Student thesis series INES nr 535

Where are the forests with highest biomass in Sweden located?

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2021

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Hugo Bergman (2021).
Where are the forests with highest biomass in Sweden located? (English)
Var finns skogarna med högst biomassa i Sverige?
Bachelor’s degree thesis, 15 credits in Physical Geography and Ecosystem Analysis
Department of Physical Geography and Ecosystem Science, Lund University

Level: Bachelor of Science (BSc)

Course duration: *November* 2020 until *January* 2021

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Bachelor thesis, 15 credits, in
Physical Geography and Ecosystem Science

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Acknowledgements

I would like to thank my supervisor Anders Ahlström who inspired the project and was there to nudge me back on track when I was not sure of where to take it. Thanks also to Julia, Lotte, Marieke, and Tanja for taking time to give valuable feedback.

Abstract

Identification of high-biomass sites can lead to further studies on their ecology with the purpose to inform climate change mitigation decisions or give an indication to which sites need stronger protection. The purpose of this study was to, via a remotely sensed data set of tree biomass, identify the locations with the highest biomass in Sweden. As biomass varies across the extent of a stand or forest, the identification was done over four different sizes: 100 ha (1000 m x 1000 m), 25 ha (500 m x 500 m), 6,25 ha (250 m x 250 m) and 1 ha (100 m x 100 m). Additionally, the distribution of the sites across geographical regions and forest management intensities was investigated.

It was found that the forests with the highest biomass nationwide were the nemoral nature reserve Osbecks bokskogar (for 100 ha, 220 t/ha), the south boreal non-protected island Upprannsön (for 25 and 6.25 ha, 251 and 277 t/ha respectively) as well as the north boreal managed forest Västansjö (1 ha, 376 t/ha). Most of the top sites for the largest size were in primary- and protected forests as these have relatively consistent biomass across their whole extent. Protected forests differ from production forests which instead consist of individual stands of varying, sometimes low, biomass which means that they were not well represented among the top sites for the larger sizes. At a smaller size, 1 ha, production forests made up a larger fraction of the highest biomass stands as individual stands late in their rotation cycle in some cases contained very high biomass. Most of the top values were found in the southern- to middle regions in Sweden, with very few being located in the northernmost areas.

Keywords: Biomass, Biomass density, Forest biomass, Boreal forests, Forest management, Primary forest, Protected forest

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1 Introduction

Increasing concentration of carbon dioxide and other greenhouse gases in the atmosphere are causing Earth's climate to change rapidly. This change in climate have profound consequences for ecosystems as well as humans across Earth (IPCC 2014). Thus, research on carbon storage is of high priority to policy-makers worldwide. Terrestrial biomass, which is mainly located in forests, is a carbon reservoir globally. The amount of carbon stored in terrestrial vegetation is approximately 550 Pg (Houghton 2007), and the forest carbon sink is estimated to be over 2 Pg C per year (Pan *et al*. 2011). Meanwhile, many forests are under threat from climate change, land degradation, and land conversion (IPCC 2001).

Land conversion, especially of old-growth forests, generally decreases the amount of carbon stored in the ecosystem and it can take hundreds of years for regrown or newly planted forests to recover the original amount of stored carbon (Harmon, Ferrell and Franklin 1990). Primary forests in Sweden have also been shown to generally both be slightly more efficient at sequestering carbon in stands of similar age (Ahlström *et al*. 2020) and at storing more carbon in the living tree biomass than comparable managed secondary forests (Johannesson 2020). Heterogeneous old-growth forests which have not yet been heavily industrialized are also important for biodiversity with dead trees being essential for many species (Fridman 2000).

While calculating general biomass across ecosystems is relatively straightforward (e.g. Keith, Mackey and Lindenmayer 2009), it is more complicated to conclude which individual forest or forest stand is that with the highest biomass over an area. The difficulty arises from biomass varying across the extent of a forest as no forest is completely homogeneous. The variation is particularly clear over managed forests as these often have stands of drastically different biomass next to each other. When identifying the sites with highest biomass it is therefore necessary to specify the scale. Is the biomass highest over $100m^2$, i.e. only including a couple of trees, or perhaps several square kilometres, i.e. including tens of thousands of trees?

Perhaps partly due to the stand size complication, the forests with highest biomass in Sweden have to my knowledge not been identified before, an apparent knowledge gap which also seems to exist for many other countries. Knowledge of sites with particularly high biomass could further lead to studies of their ecology as evidence to inform climate change mitigation measures or to identify sites that need stronger protection.

To specify, the aim of this thesis is to answer the following questions:

- What are Sweden's forests with highest biomass for 1 ha, 6.25 ha, 25 ha, and 100 ha?
- How pristine are these forests? Are they managed, formally protected, or even primary?
- In which regions of Sweden are these forests located?

To identify sites of particularly high biomass, a method based on national biomass data which had been remotely collected via airborne laser scanning as well as adjusted for different forest types (Nilsson *et al.* 2017; Johannesson 2020) was used. The dataset on which the study is based (Johannesson 2020) consists of dry, living tree biomass. The site identification is done for four different sizes, 1 ha, 6.25 ha, 25 ha, and 100 ha, to achieve a comprehensive view. There is a slightly larger focus on the largest of the sizes, 100 ha, as these are the forests which store the most biomass overall.

Besides solely identifying high-biomass sites it is further investigated in which regions, as well as types of forests, these sites are found in order to connect the topic to the wider discussion on land use. The thesis adds to the knowledge contributed by Johannesson (2020), as well as to that of biomass storage and Swedish forests in general.

2 Background

2.1 Biomass stocks between biomes

Biomass is organism material (e.g. trees) but in this report it is generally defined as the weight of organisms per unit area, also known as biomass density. Biomass storage in forests varies between biomes. The biome with highest living above-ground biomass is cool, moist temperate forest. This biome includes the forest type with the world's highest biomass: the south Australian *Eucalyptus regnans* forests with an average of 1 053 tonnes of carbon in above ground living biomass per hectare (Keith, Mackey and Lindenmayer 2009).

Sweden is to nearly 70% covered by forest, making it the country with the second highest proportion against the total land area in Europe (Swedish Forest Agency 2019), behind Finland. The biome dominating in central to northern Sweden is boreal forest (Fridman 2000). Previous studies suggest an average value of above ground living C in these moist boreal forests to be 24 t C/ha (Keith, Mackey and Lindenmayer 2009) and boreal forests sequester on average around 440 t C/ha in a year, slightly less than half of the sequestration in temperate forests (Pan *et al.* 2011). While this study focuses on living above-ground tree biomass, other important boreal forest carbon pools include dead plant material, below-ground vegetation, understorey, litter, and soils (Vucetitch *et al.* 2000; Finér *et al.* 2003).

2.2 Factors controlling biomass

The main factors determining carbon stocks, and thus also biomass, in forests have been classified into three groups: (*i*) environmental conditions, (*ii*) life history, and (*iii*) the impacts of natural disturbance (Keith, Mackey and Lindenmayer 2009). The life history aspect (*ii*) and its relationship to biomass has been further investigated in several recent studies. The accumulated results, both in Sweden and other regions, seem to indicate that relatively old, or even primary, forests contain higher biomass than comparable managed forests (Johannesson 2020; Molina-Valero *et al.* 2021). Age is the main controlling factor of biomass stocks for managed secondary forests (Seely, Welham and Kimmins 2002).

Johannesson (2020) additionally found biomass to decrease at lower temperatures, more northern latitudes, and higher altitude. A latitudinal gradient in northern Europe, with biomass decreasing to the north, has also been found by Vucetitch *et al.* (2000).

2.3 Measuring biomass and identifying high-biomass sites

Studies on biomass are usually based on plot and field measurements directly (e.g. Vucetitch *et al.* 2000; Finér *et al.* 2003; Keith, Mackey and Lindenmayer 2009). While yielding accurate results for individual stands and being necessary for evaluation of larger data sets, plot measurements on their own have limited potential to identify particularly biomass-rich sites across large regions. The identification is however something which national remotely sensed data, such as that from Nilsson *et al*. (2017) or Johannesson (2020), allows.

2.4 Definitions

- *Biomass*

Weight of organisms within a unit area, usually in tonnes (Mg) per hectare.

- *Classes*

A broad division of management intensity based on pristineness and protection status. Further described in 3.3.

- *Size / Forest size*

Size of the individual output grid cells in hectares. The sizes are based on the four resolutions used in the processing: 100 m x 100 m, 250 m x 250 m, 500 m x 500 m and 1000 m x 1000 m which lead to sizes of 1 ha, 6.25 ha, 25 ha, and 100 ha, respectively.

- *Grid cells*

Squares that are the output of the processing and make up the raster layers.

- *Peak biomass*

Within a site there are usually many grid cells, some with very similar biomass values. The peak biomass is the value of the grid cell with highest average biomass within a site.

- *Production forest*

Forest managed for economic purposes. The term “managed forest” also usually refers to production forest.

- *Productive forest*

Any forest that on average produces at least 1 m^3 of stem volume per hectare each year. (Swedish Forest Agency 2019).

- *Regions*

A broad division of Sweden into four biogeographical regions based on a report by the Swedish Forest Agency (2001) (see 3.4.).

- *Sites*

The locations, meaning different forests. Usually consist of several grid cells, the number depends on the sizes of the grid cells and the sites. For classes *primary forests* (e.g. Båtfors nature reserve) and *other protected forests* (e.g. Osbecks bokskogar nature reserve) named after the protected area they are located in. For *all other forest* either named after the closest community (e.g. Tjörnarp) or a distinguishing natural feature (e.g. Dyverdalen).

3 Method

3.1 Software

All spatial analysis, processing, and map-making was conducted in Esri’s ArcGIS Pro (v.2.5, 2020). Statistics was conducted and non-map figures made in Microsoft Excel (2016) as well as MATLAB (v.R2020b) by MathWorks.

3.2 Data

3.2.1 Data provided for the study

Table 1. Description and provider of the data.

Data description	Provided by
Rasters of dry weight tree biomass, adjusted for primary and secondary forests.	Johannesson (2020).
Extent of primary forests in Sweden.	Ahlström *et al*. (2020).
Extent of various types of protected areas in Sweden.	Swedish Environmental Protection Agency. Protected nature (sv. skyddad natur) (2020).
Boolean raster layer of Swedish productive forest cover based on NMD (national land cover) data.	Keskitalo *et al.* (2019).
Swedish county- and municipality borders.	The Swedish electoral authority (sv. Valmyndigheten) (2010).
Country borders. Used to produce maps.	Eurostat, GISCO.

Table 1 briefly describes the data used in the study. Only six different sets were needed, and they were retrieved from public authorities (e.g. Eurostat, Swedish Environmental Protection Agency) as well as previous studies (e.g. Ahlström *et al.* 2020; Johannesson 2020).

3.2.2 Biomass raster layers

A raster layer of dry weight, living above ground biomass (AGB) (Nilsson *et al.* 2017) were the primary data and allowed for this study to be made. The layer was produced between 2009 and 2015 with air borne laser scanning (ALS) combined with field data collected by the Swedish National Forest Inventory (NFI) and regression models. The field data was based on circa 11 500 permanent plot measurements taken between 2009 and 2013 from clusters of plots spread over the country, although more densely located in the southern regions as these forests are more heterogeneous than those further north. The ALS flying height was between 1700 m and 2300 m and 13 different types of scanners were used. Southern Sweden was mainly scanned in spring and autumn when the leaves were off and northern Sweden was mainly scanned in the leaf-on period of summer. On a plot level, the RMSE (root mean square error) as percent of mean field value was 23.7% in Northern Sweden, 27.3% in Mid Sweden, and 22.5% in Southern Sweden (Nilsson *et al.* 2017).

The result was layers for several different forest variables, including dry weight AGB, at a resolution of 12.5 by 12.5 metres (Nilsson *et al.* 2017). The AGB raster does not include dead wood biomass, soil stored carbon, or tree stubs. This original ABG layer by Nilsson *et al.* (2017) was in turn adjusted by Johannesson (2020) for primary forests as well as secondary or production forests respectively into the main data used in this study. This was based on adjusting values against the NFI data plots for production and primary forests separately and resulted in two layers of dry weight living tree biomass instead of AGB. However, after the adjustment the plot points and biomass raster did not have a 1:1 relationship. At a 95% confidence interval the slope was 0.67x for secondary forests and 0.75x for primary forests, meaning that the raster overestimated biomass slightly in both forest types but more strongly in secondary forests (Johannesson 2020). The correlation was however still significant ($p < 0.05$) for both types, with a Pearson correlation coefficient of 0.68 and 0.83 (Johannesson 2020).

To achieve the 1:1 relationship, the raster values which had been extracted to plot points were multiplied with the slope coefficients of the previously conducted linear regressions. The secondary forest biomass raster had a slightly better accuracy and fit with the NFI plot points than the primary forest raster due to a higher amount of data points but the relationship was still strong for the primary forest biomass raster. Johannesson (2020) concludes that both rasters are at least suitable for large scale estimation of the biomass stocks.

3.2.3 Productive forest cover layer

The layer over productive forest allowed for an exclusion of areas that did not belong to productive forests, including all non-forest areas of Sweden and all non-productive forests. It was produced by Metria and the Swedish Environmental Protection Agency and includes productive forests from the forest layers in the national land cover data (NMD). The layer was created by combining satellite-based data on landscape changes with laser scanning information, such as tree height, and map data, such as land cover and soil information (Keskitalo *et al.* 2019).

3.3 The management intensity classes

3.3.1 Definition of classes

Three classes of forest types, ranging from most to least pristine, were created to facilitate comparisons between different forests by management intensity:

1. ***Primary forest***

The *primary forest* layer was produced by Ahlström *et al.* (2020). The locations were defined as "naturally regenerated forests of predominantly native species that are currently (and historically) insignificantly disturbed by human activities" based on an inventory from 1982. The sites from the inventory were digitized, and forests felled since 1982 excluded.

2. ***Other protected forest***

For the second class: *other protected forest*, national vector maps on protection types were collected from the Swedish Environmental Protection Agency's (2020) website and aggregated into one layer. The protection types included in the class are

- Nature reserves (sv. naturreservat)
- National parks (sv. nationalparker)
- Nature conservation areas (sv. naturvårdsområden)
- Natura 2000 SCI (sites of community importance).

The decision to use these four protection types was partly based on a report from the Swedish Environmental Protection Agency (Ahlkrona *et al.* 2017) which, in its definition of protected areas, additionally includes nature protection agreements (sv. naturvårdsavtal) and biotope protection areas (sv. skogliga biotopskyddsområden). However, the nature protection agreements were excluded due to them being time-limited and dependent on private owners. The biotope protection areas were excluded due to their small size, often only a few hectares, which makes them unsuitable for the processing steps taken within this project.

Forestry can still occur in Natura 2000 SCI, nature conservation areas and nature reserves as the management status depends on the specific regulations for each individual area. It was, within the scope of this thesis, not possible to exclude each of the areas without regulations against forestry so all areas within these four protection types are included in the class. Essentially, it was assumed that these areas in general experience a lower amount of management than forests that are not formally protected.

3. ***All other forest***

The class *all other forest* includes all forest of Sweden not already included in the previous two classes. The layer was produced by creating a vector layer covering Sweden and then excluding the areas covered by *primary forest* and *other protected forest*. It by far covers the largest area of the three classes and is assumed to mainly consist of managed production forest since non-forest land, primary forests, and protected forests are all excluded and managed forests in total cover 57% of Sweden's total land area (KSLA 2015).

3.3.2 Biomass layers used for each class

As mentioned in section 3.2.2., Johannesson (2020) had produced two biomass layers from the general AGB layer (Nilsson *et al*. 2017). Following the definitions from Johannesson's study, the layer adjusted for primary forests was extracted to cover the extent of the *primary forest* layer provided by Ahlström *et al.* (2020) while the production forest biomass layer was extracted to cover the extent of *all other forest*. However, Johannesson had not adjusted any layer for protected forests that were not primary. These areas had been excluded from the adjustments completely. While it goes against Johannesson's recommendations, it was necessary to use one of the two adjusted layers for the class *other protected forest* as it was not possible, within the scope of the project, to produce a new adjusted layer. The assumption was made that the production forest layer would be more accurate for *other protected forest* as they are not primary but could have historically been used in forestry. To summarize, eventually three raster layers of biomass had been produced. Each covering the same extent as the vector layer of the class they had been assigned to.

3.4 The geographical regions

Four geographical regions were used to compare biomass across Sweden. The regions were a result of a slight adjustment of a division common in reports on Swedish forests and forestry (for example Swedish Forest Agency 2019). This division was originally made by the Swedish Forest Agency (2001). It divides Sweden into five regions that mainly follow county borders:

- **Nemoral**: Skåne, Blekinge, and Halland.
- **Boreonemoral**: Kronoberg, Jönköping, Kalmar, Västra Götaland, Östergötland, Södermanland, Örebro, Uppsala, Västmanland, Stockholm, and Gotland.
- **South boreal**: Dalarna, Värmland, Gävleborg, Västernorrland, and Jämtland.
- **North boreal**: Västerbotten and Norrbotten.
- **Mountain bordering** (sv. "Fjällnära"): The western and mountainous parts of the south boreal and north boreal regions. Not following county borders.

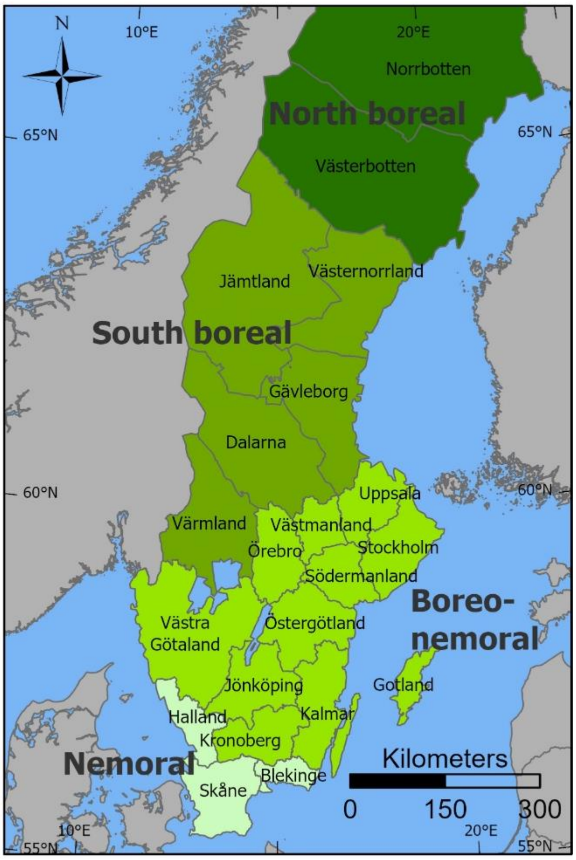


Figure 1. Map of Sweden showing the 21 counties and four regions.

However, the mountain bordering region was not classified or specified in this study due to a lack of data describing the exact extent of the region. The areas belonging to this region were instead assigned to the north- or south boreal region based on the county borders (figure 1).

Nemoral forests have in previous studies been characterised by being essentially only deciduous in terms of native species. One of the dominating species is beech (*Fagus sylvatica*). However, due to the presence of planted production forests, there also exist coniferous forests in these areas (Diekmann 1994). The nemoral region, at least its northern section, is sometimes also classified as part of the larger temperate zone of Europe (Ahti, Hämet-Ahti and Jalas 1968). The border to the boreonemoral region can be defined as where the coniferous Norway spruce (*Picea abies)* starts to occur naturally. This species, together with Scots spruce (*Pinus sylvestris*), dominates the boreonemoral region, with rare but occasional deciduous sections as most of the nemoral species are able to survive here as well (Diekmann 1994). The border to the boreal (south) can be defined as the northern distribution limit of oak (*Quercus robur*). Most nemoral tree species are absent from the boreal regions while the conifers dominate the forest landscapes (Diekmann 1994).

3.5 Processing steps

By using the layer of productive forest (from Keskitalo *et al.* 2019), non-productive forests and other land types were excluded. Layers covering each of the classes' forested extent were produced. As mentioned before, each of the biomass raster layers had a resolution of 12.5 m. The grid cells of the layers were aggregated, using the mean value, into new layers with resolutions 100 m, 250 m, 500 m, and 1000 m for each class. In cases where less than half of the output grid cell was covered by forest the grid cell was excluded as the purpose of the study regards the forest density. Including areas only consisting of sparse forest spots inherently opposes this purpose.

Twelve raster layers resulted from the processing. One layer for each class and resolution (see figure 2 for resolution 250 m), with each grid cell in the layers showing the average biomass value of the forested cells in the area covered by that output grid cell. The different class layers of each resolution were then combined, enabling identification of the individual output grid cells with the highest average biomass (see figure 3 for a flow chart of these steps).

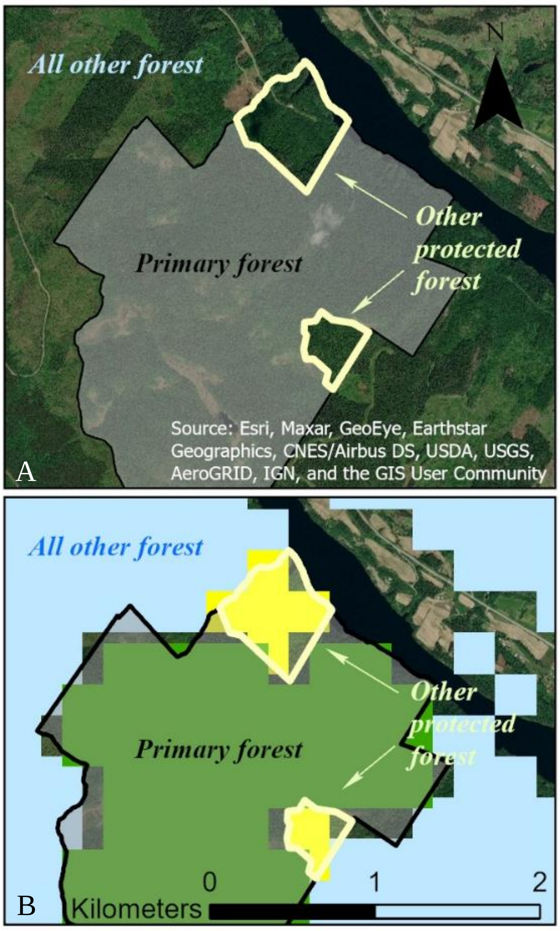


Figure 2. The vector layers of classes (A) and the cover of output grid cells of biomass for each class (B). This example is for the size 6.25 ha (250 m x 250 m) by Sundsjöåsen.

Note the resolutions 100 m, 250 m, 500 m, and 1000 m. These correspond to 1 ha, 6.25 ha, 25 ha and 100 ha (1 km^2) respectively. To avoid confusion and to better fit the purpose of the study, the word forest size and the unit hectares are henceforth used instead of resolution.

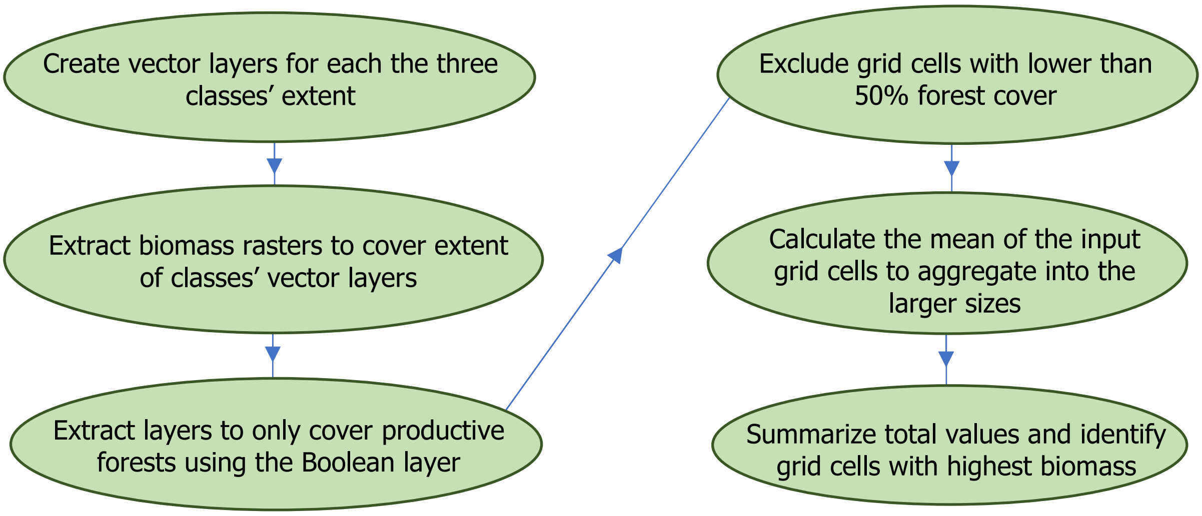


Figure 3. Flow chart of the main processing steps.

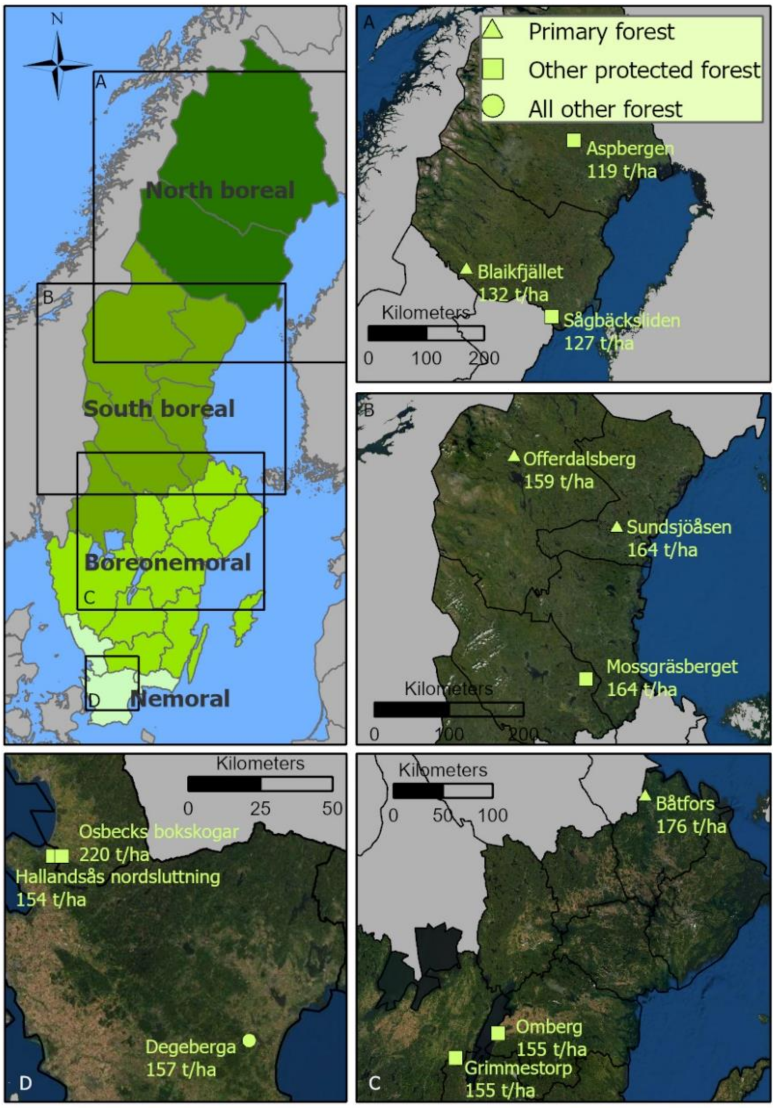
3.6 Statistics

To investigate if the regions had significantly different biomass overall, the 100 ha values were tested statistically to see if they came from the same distribution. First, the values were tested for normal distribution with a one sample Kolmogorov-Smirnov test (Massey 1951). The data was not normally distributed. Thus, the nonparametric Kruskal–Wallis H test (Kruskal and Wallis 1952) was used to investigate if the values could originate from the same population sample or if the p-value were below 0.05, which would reject the null hypothesis that the values originate from the same population (with a certain distribution) at a target significance level of 0.05.

4 Results

4.1 Sites with highest biomass

4.1.1 100 hectares



1. Osbecks bokskogar
Peak biomass: 220 t/ha
Peak grid cell centre: 375 500 E, 6 254 000 N
Region: Nemoral
Municipality: Laholm
Class: *Other protected forest*
Protection type: Nature reserve, SCI
Description: Beech forest on the northern slopes of Hallandsåsen. Planted in early 19th century.

2. Båtfors
Peak biomass: 176 t/ha
Peak grid cell centre: 628 870 E, 6 704 940 N
Region: Boreonemoral
Municipality: Tierp
Class: *Primary forest*
Protection type: Nature reserve, SCI
Description: Species-rich and mixed coniferous forest located on islands on the river Dalälven.

3. Sundsjöåsen
Peak biomass: 164 t/ha
Peak grid cell centre: 596 870 E, 6 946 940 N
Region: South boreal
Municipality: Sundsvall
Class: *Primary forest*
Protection type: Nature reserve, SCI
Description: Spruce forest located on steep, north-east facing slopes toward the large river Indalsälven.

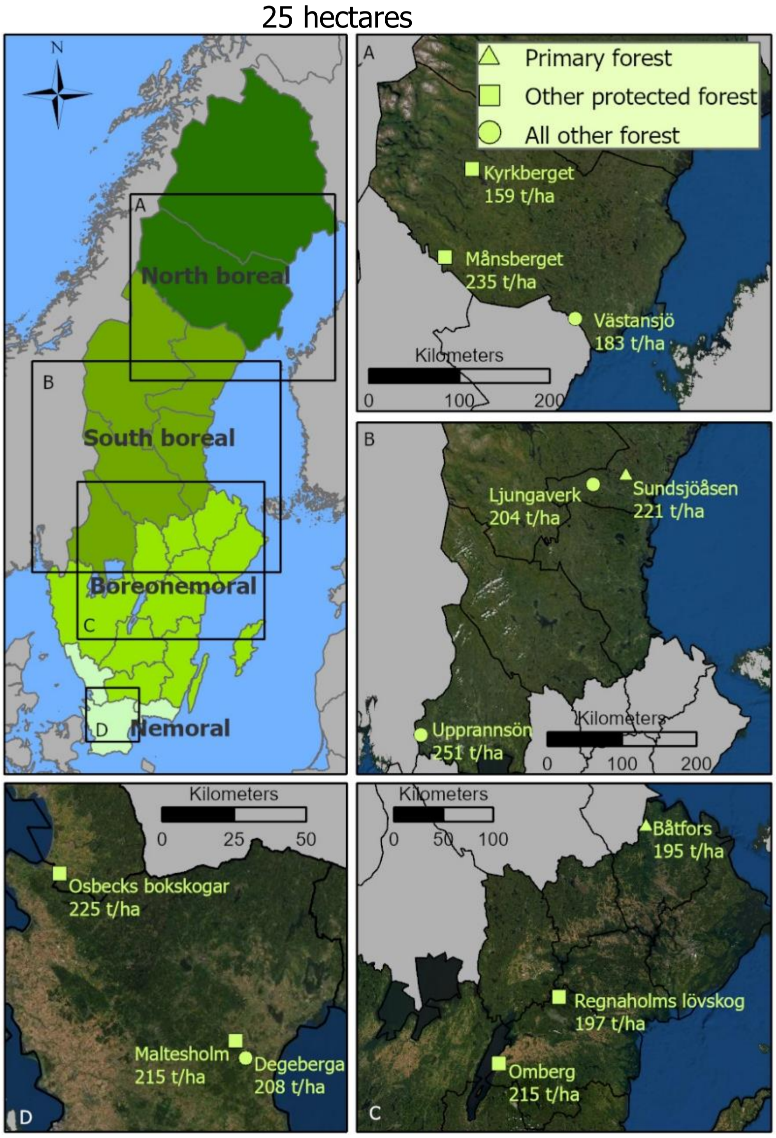
Satellite base map source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Coordinate system: SWEREF 99 TM.

Figure 4. The top three sites with highest peak biomass over 100 hectares for each region (left), as well as a description of the three sites with the highest biomass nationally (right).

The figure above (figure 4) shows the sites with highest biomass over 100 ha for each region. The site with highest biomass nationally is the nature reserve Osbecks bokskogar for which the peak grid cell records an average of 220 t/ha. The second highest site averages 176 t/ha across the 100 ha and is the *primary forest* of Båtfors nature reserve. At third nationally, with 164 t/ha, is the south boreal, *primary forest* nature reserve Sundsjöåsen.

Notable is the proximity of the two nature reserves Osbecks bokskogar and Hallandsås nordsluttning, similar in composition and essentially only separated by the highway E6. They are both in the top three sites with highest peak biomass for the nemoral region. Of the 12 sites presented in figure 3, only the forest by Degeberga, in the nemoral region, is from the class *all other forest.*

4.1.2 25 hectares



1. Upprannsön
Peak biomass: 251 t/ha
Peak grid cell centre: 321 750 E, 6 596 250 N
Region: South boreal
Municipality: Årjäng
Class: *All other forest*
Protection type: None
Description: Small island in the lake Foxen.

2. Månsberget
Peak biomass: 235 t/ha
Peak grid cell centre: 552 750 E, 7 142 250 N
Region: North boreal
Municipality: Dorotea
Class: *Other protected forest*
Protection type: Nature reserve, SCI
Description: Spruce dominated forest on a south facing slope on the mountain Månsberget.

3. Osbecks bokskogar
Peak biomass: 225 t/ha
Peak grid cell centre: 375 750 E, 6 253 750 N
Region: Nemoral
Municipality: Laholm
Class: *Other protected forest*
Protection type: Nature reserve, SCI
Description: Beech forest on the northern slopes of Hallandsåsen. Planted in early 19th century.

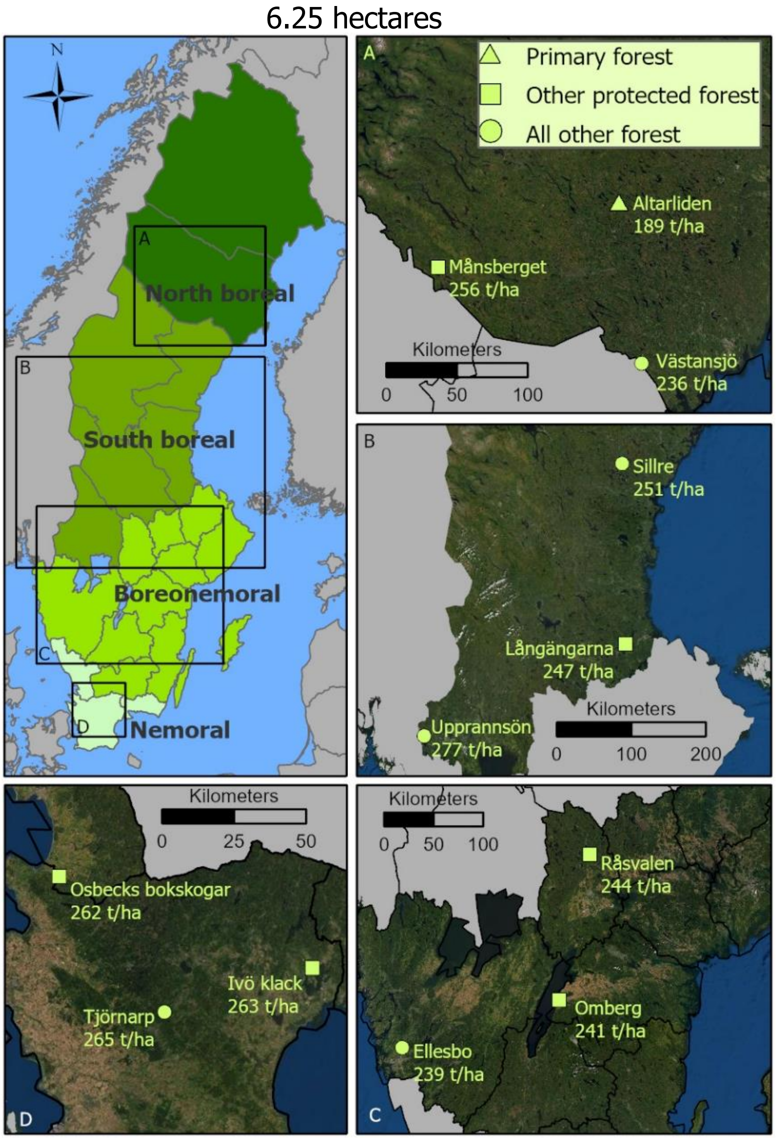
Satellite base map source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Coordinate system: SWEREF 99 TM.

Figure 5. The top three sites with highest peak biomass over 25 hectares for each region (left), as well as a description of the three sites with the highest biomass nationally (right).

For 25 hectares (figure 5) the site with the highest biomass nationwide is the south boreal island Upprannsön, part of *all other forest*, with 251 t biomass/ha. Second is Månsberget, a nature reserve on a small mountain in the north boreal region, with a peak biomass of 235 t/ha. Osbecks bokskogar this time falls to the third highest peak value of any site, with its 225 t/ha.

Degeberga is once again represented in the top three of the nemoral sites. Behind Osbecks bokskogar it is this time joined by the beech forest Maltesholm nature reserve. In the boreonemoral region, Omberg contains the highest biomass and thus overtakes Båtfors which had a higher peak value for 100 hectares. For the north boreal region, none of the three sites represented were in the top for 100 hectares, although Västansjö and Månsberget are located relatively close to Sågbäcksliden and Blaikfjället, respectively.

4.1.3 6.25 hectares



1. Upprannsön
Peak biomass: 277 t/ha
Peak grid cell centre: 321 625 E, 6 596 125 N
Region: South boreal
Municipality: Årjäng
Class: *All other forest*
Protection type: None
Description: Small island in the lake Foxen.

2. Tjörnarp
Peak biomass: 265 t/ha
Peak grid cell centre: 412 125 E, 6 206 375 N
Region: Nemoral
Municipality: Höör
Class: *All other forest*
Protection type: None
Description: Production forest. Has since data was collected become clear cut.

3. Ivö klack
Peak biomass: 263 t/ha
Peak grid cell centre: 463 375 E, 6 221 625 N
Region: Nemoral
Municipality: Kristianstad
Class: *Other protected forest*
Protection type: Nature reserve, SCI
Description: Beech forest on the north eastern slopes of the hill Ivö klack on the island Ivö.

Satellite base map source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Coordinate system: SWEREF 99 TM.

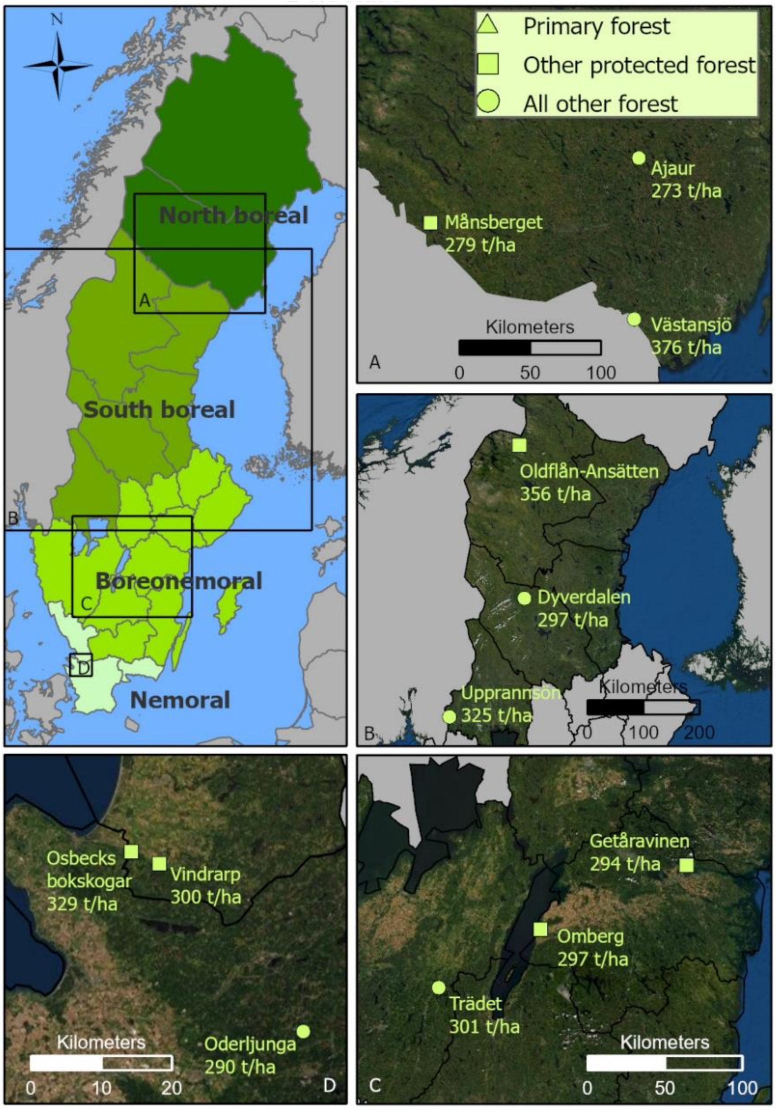
Figure 6. The top three sites with the highest peak biomass over 6.25 hectares for each region (left), as well as a description of the three sites with the highest biomass nationally (right).

Upprannsön also has the highest peak biomass over 6.25 hectares, with 277 t/ha (figure 6). The site with second highest biomass (265 t/ha) is just like Upprannsön in the class *all other forest*, it was located close to the centre of Skåne, by the community of Tjörnarp in Höör municipality. The site with third highest biomass nationally is also located in Skåne, this time on the north-eastern slopes of the hill Ivö klack, a nature reserve.

One of the notable findings is Ellesbo, with third highest biomass in the boreonemoral region as it is in a relatively urban area on the island Hisingen. Just like Osbecks bokskogar, Ellesbo also neighbours the E6.

4.1.4 1 hectare

The forest with highest biomass for 1 hectare nationally (1 ha) (figure 7), with 376 t/ha, is unprotected and located by the small lake Västansjö in Nordmaling municipality. Slightly lower, at 356 t/ha, is the nature reserve Oldflån-Ansätten, which is in the most mountainous area of the sites described so far, neighbouring the Offerdalsfjällen area.



1. Västansjö

Peak biomass: 376 t/ha
Peak grid cell centre: 696 550 E, 7 074 350 N
Region: North boreal
Municipality: Nordmaling
Class: *All other forest*
Protection type: None
Description: Production forest. Located on a low slope.

2. Oldflån-Ansätten

Peak biomass: 356 t/ha
Peak grid cell centre: 446 750 E, 7 081 650 N
Region: South boreal
Municipality: Krokom
Class: *Other protected forest*
Protection type: Nature reserve
Description: Mixed forest, mainly coniferous. Located on a low west-facing slope.

3. Osbecks bokskogar

Peak biomass: 329 t/ha
Peak grid cell centre: 374 950 E, 6 254 050 N
Region: Nemoral
Municipality: Laholm
Class: *Other protected forest*
Protection type: Nature reserve, SCI
Description: Beech forest on the northern slopes of Hallandsåsen. Planted in early 19th century.

Satellite base map source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Coordinate system: SWEREF 99 TM.

Figure 7. The top sites with the highest peak biomass over 1 hectare for each region (left), as well as a description of the sites with the highest biomass nationally (right).

At third, the nemoral nature reserve Osbecks bokskogar makes another appearance. For 1 hectare the peak biomass here is 329 t/ha. Osbecks bokskogar is among the three sites with highest biomass in the nemoral region for all four forest sizes, with the peak biomass decreasing by 109 t/ha between 100 and 1 ha (figure 4 and 7). A nature reserve in proximity to Osbecks bokskogar, Vindrarp nature reserve, is the site which has the second highest peak biomass in the nemoral region, at 300 t/ha.

Several sites have high biomass concentrated in small areas, and thus make their only appearances in the top three for their regions here. These include Vindrarp (nemoral), Oderljunga (nemoral), Trädet (boreonemoral), Getåravinen (boreonemoral), Oldflån-Ansätten (south boreal), Dyverdalen(south boreal) and Ajaur (north boreal).

4.2 Comparison of classes

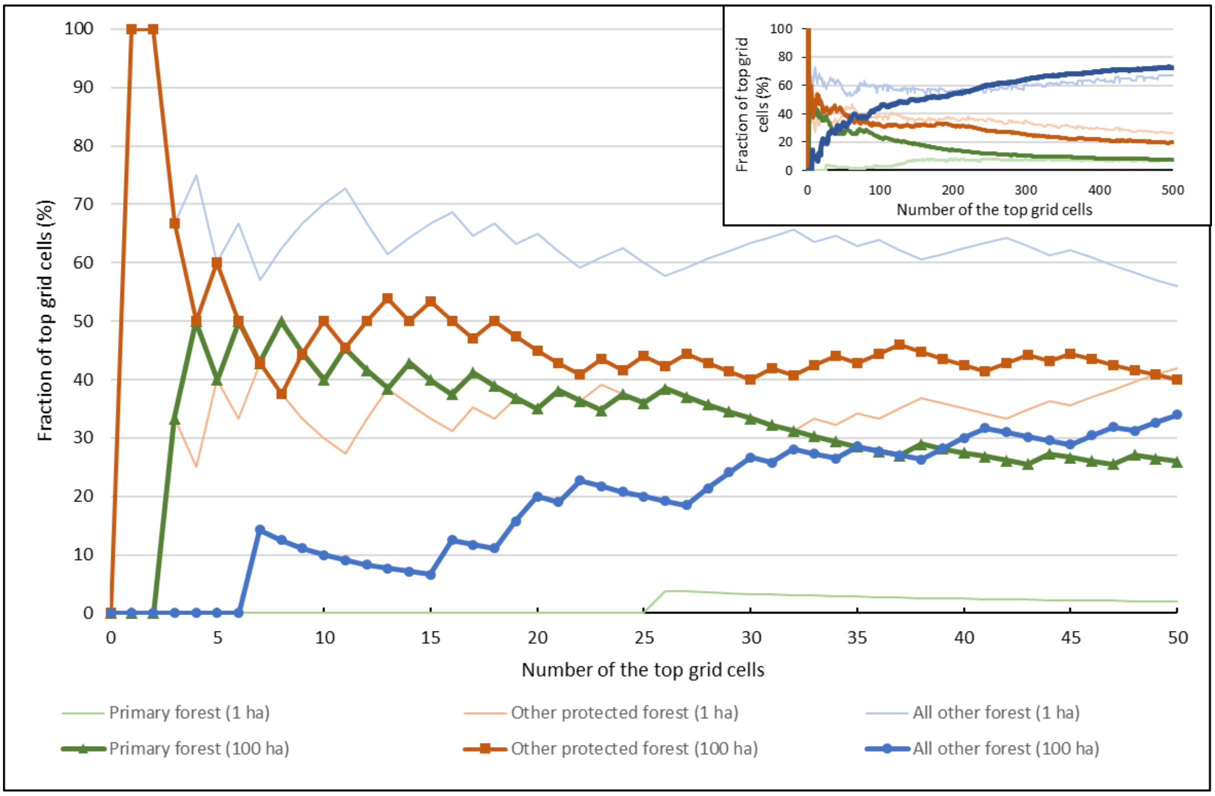


Figure 8. The cumulative fraction of the classes of at the count of each number of top grid cells for 100 and 1 ha, respectively. The inset figure in the top right includes 500 top values while the large figure only includes 50.

For 100 ha, the 6 grid cells with highest biomass are all in *primary* or *other protected forest* (figure 8) and in the top 10, only 1 is from *all other forest.* 5 are from *other protected forest* and 4 in *primary*. However, the proportion of *all other forest* increases when including more of the top grid cells. In the top 20, 20% are from *all other forest* and in the top 50, 34%. The fraction of *other protected forest* decreases slightly when including more grid cells, to 45% of the top 20 and 40% of the top 50. The fraction of *primary forest* also decreases and becomes the lowest represented class at the inclusion of 40 grid cells. The proportion of each class in the top 50 grid cells is relatively equal, with just 14% separating the most (*other protected forest)* and least (*primary forest)* represented classes.

When including even more grid cells, 100 and beyond, *all other forest* progressively makes up a higher proportion while that of the other two classes instead decreases. The fractions seemingly start stabilizing between 400 and 500 grid cells with *all other forest* at circa 73%, *other protected forest* at 20%, and *primary forest* at 7%.

At a smaller size, 1 ha (also figure 8), there are large differences with the fractions for 100 ha. The two top sites are both in *all other forest* which makes up 7 of the top 10 (70%), the three others being in *other protected forest.* The top grid cell from *primary forest* is only number 26 overall. Essentially, *primary forest* has many, and *all other forest* few, of the top grid cells for 100 ha while the opposite is true for the smaller size, 1 ha. *Other protected forest*, on the other hand, has a relatively similar fraction of the top values for the two sizes.

For 1 ha, *primary forest* only makes up around 3% of the top 100 grid cells. This increases rather quickly until the top 150 cells, for which it makes up ca 7%, a fraction which *primary* *forest* seem to stabilize around as more top grid cells are included. The fraction of *primary forest* for 100 hectares, also stabilize around 7%. There are also indications of the same pattern with the fractions of the two sizes joining around a value as more grid cells are included for both *other protected forest* and *all other forest.*

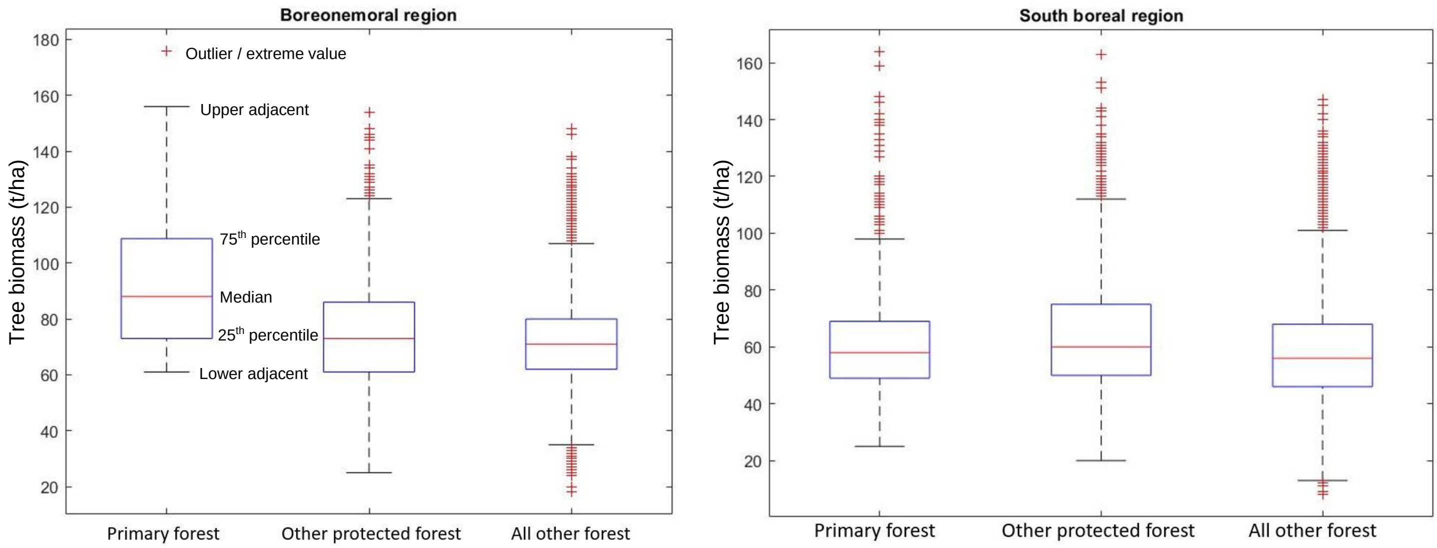


Figure 9. Box plots showing distribution of values within the two central regions for each of the classes (100 ha).

In the boreonemoral region, *primary forest* generally has the highest biomass (figure 9) with both the highest extreme value and the highest median (88 t/ha). Values for *other protected forest* and *all other forest* seem quite similar however with the medians 73 and 71 t/ha, respectively. In the south boreal region biomass is even more similar between classes. Still, *primary*- and *other protected forest* have some higher extreme values than *all other forest*. The medians are within 4 t/ha for the three classes. Additionally, the lowest values are much lower for *all other forest* than for the other two classes, occasionally below 10 t/ha. The others (*primary*- and *other protected forest*) never had values below 20 t/ha.

4.3 The geographical distribution of values

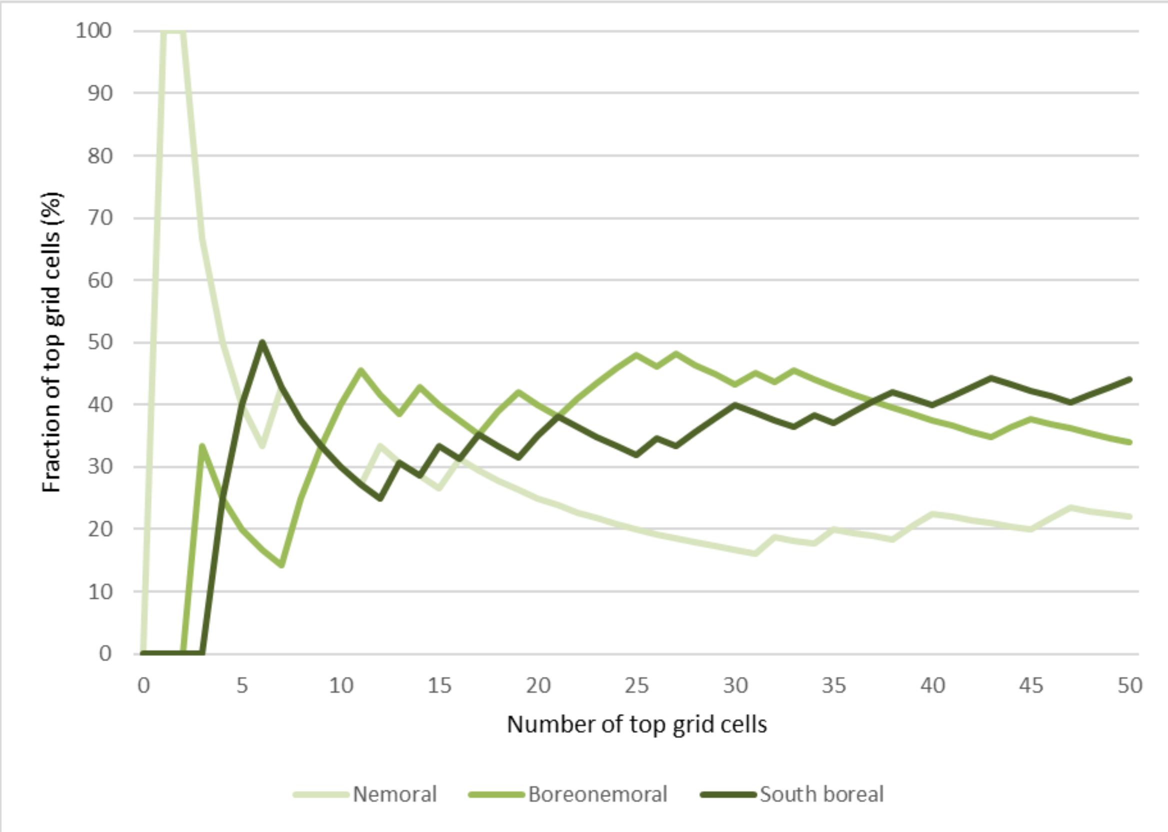


Figure 10. The cumulative fraction of the region at the count of each number of top grid cells for 100 ha.

The distribution of regions in the top ten grid cells for 100 ha nationally is relatively even between the three southernmost regions. Three are nemoral, four boreonemoral and three south boreal (figure 10). The nemoral region becomes the lowest represented region at the inclusion of 15 grid cells. The proportion however remains relatively even for the boreonemoral and south boreal regions throughout the top 50. The north boreal region had no values in the top 50 for 100 ha.

Table 2. The number of grid cells in the top 500 from each county for each size.

County/**Region**	Number of grid cells in the top 500			
	1 ha	**6.25 ha**	**25 ha**	**100 ha**
Skåne	83	59	60	67
Halland	88	59	46	46
Blekinge	1	5	4	14
Nemoral	**172**	**123**	**110**	**127**
Kronoberg	0	0	4	3
Kalmar	5	3	5	17
Västra Götaland	28	42	28	49
Östergötland	27	40	23	26
Jönköping	1	2	3	14
Södermanland	6	8	10	5
Stockholm	0	3	3	7
Örebro	15	23	20	23
Uppsala	21	31	45	37
Västmanland	10	9	16	15
Gotland	0	0	0	0
Boreonemoral	**113**	**161**	**157**	**196**
Dalarna	19	22	22	15
Värmland	68	50	41	34
Gävleborg	18	26	28	31
Västernorrland	53	69	90	65
Jämtland	32	39	47	28
South boreal	**190**	**206**	**228**	**173**
Västerbotten	25	10	5	3
Norrbotten	0	0	0	1
North boreal	**25**	**10**	**5**	**4**

From table 2 it is clear that the top 500 grid cells are more well distributed between different counties at the larger forest sizes. Gotland is the only county completely lacking representation in the top 500 for 100 ha as opposed to three more counties also doing so at 1 ha. The north boreal region is consistently lowest in terms of representation in the top 500 grid cells. It peaks at 25 (1 ha) and over the larger areas decreases to 4 (table 2). Additionally, these values are, besides one grid cell at 100 ha, exclusively made up by Västerbotten county.

The boreonemoral region has the most values of the top 500 for 100 ha, with 196, the same number for 1 ha is much lower, at 113. However, the south boreal region seems to generally contain the most values over most sizes. Across the three smaller forest sizes it is the most represented region with between 190 and 228 of the 500 top grid cells. It also becomes apparent some boreonemoral counties, in particular Kronoberg and Jönköping, contain very few of the top 500 values.

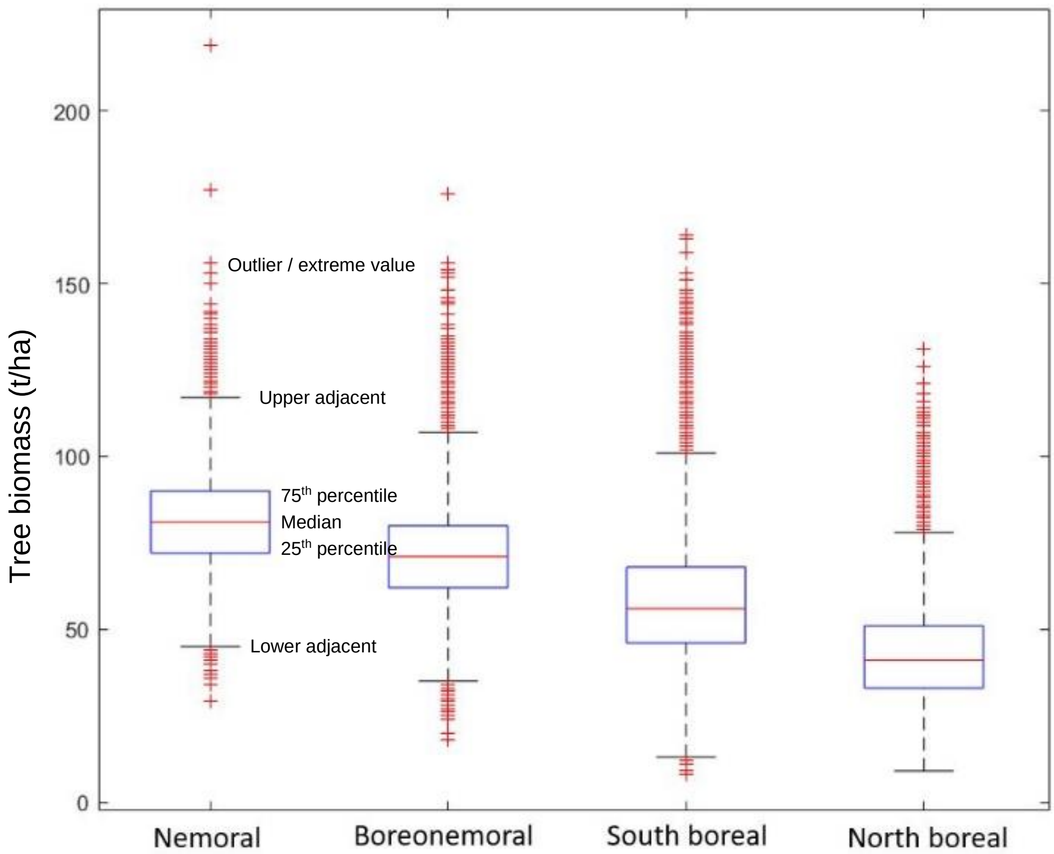


Figure 11. Distribution of values for all grid cells within each region (100 ha).

The nemoral region has the highest biomass overall for 100 hectares (figure 11). The pattern is clear, biomass progressively decrease with region latitude increasing. The biomass significantly differs ($p < 0.05$) between all regions.

5 Discussion

5.1 Relationship between the top sites, classes, and forest size

The site with highest biomass nationally changed depending on the size, as three different sites had the highest biomass over the four sizes investigated. These sites were Osbecks bokskogar (100 ha, *other protected forest*, nemoral), Upprannsön (25 and 6.25 ha, *all other forest*, south boreal), and Västansjö (1 ha, *all other forest*, north boreal).

There was a clear difference in the fraction of each class among the top 50 (and less) grid cells between the largest and smallest sizes that were investigated. For 100 hectares, *primary* and *other protected forest* made up most of the top values. The *all other forest* grid cell with highest biomass only came in at number 7 overall. While *primary forest* stands themselves contain a large mix of trees and plants of different ages, the biomass is relatively homogenous across their, sometimes large, extent. These large, high-biomass forests are the forests that store the most carbon overall. This makes the top *primary forest* sites over 100 ha, such as Båtfors and Sundsjöåsen, especially relevant for the current discussion of carbon storage and climate change mitigation.

While production forests on a stand level contain a much more homogenous set of tree ages than primary forests, the age-composition can vary drastically between the stands themselves. Over 100 hectares it is therefore for *all other forest* unavoidable that some young stands that are low in biomass are included in the grid cells. The top grid cells at the smallest size, 1 ha, instead to a higher proportion consisted of only the high-biomass stands of the productive forest. And thus, *all other forest* was much more well represented among the top grid cells for 1 ha than for 100 ha. There were seemingly very few grid cells from *primary forest* among the top for 1 ha, mainly due to the vast amount of high-biomass production forest stands dominating. It should also be mentioned that *other protected forests* had a relatively even proportion of top values between sizes, which makes sense considering that these areas at some point have been cut but afterwards managed to accumulate relatively consistent biomass stocks, in that way being a mix between the other two classes.

5.2 Comparison with biomass values of other studies

The highest values, from 376 t/ha (1 ha) to 220 t/ha (100 ha), which would be equivalent to 188 and 110 t C/ha in biomass, assuming that 50% of the biomass is C (Thomas and Martin 2012) is within the range of values seen in other studies, albeit slightly low. A study by Nord-Larsen *et al.* (2019) showed values of 186 t C/ha (~372 t biomass/ha) in a Danish semi-natural beech-dominated (nemoral) forest and 196.4 t C/ha (~393 t biomass/ha) have been found as value for above ground biomass in old-growth scots pine (boreonemoral) forest in Latvia (Ķēniņa *et al.* 2019). The medians of the regions and classes presented in the study are lower than the average values of boreal forests, circa 60 t C/ha (~120 t biomass/ha), found by Keith, Mackey and Lindenmayer (2009). The NFI plot values used to validate the original dataset had a maximum value for AGB of 516 t/ha (Nilsson *et al.* 2017), which is 38% higher than the highest 1 ha biomass (376 t/ha) presented in this thesis. This strengthens that the maximum biomass values in this study are slightly lower than the highest values both from other studies in similar environments and plots of data on which the study was partly based. The lack of high biomass found in other studies is likely largely due to two reasons:

1. Omission, or at least rare inclusion, of very high-biomass grid cells in the original biomass raster itself. However, it should be noted that there are some sites, for example Västansjö, which have individual input grid cells peaking at around 700 t biomass/ha.

2. Dilution of the high-biomass grid cells when aggregating values over the larger sizes. Even at 1 ha small individual stands with very high biomass can be diluted by the rest of the forest. It is for the same reason clear that the values progressively get lower and lower at the larger scales. At the mentioned example Västansjö, these extreme values are concentrated in small areas, with just a few grid cells with drastically lower biomass next to them decreasing the resulting value over 1 hectare, in this case from the maximum 700 t/ha to the average 376 t/ha.

5.3 Effects of management on biomass

When comparing the different classes against each other in the boreonemoral region, it became clear that the *primary forest* class on average here had higher biomass values than *all other forest*. Some reservation for drawing a conclusion regarding class with highest biomass should be left for the south boreal region. Primary forests generally having higher biomass storage than all other forests was expected as this was found in Johannesson's study (2020) which used the same data sets. However, Johannesson exclusively used comparable stands while the comparison between classes in this study was rather done across grid cells regionwide.

To my knowledge, there are not many other studies comparing the two more pristine classes in a boreal setting. However, a study in the temperate Spanish Pyrenees indicated that for silver-fir and beech forests the live biomass peaks in areas that are at an intermediate level naturalness (Molina-Valero *et al.* 2021), which could be comparable to the class *other protected forest* in this study. *Other protected forest* did indeed have a relatively high proportion of the top values in this thesis.

5.4 Geographical differences in biomass

The boreonemoral and south boreal regions had most of the top grid cells. The proportion of nemoral sites was also rather high for the sites with highest biomass at 100 ha and included the top site nationally, Osbecks bokskogar, meaning that large amounts of biomass could be stored here. The north boreal region, on the other hand, had very few of the top grid cells for all forest sizes.

Due to the nature of the processing, several grid cells in the top 500 can be in the same site for the smaller sizes. For the larger sizes, especially 100 ha, it is rarer that neighbouring cells are all among those with highest biomass as sites, which are spatially limited, can no longer contain many large grid cells. Thus, the top 500 grid cells become more well distributed around the country and between sites the larger the forest size.

The general biomass in the regions were also shown to decrease with latitude. In the NFI plot data (Nilsson *et al.* 2017), plots were assigned to three geographical regions ranging from south to north, similar to the regions in this study, in order to compare latitudinal differences. The mean of the AGB was highest for the northernmost region (157 t/ha) which is a result in stark contrast to those in this thesis. The difference indicates that there might be some uncertainty regarding the latitudinal gradient. However, most other studies (Johannesson 2020; Vucetitch *et al.* 2000) support the latitudinal gradient with biomass decreasing to the north seen in this study.

5.5 Limitations and methodology alternatives

As stated by Johannesson (2020), a limitation of studies based on the living tree biomass data is that dead wood biomass is not included in the analysis. The biomass increase from inclusion of dead wood would most likely be highest in primary- and protected forests as these generally contain higher amounts of dead wood than production forests (Fridman 2000). As mentioned in section 2.1., dead wood is just one of several other significant forest carbon pools which would have been relevant to include in the study.

Another limitation is in the processing itself. When aggregating the biomass rasters, it was not controlled which of the input grid cells of 12.5 m x 12.5 m were batched together into the output cells, and thus the output grid cell values will have been slightly dependent on which specific input grid cells were aggregated into which groups. Additionally, some of the 12.5 m by 12.5 m input grid cells with the highest values might have been located close to the edge of the forests and later been excluded in case they were featured in an output grid cell which contained less than 50% forests. Ideally, the grouping of input cells would have been conducted with a regard to the extent of forests and their shapes but doing this efficiently over a large area is complicated.

No biomass raster had been produced for the class *other protected forest* (see 3.3.2). To produce one would have been complicated with different protected areas varying in composition and existing in different environments. However, it would still have been relevant to compare the two alternative rasters over this class and via field data evaluate them to see if one is more accurate overall, or at least for the top sites. The values in these protected areas are generally ca 10% higher in the primary forest biomass raster than in the production forest raster. A value which is high enough that it may have affected the results of this study. *Other protected areas* would have had even higher values using the biomass raster adjusted for primary forests.

It would at least have been relevant with a validation of the biomass values in the forests pointed out to have the highest biomass in this study. Field data could have been collected and evaluated against the values produced to ensure that the resulting data have been relatively correct.

It could be discussed which "protection types" (nature reserves, nature conservation areas etc.) go into *other protected forest* and *all other forest.* Ideally it would have been possible to separate all forest which are used in production or not and then directly apply the separation on the classes. Upprannsön is an example of a high-biomass site which, despite being classified as *all other forest*, is probably not under heavy forestry due to its location on a, by road, inaccessible island as well as area recognised natural value and care (sv. Riksintresse för naturvård).

5.6 Possible future additions

A possibility that is opened by this study is to investigate if any environmental parameters stand out among the top sites. An example of a parameter is slope. While not completely pristine or formally protected, sites on steep slopes sites may have been more inaccessible, less exposed to industrial land use change or forestry and thus have accumulated more carbon in recent centuries. A possible study question could be: Is the slope generally steeper for the highest sites of *all other forest* than it is at sites with more "average" or random values?

Other possible additions include hydrology, soil chemistry and bedrock. The same goes for population centres and infrastructure, it might be interesting to investigate the distance between the sites with highest biomass and human activity.

6 Conclusion

Knowledge of which forests currently contain the most biomass, as well as have high potential to do so, aids policy-makers regarding forest management strategies in relation to climate change mitigation. Thus, this study aimed to identify the sites with the highest biomass across the north- and south boreal, boreonemoral and nemoral forests of Sweden.

To reach a conclusive answer regarding which forests store the most biomass, it was necessary to define spatial boundaries of the forests. Thus, high resolution grid cells in a remotely sensed dataset of biomass across Sweden were aggregated into four different sizes. In addition to just identifying the top sites, the location of these in relation to four biogeographical regions of Sweden was investigated. The same was done for the management intensity, which was divided into three broad classes.

Three distinct sites were found to have the highest biomass for at least one size:

- Osbecks bokskogar (100 ha), a protected planted beech forest (nemoral).
- Upprannsön (25 ha and 6.25 ha), an island in the south boreal region.
- Västansjö (1 ha), a managed north boreal forest.

Most of the ten sites with highest biomass density for 100 ha were located in *primary*- or *other protected forests* as forests from these two classes have similar composition of biomass over large areas. At a smaller size, such as 1 ha, the production forests in the class *all other forest* instead made up a large fraction of the high biomass sites as individual stands at a late stage of their rotation cycle in some cases contained very high biomass. *All other forest* was not as well represented for the largest size, 100 ha, as the age and biomass varies between stands. The boreonemoral and south boreal regions were the most well represented among the top biomass values. The north boreal region essentially lacked representation besides a few special cases, such as Västansjö. For future studies it would be relevant to further investigate the relationship between different environmental variables and high-biomass sites.

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