Norges miljø- og biovitenskapelige universitet

Master's Thesis 2021 30 study credits
Norwegian University of life sciences NMBU

Analysing forests naturalness in southern Norway using airborne laser scanning

Kevin Robertson Sinclair
MSC Forest science

Preface

This master thesis is the fruition of many years of experience of forestry work and education. The choice of the thesis is something that intrigues and when the opportunity arose to study naturalness it was of interest to me, the fact that there is also growing interests in protection of forests makes it a viable topic for the future. The data collected for this study was part of a larger project carried out for the Norwegian Environmental department. The field data analysis showed that stems and site index were of importance in predication of naturalness whilst these factors plus the vertical and horizontal metrics were the important variables behind the ALS analysis.

I would especially like to thank Dr. Hans Ole Ørka, and Prof. Terje Gobakken for all the advice and help I received during the project. Roar Økseter for all the preparation and help with the field work. Aksel Granhus from NIBIO for granting access to NFI data. Sander Strømsborg Solli and Per Ivar Kvammen for giving advice and help in the writing process. Finally, I would like to thank all Professors and lecturers at the Inland Norway University of Applied Sciences, Evenstad and the Norwegian University of Life Sciences, NMBU.

Table of Contents

1. INTRODUCTION 4

PROTECTION INCITIVE AND CERTIFICATION 4
OLD-NATURAL FORESTS 4
NATURALNESS 6
NATURALNESS GRADIENT 7
DEFINITIONS 8
INTRODUCTION TO REMOTE SENSING 8
RS HISTORY 9
RS TYPES 10
AIRBORNE LASER SCANNING (ALS) 11
OBJECTIVE 12

2. MATERIALS AND METHODS 13

STUDY AREA 13
FIELD REFERENCE DATA 14
AIRBORNE LASER SCANNING DATA 17
STATISTICAL ANALYSIS 18

3. RESULTS 20

EXPLORATIVE ANALYSIS FOREST ATTRIBUTES 20
EXPLORATIVE ANALYSIS AIRBORNE LASER SCANNING 24
TURKEY HSD 24
PREDICTIONS OF NATURALNESS 27

5. DISCUSSION 32

FOREST ATTRIBUTES 32
LASER PREDICTIONS OF NATURALNESS 35
TUKEYS HSD ALS 35

5. CONCLUSION 39

6. REFERENCES 40

Abstract

Biological and ecological important areas and species are in increasing focus now. Earlier protected areas have mostly excluded productive forest areas in Norway. The added focus on these areas combined with an increased interest in biodiversity has led to the production of this study. It was therefore examined to see if it was possible to categorize these degrees of naturalness and to see if it was possible to remotely sense these areas. The remote sensing technique if successful will decrease time and costs used identifying these areas in the field. In this study Airborne Laser Scanning data was used in conjunction with data collected in the field to see if it was possible to determine old natural forests and to see if it was possible to distinguish between the naturalness categories using ALS. It was decided to use Random Forest decision tree model to predict the factors from the ALS that were the most important in the predication of naturalness. Height variables were the variables that were deemed the most decisive according to the Random Forest Analysis. The aim of this thesis is to evaluate methods to map ONFs using ALS. More specifically the objective was to include methods to maps the ONFs gradient of definitions to six categories. Untouched (virgin), ancient, semi-natural, old-selective, old managed, and managed.

1. introduction

Ever since man learned to use the resources available from forests, many areas have been subjected to change due to human activity. Due to increased greenhouse gases in our atmosphere, that humans accelerated, we can no longer claim that any forest globally can be truly defined as natural. The gases have changed the biological integrity of these forests (European Environment Agency, 2014). This is one reason why studies of these types are important.

Protection incitive and certification

Due to an increased interest in our global community and the effect humans are having upon the environment we have higher focus to protect our forests in recent years. The REDD+ (Reducing emissions from deforestation and forest degradation) initiative is one such example providing means to combat deforestation and sustainable management in the tropics (Levin et al., 2008). Furthermore, the use of forest certifications has increased in the past 2-3 decades (Overdevest, 2010), Forest Stewardship Council (FSC), Programme for the Endorsement of Forest Certification (PEFC), Canadian Standards Association (CSA) and Sustainable Forest initiative (SFI), increase the care taken for biodiversity and sustainable management in forested areas (Ozinga, 2001). PEFC and FSC is the most used certification schemes in Norway (Norwegian Forest Group, s.a.) The PEFC standard has regulations for protecting areas of importance called key habitats, requirement 21 the PEFC standard, these include areas like Old-Natural Forests, ONFs, (Norwegian PEFC Forest Standard, n.d.).

Old-Natural forests

ONFs have received increased attention the latter years and ONFs are important for several reasons. Firstly, studies have shown that they are valuable as carbon sinks both in the biomass and soil (Luyssaert et al., 2008; Zhou et al., 2006). Secondly, they are important ecologically. This is because the rarity of these areas leads to rare habitats that often contain species that are also endangered globally (Brūmelis et al., 2011). Increased interest in keystone species and ecosystem engineers during the latter half of the last century has been a topic of interest for ecologists since the late 60s (Spies, 2004). The keystone and ecosystem engineers can change the surrounding habitat to an extent that they have an impact on lots of other species that share the community with them. This impact is often essential for the survival of the community. Removal of keystone species can lead to an irreversible cascade effect (Fitzpatrick et al., 2020).

Thirdly they have commercial value as the quality of timber from such forests usually are of higher quality than timber from plantations (Petit et at., 2004: Agestam et al., 1998). Old-natural forests will also produce ore-pine, which is used in the restoration of old stave churches and other old buildings. Ore-pine wood is mostly obtainable from old-growth montane forests because it develops in the heartwood of pine trees that have reached a certain age (Burke, 2020). The development of heartwood in pine trees is dependent upon several factors but age is thought to be the driving one (Gjerdrum. P. 2003). These areas can also be used as recreational purposes as they often have a pleasant species composition. There is an increased possibility to find endangered species and the area is probably protected, this may increase the attractiveness of these areas to a lot of people (Simkin et al., 2020).

There are many reasons to map ONFs, but one of the most important is the ecological aspect that ONFs involves. The European Union has had nature legislations that date back to the late 70s and they have been focusing on biodiversity since 1998 (European Environment Agency, 2014). If more ONFs was available to study, it would lead to a better understanding of these ecosystems and how important they are to the surrounding environment. This will aid in the management techniques that are applied to these areas and the ecological decisions about the future of these areas, it will not always be the case that all ONFs are of equal value. Conservation of endangered species could increase biodiversity in forests, and this can not only have a benefit ecologically, but could also improve the conditions of the species found in the forest communities. In stands that have a higher biodiversity the vitality of these stands is higher, this is due to cooperation by different species (Felton et al., 2010). It may also have benefits to commercial forestry. ONFs often contain a heterogenic structure, both in species composition and variation in development stages. Different species and development stages can also increase the vitality of the stand and result in less damage due to wind and snow. It will in turn increase the volume harvested during thinning and clear cutting. This occurs because of the shelter provided due to different heights and branching structures throughout the species diversity and the variation in age creates more difference in structure creating more shelter and support (Frivold et al., 2001). It has also been suggested that increased biodiversity could have a positive effect on the mycorrhizae community which has been suggested will aid in the fixation of nitrogen (Mikola, 1986) and aid in increased growth of these species and their hosts (Dvorák et al., 2017). Studies have been carried out to assess the amount of biomass found in Norway spruce forests in southern Sweden in connection with the number of Ectomycorrhizal fungi grown in ONFs (Dahlberg et al., 1996).

Naturalness

The term natural seems to be everywhere these days, from products we use daily to wilderness habitats that are categorized from their naturalness (Winters 2012). In fact, the naturalness of forests is directly connected to biodiversity and human activity. Several studies have been done on the subject (Michel & Winter, 2009; Ranius et al., 2009). Naturalness is often characterized by the number of adapted species that often have a high level of rareness or are even perhaps endangered. This leads us to the importance of protecting vulnerable areas to not lose these habitats (Cardoso et al., 2007). A study published in 1955 suggested dividing up the naturalness into Hemeroby classes, which is used in botany and ecology (Steinhardt et al., 1999). Hemeroby will often use the specific site conditions and vegetation present. A high level of Hemeroby equates to a high level of human activity (Jalas et al., 1955). Since Forestry is concerned with the production of timber it is logical to use the aboveground biomass to determine the naturalness of the stands. (McRoberts et al., 2012). Since the middle of the last century there has been focus on naturalness, often naturalness is combined with human influence so dating naturalness globally is difficult due to the different time periods the earth was colonized. For example, the old and new worlds cannot be the same due to the difference in the global expansion of humanity. Even parts of North American have fluctuations due to population variations. There was a higher population earlier due to the almost catastrophically effects of smallpox from Europe which decimated the indigenous population (Angermeier. 2000). Therefore, another method of classification is required, one that is based on biotic factors. The factors that contribute most to naturalness are shown in the figure below (McRoberts et al., 2012).

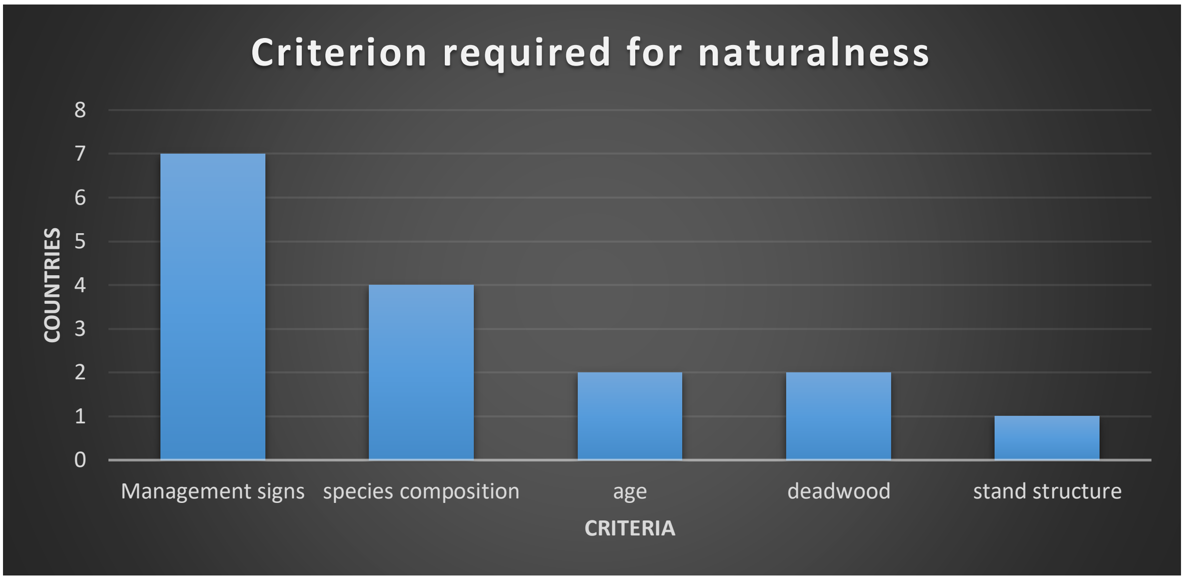

Figure 1. List of the most important factors that contributes normally to the possible detection of ONFs (McRoberts et al., 2012).

Naturalness gradient

When we consider the management practices of ONFs we need to be able to categorize these forests into different categories so we can differentiate between the varied habitats. Certain habitats will have an increased chance of sustaining endangered species. This is important in conservation (Male et al., 2005). One recognized method of deciding which gradient should be applied is the describing of naturalness in the stand. Naturalness has been described as "the similarity of a current ecosystem state to its natural state" (Christensen et al., 2005). When looking at naturalness it can often be confused with biodiversity since often areas of high biodiversity have a high level of naturalness and vice versa. This is normally only the case in areas that are not affected by high stress situations such as drought, leeching of nutrients and extreme cold. All these factors can reduce the biodiversity (European Environment Agency, 2014).

Definitions

Natural will allow for some human activity in the past but must have returned to a natural state. Virgin, on the other hand, is completely untouched and has developed without human intervention. These forests are extremely rare in Europe because of high population densities and intensive land use. Other terms used to describe forest naturalness are ancient and semi-natural forests, this describes forests that are relatively untouched for several centuries or since, the production of reliable maps. Most of these forests are growing on old prehistoric sites whilst others were cleared for agriculture but have reverted to their original state since then. The production of maps led to more detailed records being kept and it is one time in history that is used to categorize naturalness (Peterken 1993). Semi-natural forests refer to forests that have been subjected to silviculture processes but still have their natural species composition and structure of an untouched forest (Schuck et al., 1994). The terms old managed forests and old selectively logged forest are also widely used to describe forests that have seen human activity, but like the semi-natural forests these have reverted to an almost natural state (Lie, 2012). The difference between old selectively logged and old managed forests is that the old selective logged forests have a near natural tree composition and has a very high naturalness. The old managed forests have a much more homogeneous composition and are much more even aged leading to a lower level of naturalness (Sverdrup-Thygeson et al., 2016). In previously mentioned studies involving naturalness they have included the use of plantations. The term plantations refer to industrial plantations that are planted or sowed in rows in a field or on flat ground and not stands that have been regenerated by planting or sowing. Since the practice in Norway is rare this strengthened my resolve to exclude these types of stands (Evans. J., 1982). Management history of Norway's forestry has been used to calculate the naturalness with the probability of naturalness increasing the older the stands are, how much species diversity there is and likelihood of human intervention.

Introduction to Remote sensing

Studies have been carried out on naturalness and if it is possible to predict such areas with the usage of remote sensing (RS) (Potapov et al. 2008). ONFs has become more valuable for management purposes lately and information of their location is therefore key. Efficient methods providing good maps are needed. Comparisons of different methods for forest inventories have been examined for many years and studies have been carried out on the cost efficiency and inventory accuracy of these studies (Bergseng et al. 2013). There are two main methods to collect data on the forest inventory, RS, and the field method. The field method involves the physical presence of someone in the forest to record the status of the area in question. RS has an advantage over the field method because it is much cheaper and quicker, and vast tracks of land can be covered in a relatively short time. Advances in technology is continual and RS is no different, studies in increasing the accuracy of RS are ongoing (White et al. 2016). One such study showed that it was possible to distinguish between forests of high naturalness and managed forests. This was achieved by studying the structural differences in the RS data (Sverdrup-Thygeson et al. 2016). Another paper published findings on the effectiveness of using RS in predicting natural forests globally (Curtis, et al. 2018). If it was possible to predict ONFs using RS to a high degree of certainty this could reduce the costs that are ensued by using the field method.

RS history

One of the earliest surviving examples of RS is from Boston in 1860, by James Wallace Black, where a camera was attached to a balloon and an aerial photo was obtained of the city (Khorram, et al. 2016.). Both the first and second world wars were big drivers behind the advancements in RS technology. Not only did the world wars aid in the developmental use of aero technology in relation to offensive manoeuvres but were also of great importance in remote sensing and logistical purposes (Rakha & Gorodetsky, 2018). After the second world war the USSR demanded reparation fees from the allied and axis countries that now found themselves part of the USSR. They used timber to extract these fees and advancements in aerial photogrammetry increased (Nita et al., 2018). Aerial photogrammetry continued to be the main RS method until the first Landsat satellite was launched into orbit in 1972 (Roy et al., 2014). As far back as the 50s there was considerable innovation in the use of laser. USSR, USA, and Canada were the countries that led the advancements in developing these technologies. As early as the 1970s they had used laser to map sea ice and a decade later it was in use mapping forest topography (Nelson, 2013). The Landsat satellite project is a collaboration between United States Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) and has been in use for 40 years. There have been 8 satellites that have produced a constant near-global coverage. The importance of these remote sensing cannot be understated, and the uses are numerous. Wetland protection, climate change studies, disaster management, agriculture, and forest management to name a few (Roy. Et al., 2014). There are several different types of RS and many studies have been carried out on the effectiveness of their uses in connection with forestry (Hyyppä et al., 1999). In the early 1970 studies began examining the use of lasers in recording information, Light Detecting and Ranging (LiDAR). This technology was then used in conjunction with aeroplanes and terrestrial systems to map areas (Vauhkomen et al., 2014).

RS types

There are five main types of RS that are applied in practice today and that can theoretically be used to map ONFs. Digital aerial photogrammetry (DAP), airborne laser scanning (ALS), terrestrial laser scanning (TLS), high spatial resolution (HSR) and very high spatial resolution (VHSR) satellite optical imagery (White. Et al., 2016). The oldest of these is DAP since it uses a more traditional camera method. Having said this, the camera technology used today cannot be compared to early cameras. Since advances have been made in digital photography DAP has increased its usefulness in the world of remote sensing. Today 3D pictures are produced, and these pictures are of good enough quality to compete with laser scanning methods in certain fields. TLS and ALS will result in a higher quality RS than DAP but depending upon usage it is not always required to have the most detailed picture as possible. Higher detailed pictures may just increase assessment costs of future management. ALS is probably the biggest competitor to DAP, especially in conjunction with forest management (Kangas et al., 2018). ALS uses lasers to create a dot cloud of a 3D object and will penetrate the canopy of obstructing objects more than DAP and will therefore result in a more accurate picture of the vertical structure of the object in question. If an even more detailed image is required, it may be better to use TLS as it is positioned on the ground much closer to the object. TLS is much more expensive and is more time consuming than DAP and ALS (White et al., 2016).

ALS uses lasers that it directs towards the earth, there is a return sensor attached to the aircraft that then picks up the signal and then uses the delay to determine the distance the laser travelled. This will then give us a detailed picture of the contours of the ground and a better impression of the vegetation that is present there. The advancement of laser technology led to them being used in RS. The invention of higher pulsed lasers also increased their accuracy and attractiveness over other RS methods (Wehr & Lohr. 1999).

Airborne Laser Scanning (ALS)

In the last 15 years in Norway there has been much focus on RS, particularly ALS. The effectiveness of ALS as a RS method is strengthened by the amount of data that can be collected in comparison to DAP, DAP relies on the usage of ALS in mapping the contours of the forest floor in detail (Goodbody et al., 2019). The ALS enables us to determine the volume, height, density, canopy cover and variation in forest structure (Dalla Corte et al., 2020). ALS data can also be used to give us information on carbon and biomass (Turner et al., 2004), all the Nordic countries bar Iceland use ALS as a national mapping system for forestry (Kangas et al., 2018). Since the evidence of human activity and species composition is determined through field work and ALS mapping the next most important factor is age. This study uses age predominantly to assess the naturalness of forests. It was decided to exclude downed deadwood in this study because the data collected in the field did not include deadwood found on the forest floor, this was unfortunate since detritus is a very important factor when mapping ONFs. We did however include standing dead trees.

This study will concentrate on ALS since it can also be used for many other applications and is the main RS method used in Norway. Since DAP requires ALS to map the contours of the forest floor this will increase the costs of DAP compared with using only ALS. When using ALS, it is easier to register the number of dead lying wood that is registered there which otherwise might have been overlooked by using DAP. This would be useful in the future to map possible endangered species that have their living habitats in decomposing wood (Pesonen et al., 2008). This method also gives a better image of any secondary canopy and therefore will increase its ability to determine between old managed forests and old near-natural forests (Maltamo et., 2014).

Objective

The aim of this thesis is to evaluate methods to map naturalness using ALS. More specifically the objective was to include methods to maps the ONFs gradient of definitions to six naturalness categories: Untouched (virgin), ancient, semi-natural, old-selective, old managed, and managed.

2. Materials and methods

Study area

For this specific study the area of interest encompassed Telemark and Buskerud, this is where the field data was collected during the summer of 2020. In addition to this, data from the Norwegian National Forest Inventory (NFI) was also used from these two counties.

Buskerud county borders on Oslo Fjord but in its most northernly areas it is quite mountainous and rugged, the same can be said of Telemark except it has a much longer coastline (Figure 1).

Compared to countries further south in Europe and especially the tropics, Norway has few native tree species, 19 in total (Kucera. 1998). The most common forest types in Norway are evergreen, deciduous and mixed are less frequent but these can vary greatly from place to place. For example, you can be in a deciduous forest in lower Telemark and in only a couple of hours you are in a montane forest consisting mainly of conifer trees. The most common tree species found in Norway are the Norwegian spruce (Picae albies), Scots pine *(*Pinus sylvestris*)*, Downy birch (Betula pubescens) and hanging birch (Betula pendula). The birch species are the most widespread, but the conifers make up most of the standing volume in Norway because they are the most important commercial species in the country (Wielgolaski. 2005: Kullman. 1996).

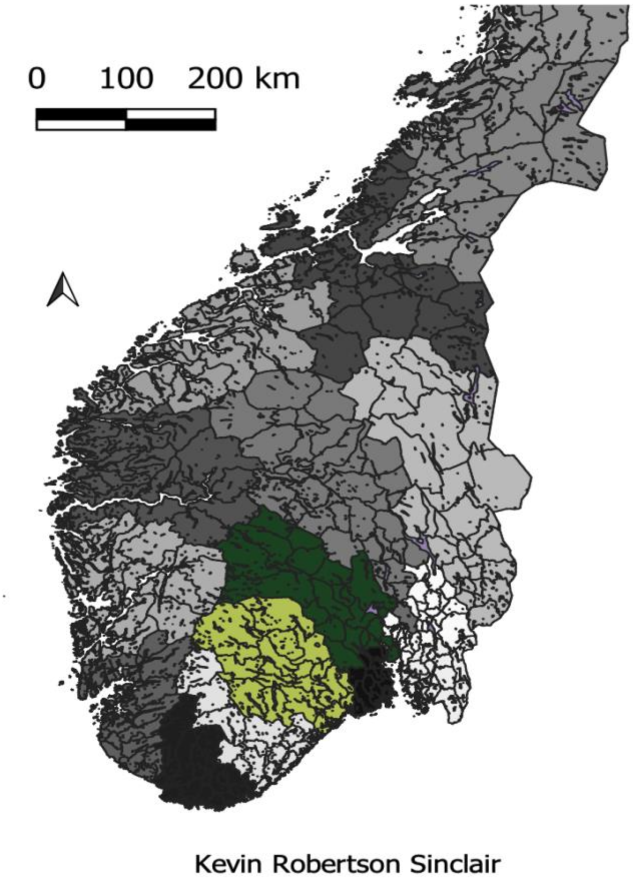

Figure 2. Study area Buskerud north and Telemark south, coloured.

Field Reference data

Two field datasets were used in the current thesis. First, most of the data that was used in this study was from the NFI between 2012 to 2019. Secondly the data that was collected during the field work in the summer of 2020. These two data sets were compatible due to the same factors being registered in the field. A third data set was used to get information from ALS. To simplify matters it has been decided to only use the virgin forest term to describe the most untouched habitats, ONFs. When looking at the difference between virgin and natural forests we must consider the amount of human activity that has occurred.

The NFI has been ongoing since 1919 when temporary plots were used. Later the establishment of Permanent Sample Plots (PSPs) between 1986 and 1993 occurred, these plots are registered once every 5 years and are 250 m^2. Due to changes in climate, some PSPs have been added to the original number in areas of higher altitude. The establishment of the NFI was done to guarantee the sustainability of the forests of Norway (Breidenbach et al., 2020).

However, as the NFI to a minor degree cover rare event such as ONFs an additional field survey was conducted, and emphasis was made to located sample plots in ONFs. The field work on this dataset was carried out in the summer of 2020. The altitude of the sites ranged from 5 m - 925 m above sea level and a good geographical variety was achieved. On the sample plots, which were 250 m^2, all trees with a diameter at breast height (DBH) greater than 5 cm were registered, on approximatlely10 trees height was recorded using a vertex Hypsometer, precise Global Navigation Satellite System (GNSS) coordinates were taken using a differential GNSS and post processed. The ages of the two trees with the largest DBH, that were of the dominant species were noted, this was accomplished by taking a core sample of these trees, core samples were processed in the field. If it was impossible to determine the age in the field the core samples were packed up and taken back to a lab to be examined.

For this study the naturalness was categorised out from a late development stage. This development stage is the stage where there is a relatively large DBH in the stand and the height is also relatively high. The next category, old managed, is a stand that has been managed but has a larger than medium Gini coefficient, this is a measurement of biodiversity. Gini coefficient is a measurement of inequality and can be used to categorise naturalness, a high Gini coefficient will indicate high levels of variation, this is something not normally found in managed forests (O´Hagan et al., 2018). The third category is the old-selective which has not seen human activity for over a hundred years. Semi natural is a stand that has seen human activity but has been left untouched for several centuries, over 200 years. For the naturalness definition that uses site index and tree species is used in the penultimate category (Table 1) and finally the forest character is the highest form of probability and is therefore used in the final category to describe virgin forests (Table 2). Forest character is determined by a stand having more than one understorey, high species composition and no obvious sign of humans and is determined in the field. The biological old forest definition is made up using different site indexes for different tree species, Table 1., (Søgaard et al., 2012).

Table 1. The penultimate category is built upon the table in that the lower age group, site index and tree species is the defining factors determining naturalness (Søgaard et al., 2012).

	Site index		
species	low 6-8	medium 11-17	high 20-26
spruce	>160	>140	>120
pine	>180	>160	>140
deciduous	>120	>100	>80

Table 2. Categories of naturalness categories and the criteria.

	Name	Definition	Naturalness	NFI plots	Field plots
0	Normal	managed forest	development stage late	444	17
1	Old-managed	> 0.6	Gini coefficient	114	0
2	Old-selective	untouched > 100	over 140 years	168	4
3	Semi-natural	untouched > 200	over 200 years	3	0
4	Ancient	Biological old forest	natural definition *	16	0
5	Virgin	Forest character	Decides from field	39	89

* Biological old forest is the natural definition that was defined out from the site index and tree species, (Table 1) (Søgaard et al., 2012).

Airborne Laser Scanning data

The ALS data that was used was from the counties of Buskerud and Telemark, the laser data that was used was from 165 Permanent Sample Plots, PSPs, averaging an area roughly 1500 km^2 and was acquired from Kartverket, (2021). The heights obtained from the ALS was used to calculate height coefficient, standard deviation, mean and maximum. In addition to the height variables the ALS also gives use the vertical and horizontal canopy height and density, these are categorized into 10 being for the vertical 2 m above the ground (Næsset. E. 2004). The different variables like average height, height coefficient, standard deviation volume, biomass, basal area and stems were calculated out from height and horizontal percentiles were also created (H10, H20…H90), and canopy density (D1, D2…D9) (Sverdrup-Thygeson et al., 2016). Both descriptions will give an indication into how the size varies in the stand and are therefore an indication as to the naturalness of a stand. This is assumed because a high variation in size distribution is very rare in managed forests

Statistical analysis

The factors used were Gini coefficient, stand age, naturalness definition (biological old forest), forest character and development class. The statistical analysis that was carried out included explorative analysis and prediction model. The explorative analysis carried out was in form of boxplots and ANOVA analyses of variance. This was done due to the categorical x factor of naturalness. Tukey Honestly Significant Difference was used to see if there was a significant difference between the categories. The mean decrease Gini is a description of the importance of the variables to the random forest analysis, i.e., their importance to the analysis in descending order. The explorative analysis was carried out on forest attributes (biomass, Gini coefficient, number of stems, volume, site index and stand age) and ALS variables. In the case of the laser data the variables used to plot the box plots were the height, height percentiles and the canopy densities. The canopy densities that were used were the minimum D1, median D4 and the maximum D9. RStudio (R Core Development Team, 2016) was used to analyse the data collected by both field registering and ALS RS.

The prediction model was created using the Random Forest classification algorithm. Random Forest is a statistical algorithm that uses nodes and branches to analyze every possible outcome. Since the data we were working with was large this also validated the use of the Random Forest algorithm. The Random Forest algorithm works by using many decision trees in conjunction with one another and is therefore more precises that individual models (Belgiu et al., 2016). Random Forest algorithm is made up of many decision trees put together to analyse more data, figure 3 below shows three decision trees put together to make a simple Random Forest. The Random Forest algorithm was employed after the confusion and error matrix were produced.

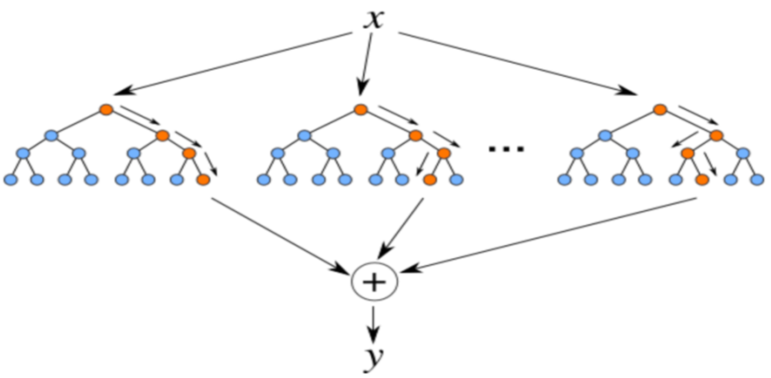

Figure 3. Random Forest with nodes and branches made up of three decision trees (Singh. J. 2020).

A confusion matrix was employed to check the performance of the Random Forest algorithm (Table 5). The confusion matrix tells us the number of true positives and true negatives that occurred in the analysis. There were only four naturalness categories used, semi natural and ancient were combined with old-selective and virgin due to the number of observations. Mean decrease accuracy and mean decrease Gini coefficient were also employed to see the weight of the variables that were tested. The mean decrease accuracy lists the factors from most important to least whilst the mean decrease Gini list the variable in importance to the nodes and branches of the Random Forest algorithm.

After producing a confusion matrix an error matrix was calculated. This gives us the probability of the user data being true and that it corresponds to an actual site in the RS areas (Congalton. 1991). The user error method was used as it corresponds more accurately with the corresponding grids in the forest and are therefore more logical to use in this instance (Story et al., 1986).

3. Results

Explorative analysis forest attributes

Effects of different forest attributes were tested, and the results of these analyses are presented in Table 3. The naturalness was plotted in boxplots against some of the same variables that were used in the models, biomass, Gini coefficient, number of stems, volume, stand age, and site index (Figure 5). The forest attributes that showed a significant difference when using ANOVA were Gini coefficient, number of stems and stand age. Biomass and volume did not have significant difference between naturalness categories.

Table 3. Results from ANOVA analysis of forest attributes, including the degrees of freedom, sum sq, mean sq, F-value, P-value, and significance *= P≥0.05, **= p≥0.01, and ***= p≥0.001

Forest attribute	Df	Sum Sq	Mean Sq	F-value	P-value	significance
			Forest			
Biomass	5	47346	9469	1.757	0.119	
Gini	5	3.569	0.7139	78	<2e-16	***
Stems	5	27315472	5463094	12.11	2.57e_11	***
Volume	5	98296	19659	1.234	0.291	
Stand age	5	583251	116650	167	<2e-16	***
Site Index	5	2956	591.3	39.89	<2e-16	***

The results of the Tukey HSD are shown below. The figure showing stand age showed only two non-significant differences, ancient versus old-managed and virgin versus old-selective (Figure 4). Gini coefficient significant differences occurred when comparing roughly 50 percent of the combinations (Figure 4). When the number of stems is considered all the finding had no significant differences except when comparing old selective with old managed and when comparing old selective and normal. Five combinations of naturalness categories showed significant differences when taking into consideration the site index (Figure 4).

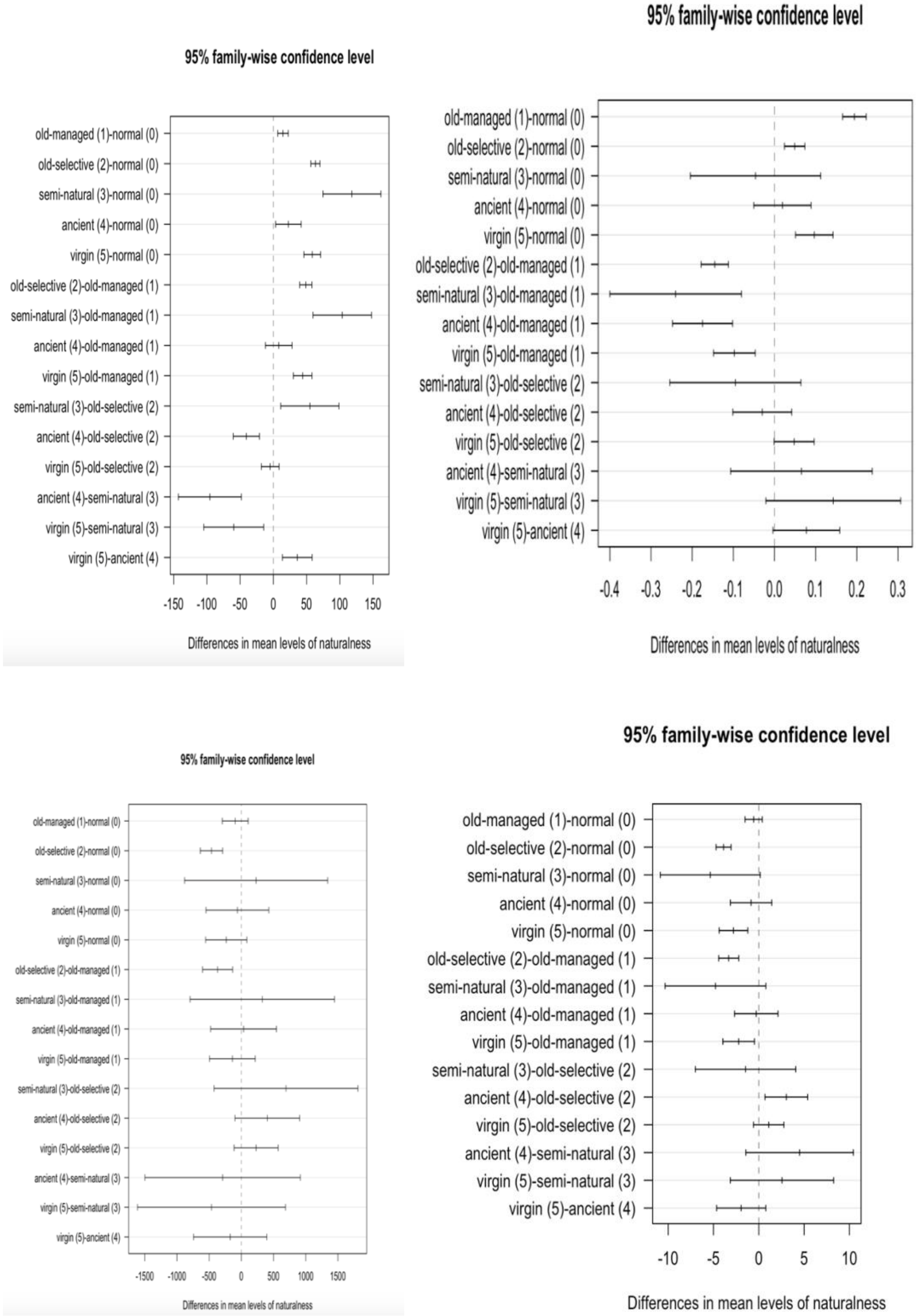

Figure 4. Top left is stand age, top right is Gini coefficient, bottom left is number of stems and bottom right is site index

Stand age showed the greatest variation between the naturalness categories, with only two categories being normally distributed. This means that the variation in the findings were skewed either positively or negatively depending upon where the median is in the box plot. The two that were normally distributed are those that are on different ends of the range normal and virgin (Figure 5a). Ancient and normal had the greatest variation whilst semi-natural had the least variation. Gini coefficient varied most in the old-selective and ancient categories. The categories that had the least variation was the old-managed and the semi-natural. There was recorded outliers in the normal forest category that were towards the lower end of the Gini coefficient (Figure 5b). Semi natural has the highest volume whilst old selective has the lowest (Figure 5c). The number of stems in the semi-natural category differed most form other categories, there was a significant difference between semi natural and the other naturalness categories (Figure 5d). Most outliers occurred in the first three naturalness categories regarding biomass (Figure 5e). Site index showed normal distribution and similar variation in the categories normal, old-managed, and ancient whilst the semi-natural was different to the other categories. There is a positive skewness in semi-natural and virgin whilst there is a negative skew in old selective. Old selective shows variation between categories but not significant (Figure 5f).

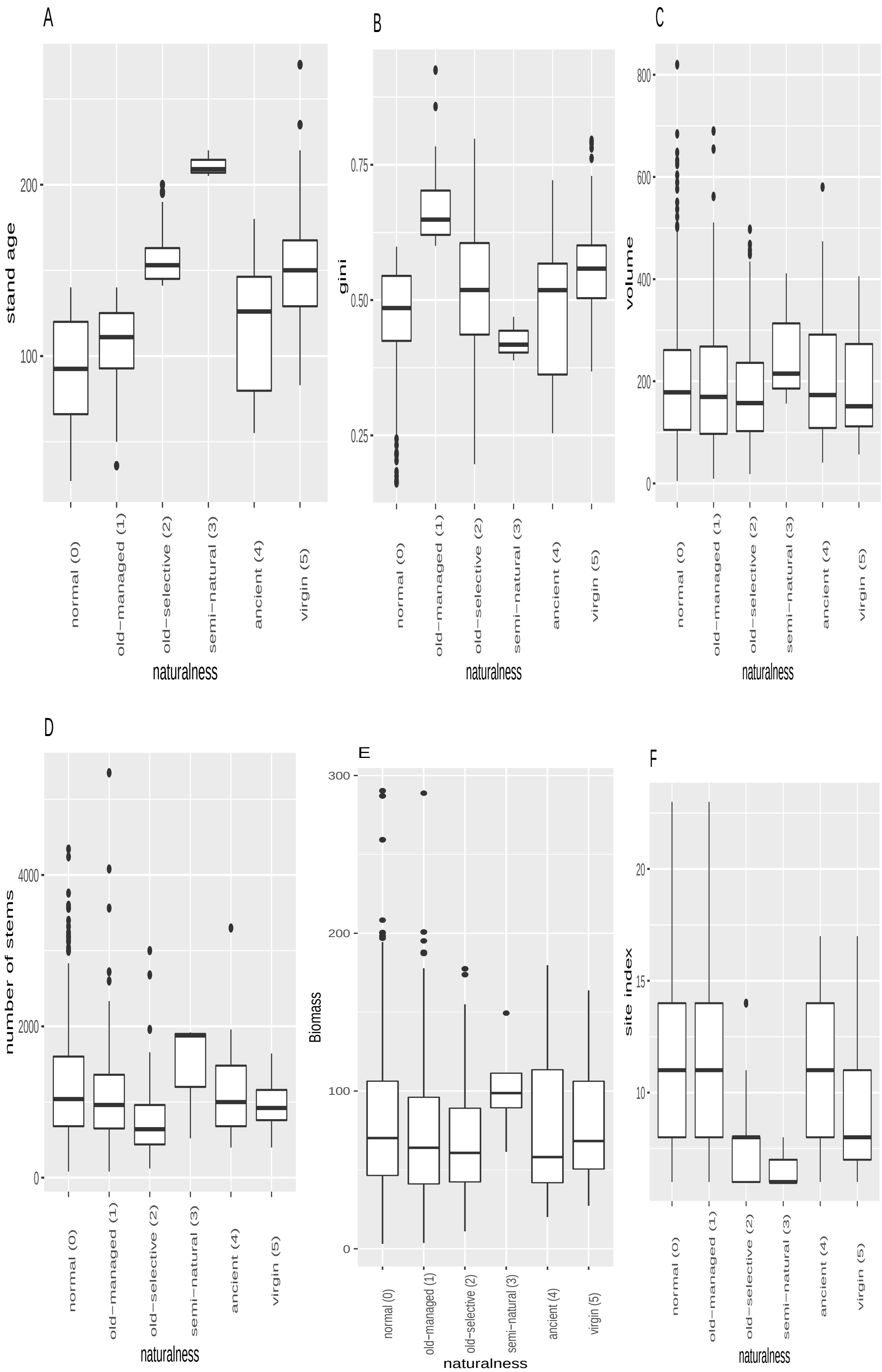

Figure 5. Naturalness categories plotted against, stand age A, Gini coefficient B, volume C, number of stems D, biomass E and site index F.

Explorative analysis airborne laser scanning

The ALS variables that were tested during ANOVA are listed below. Nine variables were tested in total and six were significant and three were not (Table 4). Height variables were significant in half of the ANOVA tests, the mean height was not significantly different. The two variables that had the most significant difference was standard deviation and coefficient of variation. The other variables that showed significant difference between the naturalness categories in the ANOVA analysis were the H10, D0, D4 and D9.

Turkey HSD

The results of the Tukey HSD are shown in the 95% family-wise confidence level height variables had over half of the combinations showed no difference whilst the mean height had almost 100% of the combination showing no differences. Four of the combinations in the figure for height standard deviation showed not significant differences (Figure 6). Only three combinations showed significant differences in the lowest height percentile (H10), old managed versus normal, old selective versus normal and virgin versus normal. The Tukey for the height percentiles (H10, H40, and H90) and for the density metrics (D0, D4, and D9) showed similar patterns with only two combinations showing a significant difference, between normal and the two categories old managed and old selective (Figure 6 and 7).

Table 4. Anova analysis, including the degrees of freedom, sum sq, mean sq, F-value, P-value, and significance for selected ALS variables

ALS	Column1	Column2	Column3	Column4	Column5	Column6
Variable	Df.	Sum sq.	Mean sq.	F-value	P-value	Significance
Hsd	5	112.5	22.506	17.56	<2e-16	***
Hcv	5	12028	240557	31.189	<2e-16	***
H10	5	315	62.94	9.503	6.80E-09	***
H50	5	100	19.94	1.365	0.235	
H90	5	245	48.95	2.651	0.0216	
D0	5	1.75	0.3492	7.746	3.50E-12	***
D4	5	2.94	0.5882	12.66	5.39E-12	***
D5	5	0.0787	0.015731	6.143	1.26E-05	***

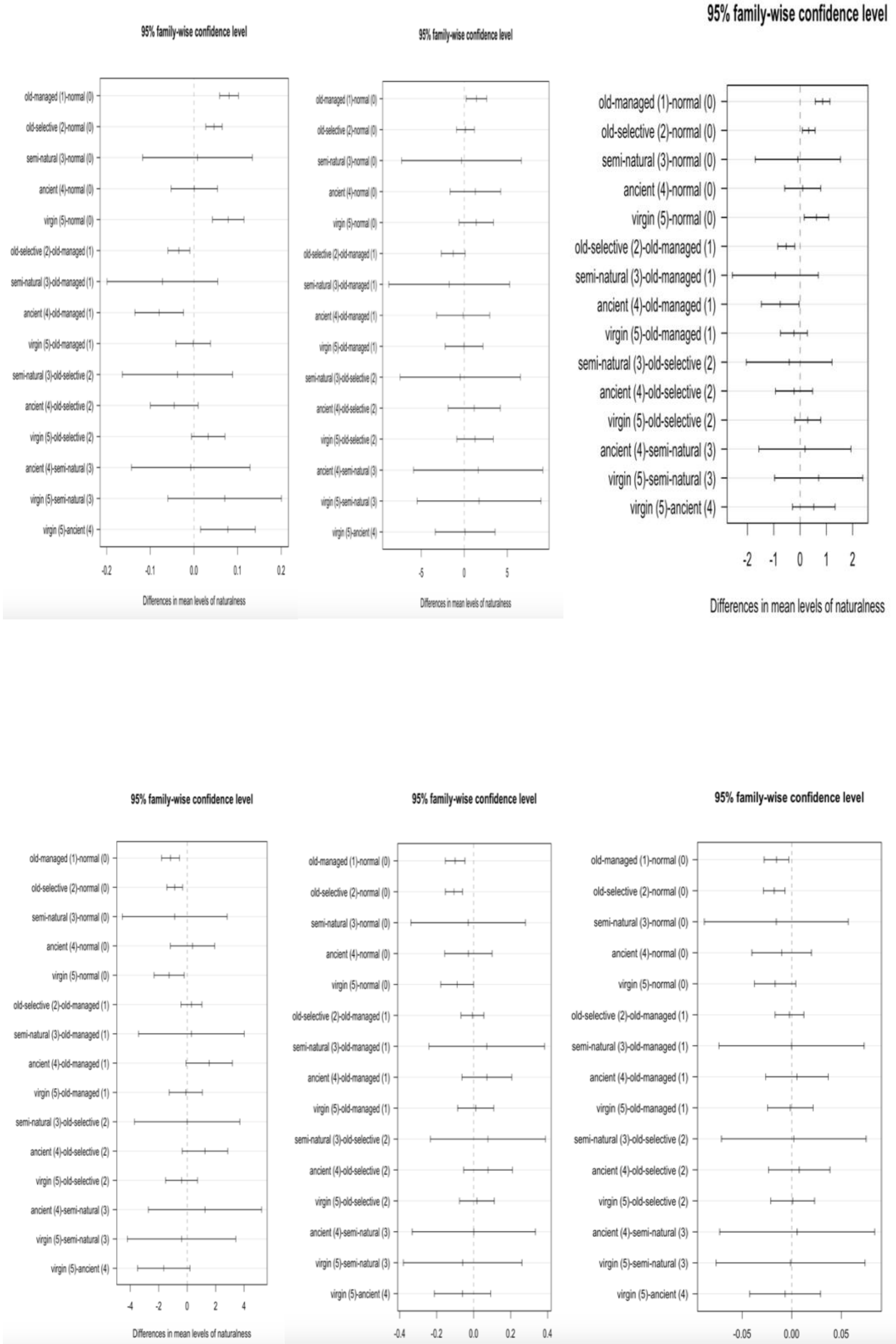

Figure 6. Height coefficient of variation top left, height mean centre and height standard deviation. Bottom H10, H40, & H90

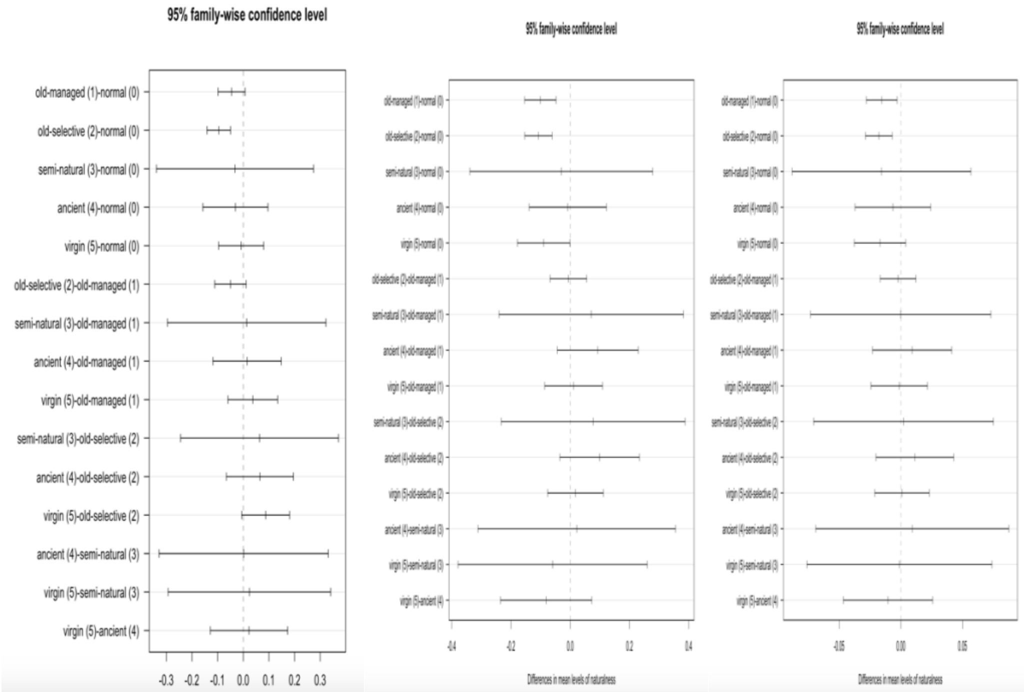

Figure 7. D0, D4, & D9.

Predictions of naturalness

The mean decrease accuracy shows the importance of each variable in descending order, Hcv was the most and canopy density D4 was of least importance. The mean decrease Gini shows that the Hcv is the most influential on the nodes and branches of the Random Forest, whilst the Hmean is the least (Figure 8). The overall accuracy was 59.8% (Table 5).

When testing the user accuracy of the confusion matrix we see that the normal category has the highest whilst virgin has the lowest. The overall accuracy of the confusion matrix is roughly 60%. The user's accuracy is high for normal and under 40% for the other three categories, the producer's accuracy ranges from 64 – 47 % (Table 5).

Table 5. Confusion matrix

		Observed					
		Normal	Old-managed	Old-selective	Virgin	Row total	User's accuracy
Predicted	Normal	580	20	56	27	683	84.9
	Old-managed	78	51	25	15	169	30.2
	Old-selective	138	17	110	11	276	39.9
	Virgin	107	14	21	47	189	24.9
	Total	903	102	212	100	1317	
	Producer's accuracy	64.2	50	51.9	47.0		

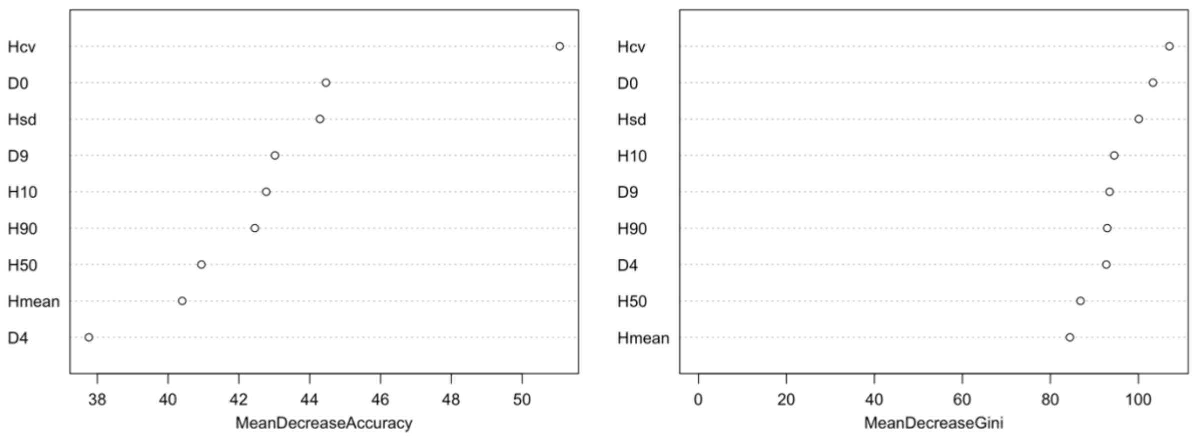

Figure 8. Random Forest left mean decrease accuracy and right mean decrease Gini coefficient.

Looking at the results for ALS variables we see that there are categories that are significantly different from the others, ancient is different than virgin and old-managed and these differences are significant. All the naturalness categories have outliers except for semi-natural (Figure 10). This pattern is almost repeated in the next figure, but here we also see that the ancient also does not include outliers. Normal, old-managed, old-selective and virgin are all normally distributed. Semi-natural has the least variation of observations while normal, old-managed, and ancient have the largest variation of observations in the data (Figure 9). Semi-natural is significantly different from the old-managed and the ancient naturalness categories in the figure presenting results for H90, the stand age has also increased in this height percentile.

There was no difference in the naturalness categories in relation to the variation in D0 canopy density. There were also few outliers, only one was observed in the normal forest category. All the naturalness categories had variation in the data, semi-natural was the category that had the densest observations (Figure 10). This pattern was repeated for the D4 observations, semi-natural observations were clustered much more closely than the other categories. This is also true for the D9 data but here the other naturalness categories were not as varied as in D0 and D4. There were also many more outliers for the D9 variable than for the two other density variables, The density in all the naturalness categories is reduced considerably in the D9 density, y axis is a smaller scale (Figure 10). We see from the canopy density variables, D0, D4, and D9, that the patterns are similar for all these variables, the variation in stand age in the categories is largest for the D0 and decreases to the D9 density, where D0 is the densest and D9 the most spacious (Figure 10).

There is a significant difference of stand age between the semi-natural, ancient, and old-managed, most outliers were observed in the normal and old-selective categories. Old-selective is positively skewed as is ancient but not to the same extent as semi-natural (Figure 11). When looking at mean height compared with stand age, we see a variety in the observations in all categories with semi-natural having the least variation. Ancient and semi-natural are positive skewed (Figure 11). The categories that are normally distributed in the height coefficient are normal, old selective and virgin. Old-managed and virgin are significantly different from semi-natural with most of the outliers in normal and old-managed.

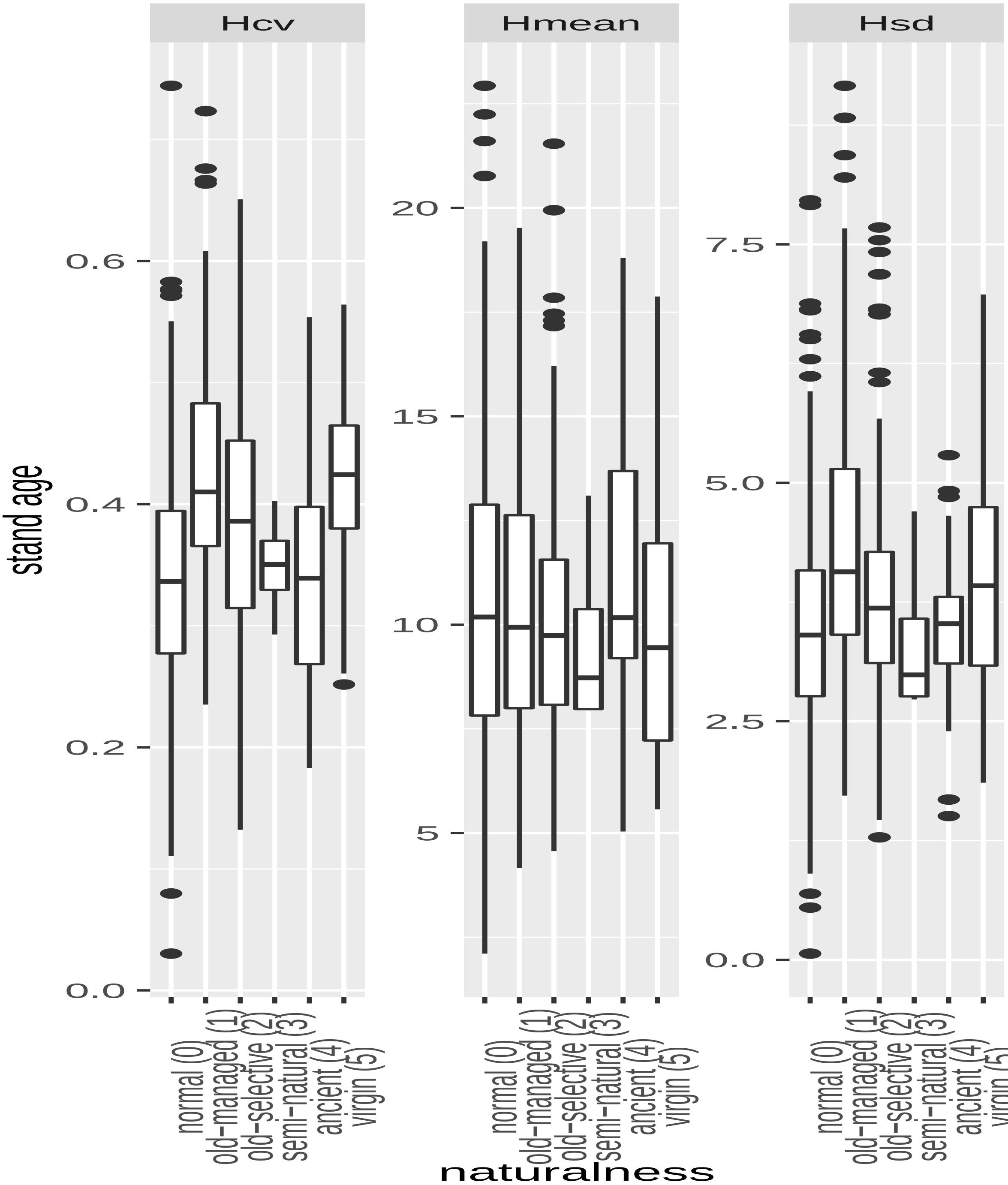

Figure 9. Height coefficient variance, height mean and height standard deviation

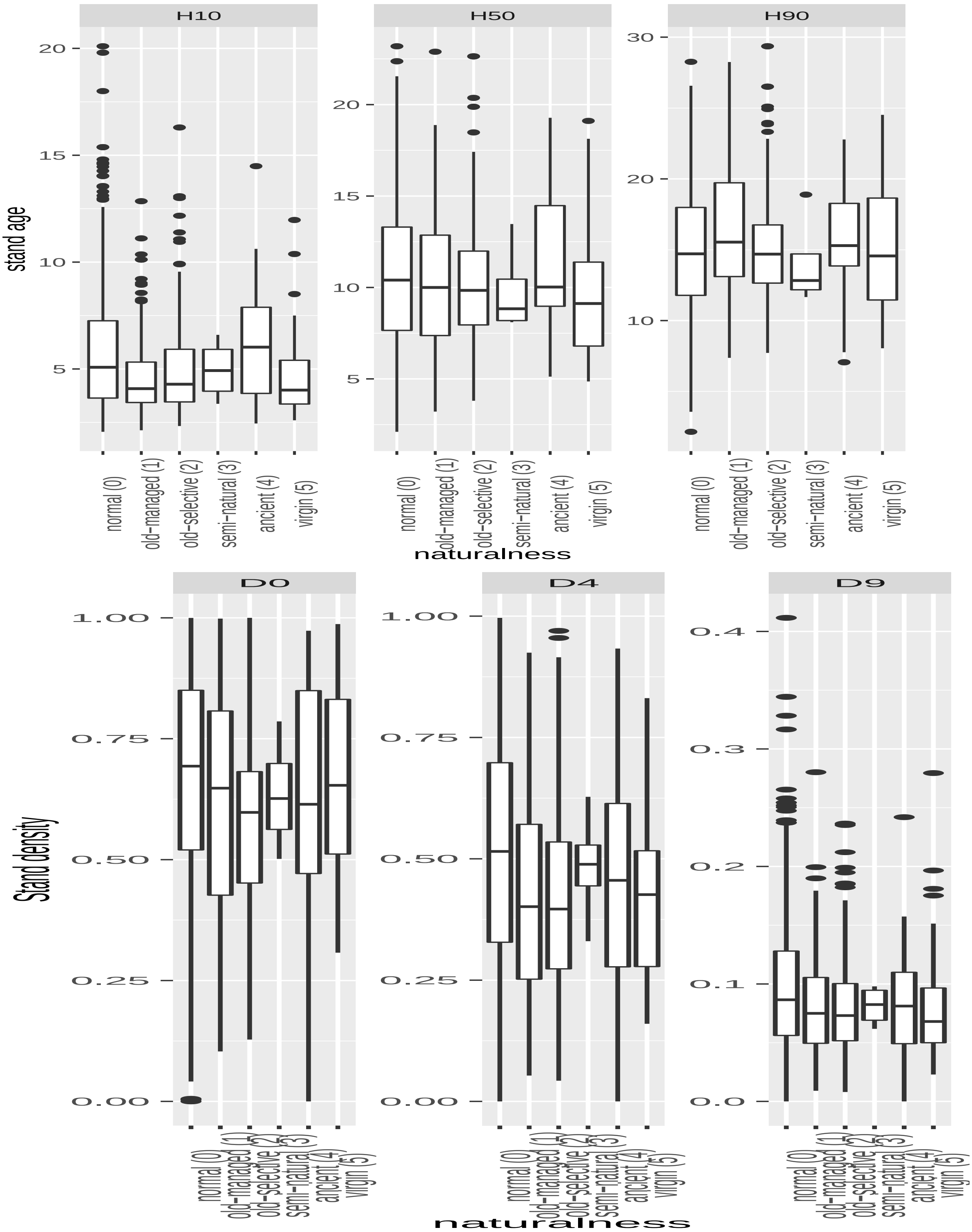

Figure 10. Height percentiles (H10, H50, and H90) Canopy density variables (D0, D4, and D9) for all the naturalness categories plotted against density that ranges from zero to 1, same index used on all three but the D9 is much lower density.

5. Discussion

A goal of this study was to categorize the ONF that is found in Norway, this was done by deciding biotic factors that lead to the creation of ONF is certain areas in Norway. The infant stage of the project was predicting ONFs using RS, next it was necessary to conduct field work to collect the data that is used in the statistical analysis of these plots. The use of the NFI data was granted access by NIBIO and the ALS data was downloaded from Karvertet (2021).

Forest attributes

The ANOVA variation analysis showed the most important forest attributes that describe the possible occurrence of ONFs. Some of the most significant forest attributes were Gini coefficient, number of stems, and stand age. Gini coefficient and stand age have a higher p-value than forest attribute number of stems. This is quite logical in that Gini coefficient is a measurement of biodiversity, generally managed stands will be more homogenic and therefore have a lower Gini coefficient than more natural stands (Rousse et al., 1999). Since natural stands have not been thinned there will be fewer trees in a managed one but if they are left to thin naturally an understorey will develop, and the overall tree number could increase, so generally speaking ONFs will have a higher number of stems than managed stands (Busing et al., 1997).

The Tukey HSD analysis was used to evaluate if the naturalness between the different categories of naturalness is significant or not. The Gini coefficient and stand age showed that only about 50% of the combinations tested were significantly different, using another variable like the number of stems gave less variation in the mean difference. This leads us to believe that perhaps Gini coefficient is not the best variable to distinguish naturalness and that in fact stem numbers, stand age and site index are better indicators for judging naturalness. It is often possible have a high biodiversity in areas where it is not expected, for example it is often possible to have high biodiversity on clear cuts depending upon the size of the clear cuts and they are as far from ONFs as it is possible to get (Pawson. S. M. 2006). Often it is not just the level of biodiversity, but the species composition is often more important. Studies have found that increased biodiversity is often linked to altitude and latitude are factors that affect biodiversity levels more than logging techniques. This could lead to these factors and biodiversity that could be none biotic variables in the classification process of categorising naturalness (Hansen et al., 1991). Studies have been carried out on continuous cover forest compared to clear cuts to evaluate the types of biodiversity found there and whether the different logging methods resulted in reduction or increased biodiversity (Seedre et al., 2018).

Stand age is a logical forest attribute to have confirmed as important for describing naturalness as a high stand age is directly used for two of the naturalness categories. The Gini coefficient was largest in the old managed stands compared to all the other, semi natural had the greatest volume and stem numbers. There are studies that show increased biodiversity in stands that are managed, which will equate to a high Gini coefficient (Didham. 2011.). The smallest Gini coefficient value was found in the semi natural, and this category also had the least variation in the data shown. The largest ages were observed for the Semi natural category. This should theoretically lead to increased biodiversity but because it is not completely untouched this may lead to a lower Gini coefficient than ONFs (Gibson et al., 2011). As mentioned earlier, the naturalness category that has the largest Gini coefficient value is the old managed, this strengthens the earlier comment about biodiversity not being a conclusive method to judge naturalness. This may be down to the fact a high Gini coefficient was used to stipulate this category and if this is the case perhaps a too high Gini was used. It is also important to remember that levels of biodiversity can be misleading due to different species composition that can create high levels in managed forests.

The number of stems show a significant difference in stand age between semi natural and all the other naturalness categories (Figure 5D). This points to the fact that perhaps number of stems are the most conclusive variable to evaluate forest naturalness. Semi natural was the category with the highest average biomass (Figure 5E). However, the biomass did not show a significant level during the ANOVA analysis. Even though the biomass did not have any significant results it is something that should be studied in the future, biomass can be used to calculate carbon sequestration. There are several factors to take into consideration not least if the soil sequestration should be accounted for or not, detritus that releases carbon should be considered or not? (Gorte, 2007: Bellassen et al., 2014). This is a subject that currently has high focus with the ever-increasing need to combat climate change and if it was possible map naturalness on a national level it could indicate the areas with potential for increased biomass and carbon sequestration.

The smallest site index values were found for the old selective and semi natural categories. Semi natural was significantly different to all other categories except old selective. Low site index in the old selective and even lower observations in the semi-natural could be caused by loss of nutrients through run off escalated the forest structure. In the case of old selected there could be a reduction of nutrients brought on by the selective logging process (Martinelli et al., 2000). Few studies have been written about site index and ONFs, this is logical since site index is a variable that is often studied in connection with industrial forestry and not conservation. One study on the subject also concluded that it was difficult to get a precise site index from ONFs because of their unique growth structure (Sturtevant el al., 2004). In addition to this site index is calculated normally in forests that are species homogeny, one characteristic of ONFs is that they are more heterogeny in species composition (Garcia. O. n.d.). Perhaps a more correct site index could be developed in the future that measures site index on mixed stands, studies do exist in mixed stands, but the focus is on mixed commercially valuable tree species and not on sites with high naturalness (Dānescu et al., 2017).

Location of these sites may also have a contributory factor to there being more old selective and semi natural than ancient and virgin. The proximity to human habitats historically could have a bearing on the naturalness categories. Areas with difficult terrain will have a higher chance of being ONFs, if they are far from human habitats too then this is a good combination for possible ONFs mapping. Perhaps the fact that they have been left untouched for centuries has increased the site index of these naturalness categories. It is thought that this is down more to site productivity, germination year and climate change in the last century that affect the nutrient cycle (Socha et al., 2021). If an ONFs has been untouched for centuries and has had an increased percentage of course woody debris over many years, then this could increase the possible nutrients in the soil and increase growth. Few studies have been conducted on the subject and those that exist are inconclusive (Feller. M. C. 2003).

Laser predictions of naturalness

Of the height variables that were tested with ANOVA the Hcv, the Hsd and the first height percentile were significantly different. The three canopy densities that were tested showed significant variation, D0, D4, and D9. These results point toward the fact that canopy density is more likely a driving factor in being able to be used as a variable to judge naturalness. One of the first studies concerning the horizontal percentiles showed that both the horizontal and vertical metrics can be used to predict the difference between near natural and managed old forest stands (Sverdrup-Thygeson et al., 2016). The important factors whilst looking at the vertical matrix from the ALS results is the height coefficient (Hcv). As mentioned earlier, the naturalness category that has the largest Gini coefficient value is the old managed, this strengthens the earlier comment about biodiversity not being a conclusive method to judge naturalness except where the Hcv, Hsd and D0 are used. However, this result is not conclusive and needs to be studied more. The results of this study show that the lowest percentile (H10) was the only vertical metrics to show significant difference, this finding is in contrast with an earlier study that found it was the highest percentile that was the most important. This earlier paper found that vertical percentiles were useful in determining between near-naturalness and old managed forest and found that it is the density metrics (D0, D5, and D9) were good indicators of these naturalness types (Sverdrup-Thygeson et al., 2016). This study also collaborated the importance of the Hcv and Hsd.

Tukeys HSD ALS

When comparing the Tukey results from the height coefficient and mean height we can see that the height coefficient is of more importance since there were more of the combinations that show a significant difference. This indicates many significant differences between the combinations and strengthens the findings of the ANOVA test. The site index Tukeys HSD was the most interesting in that almost 2/3 of the combinations tested showed a significant difference. This leads us to believe that site index is a more important factor than the height and density metrics. Perhaps more studies on site index are required in connection to forest naturalness, this is entirely possible due to the findings of earlier studies that states that site index is acquirable from RS using bitemporal ALS in disturbed and undisturbed stands (Noordermeer et al., 2020: Noordermeer et al., 2018). This could reduce cost associated with mapping naturalness categories in the future and lead to mapping of naturalness categories on a national level.

The Random Forest results shows the mean decrease accuracy and the mean decrease Gini in descending order and both the accuracy and Gini have the same first three variables, Hcv, Hsd, & D0. One of the variables that was low in both accuracy and Gini was the mean height. This suggests that the most important factors that affect the nodes and leaves in Random Forest are the same as the first three factors of accuracy. That Hcv, Hsd and D0 are the variables that both tell the importance of these variables and can be used to predict naturalness. An earlier study showed it was possible to differentiate between a national park and managed areas using ALS and the Gini coefficient (Valbuena et al., 2016).

The height percentiles showed a similar pattern throughout all the percentile ranges except H10. The H10 height percentile shows the lowest clustering of observations, but the old managed has the lowest median, virgin is almost as low. Possible reasons for this could be related to previous silviculture in the old managed or natural mortality in both the naturalness categories, in the stands due to abiotic factors, storms are high contributors to mortality in semi natural and old-managed forests (Wolf et al., 2004). The semi natural had the least variation in the largest height percentile, H90, and was significantly different to ancient and old-managed. Since the two categories of naturalness that are lower and higher than semi natural are significantly different then this points towards the H90 being affective in the predication of these categories.

In this study the height and density were prioritised when analysing the ALS data, Hsd, Hmean and Hcv. This is because height and density were easy to calculate from the data collected. The medians of both Hmean are relatively similar except for the old selective which is the lowest of all the naturalness categories. It is often stated in forestry silviculture that it is difficult to affect the height growth, but this is when a short rotation time is required. Height growth will increase given enough time depending on the abiotic and biotic factors found locally. Also, studies have shown that height will increase due to higher species composition (Marquis et al., 2021). The fact that virgin was found to have the largest variation in height of all the categories is probably down to the fact that natural succession has led to mortality, gaps opening and form the creation of several canopies in the stand. With the ongoing recruitment occurring this will then also lead to a higher variation in the age (Diaci et al., 2012). Semi natural has not only the least variation in stand age but it also has the lowest median which is significantly different to most other categories. The variation can be explained by the naturalness criteria needed for this category, greater than 200 years, but the fact that it has the lowest median is surprising. A similar pattern is seen in the Hmean results.

One aim of this study was to see if it was possible to predict ONFs from using RS. The data that was collected for this study was from a larger project. This study encompassed only two of the original eight counties that were involved in the larger project. Out from the predictions and the field work it was possible to work out the probability of predicting ONFs.

An aspect of this study that has little literature on the subject is the use of site index as a variable for detection of naturalness using ALS. We know that the measuring of site index is possible with ALS because of previous studies (Noordermeer et al., 2018:2020). If in other studies, it is found that site index can predicate different categories of naturalness then it is possible to predicate naturalness using ALS for certain naturalness categories. This is important because it will reduce costs for mapping these categories on a national basis. More study into site index and naturalness categories is required to see if these finding can be expanded upon.

One short coming of the study was exclusion of course woody detritus in the field registrations carried out in the summer of 2020. The NFI data does have it included and it could have been studied. It would perhaps be of interest to see if areas of high course woody detritus would have affected stand height or site index in ONFs or any of the other categories (Brias et al., 2005). Particularly in areas of high naturalness that have had a constant turnover of detritus that could increase the site index or the growth rates of these stands. Studying this might answer the question of why the site index of semi natural was found to be the lowest of all the naturalness categories. The site index Tukeys HSD also showed that the significant differences between the combinations were most numerous of all the Tukey HSD ALS analyses.

When looking at the accuracy of the Random Forest algorithm we see from the confusion matrix that the Producers accuracy was highest for the normal stands, 64%, 52% for the old-selected, 50% for the old-managed and only 42% for the virgin. The user's accuracy was higher in the lowest naturalness category with 85%, lowest accuracy again was the virgin, old-managed and old selective where 30 and 40% (Table 5.).

5. Conclusion

The goal of this study was to identify naturalness into six categories and to judge if prediction of these specific categories is possible with the use of ALS. An analysis of the field measured forest attributes in the boxplots showed that number of stems was a more decisive factor than stand age or Gini coefficient and that the number of stems was significantly different from all but one of the other categories, this was not the case for the Tukey HSD, it had the least significant differences between the naturalness categories. Site index was also a variable that showed a significant difference between the naturalness categories and showed the five significant differences between the naturalness categories.

The analysis of the ALS data showed that both the height and density metrics can be used to predict naturalness but that the height was most conclusive, especially metrics describing variation in height. These results were different to what I had expected when the project was started. I assumed that stand height and stand age would be found to be the defining factors in prediction and categorizing naturalness. Although they were both deemed to be of importance, they were not the most important variables. It was interesting that site index and stem numbers were two of the most decisive variables in differencing from the naturalness categories both sets of data analysis showed the important of these two variables. Looking at the accuracies of the confusion matrix we see that the producer accuracy is under than 50% for the virgin category, this leads us to believe that there are inaccuracies in the classification of these values. The user's accuracy is below 50% for all the naturalness categories that were not the managed category.

Being able to categorize naturalness and being able to distinguish these different categories using ALS RS could be extremely important to future management of these areas. Especially when conservation of biodiversity, this is of an increasing interest in the global studies of forestry.

6. References

Agestam. E., Ekö. P-M. & Johansson. U. (1998). Timber quality and volume growth in naturally regenerated and planted Scots pine stands in S.W. Sweden. Studia Forestalia suecica. 204:17.

Angermeier, P.L., 2000. The Natural Imperative for Biological Conservation. Conservation Biology 14, 373–381. doi:10.1046/j.1523-1739.2000.98362.x

Artsdatabanken. (2021). Pycnoporellus alboluteus. Available from https://www.artsdatabanken.no/taxon/Pycnoporellus%20alboluteus/56877

Belgiu, M., Drăguţ, L., 2016. Random forest in remote sensing: A review of applications and future directions. ISPRS Journal of Photogrammetry and Remote Sensing 114, 24–31.. doi:10.1016/j.isprsjprs.2016.01.011

Bergseng, E., Ørka, H.O., Næsset, E., & Gobakken, T. 2015. Assessing forest inventory information obtained from different inventory approaches and remote sensing data sources. *Annals of Forest Science* 72(1): 33–45. Available at: https://dx.doi.org/10.1007/s13595-014-0389-x.

Brais, S., Sadi, F., Bergeron, Y., Grenier, Y., 2005. Coarse woody debris dynamics in a post-fire jack pine chronosequence and its relation with site productivity. Forest Ecology and Management 220, 216–226.. doi:10.1016/j.foreco.2005.08.013

Breidenbach, J., Granhus, A., Hylen, G., Eriksen, R., Astrup, R., 2020. A century of National Forest Inventory in Norway – informing past, present, and future decisions. Forest Ecosystems 7. doi:10.1186/s40663-020-00261-0

Brumelis, G., Jonsson, B., Kouki, J., Kuuluvainen, T., & Shorohova, E. 2011. Forest naturalness in northern Europe: perspectives on processes, structures and species diversity. *Silva Fennica* 45(5). Available at: https://dx.doi.org/10.14214/sf.446.

Burke. S. (2020). Stavkirker: masterpieces in wood. Rapport from Forestry journal. Obtained from https://www.forestryjournal.co.uk/features/18140551.stavkirker-masterpieces-wood/

Busing, R.T., White, P.S., 1997. Species Diversity and Small-Scale Disturbance in an Old-Growth Temperate Forest: A Consideration of Gap Partitioning Concepts. Oikos 78, 562.. doi:10.2307/3545618

Chazdon, R. L., Brancalion, P. H. S., Laestadius, L., Bennett-Curry, A., Buckingham, K., Kumar, C., et al. (2016). When is a forest a forest?: Forest concepts and definitions in the era of forest and landscape restoration. *Ambio, 45* (5), 538-550. doi:10.1007/s13280-016-0772-y

Cardoso, P., Borges, P.A.V., Gaspar, C., 2007. Biotic integrity of the arthropod communities in the natural forests of Azores. Biodiversity and Conservation 16, 2883–2901. doi:10.1007/s10531-006-9078-x

Christensen, M., Hahn, K., Mountford, E.P., Ódor, P., Standovár, T., Rozenbergar, D., Diaci, J., Wijdeven, S., Meyer, P., Winter, S., Vrska, T., 2005. Dead wood in European beech (Fagus sylvatica) forest reserves. Forest Ecology and Management 210, 267–282. doi: 10.1016/j.foreco.2005.02.032

Congalton. G. C. (1991). A review of assessing the accuracy of classifications of remotely sensed data. Remote sens. Environ.37:35(46). Available at https://www.sciencedirect.com/science/article/abs/pii/003442579190048B?via%3Dihub

Curtis, P.G., Slay, C.M., Harris, N.L., Tyukavina, A., Hansen, M.C., 2018. Classifying drivers of global forest loss. Science 361, 1108–1111.. doi:10.1126/science.aau3445

Dalla Corte, A.P., Rex, F.E., Almeida, D.R.A.D., Sanquetta, C.R., Silva, C.A., Moura, M.M., Wilkinson, B., Zambrano, A.M.A., Cunha Neto, E.M.D., Veras, H.F.P., Moraes, A.D., Klauberg, C., Mohan, M., Cardil, A., Broadbent, E.N., 2020. Measuring Individual Tree Diameter and Height Using GatorEye High-Density UAV-Lidar in an Integrated Crop-Livestock-Forest System. Remote Sensing 12, 863.. doi:10.3390/rs12050863

Dvorák. D., Vasutova. M., Hofmeister. J., Beran. M., Hosek, J., Betak. J., Burel. J. & Deckerova. H. (2017). Macrofungal diversity patterns in central European forests affirm the key importance of old-growth forests. Elsevier. Volume 27, Part B, June 2017, Pages 145-154

European Environment Agency. (2014). Developing a forest naturalness indicator for Europe. Concept and methodology for a high nature value (HNV) forest indicator. EEA Technical report 13/2014 available at DOI: 10.13140/2.1.1726.3684

Evans. J. (1982). Plantation forestry in the tropics. 2nd ed. Oxford: Oxford University Press. Available at https://books.google.no/books?hl=en&lr=&id=h1oF-88qKRsC&oi=fnd&pg=PA3&dq=industrial+plantation+forestry&ots=9Gqr1gzE1L&sig=_aTHlTFcSYHBI0RELAl3KUK2YTE&redir_esc=y#v=onepage&q=industrial%20plantation%20forestry&f=false

Feller. M. C. (2003). Coarse woody debris in the old growth forests of British Columbia. Environment Reviews. 11(S1): 135-157. https://doi.org/10.1139/a03-008

Felton, A., Lindbladh, M., Brunet, J., Fritz, Ö., 2010. Replacing coniferous monocultures with mixed-species production stands: An assessment of the potential benefits for forest biodiversity in northern Europe. Forest Ecology and Management 260, 939–947. doi: 10.1016/j.foreco.2010.06.011

Fitzpatrick. B. R., Baltensweiler. A., Düggelin. C., Frafel. M., Freitag. A., Vandegehuchte. M L., Wermelinger. B. & Risch. A. C. (2020). The distribution of a group of keystone species is not associated with anthropogenic habitat disturbance. Biodiversity research: January 2020. DOI: 10.1111/ddi.13217

Fjeldstad. W (2007). Tankeverk – skaperverk – byggverk. Høgskolen i Hedmark. Rapport nr.9 available at https://brage.inn.no/innxmlui/bitstream/handle/11250/133814/rapp14_2008.pdf?sequence=1&isAllowed=y

Frivold. L. H. & Frank. J. (2001). Growth of mixed birch-coniferous stands in relation to pure coniferous stands at similar sites in south-eastern Norway. Scandinavian journal of forest research. Ås. Agriculture university of Norway, Department of forest sciences.

Garcia. O. (n.d.). Site index: Concepts and methods, 26.5.21. Available at https://www.researchgate.net/publication/266731647_Site_index_Concepts_and_methods

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E., Sodhi, N.S., 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. Nature 478, 378–381.doi:10.1038/nature10425

Gjerdrum, P. 2003. Heartwood in relation to age and growth rate in Pinus sylvestris L. in Scandinavia. *Forestry: An International Journal of Forest Research* 76(4): 413–424. Available at: https://dx.doi.org/10.1093/forestry/76.4.413.

Goodbody. T. R. H., Coops. N. C. & White. J. C. (2019). Digital Aerial Photogrammetry for Updating Area-Based Forest Inventories: A Review of Opportunities, Challenges, and Future Directions. Current Forestry Reports (2019) 5:55–75 https://doi.org/10.1007/s40725-019-00087-2

Hansen, A.J., Spies, T.A., Swanson, F.J., Ohmann, J.L., 1991. Conserving Biodiversity in Managed Forests. BioScience 41, 382–392.. doi:10.2307/1311745

Ho, T.K., 1995. Random decision forests. In *Proceedings of 3rd international conference on document analysis and recognition*. pp. 278–282.

Hyyppä, J., Hyyppä, H., Inkinen, M., Engdahl, M., Linko, S., Zhu, Y.-H., 2000. Accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes. Forest Ecology and Management 128, 109–120. doi:10.1016/s0378-1127(99)00278-9

Jaeglé, L., Quinn, P. K., Bates, T. S., Alexander, B., and Lin, J.-T.: Global distribution of sea salt aerosols: new constraints from in situ and remote sensing observations, Atmos. Chem. Phys., 11, 3137–3157, https://doi.org/10.5194/acp-11-3137-2011, 2011.

JALAS, J. 1955: Hemerobe und hemerochore Pflanzenarten. Ein terminologischer Versuch. Acta Soc. Fauna Flora Fenn. 72/11, 1-15.

Kangas, A., Astrup, R., Breidenbach, J., Fridman, J., Gobakken, T., Korhonen, K.T., Maltamo, M., Nilsson, M., Nord-Larsen, T., Næsset, E., Olsson, H., 2018. Remote sensing and forest inventories in Nordic countries – roadmap for the future. Scandinavian Journal of Forest Research 33, 397–412. doi:10.1080/02827581.2017.1416666

Kangas A., Gobakken T., Puliti S., Hauglin M., Næsset E. (2018). Value of airborne laser scanning and digital aerial photogrammetry data in forest decision making. Silva Fennica vol. 52 no. 1 article id 9923. 19 p.

Kartverket (2021). Available at https://doi.org/10.14214/sf.9923https://hoydedata.no.

Khorram S., van der Wiele C.F., Koch F.H., Nelson S.A.C., Potts M.D. (2016) Remote Sensing: Past and Present. In: Principles of Applied Remote Sensing. Springer, Cham. https://doi.org/10.1007/978-3-319-22560-9_1

Kucera. B. (1998). Treets oppbygning og vedanatomi. Norsk Institutt for Skogforskning. Ås

Kullman, L., 1996. Norway Spruce Present in the Scandes Mountains, Sweden at 8000 BP: New Light on Holocene Tree Spread. Global Ecology and Biogeography Letters 5, 94. doi:10.2307/2997447

Levin, K., Mcdermott, C., & Cashore, B. 2008. The climate regime as global forest governance: can reduced emissions from Deforestation and Forest Degradation (REDD) initiatives pass a dual effectiveness test? *International Forestry Review* 10(3): 538–549.

Liaw. A., And Wiener. M. (2002). Classification and regression by Random Forest- R news 2(3), 18-22

Lie, M.H., Josefsson, T., Storaunet, K.O., Ohlson, M., 2012. A refined view on the "Green lie": Forest structure and composition succeeding early twentieth century selective logging in SE Norway. Scandinavian Journal of Forest Research 27, 270–284.. doi:10.1080/02827581.2011.628950

Luyssaert, S. et al. 2008. Old-growth forests as global carbon sinks. *Nature* 455(7210): 213–215. Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455, 213–215. doi:10.1038/nature07276

Nelson, R., 2013. How did we get here? An early history of forestry lidar1. Canadian Journal of Remote Sensing 39, S6–S17. doi:10.5589/m13-011

Nita. M. D., Munteanu. C., Gutman. G., Ioan Vasile Abrudan. I. V., & Radeloff. V. C. (2018). Widespread forest cutting in the aftermath of World War II captured by broad-scale historical Corona spy satellite photography. Elsevier, 204: 322-332. https://doi.org/10.1016/j.rse.2017.10.021

Noordermeer, L., Bollandsås, O.M., Gobakken, T., Næsset, E., 2018. Direct and indirect site index determination for Norway spruce and Scots pine using bitemporal airborne laser scanner data. Forest Ecology and Management 428, 104–114. doi:10.1016/j.foreco.2018.06.041

Noordermeer, L., Gobakken, T., Næsset, E., Bollandsås, O.M., 2020. Predicting and mapping site index in operational forest inventories using bitemporal airborne laser scanner data. Forest Ecology and Management 457, 117768. doi:10.1016/j.foreco.2019.117768

Næsset, E., 2004. Practical large-scale forest stand inventory using a small-footprint airborne scanning laser. Scandinavian Journal of Forest Research 19, 164–179.. doi:10.1080/02827580310019257

Male, T.D., & Bean, M.J. 2005. Measuring progress in US endangered species conservation. *Ecology Letters* 8(9): 986–992.

Maltamo, M., & Packalen, P. 2014. Species-Specific Management Inventory in Finland. In *Managing Forest Ecosystems*, 241–252. Managing Forest Ecosystems.

Marquis, B., Duval, P., Bergeron, Y., Simard, M., Thiffault, N., Tremblay, F., 2021. Height growth stagnation of planted spruce in boreal mixedwoods: Importance of landscape, microsite, and growing-season frosts. Forest Ecology and Management 479, 118533.. doi:10.1016/j.foreco.2020.118533

Martinelli, L.A., Almeida, S., Brown, I.F., Moreira, M.Z., Victoria, R.L., Filoso, S., Ferreira, C.A.C., Thomas, W.W., 2006. Variation in Nutrient Distribution and Potential Nutrient Losses by Selective Logging in a Humid Tropical Forest of Rondonia, Brazil1. Biotropica 32, 597–613.. doi:10.1111/j.1744-7429.2000.tb00507.x

McRoberts, R.E., Winter, S., Chirici, G., Lapoint, E., 2012. Assessing Forest Naturalness. Forest Science 58, 294–309. doi:10.5849/forsci.10-075

Michel, A. and Winter, S. 2009 Tree microhabitat structures as indicators of biodiversity in Douglas-fir forests of different stand ages and management histories in the Pacific Northwest, USA. *Forest Ecol. Manage.* **257**, 1453–1464. DOI:10.1016/j.foreco.2008.11.027

Mikola, P.U., 1986. Relationship between nitrogen fixation and mycorrhiza. MIRCEN Journal of Applied Microbiology and Biotechnology 2, 275–282.. doi:10.1007/bf00933493

Modress. C. (2020). Deforestation in Iceland. Available at https://storymaps.arcgis.com/stories/a4e20c53ee77427cb587cb70252f294b

O'Hagan, S., Wright Muelas, M., Day, P.J., Lundberg, E., Kell, D.B., 2018. GeneGini: Assessment via the Gini Coefficient of Reference “Housekeeping” Genes and Diverse Human Transporter Expression Profiles. Cell Systems 6, 230–244.e1.. doi:10.1016/j.cels.2018.01.003

Overdevest, C. (2010). Comparing forest certification schemes: the case of ratcheting standards in the forest sector. *Socio-Economic Review* 8(1): 47–76.

Pawson. S.M., Brockerhoff. E. G., Norton. D. A., and Didham. R. K. (2006). Clear-fell harvest impacts on biodiversity: past research and the search for harvest size thresholds. Canadian Journal of Forest Research. 36(4). https://doi.org/10.1139/x05-304

Pesonen, A., Maltamo, M., Eerikäinen, K., & Packalèn, P. 2008. Airborne laser scanning-based prediction of coarse woody debris volumes in a conservation area. *Forest Ecology and Management* 255(8-9): 3288–3296.

Peterken, G.F., 1993: Long-term studies in forest nature reserves. In: BROEKMEYER, M.E.A.;VOS, W.; KOOP, H. (eds) European forest reserves. Proceedings of the European forest reserves workshop. Wageningen, PUDOC-DLO. 306 pp.

Petit. B. & Montagnini. F. (2004). Growth equations and rotation ages of ten native tree species in mixed and pure plantations in the humid neotropics. Elsevier. 199(2-3) 243-257. https://doi.org/10.1016/j.foreco.2004.05.039

Potapov, P., A. Yaroshenko, S. Turubanova, M. Dubinin, L. Laestadius, C. Thies, D. Aksenov, A. Egorov, Y. Yesipova, I. Glushkov, M. Karpachevskiy, A. Kostikova, A. Manisha, E. Tsybikova, and I. Zhuravleva.2008. Mapping the world's intact forest landscapes by remote sensing. Ecology and Society13(2): 51.[online] URL:http://www.ecologyandsociety.org/vol13/iss2/art51

R Core Development Team. (2021). RStudio: Integrated Development for R (Version 1.4.1106): RStudio.inc.

Rakha, T., & Gorodetsky, A. 2018. Review of Unmanned Aerial System (UAS) applications in the built environment: Towards automated building inspection procedures using drones. *Automation in Construction* 93: 252–264.

Ranius, T., Niklasson, M., Berg, N., 2009. Development of tree hollows in pedunculate oak (Quercus robur). Forest Ecology and Management 257, 303–310.. doi:10.1016/j.foreco.2008.09.007

Romijn, E., Ainembabazi, J.H., Wijaya, A., Herold, M., Angelsen, A., Verchot, L., Murdiyarso, D., 2013. Exploring different forest definitions and their impact on developing REDD+ reference emission levels: A case study for Indonesia. Environmental Science & Policy 33, 246–259. doi: 10.1016/j.envsci.2013.06.002

Rousseau, R., Van Hecke, P., 1999. None. Acta Biotheoretica 47, 1–5.. doi:10.1023/a:1002093825480

Roy, D.P., Wulder, M.A., Loveland, T.R., W., C.E., Allen, R.G., Anderson, M.C., Helder, D., Irons, J.R., Johnson, D.M., Kennedy, R., Scambos, T.A., Schaaf, C.B., Schott, J.R., Sheng, Y., Vermote, E.F., Belward, A.S., Bindschadler, R., Cohen, W.B., Gao, F., Hipple, J.D., Hostert, P., Huntington, J., Justice, C.O., Kilic, A., Kovalskyy, V., Lee, Z.P., Lymburner, L., Masek, J.G., McCorkel, J., Shuai, Y., Trezza, R., Vogelmann, J., Wynne, R.H., Zhu, Z., 2014. Landsat-8: science and product vision for terrestrial global change research. Remote Sens. Environ. 145, 154–172. http://dx.doi.org/10. 1016/j.rse.2014.02.001

Schuck, A.; Parviainen, J.; Bucking, W., 1994: A review of approaches to forestry research onstructure, succession and biodiversity of undisturbed and semi-natural forests and woodlands in Europe. Working paper 3. Joensuu, European Forest Institute. 62 pp.

Shao. G. & Zhoa. G. (1998). Conservation issues. Protection versus harvest of old-growth forests on Changbai mountain (China & North Korea): A remote sensing application. Natural Areas Association. 18 (4) (October 1998) 358-365. Obtained from https://kopernio.com/viewer?doi=10.2307%2F43911789&token=WzMxNjU3NTksIjEwLjIzMDcvNDM5MTE3ODkiXQ.fRIOwP0Izl3n-8qyFTjaqpBeQm0

Simkin, J., Ojala, A., & Tyrväinen, L. 2020. Restorative effects of mature and young commercial forests, pristine old-growth forest, and urban recreation forest - A field experiment. *Urban Forestry & Urban Greening* 48: 126567.

Singh. J. (2020). Random Forest: Pros and cons. 22.4.21 Data Driver Investor.

Socha, J., Solberg, S., Tymińska-Czabańska, L., Tompalski, P., Vallet, P., 2021. Height growth rate of Scots pine in Central Europe increased by 29% between 1900 and 2000 due to changes in site productivity. Forest Ecology and Management 490, 119102.. doi:10.1016/j.foreco.2021.119102

Spies. T. A. (2004). Ecological concepts and diversity of old-growth forests. Journal of forestry. Journal of Forestry, 102 (3): 14-20. https://doi.org/10.1093/jof/102.3.14

Steinhardt. U., Herzog. F., Lausch. A., Müller. E., & Lehmann. S. (1999). Hemeroby index for landscape monitoring and evaluation. Oxford: EOLSS. Available at https://www.researchgate.net/publication/237201744_Hemeroby_index_for_landscape_monitoring_and_evaluation

Sturtevant, B.R., Seagle, S.W., 2004. Comparing estimates of forest site quality in old second-growth oak forests. Forest Ecology and Management 191, 311–328.. doi:10.1016/j.foreco.2003.12.009

Sverdrup-Thygeson, A., Ørka, H.O., Gobakken, T., & Næsset, E. 2016. Can airborne laser scanning assist in mapping and monitoring natural forests? *Forest Ecology and Management* 369: 116–125.

Søgaard, G., Eriksen, R., Astrup, R.A., & Øyen, B.-H., 2012. Effekter av ulike miljøhensyn på tilgjengelig skogareal og volum i norske skoger. Norsk institutt for skog og landskap.

Turner, D.P., Guzy, M., Lefsky, M.A., Ritts, W.D., Van Tuyl, S., Law, B.E., 2004. Monitoring Forest Carbon Sequestration with Remote Sensing and Carbon Cycle Modeling. Environmental Management 33. doi:10.1007/s00267-003-9103-8

Wehr, A., & Lohr, U. 1999. Airborne laser scanning—an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing* 54(2-3): 68–82.

White. C. J., Coops. N. C, Wulder. M. A., Vastaranta. M., Hilker. T. & Tompalski. P. (2016) Remote Sensing Technologies for Enhancing Forest Inventories: A Review, Canadian Journal of Remote Sensing, 42:5, 619-641, DOI: 10.1080/07038992.2016.1207484

Wielgolaski. F. M. (2005). History and environment of the Nordic mountain birch. Plant ecology, herbivory, and human impact in Nordic mountain forests. DOI: 10.1007/3-540-26595-3_1

Valbuena, R., Eerikäinen, K., Packalen, P., Maltamo, M., 2016. Gini coefficient predictions from airborne lidar remote sensing display the effect of management intensity on forest structure. Ecological Indicators 60, 574–585.. doi: 10.1016/j.ecolind.2015.08.001

Vauhkonen. J., Maltamo.M., McRoberts. R. E. & Næsset. E. (2014). Forestry Applications of Airborne Laser Scanning: Concepts and Case Studies, Springer 27. DOI 10.1007/978-94-017-8663-8__1, Zhou, G., Liu, S., Li, Z., Zhang, D., Tang, X., Zhou, C., Yan, J., Mo, J., 2006. Old-Growth Forests Can Accumulate Carbon in Soils. Science 314, 1417–1417. doi:10.1126/science.1130168

Ørka. H. O., Jutras-Perreault. M. C., Gallis. J., Svensson. A., Hansen. E. & Gobakken. T. (2019). Fjernmålingsbasert kartlegging og overvåkning av økosysmet skog – på veg mot et nasjonalt heldekkende skogøkologisk grunnkart. Miljødirektoratet report 9/2018. Available at https://www.miljodirektoratet.no/globalassets/publikasjoner/m940/m940.pdf

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway