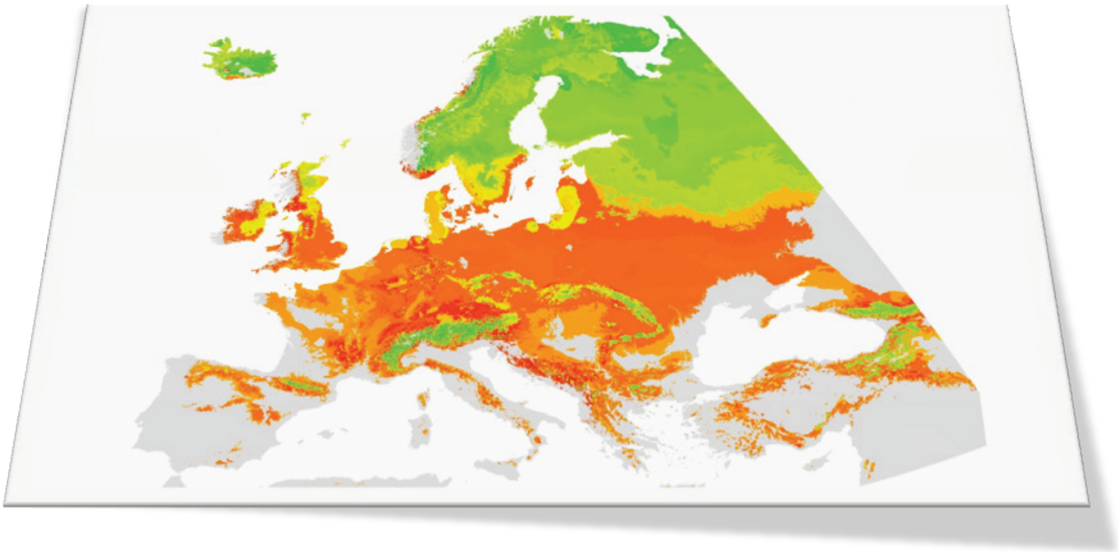
Centre for Geo-Information

Thesis Report GRS-2011-23

Impact of climate change on European Forest growing stock volumes

Aldo Bergsma

October 2011



WAGENINGEN UNIVERSITY
WAGENINGEN UR

Impact of climate change on European Forest growing stock volumes

Aldo Bergsma

Registration number 690430-057-070

Supervisors:

Dr. Ir Frank Sterck (Forestry Ecology and Management Group, Wageningen University)
Ir. Ernst van der Maaten (Institute for Forest Growth, University of Freiburg)
Dr. Ir. Ron van Lammeren (Laboratory of Geo-Information Science and Remote Sensing, Wageningen University)

A thesis submitted in partial fulfilment of the degree of Master of Science
at Wageningen University and Research Centre,
The Netherlands.

October 2011
Wageningen, The Netherlands

Thesis code number: GRS-80424
Thesis Report: GRS-2011-23

Wageningen University and Research Centre
Laboratory of Geo-Information Science and Remote Sensing

Figure front-page: Difference in growing stock volumes between 2000 and 2080 IPCC scenario A2

Preface

This report is part of my study Master of Geo-Information Science. This thesis is conducted as an follow up on former MGI thesis by Renske Terhürne entitled “Spatially expressed consequences of climate change for growing stock in Europe” (Terhürne, 2010). It has been supervised by Frank Sterck (Forestry Ecology and Management Group, Wageningen University), Ernst van der Maaten (Institute for Forest Growth, University of Freiburg) and Ron van Lammeren (Laboratory of Geo-Information Science and Remote Sensing, Wageningen University). I would like to thank all three for their ideas and support on the completion of my thesis. I would also like to thank Frits Mohren for his critical comments and suggestions on the first acquired results, which contributed in achieving more realistic outcomes. Last but not least, many thanks go to Arnold Bregt and my colleagues at the department of Geo-Information Science and Remote Sensing of Wageningen University for their patience to finish this last subject of my study Master of Geo-Information Science. It’s time to get back to work, to implement the gained knowledge and expertise!

Summary

In this study changes in European forest distribution and growing stock volumes are studied for four different tree species: Norway spruce (Picea abies (L.) Karst.), Scots pine (Pinus sylvestris L.), Pedunculate oak (Quercus robur L.) and European beech (Fagus sylvatica L.).

The extrapolated changes are determined using two different sources. The first is the European National Forest Inventory database, which includes an inventory of forest plots of thirteen European countries. From these plots, growing stock volumes were substracted at given locations. In the second source, the WorldClim global climate layers database, climate information as temperature, precipitation etc., was available. Combining the European National Forest Inventory database with the WorldClim dataset, climate information was added for each plot. Temperature and precipitation were classified and grouped. Subsequently, the 75th, 90th and 95th percentiles of growing stock volumes were calculated per temperature and precipitation group. The calculated percentile volume values were, afterwards, spatially extrapolated using the climate scenario conditions for 2000 and two independent IPCC climate scenario conditions for 2080 (pessimistic (A2), medium case (B2), covering Europe.

A second study was then performed on climate factors that can influence the species distribution. Two limiting parameters were defined and implemented to calculate the 95th percentile for the minimum temperature during the coldest month and the maximum temperature during the warmest month. This was applied for all the different plots in the forest inventory database. These two parameters were spatially extrapolated to define the potential species distribution maps covering Europe.

The extrapolated results acquired for 2000 and 2080 were subsequently analysed. The results show an extreme northward shift for all four species studied. Competition of different species will be much larger as available distribution areas are largely reduced. Stock volumes reached do approximately stay the same for 2000 and 2080 for both scenarios studied. When potential distributions are excluded from the stock volume extrapolations, average productivity is increasing for most of the species. Keeping in mind that commercial forest stands have a turnover rate of several decades, the results of both climate change scenarios studied here show that the choice of the tree species plays an important role when taking a decision on which tree species to use on a forest stand.

Table of Contents

1. Introduction

Forest covers a considerably large part of the Earth's land surface. The United Nations General Assembly declared 2011 as the International Year of Forests in order to raise awareness on sustainable management and conservation of forests. Forests significantly contribute to biodiversity, providing accommodation for different habitats, Additionally, forests play an important role in maintaining a stable global climate and environment. In the current discussions on CO_2 emissions worldwide, forests, as one of the largest carbon sinks, significantly assist to reduce the effects of global climate change.

Although the Earth has faced cycles of tremendous climatic changes on a geological scale, anthropogenic actions are currently responsible for the current global climate change. Due to the high demand of fossil fuels, the emission of CO_2 in the atmosphere worldwide has extremely increased since the last century. As a consequence, the energy balance of the Earth has considerably been altered. This alteration in energy balance inevitably results in significant climatic changes. On its turn, this change of climate has large effects on habitats and species distributions around the Earth. Some species will be capable to survive at certain locations, where others won't. As such, getting insights in the change of forest distributions due to climate change issues are very relevant.

As a large part of the forest area is used for commercial timber, together with the change in forest distribution, there will most likely be change in growing stock volumes reached with these forest stands.

A definition of Growing Stock is given at the site of The Forest Policy and Economics Education and Research (FOPER), part of the United Nations University (http://foper.unu.edu/course/?page_id=153). This definition is presented in text box 1.

> The standard measure for forest production is the volume of growing stock. Growing stock volume is the above-stump volume of living trees measured from the bark up to the treetops. It includes all living trees, the diameter of which at breast height (d.b.h.- or 1.3 m) is over 0 cm. It is the living tree component of the standing volume, which also includes dead trees (TBFRA 2000).
>
> In 2005, the total global growing stock was estimated at 434 billion m3, which corresponds to an average of 110 m3 per hectare. The countries with the largest growing stock per hectare were found in central Europe and in some tropical areas.
>
> Globally, total growing stock shows a slight overall downward tendency - mainly owing to a decrease in forest area. However, some regions show significant trends in growing stock per hectare (i.e., Europe shows an increase and Southeast Asia a decrease).

Text box 1: definition of Growing Stock and relevant information.

From the statement presented in text box 1 it can be concluded, that growing stock is an important measure for current and future forest production. It can also be noted that the major growing stock volumes are reached in European regions, which are also important regions in stock change trends. Given this information, construction of current and future growing stock stand maps for the entire European continent, is rather challenging, and give new insights in species distributions.

A bioclimatic envelope approach is an often used methodology to model effects of climate change. At the JRC, habitat suitability modelling for tree species distributions are performed (Casalegno *et al.*, 2011) based on forest field inventory plots from two different sources, classified in ten dominant forest categories. Suitability maps present the category that fits best to the environmental conditions. 56 Environmental predictors were used to model single species distribution. Three main forest groups were distinguished: Scandinavian forest, Temperate European forest and Mediterranean forest. Results of the study are presented in tree species habitat suitability maps: http://efdac.jrc.ec.europa.eu/climate.

Starting point for the present thesis is the work performed by the former MGI thesis student Renske Terhürne entitled "Spatially expressed consequences of climate change for growing stock in Europe" (Terhürne, 2010). In the thesis of Renske Terhürne, forest stands were calculated for both the situation in 2000, as well as, a IPCC scenario dealing with climate change, as it should be expected in 2080. In that thesis, the shift in forest stands are expressed as maximum growing stock volumes.

However, the use of maximum growing stock volumes is actually not realistic to express the current stock volumes and future shifts as a result of climate change, as the maximum stock volumes either express the extremes, or could be outliers. For this reason, in the present thesis the changes in growing stock will be expressed in different percentiles (the 75^{th} , 90^{th} and 95^{th}) of measures belonging to a certain climatic group. Therefore, the main objective of this study is to use percentiles to express growing stock. This will represent a more reliable growing stock representation than using maximum growing stock values. It will improve results for both the situation in 2000 as well as for the 2080 situation according two independent IPCC climate scenarios across the European continent.

This report describes the methods and steps followed to use percentiles based growing stock volumes. These determined growing stock volumes are extrapolated to the situation of 2000 and for two IPCC climate change scenarios. In this way a shift in growing stock can be determined and possible locations where species will occur in future can be presented. The first chapter of this report describes the methodology and steps followed. It is continued with a chapter which describes the results, and is finalized with discussion and conclusions.

2. Materials and methods

The methodology describes the steps followed during the present study. It mainly focuses on: 1. data-sets and -handling and 2. spatial analysis.

2.1. Data-sets and –handling

The material used in this study originated from different sources, ranging from a database with field inventories to spatially explicit climatological data, some could be acquired direct form the study of Renske Terhürne, others had to be pre-processed before they could be used in the present study. This material is listed here below. The letters of the dataset are used in the flowchart of figure 1:

a) *EU-NFI database*
An European-scale National Forest Inventory (EU-NFI) database was used, compiled by the research institute Alterra, Wageningen (the Netherlands). The database includes forest stand characteristics for 13 European countries, and is, with over 330.000 records, the largest available dataset, to date, covering a large climatic gradient.

b) *Studied tree species*
Four different tree species are studied: Norway spruce (Picea abies (L.) Karst.), Scots pine (Pinus sylvestris L.), Pedunculate oak (Quercus robur L.) and European beech (Fagus sylvatica L.).

c) *Climate data*
Climate data is used for the current situation according to the WorldClim global climate layers database with a spatial resolution of 1×1 km (Hijmans *et al.*, 2005). Future (2080) and two independent IPCC climate scenario conditions (pessimistic (A2), medium case (B2) (IPCC, 2007) calculated with the HADCM3 model, were derived from the International Centre for Tropical Agriculture (CIAT) (Ramirez & Jarvis, 2008). Both, current and future climate datasets, contain 19 climate variables each.

d) Bioclimatic envelopes
Climate envelops of the four different tree species were taken from the study of Renske Terhürne. To construct these climate envelops, the 19 climate variables from the WorldClim dataset were added to the locations of the EU-NFI database. To determine the most important variables that could explain the variation in the climate data, a principle component analysis was performed, per tree species, using the 19 climate variables allocated to the records in the EU-NFI database. The principle component analysis demonstrated that the annual mean temperature (BIO1) and annual precipitation (BIO12) were the most important variables.

e) *Tree species distributions*
Two sources of tree species distribution for the European continent were used: Atlas Flora Europeaea (Jalas & Suominen, 1972), and the distribution maps of the European Forest Genetic Resources Programme (EUFORGEN, 2009). The Atlas Flora Europeaea was unfortunately only available in an analogue form. To be able to compare the tree species distribution of the Atlas Flora Europeaea with the one obtained after the extrapolation of the climate variables annual precipitation and annual mean temperature, a rough estimate was sketched in GIS layers. For this reason, no quantitative comparisons could be performed. The distribution maps of the European Forest Genetic Resources Programme are available in digital form. For each tree species two layers are provided, one with the areas of occurrence, the other with fragmented locations.

2.2. Spatial analysis

The spatial analysis of growing stock was performed in a number of different steps which are given here below and represented in the flowchart in figure 1, the numbers in the flowchart correspond to the numbering of the steps followed.:

1. All database records in the EU-NFI database were assigned in a temperature- and precipitation-class with marges of 1.0°C and 250mm, respectively (appendix I). A combination of these two variables (temperature and precipitation) was assigned to all records of a given tree species present in the EU-NFI database. For each of these combined temperature/precipitation classes the 75th, 90th and 95th percentile of the growing stock was calculated.

2. The same combination of annual mean temperature (BIO1) and annual precipitation (BIO12) was performed on the WorldClim climate datasets, resulting in a dataset of temperature/ precipitation zones (including zones representing e.g. a precipitation class 2 (250-500mm) and temperature class 30 (6-7^{o}C)). To extrapolate growing stock volumes to the extent of the European continent, the calculated percentiles of growing stock levels were assigned to the resulting temperature/precipitation zones of the WorldClim dataset. This extrapolation was applied to the growing stock situation for the period 1950-2000.

3. Based on the results of the percentile study, one of the three (75th, 90th and 95th) percentiles is chosen to extrapolate the projected growing stock volume distributions for two future (2080) IPCC climate change scenarios to be known as A2 (pessimistic case) and B2 medium case.

4. The resulting distributions of the growing stock volumes for the situation in 2000 of four tree species were compared to the published distributions of the Atlas Flora Europaeae and distribution maps of the European Forest Genetic Resources Programme.

5. After studying the results of the distribution comparison, two additional WorldClim variables, the minimum temperature during the coldest month (BIO6) and the maximum temperature during the warmest month (BIO5), that could explain differences in the distributions pattern, are explored. Minimum temperature during the coldest month could limit survival of young shoots during winter (Woodward, 1988), whereas maximum temperature during the warmest month could explain drought limitations during summer (Casalegno *et al.*, 2011).

   These two parameters are determined by respectively the 5th and 95th percentile of all records of a given tree species in the EU-NFI database. Setting the threshold to the 5th and 95th percentile of all records in the EU-NFI database will ensure occurrence of incidental high or low temperatures will be removed. They are used to set a threshold value when selecting areas with temperatures higher than the calculated 5th percentile of the minimum temperature during the coldest month, and areas with temperatures lower than the calculated 95th percentile of the maximum temperature during the warmest month. These parameters will be used to construct potential distribution maps for the four studied tree species.

6. The potential distribution maps based on using these two additional parameters individually and combined, are compared again to the two published distribution maps for the four different tree species.

7. Subsequently, the best fitting potential distribution map, where a given tree species could grow, based on the minimum temperature during the coldest month or the maximum temperature during the warmest month, or a combination of both the parameters, is chosen, and combined with the growing stock maps (from step 2). This will be done for both the situation during the period 1950-2000 and for the future (2080) IPCC climate change scenarios (pessimistic (A2) and medium case (B2)).

8. In a last step, standing stock maps for individual tree species will be merged into a tree species suitability map. These maps intend to support an optimal tree species choice in terms of productivity by picking the highest standing-stock volume for each raster cell.

9. From the tree species suitability maps, European suitable areas and stock volumes are summarized, and compared for the situation in 2000 and the two future (2080) IPCC climate change scenarios A2 and B2.

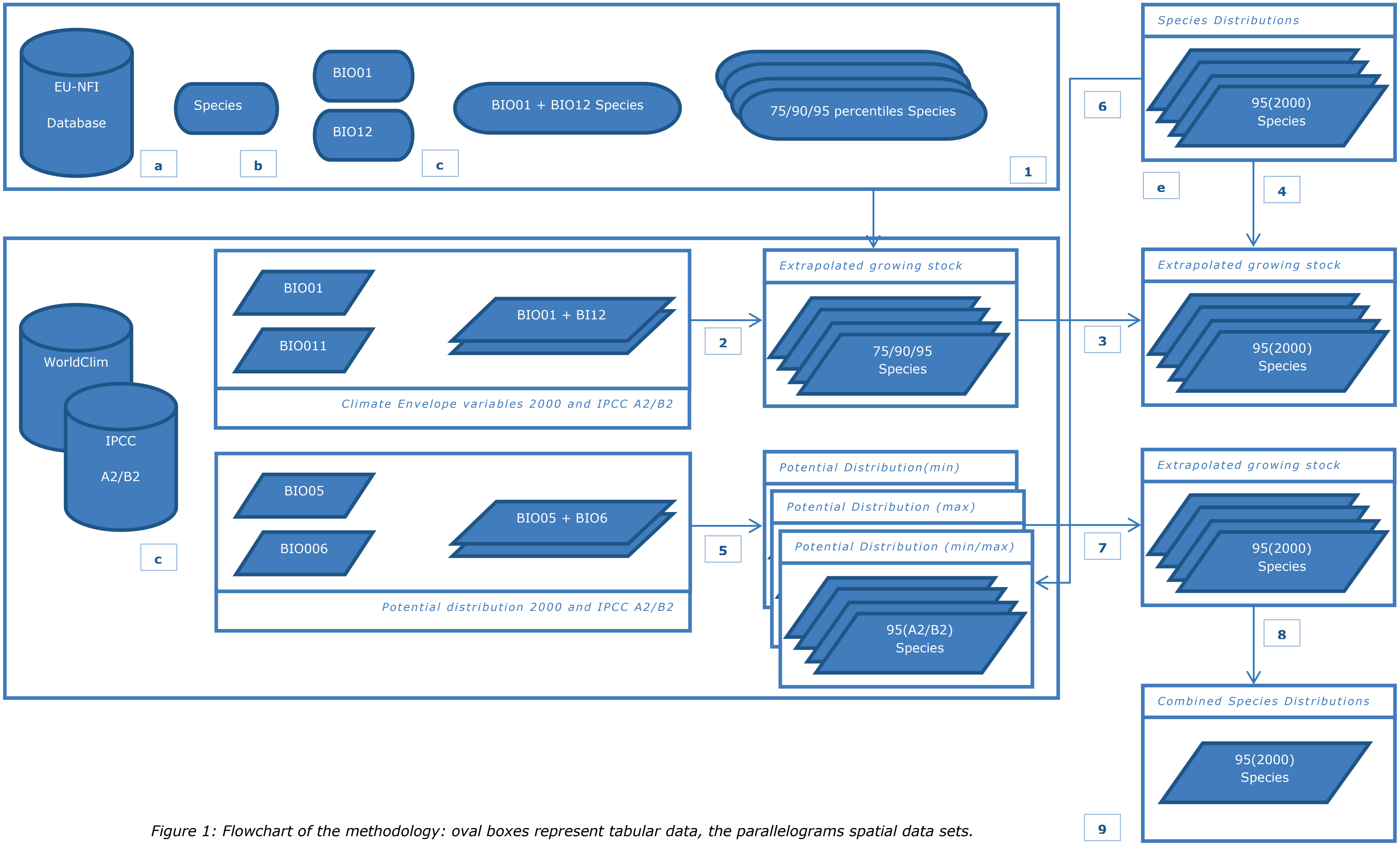


Figure 1: Flowchart of the methodology: oval boxes represent tabular data, the parallelograms spatial data sets.

3. Results

3.1 Spatial Distribution

The distributions of the visited locations available in the EU-NFI database differ throughout Europe. A rough distribution of the four tree species can be drawn, based on the EU-NFI database (figure 2). Norway spruce (a) and Scots pine (b) are predominately found in the Nordic countries, the United Kingdom and central European countries, whereas Pedunculate oak (c) and European beech (d) are mainly restricted to central Europe.

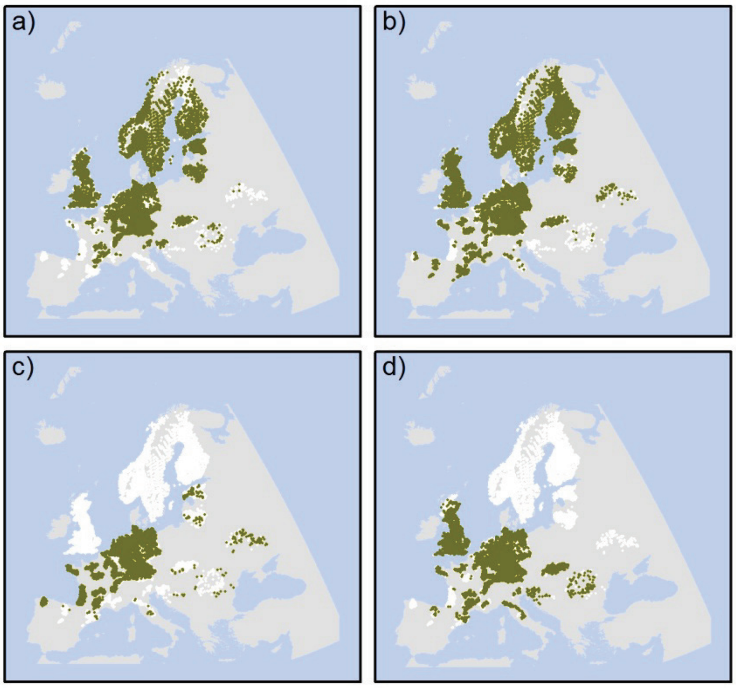


Figure 2: Distribution areas in Europe for a) Norway spruce (Picea abies (Karst.) L.), b) Scots pine (Pinus sylvestris L.), c) Pedunculate oak (Quercus robur L.) and d) European beech (Fagus sylvatica L.). Green dots indicate species presence, white dots all plot locations in the EU-NFI database.

3.2.1 Percentile classes

The annual mean temperature (BIO1) and the annual precipitation (BIO12) were reclassified. The 75th, 90th and 95th growing stock percentiles were calculated per combined precipitation and temperature class excluding $k<1/(n+1)$ or $k>n/(n+1)$. In this way minor groups of climate categories are excluded from the calculations (appendix II).

The number of visited locations on which the 95th percentile is calculated, are explored. It can be noted that the number of visited locations differ over the temperature/precipitation classes for the different tree species used (see figure 3a).

3.2.2 Per species

European Beech

For European beech, the number of plots on which the 95th percentile is calculated differ from 22 (precipitation class 5, temperature class 31) up to 4434 (precipitation class 2: 250-500 mm, temperature class 32: 8-9^{o}C) records of the EU-NFI database, which result in a growing stock ranging from 333.4 to an optimum of 726.9 m^3/ha (precipitation class 5: 1250-1500mm, temperature class 31: 7-8^{o}C).

Norway spruce

For Norway spruce, the number of plots on which the 95th percentile is calculated differ from 20 (precipitation class 7: 1750-2000mm, temperature class 28: 4-5^{o}C) up to 20123 records (precipitation class 4: 1000-1250mm, temperature class 27: 3-4^{o}C) records of the EU-NFI database. The growing stock varies from 122.0 (precipitation class 1: 250-500mm, temperature class 22: -2--1^{o}C) to 1175.5 m^3/ha (precipitation class 5: 1250-1500mm, temperature class 26: 2-3^{o}C).

Scots pine

The number of plots on which the 95th percentile for Scots pine is calculated vary from 15 (precipitation class 3: 750-1000mm, temperature class 37: 13-14°C) up to 7144 (precipitation class 2: 500-750mm, temperature class 32: 8-9°C). The calculated growing stock values range from 99.8 (precipitation class 2: 500-750mm, temperature class 22: -2--1°C) to 595.1 m^3/ha (precipitation class 4: 1000-1250mm, temperature class 33: 9-10°C).

Pedunculate oak

For Pedunculate oak, the number of plots visited on which the 95th percentile is calculated for each precipitation/ temperature class vary from 20 (precipitation class 3: 750-1000mm, temperature class 30: 6-7°C) up till 2159 (precipitation class 2: 500-750mm, temperature class 328-9°C). The corresponding growing stock values for the precipitation/temperature classes vary from 178.8 (precipitation class 2: 500-750mm, temperature class 29: 5-6°C) to 603.1 m^3/ha (precipitation class 3: 750-1000mm, temperature class 30: 6-7°C)

3.2 Extrapolation of different percentiles

Precipitation and temperature (appendix I) are classified in 54 and 14 classes, respectively. These classified datasets were combined in a map (see figure 1) representing different zones of precipitation and temperature. These zones were used to extrapolate growing stock volumes to the extent of the European continent. Growing stock is visualized per tree species for the three different percentiles used. The class-sizes used for the visualization are comparable between the tree species.

Using the 75th, 90th and 95th percentiles to extrapolate growing stock on bases of precipitation/temperature classes, it can be observed that for all tree species using the 75th percentile, the growing stock values are lower than using the 90th and 95th percentile. The differences between the 90th and 95th percentile are small, the extrapolated growing stock volumes are a little lower for the 90th percentile than using the 95th percentile.

The individual species are discussed in more detail in the next part, for each species the minimum and maximum extrapolated growing stock volume are presented, as these clearly show the difference in the possible volumes that could be reached.

3.2.1 Per species

Norway spruce

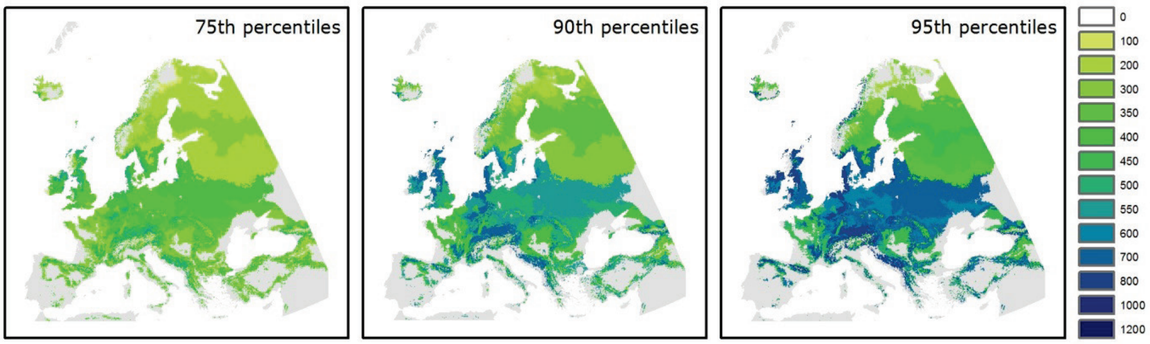


Figure 3a: Growing stock based on the given percentiles, extrapolated for the situation in 2000. (For visualization purpose, the class sizes between 300 and 600 m3/ha are smaller than the others, as they cover large parts of the volume distributions for Scots pine, Pedunculate oak and European beech. The larger volumes classes are chosen broader, as they cover a few locations of Norway spruce).

Norway spruce appears to be able to grow in most parts of the European continent, except some small areas in the south. The variety is largest using the 95th percentile, but also appears when using the other two percentiles. Growing stock values are highest when using the 95th percentile, with its optimum in the higher altitudes (the Alps, Balkan, Pyrenees and Scottish and Scandinavian coasts). The minimum and maximum values of the growing stock of Norway spruce, per percentile, are presented in table 1a

Table 1a: Growing stock range for three different percentiles

Percentiles used	Minimum growing stock (m^3/ha)	Maximum growing stock (m^3/ha)
75th	64	506
90th	114	752
95th	122	1176

Scots pine

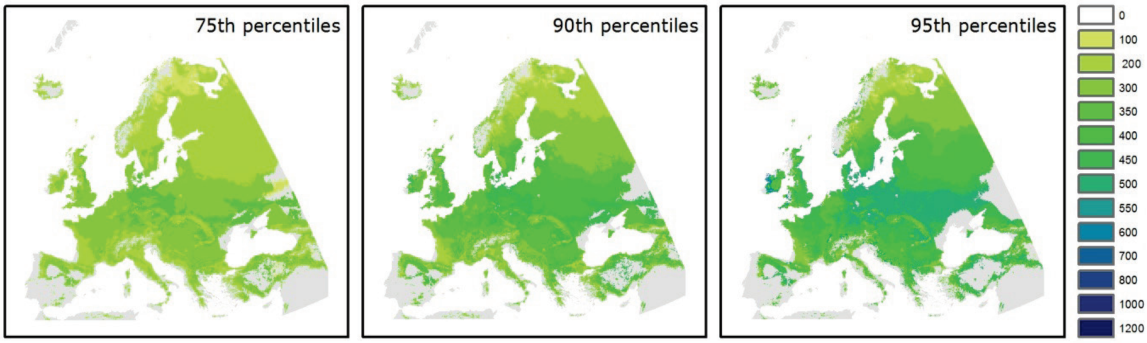


Figure 3b: Growing stock based on the given percentiles, extrapolated for the situation in 2000. (For visualization purpose, the class sizes between 300 and 600 m3/ha are smaller than the others, as they cover large parts of the volume distributions for Scots pine, Pedunculate oak and European beech. The larger volumes classes are chosen broader, as they cover a few locations of Norway spruce).

Scots pine appears to be able to grow in most parts of the European continent, except some small areas in the south. The optimum climate condition (precipitation/temperature) using the 95th percentile are located in a large area in central Europe. Using the 90th percentile, this zone is reduced to a zone that ranges from north Germany, aside the Alps to the northern boundaries of the Black Sea. The same zone as using the 90th percentile can be observed using the 75th percentile, although the growing stock values that are reached are lower. The minimum and maximum values of the growing stock of Scots pine, per percentile, are presented in table…

Table 1b: Growing stock range for three different percentiles

Percentiles used	Minimum growing stock (m^3/ha)	Maximum growing stock (m^3/ha)
75th	59	323
90th	86	428
95th	100	595

Pedunculate oak

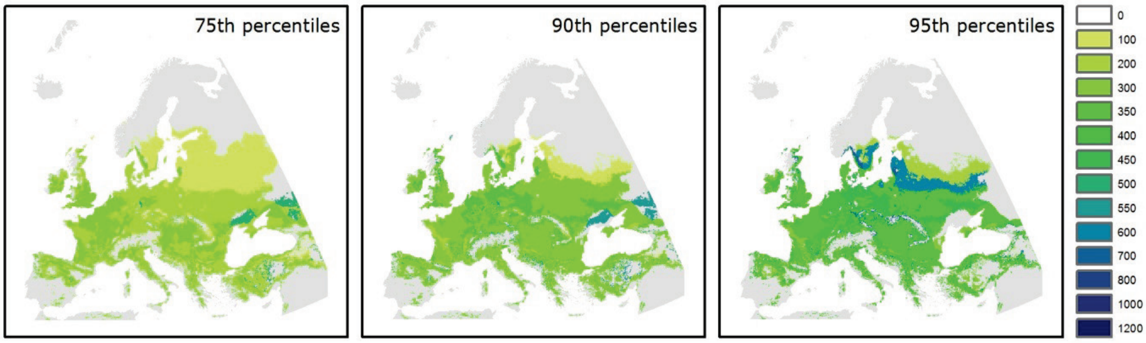


Figure 3c: Growing stock based on the given percentiles, extrapolated for the situation in 2000. (For visualization purpose, the class sizes between 300 and 600 m3/ha are smaller than the others, as they cover large parts of the volume distributions for Scots pine, Pedunculate oak and European beech. The larger volumes classes are chosen broader, as thye cover a few locations of Norway spruce).

For the 95th percentile, the Pedunculate oak shows two optimum growing areas: the first starting in the south of Scandinavia across the other side of the Baltic sea towards Russia, the second is more diverted, from the higher southern parts of Germany to the lower slopes of the Carpathian Mountains in the east of Europe, and some scattered areas in the south of France, through the Balkan and Turkey along the south of the Black sea. These areas are different for the 75th and 90th percentiles used, for both the optimum growing stock conditions can be found at the northern coast of the Black Sea, into Russia, together with some scattered locations in Germany, the Alps and Balkan. The minimum and maximum values of the growing stock of Pedunculate oak, per percentile, are presented in table…

Table 1c: Growing stock range for three different percentiles

Percentiles used	Minimum growing stock (m^3/ha)	Maximum growing stock (m^3/ha)
75^{th}	29	465
90^{th}	92	545
95^{th}	179	603

European beech

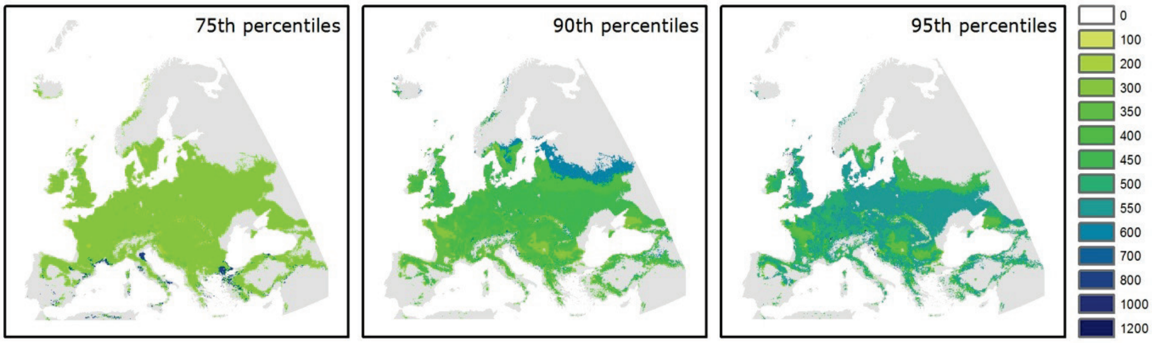


Figure 3d: Growing stock based on the given percentiles, extrapolated for the situation in 2000. (For visualization purpose, the class sizes between 300 and 600 m3/ha are smaller than the others, as they cover large parts of the volume distributions for Scots pine, Pedunculate oak and European beech. The larger volumes classes are chosen broader, as they cover a few locations of Norway spruce).

Using the 75^{th} percentile, European beech shows an extreme raise in growing stock at the southern boundaries. These extreme "jump" does not appear when using the 90^{th} or 95^{th} percentiles. Using the 95^{th} percentile, European beech has its optimum growing stock in central Europe, and the west coast of Great Britain. When using the 90^{th} percentile, this optimum is located in a zone located in the north of the Baltic stated towards Russia. 95^{th} percentile shows a larger variety in growing stock then the 90^{th} percentile. The total area where European beech can grow using the precipitation/temperature classes is largest for the 75^{th} percentile, and smallest for the 95^{th} percentile. The minimum and maximum values of the growing stock of European beech, per percentile, are presented in table…

Table 1d: Growing stock range for three different percentiles

Percentiles used	Minimum growing stock (m^3/ha)	Maximum growing stock (m^3/ha)
75^{th}	103	740
90^{th}	259	688
95^{th}	333	727

3.3 Extrapolation of growing stock

3.3.1 Current 2000 situation

For the four studied tree species and the two independent future IPCC climate change scenarios (A2 pessimistic and B2 a medium case scenario), growing stock values, extrapolated covering the European continent, are calculated from the EU-NFI database, using the 95^{th} percentile growing stock. They are compared with the situation of extrapolated growing stock figures in 2000 using the 95^{th} percentile growing stock values of the EU-NFI database.

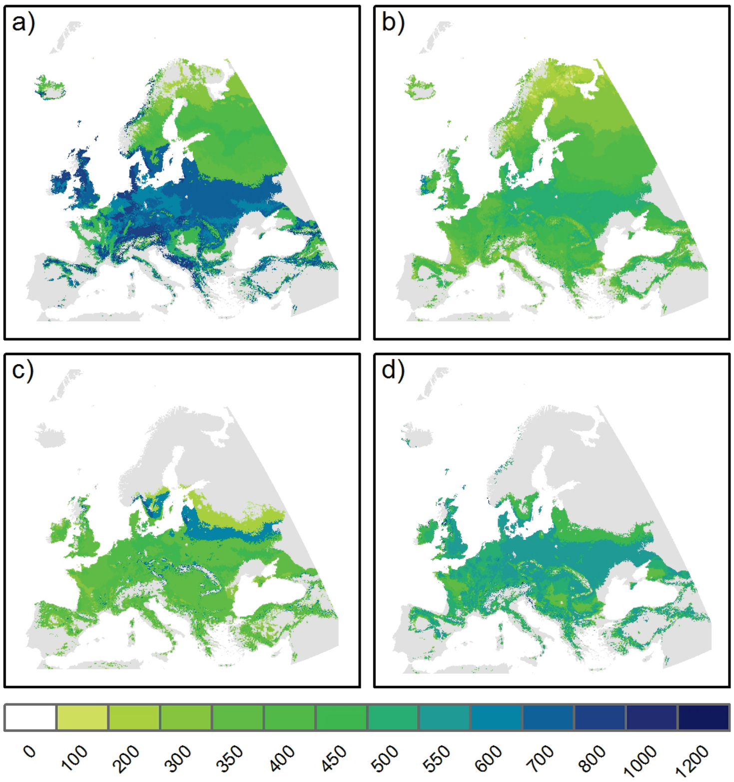


Figure 4a: Extrapolated growing stock (m^3/ha) maps under climate conditions in 2000 for four different tree species: a) Norway spruce, b) Scots pine, c) Pedunculate oak and d) European beech. (For visualization purpose, the class sizes between 300 and 600 m3/ha are smaller than the others, as they cover large parts of the volume distributions for Scots pine, Pedunculate oak and European beech. The larger volumes classes are chosen broader, as they cover a few locations of Norway spruce).

Compared to the situation in 2000 (figures 4a), it can be observed that both IPCC climate change scenarios, show a northward shift for all four tree species (figures 4b and 4c). The movement of the tree species goes up to the island of Island, which, potentially, can be completely covered by the four studied tree species. On the contrary, under climate conditions in 2000, Island only projected Scots pine trees along the north-west coast. The highest growing stock volumes are still achieved by Norway spruce for both IPCC climate change scenarios. The distribution areas in 2000 are comparable between Norway spruce and Scots pine, and between Pedunculate oak and European beech. For both studied IPCC climate change scenarios, all tree species occupy scattered areas in the higher regions of the Alps, the Carpathian Mountains, Balkans, and the southern coasts of the Black Sea.

Table 2: Potential area (sqkm) and growing stock volumes (Volume/ha) for climate conditions in 2000 and projected future IPCC climate change scenarios A2 and B2.

Tree species	2000		2080 (A2)		2080 (B2)	
	Area (sqkm)	Average Volume/ha	Area (sqkm)	Average Volume/ha	Area (sqkm)	Average Volume/ha
Norway spruce	6,044,921	501	3,124,128	535	4,339,165	517
Scots pine	6,718,085	362	4,652,682	365	5,345,847	384
Pedunculate oak	4,537,455	364	4,402,524	358	4,765,501	348
European beech	4,455,533	407	3,372,186	447	3,876,479	459

Scots pine has the largest area covered for the extrapolation under climate conditions in 2000, followed by Norway spruce. Pedunculate oak and European beech have approximately the same coverage. Norway spruce shows the largest area reduction between the climate conditions in 2000 and the future IPCC climate change scenarios, respectively 48.3% between 2000 and the A2 IPCC scenario, and 28.2% between the 2000 and the B2 IPCC scenario (Table 2) Scots pine follows with a reduction of 30.7%

between 2000 and A2 and 20.4% between 2000 and B2. Although all tree species exhibit an area reduction when comparing the climate conditions in 2000 and the future IPCC climate change scenarios, higher growing stock volumes are achieved for all tree species except Pedunculate oak, which shows for both scenarios a reduced growing stock volume.

3.3.2 IPCC pessimistic climate change scenario A2

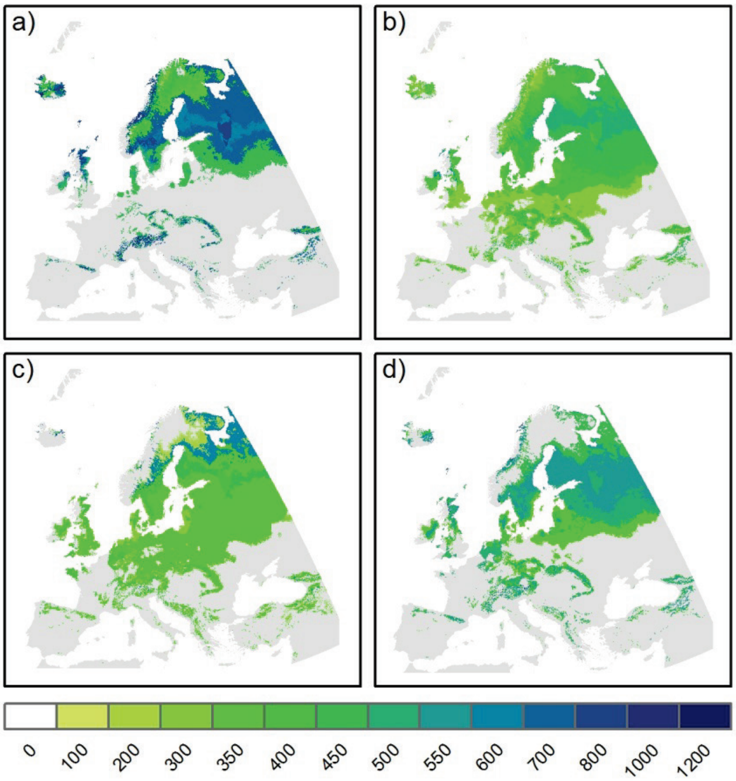


Figure 4b: Projected growing stock (m^3/ha) maps under future (2080) climate conditions for the IPCC pessimistic scenario A2 for four different tree species: a) Norway spruce, b) Scots pine, c) Pedunculate oak and d) European beech. (For visualization purpose, the class sizes between 300 and 600 m3/ha are smaller than the others, as they cover large parts of the volume distributions for Scots pine, Pedunculate oak and European beech. The larger volumes classes are chosen broader, as they cover a few locations of Norway spruce).

There is a strong shift towards the northern part of the European continent for the extreme climate change (A2 pessimistic) scenario. Based on results of this climate change scenario, the tree species included in the present study will nearly disappear from the Mediterranean region. The area in which the four studied tree species occur, is strongly reduced under the A2 conditions compared to the 2000 situation. Consequently, the four tree species will need to compete each other for a reduced growing location. Under the climatic conditions in 2000, there was mainly an overlap in the growing area between Norway spruce and Scots pine, and between Pedunculate oak and European beech. On the contrary, in the A2 situation, the overlap in the growing area among the four species becomes much larger.

The total growing areas available for all studied tree species are reduced, which is also been quantified in table 2. It can be concluded that for the most extreme IPCC climate change scenario (A2), the available area for all species is not only lower compared to the 2000 situation, but is for all species also lower compared to the IPCC medium case climate change scenario (B2).

3.3.3 IPCC medium case climate change scenario B2

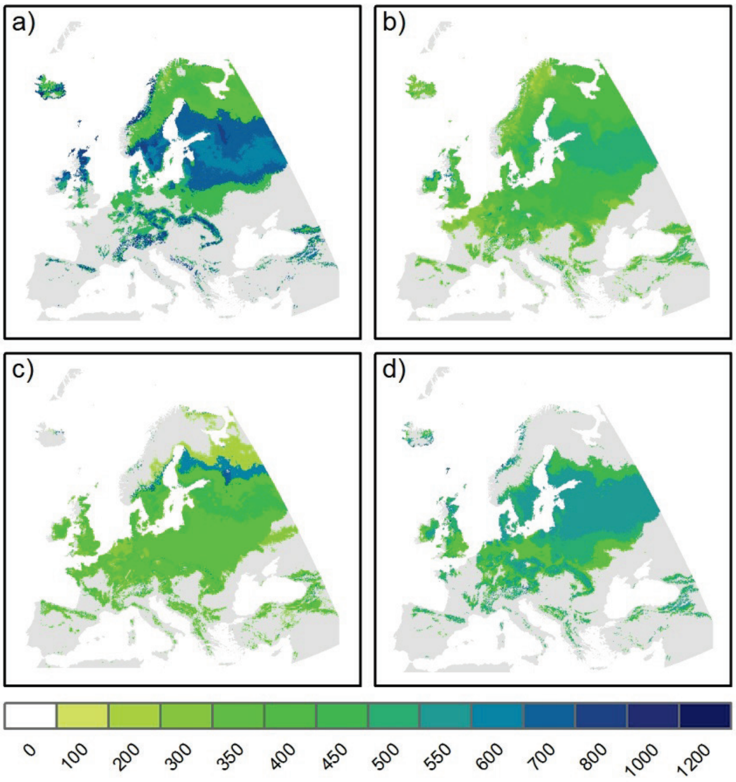


Figure 4c: Projected growing stock (m³/ha) maps under future (2080) climate conditions for IPCC medium case scenario B2 for four different tree species: a) Norway spruce, b) Scots pine, c) Pedunculate oak and d) European beech. (For visualization purpose, the class sizes between 300 and 600 m3/ha are smaller than the others, as they cover large parts of the volume distributions for Scots pine, Pedunculate oak and European beech. The larger volumes classes are chosen broader, as they cover a few locations of Norway spruce).

The shift towards the northern part of the European continent is realised to a lower extent than for the (pessimistic) A2 IPCC climate change scenario. The overlap of growing areas of the four tree species is similar to the one observed under climate conditions in IPCC scenario A2, however, this is less exaggerated under climate conditions in IPCC scenario B2.

Compared to the 2000 situation, the total areas available under the medium case IPCC climate change scenario (B2) are reduced for all tree species, except Pedunculate oak (see table 2). Pedunculate oak occupies a larger area to that when compared to the 2000 situation.

3.4 Comparing tree species distributions

The calculated distributions of the growing stock maps were compared to the actual distribution maps of the Atlas Flora Europaeae (Jalas & Suominen, 1972). When only temperature and precipitation are considered, large areas are potentially suitable as growing areas, for all studied tree species. Extrapolation of growing stock volumes based on these two climate parameters, there is a misallocation mainly situated in the south-east, eastern parts of Europe, and Great Britain, compared to the know distributions.

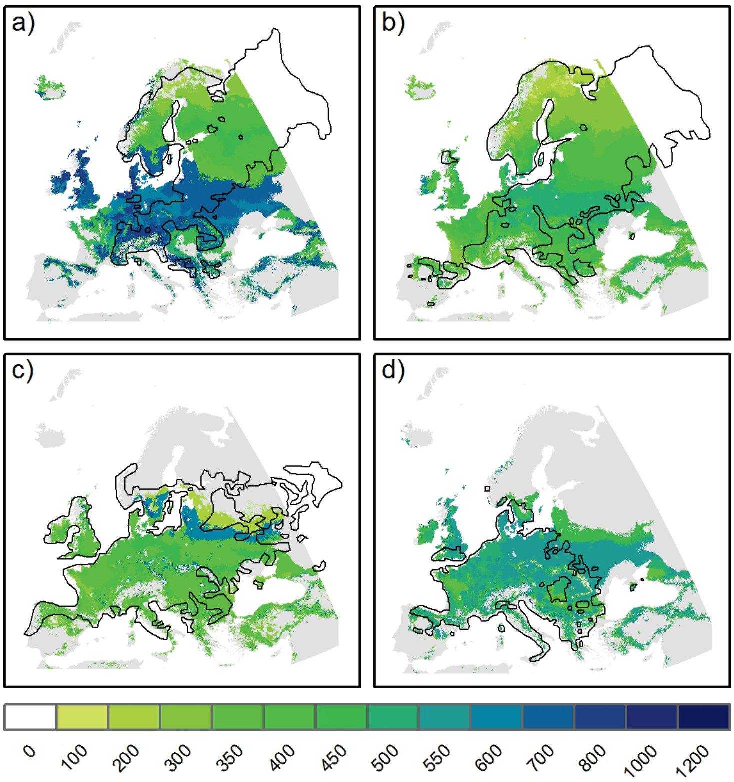


Figure 5a: Extrapolated growing stock (m^3/ha) maps under climate conditions in 2000 for four different tree species: a) Norway spruce, b) Scots pine, c) Pedunculate oak and d) European beech, compared to the known distributions of the Atlas Flora Europeaea (Jalas & Suominen, 1972).

In general, all areas included in the Atlas Flora Europaeae do also occur in the extrapolated growing stock maps. It can be observed that all extrapolated growing stock volumes exhibit misallocations mainly in the south-east of Europe. Scots pine and Norway spruce also presented misallocations in western Europe and Great Britain. Norway spruce also occurs in the north of Spain, where it should actually not appear. European beech is far too much extended to the east, Pedunculate oak is overestimated in the south-east, but also shows an underestimation in the north-east.

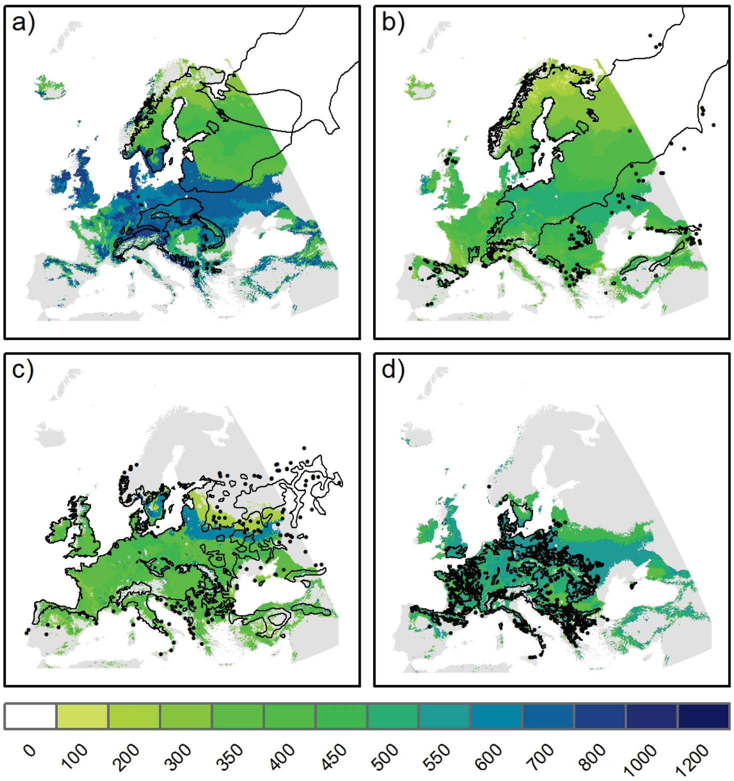


Figure 5b: Extrapolated growing stock (m^3/ha) maps under climate conditions in 2000 for four different tree species: a) Norway spruce, b) Scots pine, c) Pedunculate oak and d) European beech, compared to the known distributions of the distribution maps of the European Forest Genetic Resources Programme (EUFORGEN, 2009).

Except for Pedunculate oak all areas covered by the known distribution maps are also included in the extrapolated stock maps. For Pedunculate oak some areas in the north-east of Europe are not included in the extrapolated growing stock map, where they should be following the know distribution.

For Norway spruce, the extrapolated zone with the higher growing stock volumes, do not match the known distributions, however, the areas with lower stock volumes do match the known distributions. Also a large part of western Europe and Great Britain is included in the growing stock extrapolations, where they should not be. The same counts for the south-east part of Europe.

The extrapolation of growing stock for Scots pine overestimates large parts of western Europe and Great Britain, and large parts of the south-east of Europe, where Scots pine only occurs at rather restricted locations.

Pedunculate oak is rather underestimated in the north-east of Europe, whereas, it is rather overestimated in Spain and Turkey.

European beech occurs in many fragmented locations over Europe, it is largely overestimated in the east of Europe and in Great Britain.

3.5 Introduction of Minimum and maximum temperatures

The previous sections showed a large overestimation of species distribution in comparison with known species distributions. For this reason extremes in temperature that could possibly limit the extent of the distributions are studied, and described in the next part.

On basis of 5^{th} and 95^{th} percentiles of the minimum temperature during the coldest month (BIO6) and the maximum temperature during the warmest month (BIO5), respectively, of all records available in the EU-NFI database, the potential distribution maps of the tree species were calculated.

Table 3: Threshold values based on the 5th percentile of the minimum temperature of the coldest month and the 95th percentiles of the maximum temperature of the warmest month of all EU-NFI database records for the studied tree species.

Species	T(min) coldest month	T(max) warmest month
Norway spruce	-11.4°C	23.4°C
Scots pine	-13.7 °C	24.7°C
Pedunculate oak	-4.4 °C	26.0°C
European beech	-5.9°C	24.3°C

Calculated threshold values, based on the 5th percentile of the minimum temperature of the coldest month and the 95th percentiles of the maximum temperature of the warmest month (table 3), used to construct the potential distribution maps of the tree species, show that the minimum temperature during the coldest month strongly vary for the four tree species, with comparable temperatures between Norway spruce and Scots pine, and between Pedunculate oak and European beech. Calculated maximum temperatures during the warmest month exhibit a lower variation and show that Pedunculate oak is the least sensitive for warm temperatures.

3.5.1 Per species

Norway spruce

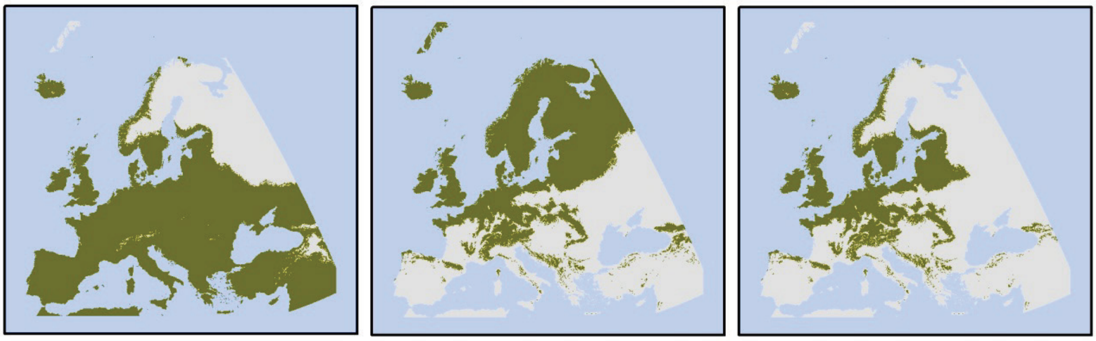


Figure 6a: Potential distribution of Norway spruce (olive), from left to right: Minimum temperatures during the coldest month (5th percentile), Maximum temperature of the warmest month (95th percentile), Minimum temperature of the coldest moth combined with the maximum temperature of the warmest month (5th percentile and 95th percentile).

Using the 5th percentile of the minimum temperatures during the coldest month for all records in the EU-NFI database, it can be observed that the extreme cold areas in the north-east and south-east of the Black Sea are excluded from the potential distribution map. All other part of Europe fall above the threshold. Using the 95th percentile for the maximum temperature, limitations in the potential distribution to the northern and higher altitude parts of Europe is observed. The combination of both parameters, shows a potential distribution of Norway spruce in central-west Europe.

Scots pine

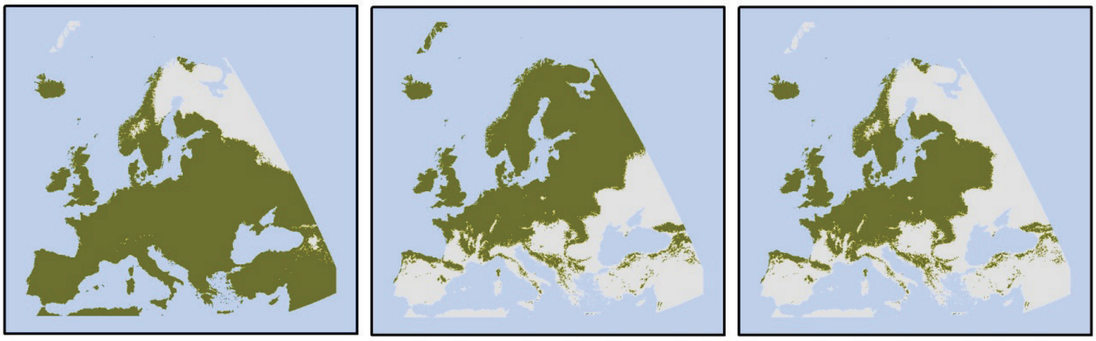


Figure 6b: Potential distribution of Scots pine (olive), from left to right: Minimum temperatures during the coldest month (5^{th} percentile), Maximum temperature of the warmest month (95^{th} percentile), Minimum temperature of the coldest moth combined with the maximum temperature of the warmest month (5^{th} percentile and 95^{th} percentile).

As it can be observed for Scots pine, only the north-east and south-east of the Black Sea are excluded from the potential distribution map, as being too cold during winter. Using the 95^{th} percentile to determine the maximum temperature during the warmest month, exclusion of the south of Europe from the potential distribution area for Scots pine is determined. The combination of both parameters shows only the central-west of Europe is available for potential distribution of Scots pine.

Oak

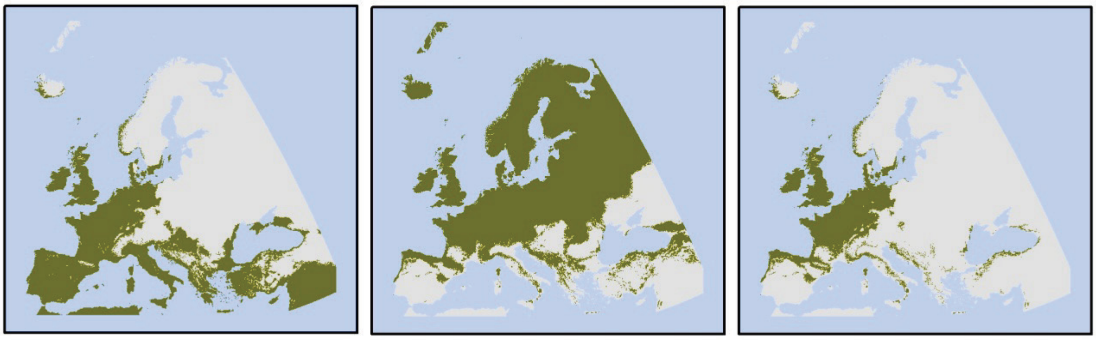


Figure 6c: Potential distribution of Pedunculate oak (olive), from left to right: Minimum temperatures during the coldest month (5^{th} percentile), Maximum temperature of the warmest month (95^{th} percentile), Minimum temperature of the coldest moth combined with the maximum temperature of the warmest month (5^{th} percentile and 95^{th} percentile).

It can be observed that large parts of east Europe are excluded from the potential distribution map of Pedunculate oak using the 5^{th} percentile of the minimum temperature during the coldest month. The 95^{th} percentile of the maximum temperature during the warmest month excludes large parts of south and south-east Europe from the potential distribution map. The combination of both parameters limits the potential distribution of Pedunculate oak to the west of Europe.

European beech

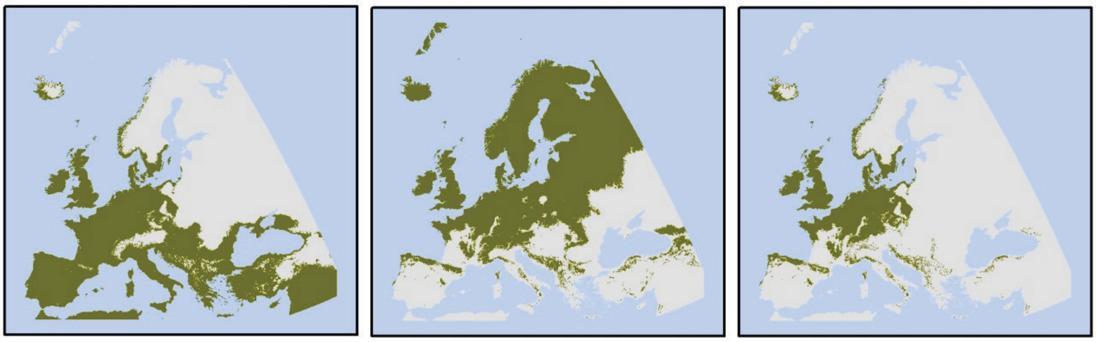


Figure 6d: Potential distribution of European beech (olive), from left to right: Minimum temperatures during the coldest month (5^{th} percentile), Maximum temperature of the warmest month (95^{th} percentile), Minimum temperature of the coldest moth combined with the maximum temperature of the warmest month (5^{th} percentile and 95^{th} percentile).

The potential distributions for European beech are comparable with those constructed for Pedunculate oak, however, the potential areas are somehow larger. Using the 5th percentile of the minimum temperature during the coldest month, limitations in the distribution of European beech to the south of Europe is shown, whereas the 95th percentile of the maximum temperature during the warmest month excludes these southern and south-eastern areas. The combination of both limits the potential distribution of European beech to west Europe including Great Britain.

3.6 Potential species distributions

As most parts of the two known distribution maps overlap, they will be compared to the calculated potential distribution maps based on the minimum temperature of the coldest month, on the maximum temperature of the warmest month and on their combination.

For three (Norway spruce, Scots pine and Pedunculate oak) of the four studied tree species, the maximum temperature of the warmest month, sufficiently explains the pattern of the known distribution maps. However, the distribution pattern of European beech can be explained based on the combination of the minimum temperature of the coldest month and maximum temperature during the warmest month.

3.6.1 Per species

Norway spruce

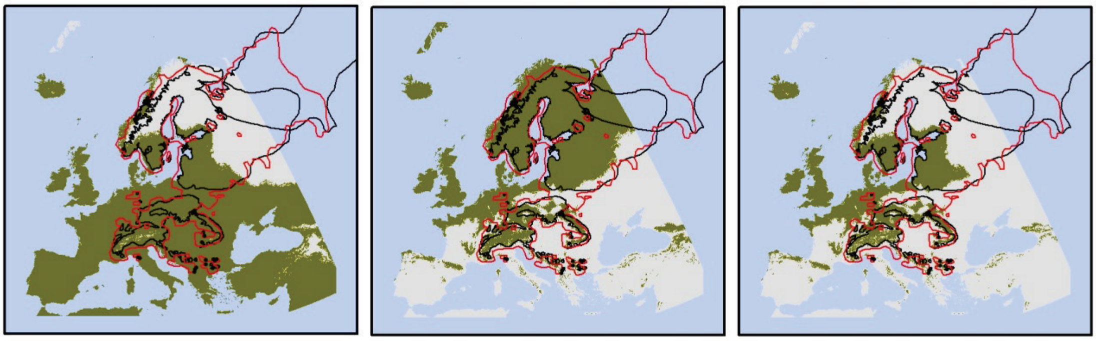


Figure 7a: Potential distribution of Norway spruce (olive), from left to right: Minimum temperatures during the coldest month (5th percentile), Maximum temperature of the warmest month (95th percentile), Minimum temperature of the coldest month combined with the maximum temperature of the warmest month (5th percentile and 95th percentile) compared to the known distributions of the Atlas Flora Europeaea in black, and distribution maps of the European Forest Genetic Resources Programme in red.

The potential distribution map based on the minimum temperature during the coldest month excludes the northern part of Europe, without any justification, and exhibits several misallocations in the south and west including Great Britain and Island.

Maximum temperature during the warmest month sufficiently explains the distribution pattern of Norway spruce. It excludes large parts in the south-east of Europe, and exhibits several misallocations along the west European coast and Great Britain.

The combination of the minimum temperature of the coldest month and maximum temperature during the warmest month restricts the potential distribution area to a remarkable small extent, as the north and south of Europe are both excluded.

Scots pine

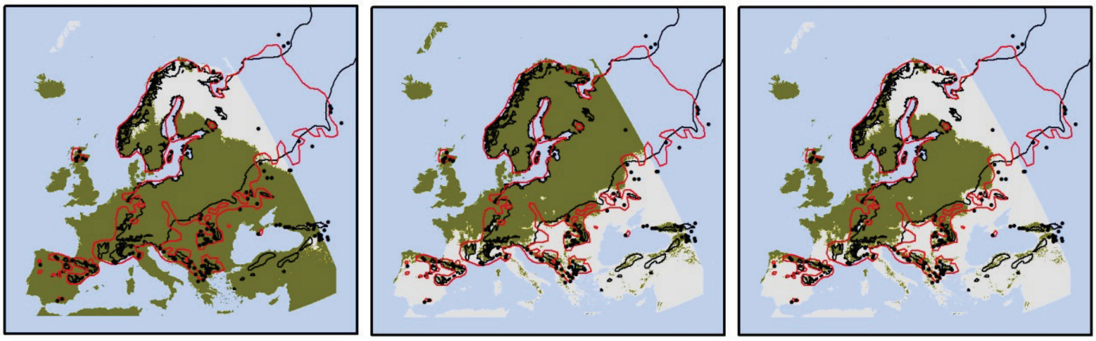


Figure 7b: Potential distribution of Scots pine (olive), from left to right: Minimum temperatures during the coldest month (5th percentile), Maximum temperature of the warmest month (95th percentile), Minimum temperature of the coldest month combined with the maximum temperature of the warmest month (5th percentile and 95th percentile) compared to the known distributions of the Atlas Flora Europeaea in black, and distribution maps of the European Forest Genetic Resources Programme in red.

The potential distribution map based on the minimum temperature during the coldest month excludes the northern part of Europe, without any justification, and exhibits several misallocations in the south.

Similarly to Norway spruce, minimum temperature during the coldest month excludes Scots pine from the northern part of Europe, without any justification, and exhibits several misallocations in the south and west of Europe, including Great Britain and Island.

Maximum temperature during the warmest month sufficiently explains the distribution pattern of Scots pine. It excludes large parts in the south-east of Europe, and exhibits several misallocations along the west European coast and Great Britain. Areas in central Europe are explained sufficiently, the northern Balkan area is excluded, where parts along the Adriatic coast and scattered areas around the Black Sea are included in the potential distribution map.

Although the potential distribution can be adequately explained by the maximum temperature during the warmest month, the combination of the minimum temperature of the coldest month and the maximum temperature during the warmest month excludes areas in the north of Europe, without any justification following the known distributions.

Pedunculate oak

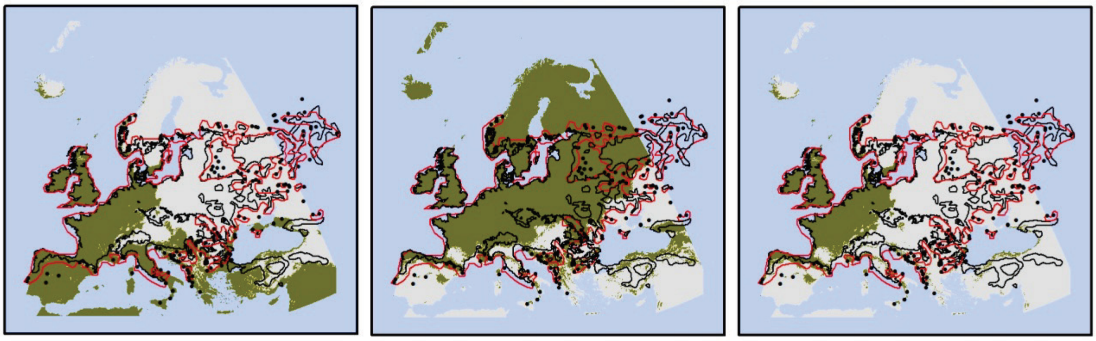


Figure 7c: Potential distribution of Pedunculate oak (olive), from left to right: Minimum temperatures during the coldest month (5th percentile), Maximum temperature of the warmest month (95th percentile), Minimum temperature of the coldest month combined with the maximum temperature of the warmest month (5th percentile and 95th percentile) compared to the known distributions of the Atlas Flora Europeaea in black, and distribution maps of the European Forest Genetic Resources Programme in red.

The potential distribution pf Pedunculate oak using the minimum temperature of the coldest month, does correctly include the western part of Europe, however, it exhibits several misallocations in the Mediterranean, and excludes, without any justification, large parts of east Europe. The use of maximum temperature during the warmest month, sufficiently explains the distribution pattern of Pedunculate oak along the southern distribution boundaries, but it exhibits several misallocations in the north of Europe. The combination of the minimum temperature of the coldest month and the maximum temperature during the warmest month limits the distribution of Pedunculate oak to a small area in the west of Europe remarkably.

European beech

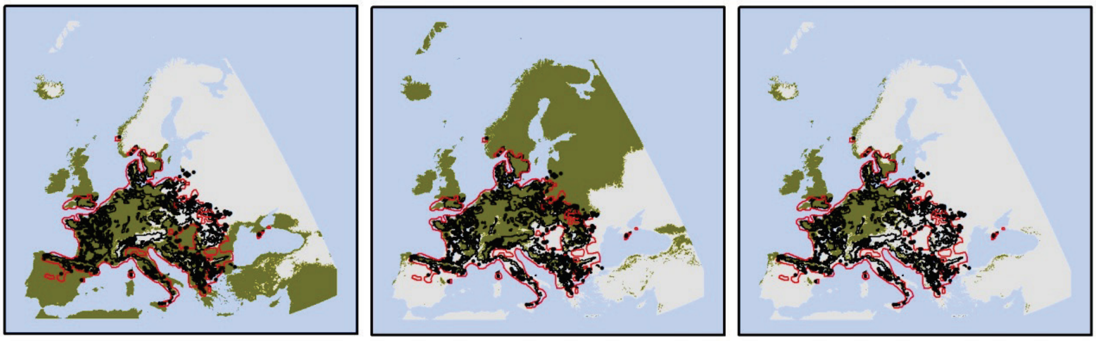


Figure 7d: Potential distribution of European beech (olive), from left to right: Minimum temperatures during the coldest month (5th percentile), Maximum temperature of the warmest month (95th percentile), Minimum temperature of the coldest month combined with the maximum temperature of the warmest month (5th percentile and 95th percentile) compared to the known distributions of the Atlas Flora Europeaea in black, and distribution maps of the European Forest Genetic Resources Programme in red.

Using the minimum temperature of the coldest month to construct a potential distribution map for European beech, does include all areas known in the published distribution maps, it only overestimates parts of Great Britain, Spain and south-east Europe. When using the maximum temperature during the warmest month, the distribution pattern fits the known distributions, but overestimates its extent in the north-east of Europe.

The combination of both the minimum temperature of the coldest month and the maximum temperature during the warmest month extends, without any justification, the distribution of European beech to Great Britain. all other parts of Europe fit well, scattered parts where European beech is fragmented distributed are included in the constructed potential distribution map. Even the isolated part at the northern coastline of the Black Sea is included.

3.7 Extrapolated growing stock volumes including potential species distributions

For the sake of unambiguous, for all tree species, the potential distribution maps based on the maximum temperature during the warmest month is chosen as a limiting factor to reduce the overestimation of allocated areas of the growing stock maps (in figures 4a, 4b and 4c).

Table 4: Potential area and growing stock volumes for current and projected future IPCC climate change scenarios A2 and B2 reduced by the potential distribution on basis of maximum temperature during the warmest month.

Species	2000		2080 (A2)		2080 (B2)	
	Area (sqkm)	Average Volume /ha	Area (sqkm)	Average Volume /ha	Area (sqkm)	Average Volume /ha
Norway spruce	3,702,709	483	945,219	502	1,309,937	460
Scots pine	4,970,110	352	1,299,005	369	1,865,384	358
Pedunculate oak	3,197,546	373	1,354,244	387	1,998,311	348
European beech	2,229,653	483	647,595	451	729,796	457

In general all tree species move upward to the north, towards Scandinavia and Great Britain.

Scots pine has the largest area covered for the 2000 extrapolation, followed by Norway spruce and Pedunculate oak. European beech has the lowest coverage. Norway spruce, Scots pine and European beech do show the largest area reduction between the situation in 2000 and projected A2 scenario, respectively 74.5%, 73.9% and 71.0%, whereas the area cover of Pedunculate oak is reduced with 57.6%. European beech has the largest area reduction of 67.3% between the situation in 2000 and B2 projected scenario, followed by Norway spruce and Scots pine with reductions of 64.6% and 62.5%, respectively. The area cover of Pedunculate oak is reduced with 37.5%.

3.7.1 Per species

Norway spruce

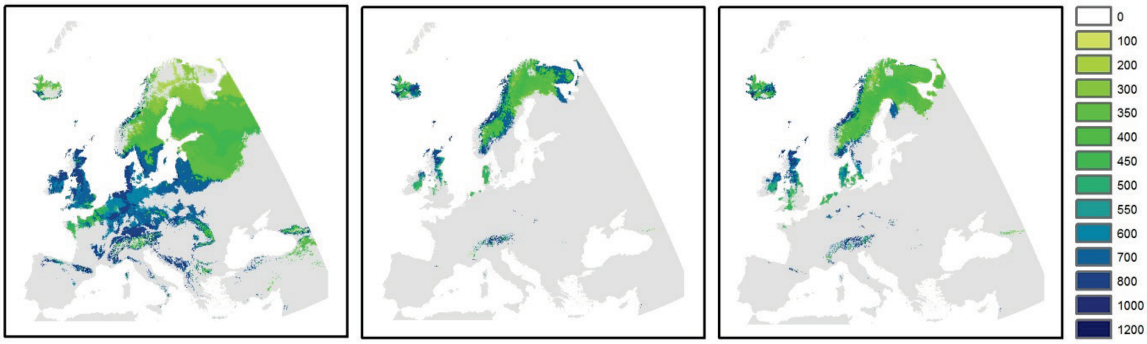


Figure 8a: Projected growing stock maps (m³/ha) from left to right: under climate conditions in 2000 and future (2080) climate conditions for different climate scenarios A2 and B2 (subtracted potential distribution areas based on 95th percentiles of the maximum temperature of the warmest month).

Locations of Norway spruce are limited in both IPCC scenarios (A2 and B2) to the most northern parts of Europe. It can be seen that for the medium case change scenario (B2), the highest growing stock volumes are reached along the northern coastlines, whereas in for the pessimistic climate scenario (A2) the highest stock volumes are reached in the south and north of Scandinavia.

Scots pine

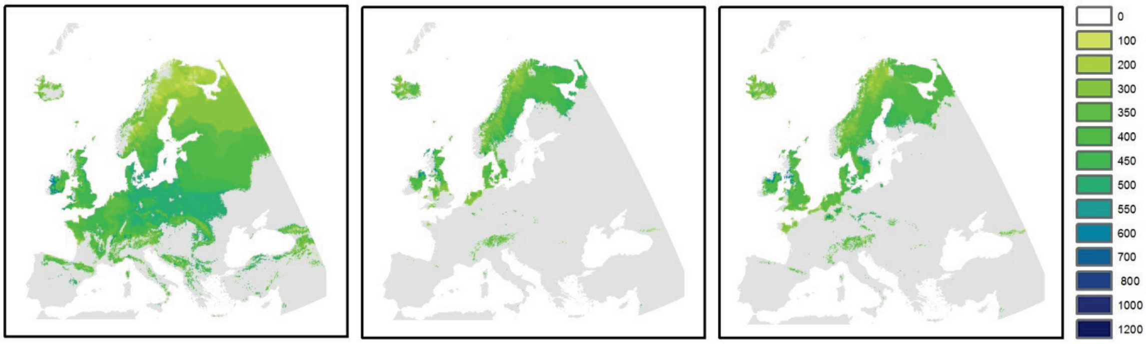


Figure 8b: Projected growing stock maps (m³/ha) from left to right: under climate conditions in 2000 and future (2080) climate conditions for different climate scenarios A2 and B2 (subtracted potential distribution areas based on 95th percentiles of the maximum temperature of the warmest month).

The areas where Scots pine is extrapolated, is under the pessimistic IPCC scenario A2 limited to Scandinavia and parts of Great Britain. The medium case IPCC climate change scenario also includes Scandinavia, but is extended to north Russia, and western Europe.

For both A2 and B2 scenarios, growing stock volumes are larger towards the east.

Pedunculate oak

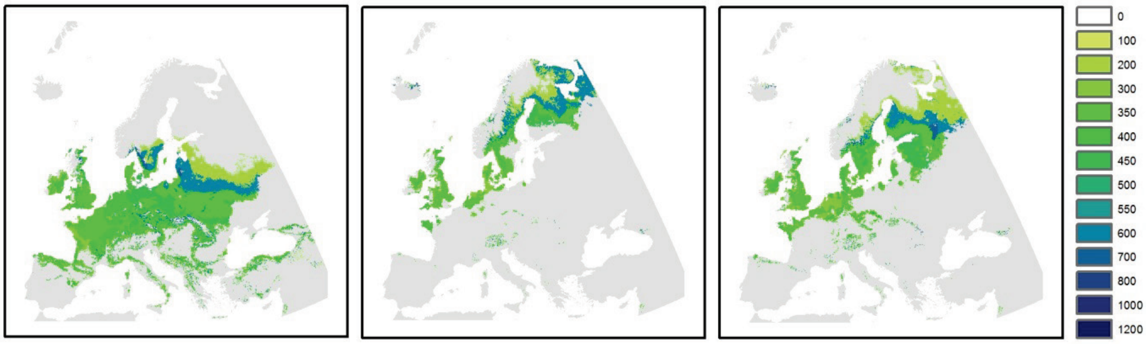


Figure 8c: Projected growing stock maps (m³/ha) from left to right: under climate conditions in 2000 and future (2080) climate conditions for different climate scenarios A2 and B2 for a) (subtracted potential distribution areas based on 95th percentiles of the maximum temperature of the warmest month).

The extrapolated maps of growing stock for Pedunculate oak show that Pedunculate oak does not appear in the whole of Scandinavia, but stays in a zone just in the south-eastern part of Scandinavia (scenario

A2) or just below, ranging from the Baltics towards the west of Europe (scenario B2), also parts of the Carpathian mountains and Alps are included. The shift is for the medium case IPCC scenario (B2) less extreme northwards than for the pessimistic IPCC scenario (A2).

For the A2 scenario, the highest growing stock volumes will be reached in the north of Scandinavia, under the B2 scenario, the optimum is located in Finland towards the north of Russia.

European Beech

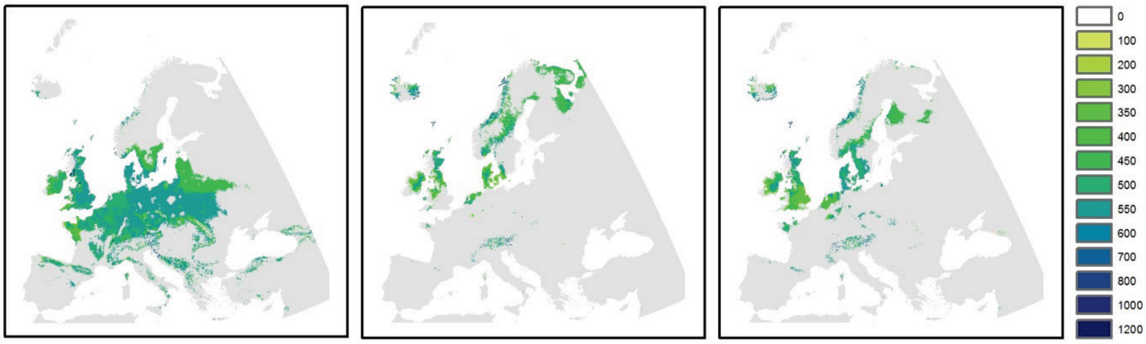


Figure 8d: Projected growing stock maps (m^3/ha) from left to right: under climate conditions in 2000 and future (2080) climate conditions for different climate scenarios A2 and B2 for (subtracted potential distribution areas based on 95th percentiles of the maximum temperature of the warmest month).

As for the other tree species studied, European beech moves upward to the north, but shows a more scattered pattern, for the pessimistic IPCC scenario (A2) ranging in flocks in the north-east of Scandinavia, to central Scandinavia, and parts of north-west Europe, Great Britain and the Alps. Under the medium case IPCC scenario (B2), the distribution includes large part of Great Britain, north-west Europe and the Norwegian coast, together with scattered locations in Russia and the Alps.

For scenario B2, a large area with lower growing stock volumes is located in the south-east of Great Britain, and north-east of Ireland. For the A2 scenario growing stock volumes are scattered, but end to be higher towards the north.

3.8 Tree species suitability maps

Combined maps are constructed for the four tree species studied. It can be observed that the maps calculated for both scenarios do clearly show zones in which one of the species is dominant in its growing stock volumes.

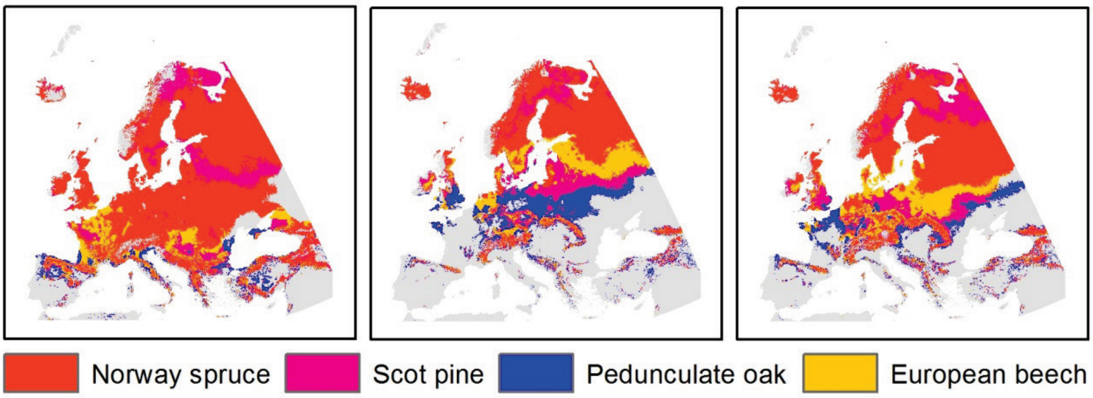


Figure 9a: Climatic suitability of Europe for different tree species under climate conditions of 2000 and future scenarios (A2 middle, B2 right) climatic conditions. Maps are based on a comparison of projected growing stock levels (see figure 4a, 4b and 4c).

Under the climate conditions of 2000, Norway spruce is the dominant species in Europe, up from central Europe to the north, Norway spruce has the highest growing stock volume performance.

Scots pine performs well at some intermediate zones of Norway spruce, which under the climate conditions in 2000 represent a zone from the Baltics towards Russia, and in the north of Scandinavia. These zones are moved northwards for the B2 scenario, and a southern shift can be observed for the A2 scenario.

Under the climate conditions of 2000 growing stock volumes of Pedunculate oak are dominant at some scattered locations in the south of Europe. For both scenarios A2 and B2 Pedunculate oak tend to perform the best at the most southern regions. Under both scenarios the area covered by Pedunculate oak becomes larger than the area covered in the 2000 situation. The area of Pedunculate oak is for scenario A2 larger than for scenario B2.

Under the climate conditions of 2000, European beech performs the best in large parts of France, Czech and Slovakia and east of the Sea of Azov. The zone is shifted to the north for both scenarios. The shift is more extreme for scenario A2, located in west Europe and south Scandinavia and the northern Baltics towards Russia. For the B2 scenario, scattered locations are present in central and west Europe, and a large zone can be observed in central-east Europe, staring from Poland toward the east.

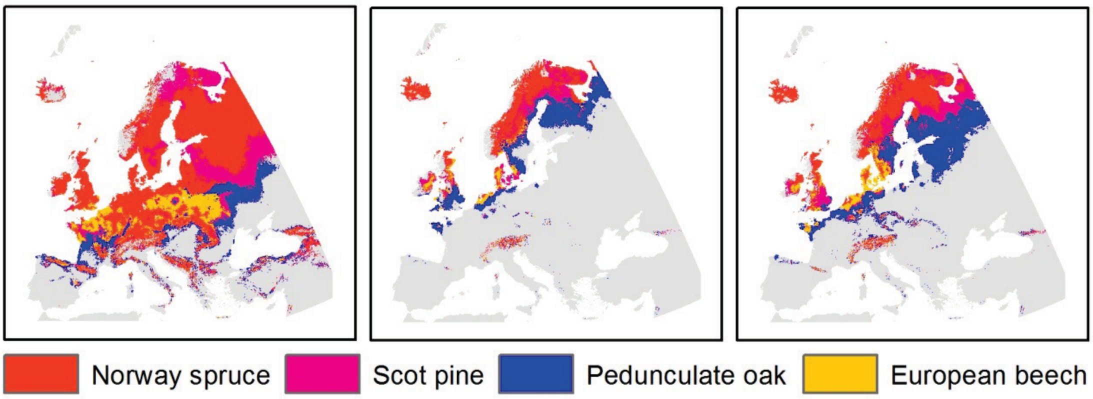


Figure 9b: Climatic suitability of Europe for different tree species under climate conditions of 2000 (left) and future scenarios (A2 middle, B2 right) climatic conditions. Maps are based on a comparison of projected growing stock levels (figures 8a, 8b, 8c and 8d), including potential distributions using maximum temperature during the warmest month.

The available space is largely reduced using the maximum temperature during the warmest month to limit the distribution space. For the extrapolated scenarios, the available area is more reduced than for the extrapolations in the 2000 conditions.

Norway spruce is still the best performing dominant species of Europe under the climate conditions in 2000 extrapolation. The zones occupied by Scots pine from the Baltics towards Russia, and in the north of Scandinavia, are similar to those when the potential distribution limit is not used. For European beech, they are allocated at complete different locations in central Europe, whereas the area in France is still occupied, but is reduced in size. Parts of these areas in France are now covered by Pedunculate oak, which also occurs in the central-east of Europe.

Norway spruce and Scots pine are in both future scenarios performing the best at the north of Scandinavia. Pedunculate oak performs the best for both scenarios in a large zone at the north-east of Europe. This zone is larges for scenario B2 than for A2. The optimum performance of European beech is for scenario B2 limited to a small area around the Netherlands, north Germany and Denmark. In the A2 scenario European beech does hardly perform best of all four species, only a few locations in the Netherlands and Denmark can still be observed.

4. Discussion

4.1 Percentiles classes

The difference in class size to determine the 75th, 90th and 95th percentile for growing stock, shows that the plots available in the EU-NFI database are not equally spread over the determined temperature/precipitation classes of the European continent. This is a result of merging national observations together in a Europe wide covering database. Specifically, the number of plots visited are much more dense in the west of Europe (in countries like Germany, France and Great Britain) compared to countries in the east of Europe, such as Poland, Rumania or Ukraine. In many cases, there are large gaps between the visited plots, and when looking in more detail, there is a large difference in the spatial distribution and methodologies of the countries. For example Germany uses a regular grid for the visited plots, whereas France is visiting its locations on an irregular sample grid. Differences in the data collection methodologies are unknown, and could be standardized among the European countries.

There are large differences in the number of plots falling in one of the combined precipitation/temperature classes, on which the 75th, 90th and 95th percentiles were calculated. This results in much higher accuracy of the calculated percentiles for some of the precipitation/temperature classes than for others. For precipitation/temperature classes that had too low number of visited plots in the EU-NFI database, no percentiles could be calculated (appendix II).

4.2 Extrapolation of the percentiles

The 95th percentiles do show a larger variability in the extrapolated growing stock maps than the 90th and 75th percentiles. The lower the percentile chosen, the less reliable the extrapolated growing stock volumes. This is actually an effect of the methodology, as large parts of the distribution of growing stock volumes available in the EU-NFI database are ignored; in the case of the 75th percentile, 25% of the observations are not used. For this reason it has been decided to perform the analysis using the 95th percentile growing stock volumes, as presenting reliable stock volumes.

As the extrapolations are based on two climate variables (precipitation and temperature) only, the four tree species are capable to occur in large parts of Europe. Anthropogenic and management influences have not been integrated in the present study, however, their influence should not be neglected.

The distributions of the extrapolated growing stock maps do not match the actual distributions of the four tree species. To compensate these overestimations of the extrapolated distributions, other temperature parameters are introduced (Woodward, 1988), during the on-going of this study. Sykes and co-authors (Sykes *et al.*, 1996) introduced the minimum temperature as a parameter to model tree species distributions. In our study, the minimum temperature of the coldest month and maximum temperature of the warmest month are explored and shown in figures 6a, 6b, 6c and 6d. The threshold values are based on respectively the 5th percentile of the minimum temperature of the coldest month and the 95th percentiles of the maximum temperature of the warmest month of all EU-NFI database records for four different tree species.

4.3 Minimum and maximum temperatures

The locations included in the EU_NFI database are not equally spread over Europe. As a result of this, it could be possible that the used thresholds to determine the 5th and the 95th percentile for the minimum temperatures during the coldest month and maximum temperature of the warmest month, respectively, are not valid, as not all areas in Europe are equally represented in the data set, which can be seen in the densities of plots per sqkm for the four different species in figure 10.

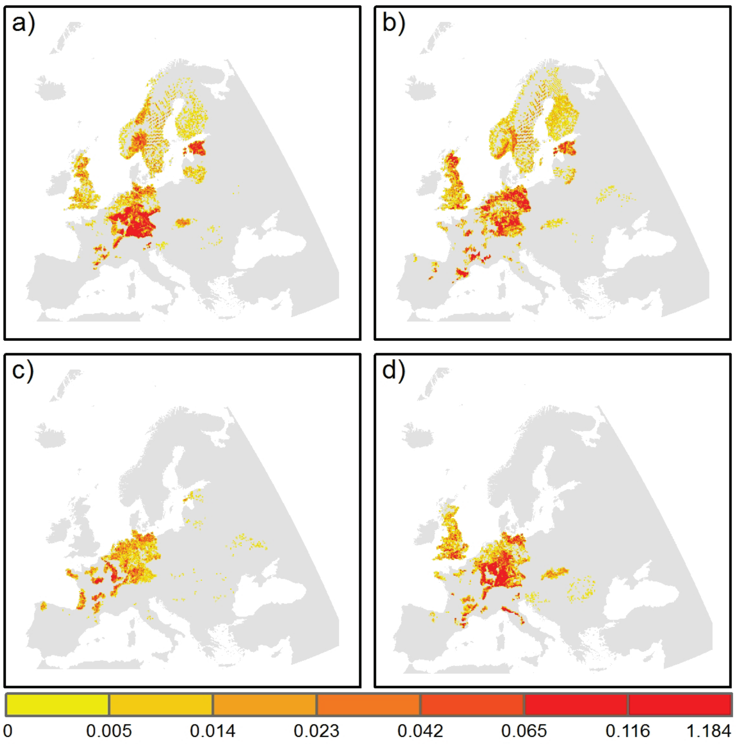


Figure 10: Plot density of the four species in the EU-NFI database (number of plots per sqmk): a) Norway spruce, b) Scots pine, c) Pedunculate oak and d) European beech (the scale is nonlinear as the density at most of the locations are les then one per sqkm).

Combination of a minimum and maximum temperature during the coldest and warmest month of the year, respectively, although it excludes only a limited number of areas, results in large areas which are missing. When one of the two parameters is used in a single application (minimum temperature during the coldest month or the maximum temperature during the warmest month), the areas that are left, differ per tree species, for some, the areas are too large, for others the results correspond to the known distribution maps. Using minimum temperature during the coldest month only, results in allocation of a high number of locations in the south of Europe for European beech. Norway spruce is spread all over Europe, except in the north where is should be distributed, the same can be observed for Scots pine. Pedunculate oak corresponds to the results of European beech, too much towards the south of Europe, but also large parts in east Europe are missing.

When using maximum temperature during the warmest month only, European beech is allocated correctly over south and west Europe, but also claims areas in the north, which should be left aside, the same can be observed for Pedunculate oak. Correct over south and west Europe, but also allocates in the north of Europe, where it should not be allocated. Norway spruce and Scots pine show corresponding results, the allocation in the north and east of Europe is correct, but also areas in the north-west are available, which should following the distribution maps of the European Forest Genetic Resources Programme not be included.

The threshold values calculated are based on the EU Forest Inventory database, which means only data from a limited number of countries is taken into account. Many countries in eastern Europa are not included in the database, which means that measurements in these areas are not included in the calculation of the 5th and 95th percentiles of the minimum and maximum temperature values, respectively. Thresholds that were calculated from the 5th and 95th percentile of the records in the EU Forest Inventory database differ from those used by Sykes (Sykes *et al.*, 1996) in their bioclimatic model to calculate tree species distributions. They only used the parameters for minimum and maximum temperatures during the coldest month, whereas, maximum temperature during the warmest month is not used. Together the two parameters of the coldest month, growing degree days (GDD) based on the length of the chilling period, and three species constants are used, these are complemented with a coefficient for water availability.

To get a better insight in the influence of the chosen parameters that can limit the distribution of the tree species, distribution maps using the following model parameter values as used by Sykes (Sykes *et al.*, 1996) for minimum and maximum temperature of the coldest month were simulated:

Norway spruce:	none - -1.5°
Scots pine:	none - -1.0 °
Pedunculate oak:	-16.0 ° – none
European beech:	-3.5° - 6.0°

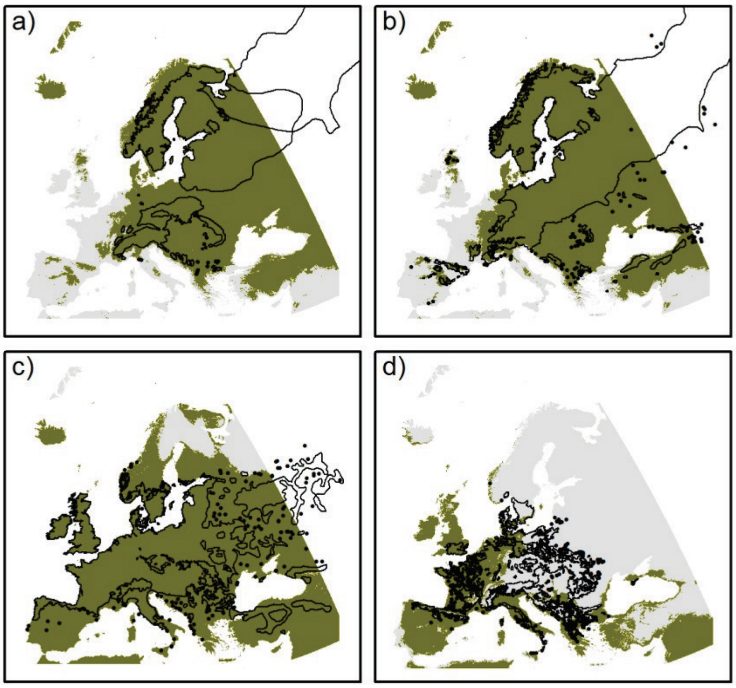


Figure 11: Potential distribution maps using the parameter values as used by Sykes (Sykes et al., 1996)

The results using these parameter do not show better results when comparing them to the known species distribution maps of the Atlas Florae Europaeae & European Forest Genetic Resources Programme, then previous calculations made on bases of the EU Forest Inventory database. They are comparable to the results using only the 95% percentile of the minimum temperatures during the coldest month. Using Sykes values, for European beech, large parts of eastern Europe are missing, and the south of Europe is included, which should not be. Also for Pedunculate oak the south of Europe is included, which should not be, and a to large part of Scandinavia is included. Norway spruce and Scots pine do show to much area in the south-east of Europe.

Different strategies could be chosen to come to more reliable potential species distributions, for example different climate and anthropogenic parameters could be added, or rule based combinations of parameters could be used as distribution limiters. One could also use construct a climate envelope for the known species distributions use those to extrapolate species distributions of the projected IPCC climate change scenarios.

4.4 Extrapolated growing stock volumes combined with potential distributions

For all studied tree species a northward distributional shift is indicated, besides an upward altitude shift in mountainous areas of the Alps, which is in line with the findings of Meier (Meier *et al.*, 2011) that studied co-occurrence patterns of trees. Elevated temperatures and reduced precipitation amounts for the Mediterranean region (Christensen *et al.*, 2007) will highly prevent the species growing and surviving here. This also underpins the exclusion of areas with a larger temperature then the threshold determined based on the maximum temperature of the warmest month. Optimal growing conditions in terms of climate are projected to shift accordingly. The differences in growing stock between 2000 and the projected climate change scenarios all show a northward shift, in most cases the four species are allocated at locations where it was not present in 2000, and vice versa, at locations where they did occur in 2000, the species disappear in 2080 (see fig… which gives the most extreme example in growing stock change between 2000 and IPCC scenario A2 in 2080). Production of Norway spruce and Scots pine will for the most pessimistic scenario (A2) is mainly limited to Scandinavia and the upper Alps regions. For the medium case scenario (B2), the northward shift is less extreme for all species. Pedunculate oak shifts upward to northern regions, but does not go as far as the Norway coastline. For Pedunculate oak, the pessimistic scenario (A2) shifts more extreme to the north than the medium case scenario (B2). In the medium case scenario (B2), the four species seem to become less competitive in their distribution, a gradient in appearance can be observed. For the pessimistic scenario (A2), all species are mainly allocated in Scandinavia, where they should be each other's competitors.

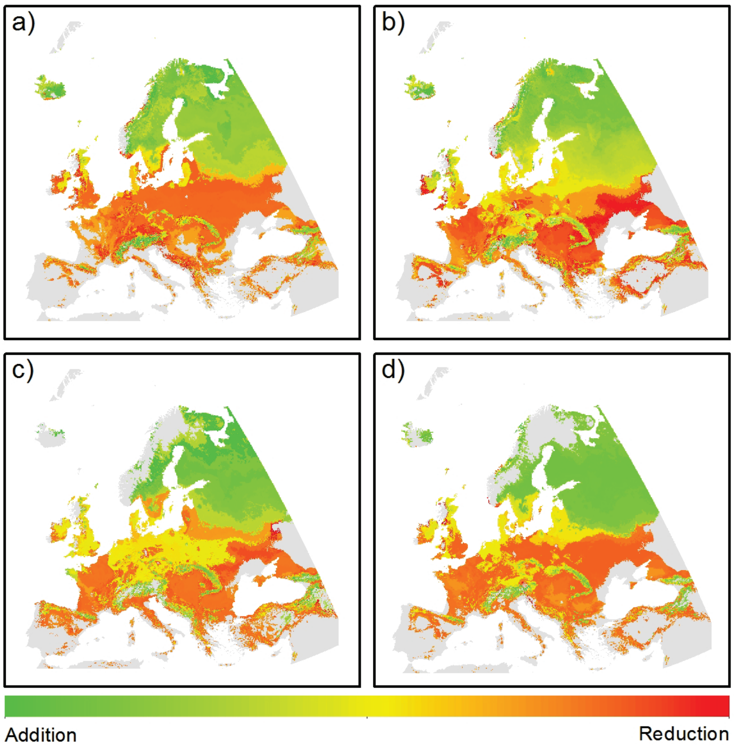


Figure 12: Differences in growing stock (m^3/ha) under future (2080) climate conditions for the IPCC pessimistic scenario A2 for four different tree species: a) Norway spruce, b) Scots pine, c) Pedunculate oak and d) European beech. The most intense red describes the locations where the most extreme reduction of a given species is observed, the most intense green are the location where the most extreme addition in growing stock volume of a given species is present.

Taking into account these extreme distributional shifts take place in 80 years, which is approximately the same as a lifecycle of a forest stand, forest managers of today should already take these rapid shifts into account taking a discussion on species to be planted at presence.

4.5 Tree species suitability maps

Combined precipitation/temperature classes are clearly visible in the climate change scenario maps, and influence the results of projected, extrapolated growing stock volumes. Especially in the combined species maps, these zones cover the one species with the highest stock volume in the given climate zone.

It can be observed that for all species the projected distribution areas, in both scenarios, are much reduced compared to the current distributions. Individual standing stock maps were combined into species suitability maps for current and future climatic conditions by picking the highest standing stock value. Resulting figures (figures 9a and 9b) allow comparisons and support an optimal tree species choice. Whereas Norway spruce dominates under current climate, European beech is predicted to perform best in terms of standing stock potential under future climatic conditions in large parts of Europe.

5. Conclusions

The present study assesses current and future tree species distributions and trends in growth performance of European forests based on temperature and precipitation. Starting from bioclimatic envelopes that describe actual climate limitations on tree species distributions, standing stock maps were developed (figures 4a, 4b and 4c). The maps indicate potential growth performance of tree species under current and future climatic conditions as well as distributional shifts. More specifically, using a pessimistic (A2) and medium case (B2) climate change scenario, tree species distributions as well as productivity trends of European forests have been determined. This resulted in northward distributional shifts as projected for Norway spruce, Scots pine, Pedunculate oak and European beech. In both scenarios, climate conditions in the Mediterranean region will become unsuitable for tree growth and the studied tree species are expected to disappear due to changes in summer drought (Dale *et al.*, 2001). Growing conditions are generally improving in the boreal region and Pedunculate oak and European beech are expected to colonize this southern parts of this region. In the continental and Atlantic region impacts are more diverse. Whereas current, Norway spruce is the dominating species on standing stock volumes in Europe, in both future scenarios the distribution will be limited to the (current) boreal region, in central Europe Norway spruce is likely to disappear and be replaced by a number of multi-species (Yousefpour *et al.*, 2010). Averaged growth performances of the studied species do increase for Norway spruce, Scots pine and Pedunculate oak under the pessimistic scenario (A2), but for the medium case scenario (B2) only Scots pine performs better than the current stock performance. For both scenarios, the potential distribution areas are reduced compared to the current situation.

The extrapolated maps show large overestimations of potential areas in the south and south-east of Europe. These overestimations are compensated using a limiting parameter based on the 95th percentile of all records in the database of the maximum temperature of the warmest month (figures 6a, 6b, 6c and 6d), resulting in more reliable standing stock maps (figures 8a, 8b, 8c and 8d)

A clear northward distributional shift is indicated for all studied species, besides shifts in optimal standing stock. The trend of a northward shift are in line with other studies. Bakkenes (Bakkenes *et al.*, 2002) mentions a general trend is a northeast by 2050. A change in tree species composition is found, and areas with species loss and species gain are determined. Maracchi (Maracchi *et al.*, 2005) specifically underlines that the north effects are rather positive with higher yields, larger suitable area, while in the south mainly negative effect of droughts and forest fires will dominate.

The indicated shifts highlight the importance of tree species choice under climate change that aim at maintaining productive forests. To support an optimal tree species choice, a suitability map was developed (figure 9a and 9b).

The present study, strongly depends on the chosen variables to construct the climate envelopes. It should be noted that bioclimatic "envelope" models are correlative and so sensitive to data and mathematical functions used to describe the species distribution in relation to bioclimatic parameters (Araújo & New, 2007). Using percentile growing stock volumes based on climate envelopes, makes extrapolation of growing stock volumes over large areas possible, but as a result of this methodology, distribution patterns which are influenced by extremes in climate variables and/or are of anthropogenic origin are not captured.

The assumption of a strong relation between plant distribution and environmental factors is not always valid in Europe, due to anthropogenic impacts. Besides temperature and water constraints, drought and maximum low-temperature limits play an important role (Casalegno *et al.*, 2011). Growing stock volumes are calculated based of the EU-NFI database records, influences of drought and warm winters will increase pest population, and will weaken forest (Lavalle *et al.*, 2009). Management factors which have a large influence on growing stock and productivity cannot be taken into account by the used methodology.

To prevent false conclusions resulting from under- or overestimations of climatic tolerances it is recommended to analyse actual distribution data and assess growth and vitality of species within its actual niche in more detail.

The methodology has been proven to work for four studied tree species, and could be worked out for different species of the EU_NFI database. Doing so, species suitability maps can be refined, to derive the species with the highest growing stock volumes for different locations.

References

Araújo MB, New M (2007) Ensemble forecasting of species distributions. *Trends in Ecology & Evolution,* **22**, 42-47.

Bakkenes M, Alkemade JRM, Ihle F, Leemans R, Latour JB (2002) Assessing effects of forecasted climate change on the diversity and distribution of European higher plants for 2050. *Global Change Biology,* **8**, 390-407.

Casalegno S, Amatulli G, Bastrup-Birk A, Durrant TH, Pekkarinen A (2011) Modelling and mapping the suitability of European forest formations at 1-km resolution. *European Journal of Forest Research*, 1-11.

Christensen JH, Hewitson B, Busuoic A *et al.* (2007) Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* (eds Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL) pp Page. Camebridge (United Kingdom) and New York (USA), Camebridge University Press.

Dale VH, Joyce LA, Mcnulty S *et al.* (2001) Climate change and forest disturbances. *BioScience,* **51**, 723-734.

Euforgen (2009) In: *Distribution maps Fagus sylvatica, Picea abies, Pinus sylvestris and Quercus rober.* pp Page.

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology,* **25**, 1965-1978.

Ipcc (2007) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: *IPCC report.* (ed M.L. Parry OFC, J.P. Palutikof, P.J. Van Der Linden and C.E. Hanson) pp Page, Cambridge,United Kingdom.

Jalas J, Suominen J (1972) *Atlas Florae Europaeae. Distribution of Vascular Plants in Europe. Vols 1-9.,* Helsinki, Akateeminen Kirjakauppa.

Lavalle C, Micale F, Houston TD *et al.* (2009) Climate change in Europe. 3. Impact on agriculture and forestry. A review. *Agronomy for Sustainable Development,* **29**, 433-446.

Maracchi G, Sirotenko O, Bindi M (2005) Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe. *Climatic Change,* **70**, 117-135.

Meier ES, Edwards Jr TC, Kienast F, Dobbertin M, Zimmermann NE (2011) Co-occurrence patterns of trees along macro-climatic gradients and their potential influence on the present and future distribution of Fagus sylvatica L. *Journal of Biogeography,* **38**, 371-382.

Ramirez J, Jarvis A (2008) High Resolution Statistically Downscaled Future Climate Surfaces. pp Page.

Sykes MT, Prentice IC, Cramer W (1996) A Bioclimatic Model for the Potential Distributions of North European Tree Species Under Present and Future Climates. *Journal of Biogeography,* **23**, 203-233.

Terhürne RL (2010) *Spatially expressed consequences of climate change for standing stock in European forests : an explorative study,* [S.l., s.n.].

Woodward FI (1988) Temperature and the distribution of plant species and vegetation. In: *Plants and temperature : [proceedings of a symposium held at the University of Essex, England 7 - 9 September 1987].* (eds Long SP, Woodward FI) pp Page. Cambridge, Univ. of Cambridge.

Yousefpour R, Hanewinkel M, Le Moguédec G (2010) Evaluating the suitability of management strategies of pure Norway spruce forests in the Black Forest area of Southwest Germany for adaptation to or mitigation of climate change. *Environmental Management,* **45**, 387-402.

Appendix I: Temperature and precipitation classes

Class number	Temperature range (°C * 10)	Class number	Precipitation range (mm)
0	-240 / -231	0	0 / 249
1	-230 / -221	1	250 / 499
2	-220 / -211	2	500 / 749
3	-210 / -201	3	750 / 999
4	-200 / -191	4	1000 / 1249
5	-109 / -181	5	1250 / 1499
6	-180 / -171	6	1500 / 1749
7	-170 / -161	7	1999 / 2249
8	-160 / -151	8	2250 / 2499
9	-150 / -141	9	2500 / 2749
10	-140 / -131	10	2750 / 2999
12	-130 / -121	11	3000 / 3249
12	-120 / -111	12	3250 / 3499
13	-110 / -101	13	
14	-100 / -91		
15	-90 / -81		
16	-80 / -71		
17	-70 / -61		
18	-60 / -51		
19	-50 / -41		
20	-40 / -31		
21	-30 / -21		
22	-20 / -11		
23	-10 / -1		
24	0 / 9		
25	10 / 19		
26	20 / 29		
27	30 / 39		
28	40 / 49		
29	50 / 59		
30	60 / 69		
31	70 / 79		
32	80 / 89		
33	90 / 99		
34	100 / 109		
35	110 / 119		
36	120 / 129		
37	130 / 139		
38	140 / 149		
39	150 / 159		
40	160 / 169		
41	170 / 179		
42	180 / 189		
43	190 / 199		
44	200 / 209		
45	210 / 219		
46	220 / 229		
47	230 / 239		
48	240 / 249		
49	250 / 259		
50	260 / 269		
51	270 / 279		
52	280 / 289		
53	290 / 299		

Appendix II: Percentile classes

The number of plots in the EU-NFI database for each combined precipitation/temperature class used to calculate the 75th, 90th and 95th percentiles growing stock for four different tree species.

Norway spruce

	Precipitation classes												
Temperature classes	***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
20		1											
21		32	13				1						
22		12	127	18									
23		14	340	32	1								
24		12	463	92	22	3							
25		1	665	187	59	26	7						
26			551	239	20123	70	21	13	6	1	1	2	
27			1209	266	257	75	55	20	12	5	5		
28			1971	587	345	277	34	23	11	7	1	1	
29			1156	1091	1067	623	7	7	3	6	1		
30		1	2053	3746	2948	72	3	5	4	1			
31			3440	4390	1315	1							
32			688	1399	113	3							
33			99	154	6								
34			1	91									
35			17	1									
36			3										
37													
38		1											

Count

	Precipitation classes												
Temperature classes	***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
20													
21													
22		84	132										
23		124	138	195									
24		187	159	164									
25		198	193	157	158	148							
26			230	186	190	155	121						
27			253	211	395	166	171	136	174				
28			172	263	368	137	341	177	123	200	346		
29			137	392	504	422	315	171	274	357			
30			369	414	481	438	264	386	351	112			
31			356	472	477	347	167	197	424				
32			313	425	506								
33			326	355	375	64							
34			242	265	311								
35				237									
36			261										
37			362										
38													

75th Percentile

	Precipitation classes												
Temperature classes	***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
20													
21													
22		114	171										
23		242	163	520									
24		279	214	267									
25		263	302	217	259								
26			304	318	289	517							
27			347	311	576	253	290	437					
28			287	381	545	290	483	274	190				
29			257	547	752	575	489	347	489				
30			519	594	667	625							
31			513	674	649	632							
32			481	619	646								
33			476	502	527								
34			374	397									
35				389									
36			514										
37													
38													

90th Percentile

	Precipitation classes												
Temperature classes	***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
20													
21													
22		122											
23			214										
24			278	413									
25			380	302	300								
26			365	378	365	1176							
27			401	373	695	351	331						
28			367	450	675	354	569	969					
29			339	606	911	690	530	588					
30			636	700	788	713							
31			612	791	768	775							
32			597	748	723								
33			608	592	624								
34			428	481									
35				445									
36													
37													
38													

95^{th} Percentile

Scots pine

Temperature classes	Precipitation classes												
	0	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
20													
21		19											
22		114	19										
23		88	213	6									
24		51	649	28			17						
25		36	591	36	1	3	1						
26		28	866	47	18	25	1						
27		1	685	119	55	52	3	3		1			
28			979	186	90	47	15	12	6	5	3	1	
29			1590	220	125	64	29	23	14	12	7	5	
30			584	415	365	74	20	9	3	13	2		
31		5	1671	1008	619	13	9	1	9	7			
32		2	7144	2467	237								
33		13	2038	2810	33								
34			816	943	25								
35			227	307	9								
36			37	113	1								
37			18	15									
38			1	6									

Count

Temperature classes	Precipitation classes												
	0	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
20													
21		74											
22		81	59										
23		106	80	125									
24		164	105	157			239						
25		83	114	148		108							
26		133	158	131	94	104							
27			183	153	109	105	102	120					
28			197	174	162	147	157	168	146	182	249		
29			200	167	204	199	191	190	190	136	209	132	
30			261	183	194	183	187	242	119	178			
31		81	282	215	195	216	179		155	213			
32			322	223	196								
33		323	286	236	185								
34			249	205	223								
35			211	170	173								
36			119	127									
37			135	127									
38				133									

75th Percentile

Temperature classes	Precipitation classes												
	0	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
20													
21		96											
22		115	86										
23		155	112										
24		221	167	200			338						
25		140	174	190									
26		173	224	179	146	199							
27			261	209	158	228							
28			291	236	221	221	175	274					
29			303	239	278	257	277	273	214	279			
30			363	267	280	223	420	409		236			
31			399	344	310	386	398		204				
32			428	335	269								
33		408	372	304	418								
34			336	299	278								
35			309	254	235								
36			173	190									
37			204	269									
38													

90th Percentile

	Precipitation classes													
Temperature classes		***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
	20													
	21		107											
	22		161	100										
	23		174	159										
	24		287	211	233									
	25		168	224	337									
	26		183	270	303		324							
	27			326	289	317	344							
	28			355	263	263	247							
	29			379	310	444	355	345	511					
	30			447	358	332	305	474						
	31			460	435	393								
	32			498	409	358								
	33			435	347	595								
	34			405	358	384								
	35			378	304									
	36			205	263									
	37													
	38													

95th Percentile

Pedunculate oak

		Precipitation classes												
Temperature classes		***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
	20													
	21													
	22													
	23													
	24													
	25													
	26													
	27			6										
	28			82	1									
	29			24	20	12								
	30			293	405	73								
	31		1	2159	1327	131								
	32		13	935	2020	103								
	33		3	1154	519	77								
	34		381	329	65	1								
	35			25	631	121								
	36			9	21	70	15							
	37													
	38													

Count

		Precipitation classes												
Temperature classes		***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
	20													
	21													
	22													
	23													
	24													
	25													
	26													
	27			29										
	28			47										
	29			84	246	79								
	30			164	153	187								
	31			191	189	179								
	32		465	209	250	204								
	33		121	202	212	199								
	34		164	200	154									
	35			189	219	169								
	36			175	140	222	291							
	37													
	38													

70th Percentile

		Precipitation classes												
Temperature classes		***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
	20													
	21													
	22													
	23													
	24													
	25													
	26													
	27													
	28													
	29			92										
	30			254	351	511								
	31			266	251	348								
	32			320	294	256								
	33		545	291	330	287								
	34			275	296	259								
	35		232	281	197									
	36			288	294	254								
	37			240	217	308	349							
	38													

90th Percentile

	Precipitation classes													
Temperature classes		***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
	20													
	21													
	22													
	23													
	24													
	25													
	26													
	27													
	28													
	29			179										
	30			576	603									
	31			346	345	474								
	32			417	383	298								
	33			347	394	327								
	34			323	377	326								
	35		279	338	231									
	36			348	346	365								
	37				371	362								
	38													

95th Percentile

European beech

Temperature classes	Precipitation classes												
	0	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
20													
21													
22													
23					1								
24													
25						1	1						
26					1	2							
27				2	13	5							
28				17	80	5	6						
29			13	182	166	103	1						
30			53	959	453	199							
31			1098	3626	1313	22							
32			4134	4427	1089	2							
33		1	1794	3023	160	4							
34			510	511	30	2							
35			23	264	17								
36			5	35									
37			3	1	1								
38													

Count

Temperature classes	Precipitation classes												
	0	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
20													
21													
22													
23													
24													
25													
26					284	203							
27				311	221	169	103						
28			255	193	229	284							
29			248	227	325	264							
30			294	280	270	330							
31			272	251	229								
32			256	281	242	209							
33			253	251	187								
34			224	218	199								
35			207	222									
36			740										
37													
38													

75th Percentile

Temperature classes	Precipitation classes												
	0	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
20													
21													
22													
23													
24													
25													
26													
27					634								
28				440	397								
29			586	284	418	432							
30			379	350	449	401							
31			440	417	397	688							
32			421	397	333								
33			405	402	351								
34			385	372	280								
35			259	312	283								
36				306									
37													
38													

90th Percentile

	Precipitation classes													
Temperature classes		***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
	20													
	21													
	22													
	23													
	24													
	25													
	26													
	27													
	28					465								
	29				362	526	503							
	30			441	441	584	472							
	31			512	507	496	727							
	32			509	483	410								
	33			501	490	449								
	34			454	502	333								
	35			346	398									
	36				456									
	37													
	38													

95th Percentile