated and non-vegetated areas. Moreover, the combination of both bands also presents some clear patterns within vegetated areas and can bring more information about species composition than those bands separately (Zargar et al., 2011 in Dechesne et al., 2017). Hence, differentiating grasslands, shrub communities and forests become a feasible task using this index. Forested areas can also be classified according
to this index, in general terms. Most of conifer woodlands show a substantial difference in relation with broad-leaved ones in terms of NDVI, having the broad-leaved forests higher NDVI than conifers. Studies such as Radoux & Defourny (2007), Machala & Zejdoňá (2014) and Dechesne et al. (2016) provide differentiation between the above-mentioned groups using multispectral VNIR bands. Apart from the restricted discriminatory ability of three or four VNIR bands over forest species, the common situation of mixed forests adds more difficulty to stand classification based on species composition. Diedershagen et al. (2004) backs this point, stating that multispectral data may not improve segmentation based on LiDAR in areas composed by mixed forests. Classifications using hyperspectral imagery can provide better discrimination amongst species. Sensors such as the Compact Airborne Spectrographic Imager (CASI), allowed Leckie et al. (2003) to address species classification using CASI’s eight VNIR bands. In this research six species (four conifers and two broad-leaved species) could be differentiated with a maximum error per stand of a 13%.

LiDAR data is produced by an active sensor which enables distance measurement between the emitting device and the objects it scans. This technique consists of releasing pulsed laser beams and measuring the time it takes for those pulses to return to a receiver, after the beam has reflected in one object. Laser velocity is constant and equals the velocity of light, so distances can be induced from that time measurement and triplets of XYZ coordinates of the impacted objects can be generated. LiDAR devices may be terrestrial or airborne mounted, being the latter the most common situation and the source for studying land-use and forests. LiDAR sensors are capable to accurately record various returns over the same point, defining the height of several returned impacts. This specificity strengthens LiDAR suitability to describe forests’ inner structure in front of other remotely-sensed data, such as spectral imagery or radar (Zhao et al., 2011). In forests, the first return typically comes from the canopy and the last one from the ground (Shendryk et al., 2014), even though the ground might not be reached by the laser. One of LiDAR’s most important characteristics is pulse density because that determines how accurately surfaces can be described. Despite a high point density is desirable for the sake of having more information, increasing density involve a higher investment and may lead to unnecessary, redundant information as well as storage restrictions. For instance, Varo-Martínez et al. (2017) found that an increase of density from 0.5 pulses/m² to 10.5 pulses/m² was not improving significantly basal area predictions but it was affecting top height’s.

There are two basic approaches to address LiDAR data concerning forests: single tree segment-based and area-based (Corona et al., 2012 in Teobaldelli et al., 2017). Both methods have been tested successfully and while the first one involves the detection of single trees, the second method is based on the analysis of the point cloud as a whole. Area-based methods present the inconvenient of not identifying single trees (Latifi et al., 2015) and, therefore, a stand parameter as important as tree density, but it is considered the most cost-effective option (Yu et al., 2010). Tree detection is based on watershed segmentation algorithms which can recognize local maxima and identifies those points as
the top of a tree crown. It is convenient to use this kind of approach with certain precautions and with a knowledge of how the overall structure of a forest is. In multi-storied forests or forests having an important layer of suppressed or dominated trees, single tree segment-based methods may not recognise some individuals for being under a dominant tree’s canopy.

LiDAR metrics are the descriptive statistics calculated over the point cloud in relation with a specific grid size. Examples of metrics derived from LiDAR are maximum height, mean height, standard deviation of heights, total count of returns, first return, second return, percentile values, etc. These metrics are useful for describing structural or biophysical forest parameters through modelling. Thus, crown canopy cover, basal area, top height and timber volume, amongst other essential parameters, are predictable through the analysis of LiDAR metrics (Næsset, 2002; Popescu & Wine, 2004 in Zhao et al., 2011). In order to adjust predicting models from LiDAR metrics a network of well geo-positioned forest plot inventories is needed as ground truth. Then, different modelling strategies are set to predict every specific parameter. The simplest parameter to predict is the canopy cover, which Næsset (2002) estimates through the percentage of first returns over a threshold height of 2 m. For the rest of the parameters analysed (canopy cover, mean height, top height, DBH and BA), this author used multiple regression analysis to establish a series of multiplicative models, which were found statistically significant except for the tree density model. Similarly, Varo-Martínez et al. (2017) set a series of forest inventory plots and adjusted models to predict top height and basal area through multiple linear, power and exponential regressions. In this case, again, models were found robust and bias produced by them were non-significant.

2.3 Object-based image analysis

OBIA is a technique to segment and classify images, not only based on pixel values but also in the so-called objects, produced by the grouping of pixels or other parametrised features of an image. The segmentation stage aims at grouping pixels to deliver meaningful objects under user-defined homogeneity criteria. OBIA is commonly used with spectral data and is capable to handle numerous bands of different information, which are conveniently weighted in the different steps of the analysis. Segmentation through OBIA has been successfully used for forest stand delineation in many studies (Mustonen, 2008; Varo-Martínez, 2017; Dechesne, 2017) and has been used with both multispectral and LiDAR data for this purpose. When using OBIA with LiDAR input data may contain some of the LiDAR-derived metrics instead of the digital numbers (DN) provided by spectral sensors. If LiDAR data has been previously modelled to predict some forest parameters out of the original metrics, this information can also be inputted in the OBIA process. The potential complexity of OBIA for segmenting and classifying forest stands is considerable. Amongst the collection of segmentation algorithms and features available, the multiresolution segmentation algorithm provides favourable quality of the resulting objects according to Mauro et al. (n.d.). Watershed segmentation algorithms are especially useful for detecting tree crowns. They are based on a local
maxima approach to identify tree tops and the creation of a digital surface model (DSM) from the LiDAR point cloud. Over the inverted DSM, hydrological algorithms are executed to determine the scope of each watershed and assimilate it to a tree crown.
3 Materials and methods

3.1 Study area

This thesis is geographically based in the Chartered Community of Navarra, one of the administrative regions of Spain. In particular, the study has been focused on a group of five forests, which have developed a FMP in recent years and mostly belong to communal entities and local authorities. Physically, these forests are located in the southern part of the Western Pyrenees (Figure 2) and are groupable in two sets, according to their proximity, elevation and other characteristics: the western forests and the eastern forests. The western forests are Etxalar (F04) and Junta Bidasoa-Berroaran (F11) and the eastern ones are Ezkarroze (F05), Oronz (F12) and Uztarroze (F16).

![Figure 2. Map of Navarra (Spain) showing the location of the studied forests.](image)

The altitude of the western forests, closer to the Cantabric Sea, ranges from 300 m to 600 m, whereas the eastern ones are located between 700 m and 1200 m high, more in the context of the Pyrenean mountain range. Lithologically, western forests are settled on metamorphic rocks, mainly composed by schist and slate, which are typical materials of the axial Pyrenees. The lithology of the eastern forests, however, is dominated by sedimentary rocks, in particular by Flysch. The climate of these forests corresponds to
oceanic climate, according with Köppen classification, which is based on the empirical relationship between climate and vegetation. Oceanic climate is dominated by overcast weather, with cool summers produced by the proximity of the ocean and relatively mild winters. Forest located on the western part are enclosed within the subtype Atlantic Zone, where rain and fog is especially abundant throughout the year. The eastern forests, at higher altitude, belong to the subtype Pyrenean Zone, more continental and having colder winters than the previous subtype.

The differences in height, climate, lithology and, subsequently, soil properties, determine an important diversity in terms of forest types and species. Thus, eastern forests are mostly composed by Fagus sylvatica, Pinus sylvestris and, to a lesser extent, by Quercus humilis. Western forests, located in milder climate and smother and more accessible terrain have a wider range of species, due to a more intense human intervention. Despite most of those western forests would be populated by Quercus robur in natural conditions, a large list of introduced species is present beside the oak: Pseudotsuga menziesii, Castanea sativa, Pinus radiata, etc.

3.2 Material

3.2.1 Data

Three main data sources have been employed in this research. Firstly, vector data corresponding to the forests analysed and its corresponding attributes of forest variables; next in order, LiDAR data covering the study area and, finally, spectral data of the same area. Vector data were provided by a Spanish forestry consulting firm (Basartea SL) and were extracted from FMPs that the firm conducted in recent years (Table 1). They consist of stand delineations of each FMP, stored in polygon feature classes within personal geodatabases. The list of attributes describing stands range from 100 to 150, depending on the forest, and mainly refers to botanical, ecological, dendrometric and management characteristics. Some of them are mere descriptors with no relevance for differentiating stands whereas some others are potentially decisive for that purpose.

LiDAR data was available through the IGN’s website (http://centrodedescargas.cnig.es/). This public body provides LiDAR data of most of Spain, within the frame of the PNOA. LiDAR data is offered in compressed las files (laz format), which are a non-proprietary format developed by the American Society for Photogrammetry and Remote Sensing (ASPRS) and it is, nowadays, the standard for LiDAR data. The PNOA product consist of a 2 x 2 km tiles of point clouds with a mean density of 0.5 points/m² and an automatically produced classification, in accordance with the ASPRS standards. The date of data capture was 2012 for the study area, as shown in Table 1.

The selected source of multispectral data for this study was the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), downloaded from
https://earthexplorer.usgs.gov/. ASTER is an instrument boarded on NASA’s satellite Terra and it is composed of three subsystems providing different spatial and spectral resolution. The appropriate subsystem to analyse vegetation is the Visible and Near Infrared (VNIR) subsystem, providing 15 m spatial resolution data. It contains three bands: blue (520 nm-600 nm), red (630 nm-690 nm) and near-infrared (760 nm-860 nm). From the different ASTER products available, the ASTER Level 1 Precision Terrain Corrected Registered At-Sensor Radiance (AST_L1T) was selected. ASLT_L1T has calibrated at-sensor radiance and it has been geometrically corrected and rotated towards the north (UTM projection).

<table>
<thead>
<tr>
<th>Forests</th>
<th>Dates</th>
<th>LiDAR</th>
<th>ASTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etxalar</td>
<td>May-June 2016</td>
<td>2012</td>
<td>24/06/2015</td>
</tr>
<tr>
<td>Ezkaroz</td>
<td>April-June 2015</td>
<td>2012</td>
<td>03/08/2015</td>
</tr>
<tr>
<td>Oronz</td>
<td>June-July 2015</td>
<td>2012</td>
<td>03/08/2015</td>
</tr>
</tbody>
</table>

3.2.2 Software

The ESRI’s software package ArcGIS 10.4 was used for most of general GIS operations. Model Builder, which is a visual programming language embedded in the ArcGIS, was employed to build geo-processes involving many GIS and database operations. QGIS was used to export LiDAR metrics from csv format to shp format. LasTools is a software suite which enables a series of operations with LiDAR data and was used to unzip laz format LiDAR files, obtained from the IGN’s website, into the standard las format. The software Fusion 3.60 LiDAR was used to manipulate uncompressed LiDAR data through Fusion LiDAR Toolkit (Fusion LiDAR-LTK), which comprises a number of processing programs for DOS environment. Fugro Viewer 2.2, Cloud Compare 2.9 and ArcScene 10.0 were effectively employed for 3D visualisation. Object-based image analysis was performed with eCognition Developer 9.

3.3 Methods

The methods employed in this research work are grouped in several blocks. The first block deals with the treatment of LiDAR data to extract the information about the vertical structure of the stands, in particular, the mean height, the percentage of canopy cover and a DSM. A second section is devoted to ASTER imagery and the study of the NDVI within the different species and vegetation groups. Both LiDAR-derived and ASTER-derived data are the basis for the third block, focused on OBIA and the automatic delineation of forest stands. The fourth part of this section describes the accuracy assessment of the executed delineation, in terms of its morphological outcome. Finally, the procedures for an adjacency analysis of the forest stands are explain. This part of the methods section
brings an essential insight over the results and, especially, over the accuracy assessment.

3.3.1 Analysis of LiDAR data

The workflow of LiDAR data processing is illustrated in Figure 3. In this section all processes involved in the extraction of forest stand structural parameters from LiDAR datasets are described. Overall, a DEM and a normalised DSM were created, along with a tree segmentation, so that parameters of crown canopy cover and mean height could be estimated.

3.3.1.1 Preliminary processing of LiDAR data

As a first step, LiDAR data were decompressed using Las Tools into the standard las format whereas the rest of processes were run using Fusion LiDAR LTK. LiDAR data is delivered by the IGN in 2 x 2 km² tiles, representing between 3 and 4 million points per tile. As the studied forests cover between 2 and 7 tiles each and the threshold for Fusion to avoid instability is 20 million points (McGaughey, 2016), a clipping action per tile was performed to discard unnecessary data. This operation was executed using the boundary of the forest stands as a clipping shape over the point cloud. The processing of LiDAR data produces important distortions on the edges of the dataset, so the extent of the clipping shape was previously enlarged with a buffer of 100 m. Afterwards, the clipped portions were merged into one single file.

The LiDAR product used in this study contained outliers, which might have been produced by birds or some kind of error during the data capture. Therefore, it was necessary to remove these outliers beforehand; otherwise, the presence of abnormal values would have altered subsequent outcomes. For outlier removal, Fusion utilizes an algorithm based on a user-defined window size and computes the mean elevation and standard deviation at each resulting cell. Later, it establishes a distance range around the mean elevation, derived from the product of standard deviation and a user-defined parameter, and preserves all returns within that range. After testing several parameters, a window size of 20 m and a standard deviation multiplier of 2 were selected.

3.3.1.2 Creation of a LiDAR-derived DEM

Calculating the structure of the point cloud in relation to the ground is what brings useful information about the vegetation’s structure and, eventually, leads to a differentiation of forest stands. The process by which the initial height values are converted into height values over the ground is known as a normalisation of the point cloud. This normalisation implies the creation of a correct DEM, as a means to have the right values of LiDAR returns over the ground. DEM creation has two steps, namely, the filtering of returns classified as ground points, and the creation of a grid from those filtered points. Fusion’s filtering algorithm is based on linear prediction (Kraus & Pfeifer, 1998 in McGaughey, 2016) and involves a series of iterations, where intermediate virtual ground surfaces are generated, and increasingly reliable DEMs produced. Initially, all points are given the same weight and a first surface is produced. This first virtual surface is likely to be
between the real ground and the canopy. Then, points are weighted to produce a second virtual surface, according with some user-defined parameters. According with equation (1), the shift value $g$ represents a distance under the virtual surface and all points below the height represented by $g$ get the maximum weight for the next iteration. The parameter $w$ represents an interval around the height represented by $g$ having an influence (weight >0) in the generation of the next virtual surface. Points being over the height represented by $g+w$ have weight 0 and, therefore, are discarded for future iterations. Parameters $a$ and $b$ define the steepness of the weight function.

Figure 3. Flow chart of LiDAR data processing.

McGaughey (2016) indicates that default values provided by Fusion produce good results in point cloud densities over 4 points/m$^2$. For lower densities, this author states that some experimentation should be undertaken to adjust the parameters. In this research, point density is 0.5 points/m$^2$ in average and the parameter $w$ has been modified to 2.0. Spatial resolution for intermediate surfaces was fixed to 1 m. Automatic classification contained in the LiDAR product was not used to detect ground points as it contained many bumps corresponding to misclassified vegetation elements. Once ground points were detected, a gridded surface in dtm format was created, using the previously generated ground points as data source. The algorithm used in Fusion for this task takes into account the mean height of the points classified as ground in the last stage. The resulting DEM was a
necessary step for the normalisation of the point cloud, that is to say, for the expression of point heights in relation to the ground instead of the original absolute heights.

\[
P_i = \begin{cases} 
1 & v_i \leq g + w \\
\frac{1}{1 + (a(v_i - g))^p} & g < v_i \leq g + w \\
0 & g + w < v_i
\end{cases}
\]

(I) Function to compute weights to determine ground LiDAR points (McGaughey, 2016).

3.3.1.3 Extraction of LiDAR metrics

LiDAR metrics are collections of descriptive statistics calculated over the point cloud in relation with a specific grid size. Examples of metrics derived from LiDAR are maximum height, mean height, standard deviation of heights, total count of returns, count of first, second, etc. returns, percentile values (from 1 to 99), etc. When these metrics are calculated over the normalised point cloud, the statistics refer to the height of vegetation over the ground, instead of the absolute heights. LiDAR metrics were calculated from the corrected point cloud and the DEM. The two user-defined parameters for this operation were the grid’s spatial resolution and \textit{heightbreak}, whose value indicates the height at which the canopy cover is calculated. \textit{Heightbreak} works as a threshold height, taking into account the first returns over an under the specified threshold. As an example, 60\% of first returns over the pre-defined \textit{heightbreak} would be interpreted as 60\% of crown canopy. Therefore, the value for \textit{heightbreak} should be set as the minimum height for what it can be considered as tree crowns. An additional input for this process is the \textit{minimum height criterion}, which specifies the height above ground level from which metrics are calculated. It must be defined by a user-dependent expert knowledge and, depending on the specific case, may be set between 2 and 7 m (Eysn et al., 2012). Both \textit{heightbreak} and the \textit{minimum height criterion} represent biological characteristics of a forest which may be highly variable, even within a specific forest. Nevertheless, a compromise value should be fixed, as the most common situation for a given range of forest types. In this case, a value 3 m, for both \textit{heightbreak} and the \textit{minimum height criterion} were fixed. The outcome of this operation was a set of text files in \textit{csv} format, one of which was the file containing the statistics of heights concerning the focus of the present analysis.

3.3.1.4 Digital surface model and tree segmentation

A normalised DSM was generated in order to have a 3D representation of the forest at 1 m resolution. This operation was done with an algorithm which outputs a DSM from the first returns of the point cloud. This DSM is normalised, that is to say, performs a subtraction between the non-normalised DSM and the previously generated DEM. The algorithm to create the DSM solves the problem of possible holes on the DEM by filling them with a distance-weighted interpolation method.
A watershed segmentation of the normalised DSM was done to extract the segments representing tree crowns. This algorithm detects differentiated trees and models segments around every local maximum. It is based on a hydrological principle consisting in transforming the DSM’s local maxima into local minima and simulating a flooding process. Then, when water spills out from a concavity the level of the surface delineates a tree corresponding with the local minima. A threshold height for object segmentation was set at 3 m, in accordance with previous steps. The output does not necessarily identify every single tree, unless trees are sufficiently sparse. Dominated trees are likely to be included in segments containing a dominant or codominant tree. Two vector layers, one representing the top point of every tree or clump of trees and their height value, and a polygon vector layer representing their crown projection composed the output. The stands’ mean height participating in the OBIA was estimated through the calculation of the mean height of points generated at this stage. Figure 4 shows the result of a tree segmentation process as well as the canopy model of one of the studied forest.

![Figure 4](image)

**Figure 4.** DSM (A) and watershed segmentation (B) of an area of forest F16.

Note: Digital surface model at 1 m resolution. The image is displayed at a vertical scale of 0.6. In the watershed segmentation, segments represent trees or tree clusters and their maximum height. DSM set at 1 m spatial resolution and minimum height set at 3 m.

### 3.3.2 Analysis of NDVI

An analysis of the spectral characteristics of the main species involved was carried out to see up to what point these species were likely to be differentiated using ASTER VNIR bands. NDVI was generated for the study area as well as the mean value per stand, through a zonal statistics operation. Some stands were rejected from the analysis when their characteristics were likely to produce distortion in the result. With regard to the size and shape of stands, only polygons over 2 ha and a low perimeter ratio (perimeter²/area<40) were considered. This constraint was defined to reduce the boundary effect of peripheral pixels with distorting spectral values. As per the attributes of the stands, only those defined as monospecific and a canopy cover over 50% were preserved. On the one hand, the mixture of species would not allow a species-based NDVI analysis. On the other hand, a low canopy cover would have produced NDVI values influenced by the lower vegetation and the ground. From the resulting sample, stands represented by residual species, mainly allochthones, were also discarded. The mean values of NDVI for different
species and group of species were studied through an analysis of variance (ANOVA) and a least significant difference (LSD) test.

### 3.3.3 Object-based image analysis (OBIA)

OBIA was executed with six layers: the three VNIR ASTER bands, and three layers derived from LiDAR: the canopy model, the raster of canopy cover extracted from LiDAR metrics and the raster of mean height extracted from the watershed segmentation. The OBIA comprised two main steps, namely, multi-resolution segmentation and spectral difference segmentation. A final generalization was fixed in the rule set to fuse residual segments, resulting from the previous steps, with those which were enclosing them totally or partially.

Multi-resolution segmentation is a bottom-up segmentation algorithm initiated with single pixels, and objects are recursively merged with adjacent ones on the basis of minimising the increment of $n \cdot h$ ($n$ being the size of the object and $h$ the so-called coefficient of heterogeneity) (Mauro et al., n.d.). Three parameters are involved in this algorithm: scale, compactness and shape. Scale refers to differences in spectral values within segments and affects the resulting size of them. Shape weights the importance of the morphology of the segment in relation with its spectral value and compactness controls the density of the shapes. Multi-resolution segmentation was done over the canopy model (1 m resolution), since it has a better spatial resolution than ASTER layers the two other LiDAR-derived rasters.

Spectral difference segmentation is a process in which segments are merged based on the spectral values they contain. A weighting mechanism is implemented to deal with objects having various layers, so that some specific layers may have a bigger influence than others in the algorithm’s outcome. Spectral difference segmentation was applied over the result of multi-resolution segmentation, using the six input layers, testing different weight combinations.

A pilot forest (F05) was used to test the parameters involved in OBIA. With respect to the multi-resolution segmentation process, scale, compactness and shape were tested at different degrees in order to establish a range of values compatible with the actual delineation provided by the FMP. In relation to the spectral difference segmentation process, different weights were checked for the 6 variables considered, with identical purpose. The results of these trials were introduced in a delineation assessment procedure which is explained in a later section. As a result of this assessment, one of the tested combinations of parameters and weights was chosen as the most suitable and it was then applied to the rest of forests.

### 3.3.4 Analysis of forest stands

The characteristics of the five studied forests provided by the FMPs were analysed to
understand their intrinsic characteristics and the topological relations amongst them. Ultimately, the nature and dimension of such relations are the basis for forest stand delineation. This analysis was crucial to evaluate the performance of the OBIA in terms of whether stands were highly or poorly differentiable.

3.3.4.1 Characteristics of stands

First of all, a selection was done to eliminate attributes considered as irrelevant for the study. The used attributes were canopy cover, mean height, basal area and tree species composition. A general check was done afterwards to detect stands with missing data, errors or inconsistencies. After this filtering the data structure was transformed to adapt it to the purpose of this study, as the original values were provided at species level and stand-wise values were needed.

Simplified categories in terms of species composition, were established to achieve this transformation. This classification was done to evaluate the performance of ASTER in discriminating the two main groups of species: conifer and broad-leaved species. Two broad categories were set to differentiate conifer and broad-leaved species when all main species in a stand belonged to one of both groups. These two categories were subdivided into a monospecific class (when a single species represented more than the 85% of the stand’s basal area) and a plurispecific class in the rest of cases. A category of plurispecific mixed species was added to depict the stands with several species belonging to both conifer and broadleaved groups. A specific category was set for stands only covered by grass, shrubs or small trees under 3 m height. Finally, a class of undetermined content was established to include stands where original data did not allow any systematic or clear classification. A numeric code was assigned to these categories in order to detect species-wise differences amongst stands in a further step. Species classification and codes are shown in Figure 5.

Two additional attributes were calculated in relation with the species composition: the main species per stand and its percentage over the whole tree population. The proportion of basal area per species was used to determine both values, since this parameter is highly correlated with crown projection, which is the target of spectral sensors. The attribute Canopy cover was kept untouched because it is a stand-wise feature, basal area was summed up and mean height was transformed into single values, using the percentage of

![Figure 5. Classification of the main groups of species into numeric codes.](image-url)
basal area as a weight.

3.3.4.2 Adjacency analysis

An adjacency analysis of the FMP stand delineation was accomplished to systematically determine the main differences between adjacent stands, according to the data provided by existing forest management plans. Ultimately, this analysis was conceived as a tool to see up to what point the automatic delineation proposed and the actual differences in dendrometric parameters of contiguous stands were related. It is expectable that important differences of such parameters between two adjacent stands should lead to a better fitting between the limit drawn by the automatic delineation procedure and the one delineated in the FPM. Likewise, stands with similar dendrometric characteristics are expected to present a worse fitting between both delineation methods. This analysis was made through a model design in the ArcGIS Model Builder environment and its simplified flowchart is shown in Figure 6.

Figure 6. Flowchart of processes involved in the adjacency analysis model.
Figure 7. Example of adjacency analysis of forest F05.

Note: Points represent forest stands, according with FMPs, and lines represent adjacency. Upper diagram’s point sizes symbolise basal area and lower one’s represent species groups. In both cases, line thickness denotes differences between pairs of values.
In particular, mean height, canopy cover, coded species composition and basal area were compared through the geographical model. Initially, this model detected, for every single stand, a list of their neighbouring stands. Thus, a table of connected stands was created and both ends of each connection were linked to their respective attributes. Consequently, differences between the attributes of connected stands were susceptible of comparison. Figure 7 illustrates the outcome of this analysis with two examples, where nodes represent the attributes of each stand and lines represent the existing connections between them and the value of the differences for a particular attribute.

3.3.4.3 Delineation assessment

Tiede et al. (2004) stated that, in terms of accuracy assessment, geometrical fitting is a problematic issue and no standardised method was available. To overcome this methodological gap, a mechanism was designed to quantitatively assess the geometrical fitting between OBIA segmentation and the FMP delineation. The starting point of this mechanism, which is area based, is an intersection of the stands representing the ground truth with the segments produced in OBIA. Conceptually, this mechanism is built on two geometrical facts: the contribution of each overlapping segment over a reference stand and the exclusiveness each segment in relation with the stand. The first concept describes how well a particular stand is defined by its main overlapping segment. The second concept refers to how exclusive to a reference stand, the overlapping segments are. Figure 8 illustrates these two concepts.

![Figure 8. Contribution and Exclusiveness of a segment over a reference stand.](image)

Note: A, B and C represent stands which are, respectively, highly, poorly and entirely represented by the overlapping segment. D, E and F represent segments which are, respectively, little exclusive, very exclusive and totally exclusive of the reference stand.

More in detail, the contribution index corresponds to the proportion of a stand, which is covered by the main overlapping segment. The exclusiveness index for a stand is the
proportional area of overlapping segments falling inside the stand, weighted by their contribution. Both concepts are expressed as a percentage and the product of contribution and exclusiveness would produce a fitting index at stand level. These indices were calculated for both stands and forests. At forest level, indices were weighted by the surface of each stand. Inner homogeneity is also an indicator of well fitted segments, as stands are envisaged to contain homogenous patches of forest. Therefore, a comparison of standard deviation for mean height, canopy cover and NDVI was done for both stands and segments.
4 Results and discussion

In this section the main results of this research are shown as well as the central discussion of such results. First of all, the analysis of the most relevant species of the area is exposed in relation with the NDVI obtained in different stands. The discrimination of species or groups of species by NDVI is a preliminary, essential step to conclude which species can be differentiated and up to what point. The second part of this section deals with the results of stand delineation through object-based image analysis, where multispectral data (regarding species composition) and LiDAR data (regarding forest structure) are combined to obtain workable layouts of the stand composition of the forests.

4.1 Analysis of NDVI

4.1.1 Results

Mean NDVI was calculated for 187 stands, representing the 6 main species in the study area. Values for stands populated by conifer species (*P. sylvestris*, *P. nigra* and *A. alba*) presented lower values than stands of broadleaved trees. Table 2 shows the stands analysed, grouped by species, with the mean NDVI per group. Standard deviation was calculated for each group of stands to show the variability within groups and, hence the likelihood of an overlapping effect between species.

![Figure 9. Mean NDVI and standard deviation for 6 species in 187 sampled stands](image)

A one-way ANOVA was performed to evaluate whether there was an effect of the species as a factor over the NDVI. In this case, an F-test returned an F-statistic of 116.5, a value far higher than the 2.21, which is the critical F-value for a level of significance (α) of 5%. The variation explained by the factor is much higher than the experimental error, which indicates the existence of such effect. The same test was executed over the same stands classified in two categories: broadleaved and conifer species. Similarly, the value of the
F-statistic (566.6) was high enough to confirm the significant effect of these two categories over the NDVI.

The ANOVA analysis was followed by a mean separation using Least Significance Test (LSD) over the 6 species analysed, to evaluate possible significant differences in the mean NDVI of each species. The LSD test showed, for a level of significance ($\alpha$) of 5%, that the null hypothesis, by which means are equal, was to be rejected in most of combinations. Conifers and broadleaved species showed significant difference amongst them in terms of mean NDVI. However, this differences were not found amongst the species within each group, except for \textit{P. sylvestris and A. alba}. In the case of these two conifers, the hypothesis of equal mean NDVI was rejected (Table 2).

\textbf{Table 2. Sampled stands for the 6 species analysed.}

Note: Stand values are grouped by dominant species. Means with different letter are statistically different (p<0.05).

<table>
<thead>
<tr>
<th>Groups</th>
<th>Surface (ha)</th>
<th>Count</th>
<th>Mean NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{Pinus sylvestris}</td>
<td>318.6</td>
<td>77</td>
<td>0.35805</td>
</tr>
<tr>
<td>\textit{Pinus nigra}</td>
<td>101.8</td>
<td>15</td>
<td>0.36779</td>
</tr>
<tr>
<td>\textit{Abies alba}</td>
<td>25.4</td>
<td>5</td>
<td>0.38564</td>
</tr>
<tr>
<td>\textit{Quercus robur}</td>
<td>70.5</td>
<td>16</td>
<td>0.44811</td>
</tr>
<tr>
<td>\textit{Castanea sativa}</td>
<td>38.1</td>
<td>6</td>
<td>0.44982</td>
</tr>
<tr>
<td>\textit{Fagus sylvatica}</td>
<td>585.8</td>
<td>68</td>
<td>0.45188</td>
</tr>
</tbody>
</table>

\textbf{4.1.2 Discussion}

Combination of ASTER VNIR bands can mostly differentiate conifers and broadleaved species as per the results of the NDVI analysis for the main species in the area. The only species which could be ascribed to either group on statistical grounds was \textit{Abies alba}, as it can be seen in Table 2. The value of mean NDVI for \textit{A. alba} is closer to those of pine trees than to broadleaved species and it is the highest for the three conifers analysed. The hypothesis of equal mean NDVI cannot be rejected for \textit{A. alba} in relation to neither \textit{P. nigra} nor the broadleaved species. This irregularity might have some connection with the fact that \textit{A. alba} is the species with a smaller sampled area (2.2% of the sampled area) and makes it more likely to be affected by some sort of bias.

Conifer forests are mainly represented by \textit{Pinus sylvestris} (71.5% of the area of sampled conifers forests) and \textit{Fagus sylvatica} reflects a similar situation in its forest group (84.4% of the sampled area of broadleaved forests). Thus, both species are the most abundant ones in their respective groups, but also in the overall surrounding area. \textit{P. sylvestris} and \textit{F. sylvatica} also produce the most extreme values for NDVI, within the species list. This circumstance strengthens the idea by which both groups can be well differentiated by ASTER VNIR bands in the majority of the surveyed land.

The utility of ASTER VNIR bands for differentiating species within conifers or
broadleaved groups is more limited. Consequently, this data source is suitable for discriminating populations of trees belonging to either group but not to determine which specific species a given stand is composed by. The fact that mixed forests are a common situation also reduces the scope of ASTER VNIR bands for predicting a detailed map at species level. A similar assumption is given by Diedershagen et al. (2004) for forests in Germany, where mixed communities predominate throughout the country’s landscape.

4.2 Stand delineation through object-based image analysis

4.2.1 Results

Segmentation through OBIA produced a higher number of stands in all forests than the reported ones by the FMPs. The ratio between the number of stands produced by OBIA and the FMP range from 1.4 to 2.4. In accordance with this values, the overall mean area produced by OBIA was 2.68 ha whereas this value was 4.81 ha in the FMP. In general, lower values for standard deviation of stands’ areas was found in OBIA with respect to those of the FMPs. Table 3 shows the summarised results of stands’ areas produced in OBIA and the same statistics for the FMPs stands.

<table>
<thead>
<tr>
<th>Forest</th>
<th>FMP Stands</th>
<th>OBIA Stands</th>
<th>FMP Area (ha)</th>
<th>OBIA Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>F04</td>
<td>59</td>
<td>108</td>
<td>0.16</td>
<td>53.33</td>
</tr>
<tr>
<td>F05</td>
<td>42</td>
<td>78</td>
<td>0.50</td>
<td>18.36</td>
</tr>
<tr>
<td>F11</td>
<td>130</td>
<td>181</td>
<td>0.20</td>
<td>70.16</td>
</tr>
<tr>
<td>F12</td>
<td>61</td>
<td>88</td>
<td>0.14</td>
<td>33.74</td>
</tr>
<tr>
<td>F16</td>
<td>40</td>
<td>99</td>
<td>0.51</td>
<td>26.02</td>
</tr>
<tr>
<td>Mean</td>
<td>0.30</td>
<td>0.44</td>
<td>40.32</td>
<td>4.81</td>
</tr>
</tbody>
</table>

The 15 treatments tested in OBIA for the pilot forest F05 and the resulting fitting indices are shown in Table 4. The highest fitting indices were obtained using scale 4 in the multi-resolution segmentation process. Amongst these results, the highest fitting index was 38.4 and corresponded to treatment 4_121211, where the NIR band and the canopy model had double weight with respect to the rest of factors. Figures 10 and 11 show the delineation of forest F16 produced by OBIA using the treatment 4_121211. Stand 27, for instance, appears well delineated, so contribution and exclusiveness indices are high and, consequently the fitting index is high too. Two visible examples of stands with contrasted indices are stands 4 and 20. Stand 4 appears subdivided in different segments, which are contained in the stand itself, so the exclusiveness index is high, unlike its contribution index. In contrast, stand 20 appears enclosed in a big segment, so the contribution index is high but the exclusiveness is low. Table 5 shows the three indices, using treatment 4_121211, for the five studied forests. The fitting index for those forests ranges from 30.2
Table 4. List of OBIA treatments applied to forest F05.

Note: The table shows the different weights used in the spectral difference segmentation and the resulting fitting indices.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Scale</th>
<th>Spectral difference segmentation (weights)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4_111111</td>
<td>4</td>
<td>Band R 1</td>
</tr>
<tr>
<td>4_111211</td>
<td>4</td>
<td>Band R 1</td>
</tr>
<tr>
<td>4_121111</td>
<td>4</td>
<td>Band R 1</td>
</tr>
<tr>
<td>4_121211</td>
<td>4</td>
<td>Band R 1</td>
</tr>
<tr>
<td>4_121211</td>
<td>4</td>
<td>Band R 1</td>
</tr>
<tr>
<td>5_111111</td>
<td>5</td>
<td>Band R 1</td>
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<td>5</td>
<td>Band R 1</td>
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<td>5_121111</td>
<td>5</td>
<td>Band R 1</td>
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<tr>
<td>5_121121</td>
<td>5</td>
<td>Band R 1</td>
</tr>
<tr>
<td>5_121211</td>
<td>5</td>
<td>Band R 1</td>
</tr>
<tr>
<td>6_111111</td>
<td>6</td>
<td>Band R 1</td>
</tr>
<tr>
<td>6_111211</td>
<td>6</td>
<td>Band R 1</td>
</tr>
<tr>
<td>6_121111</td>
<td>6</td>
<td>Band R 1</td>
</tr>
<tr>
<td>6_121211</td>
<td>6</td>
<td>Band R 1</td>
</tr>
<tr>
<td>6_121211</td>
<td>6</td>
<td>Band R 1</td>
</tr>
</tbody>
</table>

Figure 10. Comparison between the delineation of a FMP and OBIA in forest F16.

Note: The delineation of the FMP of forest F16 is displayed in black lines and the delineation produced by the treatment 4_121211 in OBIA is displayed in colours.
Table 5. Fitting indices obtained for the five studied forests.

<table>
<thead>
<tr>
<th>Indices</th>
<th>F04</th>
<th>F05</th>
<th>F11</th>
<th>F12</th>
<th>F16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contribution</td>
<td>46.8</td>
<td>63.7</td>
<td>63.9</td>
<td>53.8</td>
<td>62.9</td>
</tr>
<tr>
<td>Exclusiveness</td>
<td>65.1</td>
<td>60.3</td>
<td>51.8</td>
<td>56.0</td>
<td>66.9</td>
</tr>
<tr>
<td>Fitting</td>
<td>30.5</td>
<td>38.4</td>
<td>33.1</td>
<td>30.2</td>
<td>42.0</td>
</tr>
</tbody>
</table>

The comparison of standard deviation for CC, Hm and NDVI is shown in Table 6. No important differences are observed in most of cases. However, it must be underlined that segments have lower values than stands in all cases except for CC in F04 and F11 and NDVI in F04.

Table 6. Mean values for CC, Hm and NDVI standard deviations for stands and segments.

<table>
<thead>
<tr>
<th>Forest</th>
<th>CC</th>
<th>Hm</th>
<th>NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Segments</td>
<td>Stands</td>
<td>Segments</td>
</tr>
<tr>
<td>F04</td>
<td>18.8</td>
<td>18.7</td>
<td>3.52</td>
</tr>
<tr>
<td>F05</td>
<td>13.0</td>
<td>13.2</td>
<td>3.41</td>
</tr>
<tr>
<td>F11</td>
<td>18.0</td>
<td>17.1</td>
<td>3.01</td>
</tr>
<tr>
<td>F12</td>
<td>13.9</td>
<td>15.1</td>
<td>3.20</td>
</tr>
<tr>
<td>F16</td>
<td>15.2</td>
<td>16.0</td>
<td>2.89</td>
</tr>
</tbody>
</table>

The adjacency analysis of the FMP brings, for every pair of connected stands, the differences in Hm, CC, BA and species composition. A summary of the mean value of these differences per forest can be observed in Table 7. Forest F16, which has the highest fitting index, also presents the highest differences between adjacent stands for CC, BA and species composition, but not for the Hm. The amount of connections between
adjacent stands of the five studied forests is 1606 but not all of them have been included in the results due to problems of consistency in the original data, as mentioned in the Method section. Percentages of valid connections differ from one parameter to the other. Mean height and basal area were comparable in 70% of connections, canopy cover in 77% and species composition in 81%.

**Table 7. Mean difference values between adjacent stands.**

Note: Mean differences (between adjacent stands) of 3 forest parameters and species composition, according with the classification described in Figure 5.

<table>
<thead>
<tr>
<th>Forest</th>
<th>CC (%)</th>
<th>BA (m²/ha)</th>
<th>Hm (m)</th>
<th>Species</th>
<th>Fitting index</th>
</tr>
</thead>
<tbody>
<tr>
<td>F04</td>
<td>18.68</td>
<td>9.40</td>
<td>6.66</td>
<td>3.00</td>
<td>30.5</td>
</tr>
<tr>
<td>F05</td>
<td>8.63</td>
<td>20.00</td>
<td>5.83</td>
<td>3.59</td>
<td>38.4</td>
</tr>
<tr>
<td>F11</td>
<td>16.7</td>
<td>12.26</td>
<td>6.11</td>
<td>2.06</td>
<td>33.1</td>
</tr>
<tr>
<td>F12</td>
<td>6.5</td>
<td>12.81</td>
<td>4.54</td>
<td>2.45</td>
<td>30.2</td>
</tr>
<tr>
<td>F16</td>
<td>25.09</td>
<td>23.72</td>
<td>6.06</td>
<td>4.00</td>
<td>42.0</td>
</tr>
</tbody>
</table>

4.2.2 Discussion

The treatment which gave a better result in relation with the delineation assessment indices was the treatment 4_121211, which involves a higher weight of the NIR band and the CM in OBIA. In relation with the NIR band, this fact is endorsed by the higher importance of the NIR reflectance to discriminate vegetation types compared with the red and green wavelengths. The CM was also found to be a relevant factor to reach a well-fitted segmentation compared to Hm and CC. The reason for this is not conclusive but might be connected to the much higher spatial resolution of the CM layer (1 m). The layers Hm and CC had a spatial resolution of 20 m which involve a higher generalisation and this could have affected the boundaries of segments. Actually, the concepts of CC and Hm are meaningless if applied to small areas so a higher spatial resolution of them would have been aberrant in forestry terms.

The 15 different combinations over the pilot forest systematically derived in higher values for the contribution index than the exclusiveness index (table 4). This unbalance is a consequence of the scale parameter in the multiresolution segmentation. The smaller the segments produced the more likely to have a higher exclusiveness index because the probability for a segment to completely fall inside a delineated stand is higher. Likewise, the contribution of an increasingly smaller segment to a given stand is also increasingly smaller, due to the fact that only a little portion of the segment is representing the stand. On the contrary, bigger segments produced by a bigger scale parameter are likely to have higher contribution and lower exclusiveness. This can be seen in Table 4, where the average contribution index for treatments with scale 4, 5 and 6 were, respectively, 62.96, 71.54 and 78.3. Also in accordance with the previous explanation, the average exclusiveness index for the same treatment groups were 58.68, 48.46 and 40.26. Thus, the variation of the scale parameter increases one index while simultaneously decreasing the other. The selection of the best fitting treatment was done, however, considering the...
The fitting index is not the two indices which originate this final index. The fitting index takes higher values when exclusiveness and contribution indices are closer between them, as it can be seen in Table 4.

Figure 12. Delineation produced by FMPs and corresponding fitting indices of 5 forests.
In relation with the inner heterogeneity of the segments derived from the OBIA, two points can be appreciated, even though no strict statistical analysis has been done over these values. The first one is that CC, Hm and NDVI standard deviations do not differ much between segments and stands. This might indicate that both segments and stands have been produced considering these parameters in a similar way. The second remark is that segments produced by OBIA show higher homogeneity than delineated stands in most of cases. The reason for this result cannot be asseverated without a deeper analysis. One cause might be related to the fact that segments are, in average, smaller than stands, but another feasible (though not excluding) reason could be related to a better fitting of segments in relation with dendrometric features of the forest.

The standard deviation of the distribution of areas (table 3) is higher for the FMP than for OBIA. That suggests that some stands in the FMP have been enlarged or shrunken in relation with what it could be expected. Existing physical factors such as protected wildlife, pests and diseases, timber quality, etc., are unnoticeable factors for remote sensors but sometimes are reflected in the FMP delineation, enlarging or dividing stands beyond dendrometric grounds. Furthermore, the future planning of certain areas, such as new open areas for grazing or planned firebreaks may be reflected in the stand delineation, even though they have not been implemented. Figure 14 shows how stand 19 was delineated in the FMP as a single stand, whereas automatic delineation divided it into two, more according with the real state of the vegetation. In this case, simplification was rightly applied in the FMP, as the aim of that stand was to act as a firebreak, as reported by the FMP.
5 General discussion

As mentioned before, ASTER VNIR bands can differentiate conifers and broadleaved species using the NDVI approach for the most relevant species in the area. However, the results of using different bands separately in OBIA was better than using NDVI, so the former option was kept for the test combinations, shown in Table 4. Dechesne et al. (2017) also finds, after using several vegetation indices, that separate bands are more explanatory in forest stand segmentation.

When relatively small, homogeneous stands composed by either conifers or broadleaved trees alternate, information provided by ASTER becomes more effective for stand delineation. Forests F12 and F16 represent two extreme examples in this aspect: whereas F16 spatially alternates both groups, F12 has many stands of each group clustered together, apart from having much of the area covered by plurispecific mixed stands (Figure 13). This fact probably contributes to explain a better overall performance of OBIA in F16 (Table 5).

In relation with the spatial resolution of ASTER VNIR bands, two limitations have been observed. The first one concerns the limited suitability of such resolution for precisely delineating stands. This disadvantage shows up when trying to execute a multi-resolution segmentation using ASTER bands (15 m resolution) along with the 1 m resolution canopy model. The outcome of such combination produced segments with unnatural shapes, which would have produced undesirable boundaries. The second limitation is in relation with forests presenting a mixture between conifers and broadleaves. A standard 0.5 m NIR orthophoto would have likely produced a more satisfactory performance, allowing the differentiation and characterisation of single trees in the dominant and co-dominant strata. ASTER was chosen as the source for spectral data because freely available NIR orthophotos are compressed and NDVI cannot be extracted from them. However, since the performance of single bands was better than NDVI in OBIA, replacement of ASTER by 0.5 m NIR orthophotos seems a good option.

The resulting number of stands after applying the treatment 4_212211 (Table 4) exceeds the number of real stands of the FMPs. In relation to this point, there are three possible strategies to follow in the segmentation process. The first one is trying to adjust rule sets in OBIA outputting a number of stands that approximately fits what a manual delineation would produce. The second and third ones are over-segmenting and under-segmenting the forest deliberately. Whereas the first option might seem the best one, in terms of practical management, a certain degree of over-segmentation provides some advantages. Over-segmentation creates a higher number of boundaries to be retained after the field inspection and, therefore, less new boundaries need to be delineated in the field, which is a complicated task. In contrast, this approach brings a higher number of ‘false’ boundaries which should be removed, eventually. Operationally, it is easier to evaluate two adjacent segments in the field and conclude that they are as similar as to be merged, than inspecting
one heterogeneous segment and delineate where the inner boundaries should be placed. The proposed over-segmentation should not be excessive because many segments composing a real stand would also be counterproductive.

Figure 13. Classification of stands in F12 and F16 according with the main group of species.

Figure 14. Delineation reflecting the objective of the FMP instead of the actual vegetation.

Note: Stand 19 is delineated in the FMP (black lines) reflect the objective of having a cleared area to prevent the propagation of forest fires. OBIA segmentation (red lines) reflects the actual vegetation.

Manually-delineated forest maps over orthophotos have limited quality and are susceptible to subjectivity (Eysn et al., 2012). Therefore, manual delineation provided by FMPs cannot be considered as ground truth, since they include abstraction and subjectivity (Tiede et al., 2004) and may include misinterpretation and gross errors, even after field inspection. Several delineations over a specific area, then, might be equally
valid, if justified, when evident, sharp differences are not present, as suggested by González et al. (2004). The method proposed in this thesis to compare OBIA segmentation with stands from the FMPs cannot be considered, then, as an accuracy assessment. The fitting index, which is built upon the contribution and exclusiveness indices, is a mere index to measure the geometrical coincidence of both sources of polygons but it is not a comparison with the ground truth. The fitting indices found for the studied forests are rather low (Table 5) but they have to be contextualised in the previous comments. Figure 15 shows a good performance of automatic delineation where photo-interpretation cannot set a clear line based on some forest parameters differences. The main difference between stand 22 and stand 24 is the height (7 m), which is perceptible in the CM but not so much on the orthophoto. Consequently, the extent of stand 22 has been doubtfully prolonged to the south in the manual delineation.

![Figure 15. Manual and automatic stand delineations in an area of forest F16.](image)

Note: Left: orthophoto of 0.5 m spatial resolution with the manual stand delineation provided in the FMP. Labels indicate the code of the FMP stands along with the reported canopy cover and mean height. Right: same area with the CM as background and the manual (black) and automatic (red) delineations.

The results of the adjacency analysis revealed a trend, by which important differences amongst adjacent stands involve higher values for the fitting index. This effect is related to the landscape heterogeneity amongst stands but not within stands. So the higher the heterogeneity amongst stands and the lesser their inner variability, the more clearly fitting delineations. However, this kind of sharp divisions are also more suitable for correct photo-interpretation. Thus, it is in the more complex and mixed landscapes where OBIA can provided an added value in relation to photo-interpretation.

Scale has multiple definitions, some of which seem to be contradictory (Jiang & Brandt, 2016). The concept of scale in this study is narrowly related to the concept of map generalization. It is influenced by the spatial resolution of the data sources (LiDAR and ASTER) and the managerial purposes the final outcome is aimed at. Thus, a forest stand delineation where boundaries were changing directions at a centimetre level would be considered as excessively detailed and useless under a practical point of view. On the contrary, forest stands composed by too large segments would result in an excessive simplification which would have pernicious consequences in managing the forest. As it was said before, data sources also play an important role in determining scale, understood
as image resolution. The first decision to be made was the spatial resolution to be employed with ASTER images and the LiDAR-derived models. ASTER resolution was kept as 15 m as it is larger than the detail pursued in a standard forest stand delineation. LiDAR-derived canopy model was used for the multiresolution segmentation, which was executed at 1 m resolution and the scale, compactness and shape factors were probed, according with acquired own experience, on a trial and error basis. The implications of this procedure in relation with the scale are an outcome which fits the detail of forest delineations made for FMPs.

The problem of finding an appropriate method for comparing overlapping polygons in the literature, so that real stands and OBIA-produced segments could be compared, fueled the option of stating a method (the fitting index method), created on purpose for this study. The fact that such method has not been found in the literature does not necessarily imply that it has not used before, but rather that the scope of this study has not allowed a deeper research on this issue. The feature agreement statistic of modelled and actual (Raber et al., 2007, in Brandt & Lim, 2016) consists of finding the percentage of the overlapping portion of both modelled and actual areas (segments and stand, by analogy). The larger the overlapping area with respect with the total area, the better fitting or agreement. This method solves the problem of assessing the agreement of overlapping polygons in a simple context. However, it does not fulfil the necessities for this study, where modelled polygons (segments) do not correspond one to one to the original forest stands. As an example, one original stand sometimes contains multiple modelled polygons and some modelled polygons are usually overlapping different stands at the same time. This complex environment required a method considering the whole population of polygons in the way it has been described in the Method section. A detailed, simplified example of this method is shown in the Appendix.
6 Conclusions and future work

In this section some conclusions are stated, according with the obtained results and further discussion. The following conclusions, as a whole, ought to be read considering the practical aim for which this study was conceived. Therefore, issues such as data availability, cost and the current context of medium-small forestry Spanish firms are primary points which are important to correctly interpret this section. Apart from the conclusions themselves a separate subsection of future work has been included too. In that subsection some further strategies are pointed out as possible improvements to contribute to forest stand delineation through remote sensing.

6.1 Conclusions

Low-density LiDAR data produced DSMs with enough accuracy as to delineate forest stands with more detail than the manually-produced ones. Time lapse between the data capture and the FMP had a lower impact as a data source for stand delineation, since differences amongst stands persist over the years with relatively small changes. Multispectral data was essential for a good stand delineation, and the use of single, separate ASTER VNIR bands produced better results than NDVI. However, the outcome of combined LiDAR and multispectral data could probably be improved with the freely-available 0.5 m NIR orthophotos.

Object-based image analysis produced forest segmentation quickly and overcoming the issue of subjectivity, which was especially visible in stands with blurred changes and mixed species, where human ability to discriminate changes becomes limited. A light over-segmentation seems to be a good option to reduce further delineation in the field. However, OBIA requires an important degree of expertise and a deep training to extract its potential as a tool for forest stand delineation. Therefore, it is not likely to be accepted by small-medium forestry firms for dealing with their forest management plans. This assumption is derived from the own experience in this research work and considering the difficult budgetary context of forest management planning in Spain for such firms. However, OBIA appears as a good solution for major companies and public forestry institutions.

Accuracy assessment of segmentation over existing stands cannot be achieved since manually delineated stands do not represent a real grown truth, as stated previously. However, the method proposed to compare manual delineation and segmentation produced by OBIA seems to be an adequate solution to indicate delineation fitting.

6.2 Future work

The most immediate suggestion for future work is the use of NIR orthophotos instead of ASTER imagery, even if orthophotos have a certain degree of compression and a possible
loss of spectral accuracy has taken place. Spatial resolution for forest stand delineation is an essential matter which should prevail. In contrast, even though spectral information is fundamental, discrimination amongst stands reached by this means is not likely to be achieved beyond the separation of conifers and broad-leaved stands (and mixed ones). Therefore, a lower accuracy in the spectral side would not greatly affect the results, whereas a much higher spatial resolution would improve them.

A better description of forest structure will be possible after increasing LiDAR density, which is something planned by the Instituto Geográfico Nacional for the next years. This improvement may lead, not only to a more accurate estimation of tree mean height and canopy cover, but also to consider estimating other forest parameters which cannot be well predicted with the current density.

The use of drones to capture spectral information as well as LiDAR data represents an interesting line of work for the future because it can provide much better spatial accuracy than the freely-available products used in this study. However, the additional cost of a drone mission, considering planning, flight and data processing is nowadays, an unjustifiable extra-expenditure in the context of the Spanish forestry sector, especially when reasonably accurate free data is provided by public institutions. The rapid development of drone technology will possibly change this scenario soon but the usage of drones at the moment is still too expensive in relation with the cost of average forest management plans.

Finally, an interesting point to develop is the way OBIA segments and manually-delineated stands are compared. The method proposed in this thesis for such purpose has not been found in other studies and further examination in similar environments would be necessary to corroborate its validity and, possibly, to improve the algorithm.
Appendix

The following example illustrates the mechanism of the delineation assessment through a simplified situation. The following fictitious forest is composed by 3 stands which were manually delineated (stands 1 to 3) and it was divided, afterwards, into 6 segments in the OBIA process (segments A to F). The areas occupied by each stand are: 144 units (Stand 1), 48 units (Stand 2) and 144 units (Stand 3). Stands and segments are represented in the following figure:

The delineation assessment firstly consists in overlapping and intersecting both layers, so 10 intersections were obtained (intersections a to j), which are shown below:

Contribution of segments to stands (Contribution Index)

Stand 1 is overlapped by 3 segments. The most contributing segment is Segment A (90%). In other words, Intersection a represents a 90% of the area of Stand 1.

In a quite different situation, Stand 3 is overlapped by 5 segments. The most contributing segment is Segment E (33%), corresponding to Intersection j.
The fact that Stand 1 falls into Segment A in a 90% implies that Segment A represents fairly well the characteristics of Stand 1. However, Stand 3 falls into 5 different segments and none of them is representing Stand 3 in a high percentage. That means that Stand 3 is not much more similar to Segment E than it is to Segment A or Segment D, for example.

**Contribution of stands to segments**

The opposite analysis is undertaken with respect to how every segment is distributed amongst different stands. The following values are a rough equivalence to what it was depicted as a simplified example.

Segment A:
- 60% of Segment A falls into Stand 1
- 15% of Segment A falls into Stand 2
- 25% of Segment A falls into Stand 3

Segment B:
- 100% of Segment B falls into Stand 1

Segment C:
- 50% of Segment C falls into Stand 1
- 50% of Segment C falls into Stand 3

Segment D:
- 50% of Segment D falls into Stand 2
- 50% of Segment D falls into Stand 3

Segment E:
- 100% of Segment E falls into Stand 3

Segment F:
- 100% of Segment F falls into Stand 3

**Weighted exclusiveness of segments to stands**

Stand 1:
- Segment A: most of Segment A falls into Stand 1 (60%). This segment represents a 90% of Stand 1 surface. So it can be said that 90% of Stand 1 is overlapped by a segment which is moderately exclusive to it (60%).
- Segment B: this segment entirely falls into Stand 1, so it is totally exclusive to Stand 1.
- Segment C: it shares its surface between Stand 1 and Stand 3 in the same proportion (50%). Whatever the percentage, this part of Stand 1 is only a 3% of its surface, so the influence in the overall calculation is little.
The weighted exclusiveness for any stand overlapping n segments can be expressed as follows (where Cont stands for Contribution, Seg stands for Segment and S stands for Stand):

$$\text{Excl Seg}_A \cdot \text{ToS}_m \cdot \text{Cont Seg}_A \cdot \text{ToS}_m + \text{Excl Seg}_B \cdot \text{ToS}_m \cdot \text{Cont Seg}_B \cdot \text{ToS}_m + \ldots + \text{Excl Seg}_n \cdot \text{ToS}_m \cdot \text{Cont Seg}_n \cdot \text{ToS}_m$$

In the case of Stand 1, 3 segments are overlapping it and the weighted exclusiveness is 62.5%:

Weighted Exclusiveness = $0.6 \cdot 0.9 + 1 \cdot 0.07 + 0.5 \cdot 0.03 = 0.625$

The result is logically close to the 60%, because this is the percentage with which Segment A is exclusive to Stand 1, and it is weighted with a 90% (contribution of the segment to the stand).

Following the same reasoning for Stand 2, 36.3% is obtained as the weighted exclusiveness of the 2 overlapping segments (A and D) to this stand.

Weighted Exclusiveness = $0.1 \cdot 0.33 + 0.5 \cdot 0.66 = 0.363$

Similarly, for Stand 3, the result is:

Weighted Exclusiveness = $0.2 \cdot 0.25 + 1 \cdot 0.08 + 0.5 \cdot 0.2 + 0.5 \cdot 0.33 + 1 \cdot 0.14 = 0.535$

Fitting index at stand level

The fitting index, which is the value trying to express how well a particular segment is fitting the segment or segments overlapping it, is achieved through the multiplication of the contribution index and the weighted exclusiveness. If both indices are close to 1, the fitting index will be also close to 1. If, for instance, the contribution index is 1 but the weighted exclusiveness is a 40%, the fitting index will result in a 40%. The values of fitting indices at stand level for the simplified example of this appendix are the following:

Fitting index$_1$ = $0.9 \cdot 0.625 = 0.5625$
Fitting index$_2$ = $0.5 \cdot 0.363 = 0.1815$
Fitting index$_3$ = $0.33 \cdot 0.535 = 0.17655$

Stand 1 has the higher value due to the fact that Segment A occupies most of the stand and, even though it is not exclusive to it, a large portion of Segment A belongs to Stand 1. In contrast, Stands 2 and 3 have much lower value due to different reasons each. The two segments overlapping Stand 2 are not very exclusive to the stand and they represent other stands in the same or even bigger proportion. Stand 3, however, has five segments so this stand cannot be explained by the characteristics of any of them in a high percentage.
Fitting index at forest level

The overall assessment of a forest in terms of segment fitting takes into account how well the stands fit the segmentation, which varies from stand to stand. Therefore, a value for the whole forest is calculated weighting the fitting index of each stand with the area they occupy in the forest. Following the same simplified example, the overall index for the forest would be 34.27%:

Overall Fitting Index = (144 · 0.5625 + 48 · 0.1815 + 144 · 0.17655) / 336 = 0.3427
Glossary of forestry terms

**Basal area**: cross-section of tree trunks at 1.30 m above the ground with respect to a surface unit. It is normally expressed in m²/ha. It is one of the most common concepts used in dendrometry, forest management and forest ecology.

**Compartment**: permanent subdivision of a forest property, defined for management purposes. Permanency of compartments involve that their boundaries must coincide with enduring and clear features, either natural (streams, crests, etc.) or artificial (roads, power lines, etc.).

**Dasocracy**: part of forestry concerned with forest management planning, aiming at maximising the annual rent coming from logging and other forestry-related activities.

**Dendrometry**: science concerned with the measurement of trees and forest stands.

**Diameter at breast height (dbh)**: diameter of a trunk measured at 1.30 m above the ground. This is the standard method to express a tree’s diameter.

**Dominant tree**: tree with crowns which outstand the main level of the forest canopy and is exposed to full light from above and from the sides. Its trunk diameter is over the average and it is related to the concept of *dominant height* or *top height* (see below).

**Dominated tree**: tree with a crown covered by other neighbouring trees.

**Codominant tree**: tree belonging to the main canopy level, clearly exposed to light from above but not entirely from the sides.

**Mean height**: mean of the height of all trees in a forest stand.

**Multi-storied**: it refers to forests having several layers of trees

**Pole stage**: stand stage at which trees have started experiencing self-pruning. This stage ends when the dbh reaches 20 cm.

**Silviculture**: part of forestry concerned with the techniques addressed to the cultivation and care of forests and trees.

**Stand**: temporary subdivision of a forest property, defined for management purposes.

**Timber volume**: volume of wood contained in the main trunk.

**Timber stage**: stage referred to a stand with trees over 20 cm of dbh. It represents the highest development in tree maturity.

**Top (or dominant) height**: mean height of the trees which occupy the dominant stratum of a forest or a stand. In practical terms, the top height is usually expressed as the mean height of the 40 thickest trees (at breast height) per hectare.

**Working circle**: part of a forest organized in a differentiated way, under a silvicultural point of view and having a sustained production of forest goods.
### Glossary of tree species

<table>
<thead>
<tr>
<th>Scientific name</th>
<th>English</th>
<th>Swedish</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Abies alba</em></td>
<td>Silver fir</td>
<td>Silvergran</td>
</tr>
<tr>
<td><em>Castanea sativa</em></td>
<td>Chestnut tree</td>
<td>Äkta kastanj</td>
</tr>
<tr>
<td><em>Fagus sylvatica</em></td>
<td>Beech</td>
<td>Bok</td>
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<td>Ullek</td>
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<td><em>Quercus robur</em></td>
<td>Pedunculate oak</td>
<td>skogsek</td>
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References


