



Article Evaluating Recent and Future Climatic Suitability for the Cultivation of Norway Spruce in the Czech Republic in Comparison with Observed Tree Cover Loss between 2001 and 2020

Petr Čermák ^{1,*}, Tomáš Mikita ², Jan Kadavý ² and Miroslav Trnka ^{3,4}

- ¹ Department of Forest Protection and Wildlife Management, Mendel University in Brno, Zemědělská 3, 613 00 Brno, Czech Republic
- ² Department of Forest Management and Applied Geoinformatics, Mendel University in Brno, Zemědělská 3, 613 00 Brno, Czech Republic; tomas.mikita@gmail.com (T.M.); jan.kadavy@mendelu.cz (J.K.)
- ³ Global Change Research Institute of the CAS, Bělidla 986/4a, 603 00 Brno, Czech Republic; mirek_trnka@yahoo.com
- ⁴ Institute of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic
- * Correspondence: cermacek@mendelu.cz

Abstract: The high portion of secondary Norway spruce in Central European forests constitutes a major problem because a significant part of these forests is moving further away from their original bioclimatic envelope. The precise evaluation and prediction of climatic suitability are needed for the implementation of forest adaptation strategies. We evaluated climatic suitability for the cultivation of Norway spruce in the Czech Republic forests, making use of the Random Forest combined learning statistical method. The evaluation presented was based on a comparison with the climatic normal period 1961–1990; change analysis was carried out for the period 1991–2014 and projected for 2021–2040 and 2041–2060. We found that suitable conditions for Norway spruce will remain only in 11.3% by area of Czech forests in the period 2041–2060 vs. 46.0% in the period 1961–1990. We also compared tree cover loss data (using Global Forest Watch) from 2001 to 2020 with statistics on salvage logging. In the period, the cover loss affected 19.5% of the area with more than 30% Norway spruce. The relationships between relative tree cover loss and the percentage of salvage logging caused by insects were conclusive and statistically significant.

Keywords: *Picea abies;* global climate change; climatic suitability; planning of tree compositions; bark beetles; adaptation strategies

1. Introduction

The global mean temperature for 2020 was 1.2 ± 0.1 °C above the 1850–1900 baseline. Moreover, the last five-year (2016–2020) and 10-year (2011–2020) averages were the warmest on record [1]. The rise in global surface temperature is caused by increasing concentrations of CO₂ and other greenhouse gases in the atmosphere [2]. The earth is expected to experience or exceed 1.5 °C of warming compared with 1850–1900 during the next 20 years; it may be more than 2.5 °C above this baseline by the year 2050 if the least favorable greenhouse-gas emissions projections are met [2]. An integral part of the climatic trend is likely to be a change in precipitation distribution across Central Europe. All the environmental changes anticipated will markedly affect forest ecosystems.

Forests currently cover 31% of the global land area. Between 2010 and 2020, the global forest area declined by 1.2% (with the greatest reductions in Africa and South America). However, at the same time, Asia, Europe, and Oceania forest areas increased [3]. The United Nations Strategic Plan for Forests 2030 as the global framework for action to sustainably



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). manage all types of forests was published in 2019 [4]. The plan has six Global Forest Goals (GFG). Among the partial targets of the GFG are to maintain and extend the world's forest carbon stocks, to manage all types of forest sustainably, to restore degraded forests, substantially to increase afforestation, and to help increase the resilience and adaptive capacity of forests to the impacts of climate change [3]. The same targets are included in European strategies such as the New EU Forest Strategy for 2030 [5] and national strategies such as the National Program to Abate Climate Change Impacts in the Czech Republic [6]. The targets are also supported by various international programs, funds, and actions—for example, the Bonn Challenge [7].

We need healthy forests with suitable structure and species composition to achieve these global and European strategic targets. The distribution of tree species in natural forests is a function of climatic and topographic parameters. Climate change is a key driver of distribution changes—directly through climate change-induced vegetation shifts and indirectly through changes in forest management induced by the need to adapt. Such changes will probably have an important effect on forest growth and stability and on the economic value of European forests [8].

Norway spruce (*Picea abies* L. Karst), representing 50% of the Czech forest area and covering more than 1.3 million hectares, is the most widespread and socio-economically valuable tree species in the Czech Republic. Since the natural share of Norway spruce in the species composition of Czech forests is only ca. 11% [9], it is clear that spruce was very often planted far beyond the limits of its natural range. The disproportion is characteristic of Central European forests [10].

Many research studies confirm the premise that European forests will undergo considerable changes in tree species distributional ranges and the composition of forests during the 21st century [8,11–14]. Some studies also predict that, due to increasing risks of drought-induced mortality, Norway spruce is likely to become unhealthy and unprofitable and consequently significantly decrease in abundance in large parts at low altitudes in Central European forests [12,14,15]. These secondary spruce forests are very vulnerable and urgently require substantial active adaptation [16].

The sequence of recent European summer droughts since 2015 is unprecedented in the past 2110 years (from 91 BCE to 2018 CE) [17] and has had a devastating effect on Norway spruce stands. The Czech Republic is one of the European countries most affected by the ongoing bark beetle calamity as a result of the described high proportion of Norway spruce in forests and the extreme drought and warm conditions. The amount of timber salvaged following insect attacks (above all, the Norway spruce bark beetles *Ips typographus, Ips duplicatus, and Pityogenes chalcographus)* was more than 41 mil. m³ in the Czech Republic during 2017–2019 [18] and rose to 26.2 mil. m³ in 2020 [19]. Massive damage was also documented in northern Austria [20] and in some parts of Germany, Poland, and Slovakia [21–24]. The role of warmer conditions and acute drought as an important driver of bark beetle infestation has been documented [25,26]. Host resistance is one of the key regulators of bark beetle population dynamics; host abundance and host connectivity are also very important factors affecting outbreak severity [27]. A combination of sufficient host availability, favorable temperature conditions for bark beetle development, and a high disposition of trees to attack caused by drought stress intensifies bark beetle population growth and can lead to mass outbreaks [26].

Because the ongoing climatic changes are very dynamic [1], the area with Norway spruce stands in climatically unsuitable conditions will probably quickly increase. Moreover, in the second half of the 21st century, optimal growing conditions for some other main tree species, especially European beech, may also be restricted to those areas where they currently occur [28]. All these changes are very important for forestry planning. Long-term general forestry planning uses time horizons of 20 years or longer. During rapidly changing conditions, this is too long a period for static planning [29]. Long-term plans should support operational decisions responding to the state of the stands. Precise national or regional predictions of the climatic suitability/unsuitability for the main tree species, preferably using several climatic variables and forest inventory data, can help to optimize species composition and choose the right silviculture system. Both are very important for the adaptability and functional stability of forests.

Within the framework of the FRAMEADAPT project [30], we tested the possibility of evaluating and predicting climatic suitability for the cultivation of Norway spruce in the Czech Republic. Our final evaluation, making use of the Random Forest method, classified climatic suitability for periods to 1990 (the climate normal period 1961–1990) and 1991–2014 and predicted the suitability of the periods 2021–2040 and 2041–2060. The main goals of the study were to (1) present a methodology and the outputs of our evaluation of climatic suitability and (2) compare the outputs with tree cover loss in the Czech Republic during 2001–2020 using Global Forest Watch data. We supposed that tree cover loss affected above all Norway spruce stands in areas classified as climatically unsuitable during an episode in which drought and bark beetle calamity coincided.

2. Material and Methods

2.1. Description of Forests in the Czech Republic-Study Area

Forest covers an area of approximately 2.7 million ha or 33.1% of the Czech Republic [31]. About 74% of the total forest area is used for economic purposes; the rest is represented by protective forests (2%) and special-purpose forests (24%). The tree composition is dominated by coniferous species (71%), of which the commonest is Norway spruce—about 50% (area 1.3 mil. ha). Of the deciduous species, European beech is the most represented in the forests of the Czech Republic (approx. 9%, area 230 kha). In the natural composition of the forest, Norway spruce should reach approximately 11% and European beech 40%. Approximately 20% of stands can be described as mixed. The age structure of forests in the Czech Republic is uneven. In recent years, there has been an increase in the area of obsolete stands (over 120 years); the area of stands under 60 years old has below-parity representation. Due to these facts, the average age of woody plants is gradually increasing. The average growing stock per hectare of forest land is 270 m³ u.b., while the total wood reserves thus reach a value of 704.9 million m³ u.b. The annual average total increment per hectare of forest land is 7.1 m³ u.b.; in terms of all forests in the Czech Republic, it represents a value of approximately 18.5 million m³ u.b. [31].

2.2. Evaluating Climatic Suitability for the Cultivation of Norway Spruce in the Czech Republic

The evaluation and prediction of climatic suitability for the cultivation of Norway spruce in the Czech Republic were based on an analysis of climatic data for the period 1961–1990, followed by an assessment of changes for the period 1991–2014 and a subsequent prediction of the development in the near future. An estimation of the possible evolution of the climate as a function of the increase in emissions of radiatively active gases was made for the periods 2021–2040 and 2041–2060.

Long-term measurements of daily meteorological data from 268 climatological and 787 rain gauge stations of the Czech Hydrometeorological Institute were used to describe climate conditions during the 1961–1990 and 1991–2014 periods. These data combine all key weather variables, including daily mean, 2 p.m., maximum and minimum temperatures [°C]; daily mean air relative humidity [%]; precipitation [mm·day⁻¹]; global solar radiation [MJ-m⁻²·day⁻¹] and wind speed [m·s⁻¹], from the national drought monitoring system [32], covering the whole country with daily weather inputs interpolated to 500 × 500 m grids. The data are interpolated by kriging regression, which uses geographical coordinates, elevation, and other terrain characteristics as predictors with locally tested methods [33,34]. In the Czech Republic, the average minimum distance between two neighboring stations is approximately 22 km for variables measured at climatological stations and less than 10 km for those measured at precipitation stations [35]. The daily incident solar radiation accounts for slope, aspect, and horizon obstruction. Precipitation was measured from 7 a.m. of the given date to 7 a.m. of the following day. All other weather parameters were measured over a 24 h period each day. The daily weather data

were used to calculate 21 variables that were used as input into the suitability modeling process. These were composed of annual mean temperatures, precipitation, and global radiation; mean values of temperature, precipitation, and radiation in March to May, April to June, and June to August; soil moisture at depths of up to 40 cm and up to 100 cm; the number of days with drought stress at the given depths (days with critically low soil water reserve, i.e., soil moisture under 30%), with drought stress, with less than 1 mm of precipitation, with an average temperature above 10 °C in a continuous period, with maximum temperature above 30 °C and with temperature above 5 °C; moisture sufficiency; and global radiation.

According to the literature [36,37], Norway spruce is a tree species with an original distribution in Central Europe bounded by an annual isohyet of 800 mm (with total growing-season precipitation of 490–580 mm) or a De Martonne aridity index of Iar >60 [38]. The Norway spruce is an edificator and stand-forming tree species from the 6th forest vegetation zone to the forest boundary in the Czech Republic. In azonal water-influenced habitats, spruce also descends to the lowest altitudes [39–41]. For our evaluation, we took areas from the 5th forest vegetation zone and above and together with an average annual temperature of 6.5 °C and lower and an average annual rainfall of 700 mm and higher as the climatically suitable habitats for the secure cultivation of Norway spruce in the Czech Republic. The boundary between 1st–4th and 5th–9th forest vegetation zones is essential mainly because the results of Czech typological mapping show that from the 5th to 9th zones, Norway spruce occurs naturally and that in the 5th forest vegetation zone it has its production optimum [40].

To model climatic suitability for the cultivation of Norway spruce, we used spatial data of forest vegetation zones from the Forest Management Institute (FMI), where all forest vegetation zones from the 5th and above were selected as suitable and others as unsuitable. The data were converted to a continuous raster with a resolution of 500×500 m so that they could be compared with the above-named climatic variables (forests in military areas of about 80,000 hectares were not included in the analysis). This raster layer was then combined with climatic variables for the climatic normal of 1961–1990 with the same resolution as the mapping of forest vegetation zones in the Czech Republic corresponding to this period. This resulted in a table of all pixels suitable or unsuitable for spruce with information on the 21 climatic variables. This table was subsequently analyzed by Random Forest analysis.

The multivariate statistical method Random Forest in STATISTICA 10 software was used for modeling. Random Forest is a combined learning method for classification and regression that creates multiple decision trees during learning and then outputs the modus (most frequent value) of the classes returned by each tree. The term comes from random decision forests introduced by Ho [42]. The method combines the idea of "bagging" [43] with random feature selection to construct a set of trees with controlled variance. The procedure of using random forests is one of the most promising methods. The principle of the method is to construct a group of M trees P1, ..., Pm to decide the classification of an object into given classes. Thus, it is necessary to combine the classification functions of the individual trees appropriately [44].

The advantage of Random Forest analysis in STATISTICA 10 is the automatic splitting of the input data set into test and validation parts; it is not necessary to select test and validation samples beforehand. Initially, 100 random trees were selected for computation, and the number of trees was adjusted to 38 based on the misclassification rate results for the training and test data. Based on the calculated predictor importance, only the variables with the greatest importance were selected. Variables with low importance were removed from the analysis, and the calculation was performed again. This simplified the model without a significant loss of accuracy. The calculation of suitability for spruce cultivation for the following periods was performed using the Goodness of Fit tool of STATISTICA 10 software based on a combination of selected significant variables for the given periods 1991–2014, 2021–2040, and 2041–2060.

Climate predictions were made using so-called Global Circulation Models (GCMs), which are models of the general circulation of the atmosphere coupled to an ocean model. These are computer models of the climate system that are used to calculate likely future climate conditions. As the methodology is computationally very intensive, we focused on the proof of the concept on the model representing the central estimate (Figure 1). We evaluated 40 GCMs of CMIP5 models with 27 available runs of 13 different GCMs having all required meteorological parameters available for the RCP 4.5. RCP 4.5 is an intermediate and most probable baseline scenario of greenhouse gas concentration development adopted by the IPCC. Emissions in RCP 4.5 are estimated to peak around 2040 and then decline. The selection of the central model was based on the methodology developed by Dubrovský et al. [45], which resulted in the selection of the French IPSL global climate model based on the evaluation of annual and seasonal changes of precipitation and temperatures. The IPSL model provides estimates of future climate conditions closest to the median of the tested CMIP5 model ensemble over the Czech Republic (Figure 1). Using IPSL estimates, the increase in mean annual temperature in the range of 2.0–2.5 °C compared to 1961–1990 could be expected by 2060, with only a slight increase or even decrease in total precipitation in particular parts of the Czech Republic; average values of selected climate variables are in Table 1.



Figure 1. Absolute changes in mean annual temperature (°C) and relative changes in annual mean precipitation calculated for the Czech Republic between future 2041–2060 and GCM baseline 1995–2005 for 27 runs of 13 GCMs from the CMIP5 ensemble. GCMs list is given in Supplementary Table S1. The IPSL model run is marked in red, and the median value of all visualized GCM runs is in black.

Table 1. Past (measured data) and future (IPSL model) climate development—average annual values of selected climatic variables for the assessed periods. The average values were calculated for all the Czech forest areas.

Climate Variable	1961-1990	1991-2014	2021-2040	2041-2060
Annual mean temperature (°C)	7.00	7.95	9.11	9.43
Mean spring temperature—March–May (°C)	6.91	7.82	8.71	9.14
Spring global radiation—March–May (MJ·m ⁻²) *	775.78	860.10	926.34	916.33
Number of days with temperatures above 10 °C	132.27	145.55	161.41	164.51
Annual precipitation (mm)	708.56	752.59	753.10	707.16
Number of days with drought stress in the 0–40 cm layer	2.45	3.85	7.10	8.48

* amount of global radiation on days with temperatures above 5 °C (without snow and frost) and plenty of water.

Changes in the spatial distribution of areas suitable for spruce cultivation in subsequent periods were modeled based on variables that emerged as significant from the Random Forest analysis.

For the period 1991–2014, interpolated data measured at meteorological stations were used, and for the periods 2021–2040 and 2041–2060, data from GCM IPSL with RCP 4.5 predictions were used.

We present our analysis for forest areas with more than 30% of Norway spruce, as these are areas where spruce is an important species for forest stand structure and other stand characteristics. It can be assumed that a possible failure of spruce from the wood composition of the stands can lead to a significant change from spruce communities to a completely different community.

2.3. Comparison of Outputs of Evaluating Climatic Suitability with Tree Cover Loss in 2001–2020

The results were compared with the actual harvesting of forest stands as a result of bark beetle calamity. At the global level, changes in biomass distribution are monitored using satellite imagery. The tree cover loss layer from Global Forest Watch was chosen to detect logging [46]. Tree cover loss is defined as a stand-replacement disturbance or a change from a forest to a non-forest state. This data set, a collaboration between the GLAD (Global Land Analysis & Discovery) lab at the University of Maryland, Google, USGS, and NASA, measures areas of tree cover loss across all global land (except Antarctica and Arctic islands) at approximately 30×30 m resolution. The data were generated using multispectral satellite imagery from the Landsat 5 Thematic Mapper (TM), the Landsat 7 Thematic Mapper Plus (ETM+), and the Landsat 8 Operational Land Imager (OLI) sensors. Tree cover loss is defined as "stand replacement disturbance" or the complete removal of the tree cover canopy at the Landsat pixel scale. Tree cover loss may be the result of human activities, including forestry practices such as timber harvesting or deforestation [47].

The tree loss raster layer was downloaded from the Global Forest Watch website and clipped with the borders of the Czech Republic. The results of potentially suitable forest stand for spruce cultivation for each period were combined with the tree loss layer, plotted in the form of graphs, and statistically evaluated.

3. Results

3.1. Evaluating Climatic Suitability for the Cultivation of Norway Spruce in the Czech Republic

A success rate of 95% was achieved in modeling areas suitable for spruce cultivation using Random Forest Analysis. The most significant variables were determined to be the mean annual air temperature, followed by the temperature in the spring months from March to June, global radiation in the spring months, and the number of days with temperatures above 10 $^{\circ}$ C.

The results of the Random Forest analysis showed a disagreement of 4.78%. The agreement between observed and predicted values in the form of a classification matrix is shown in Tables S2 and S3. The tables show that the developed prediction model slightly underestimates the category of areas suitable for spruce.

The area of the Czech Republic climatically suitable for the cultivation of Norway spruce rapidly decreased between 1990 and 2014. Our forecast for the following periods 2021–2040 and 2041–2060 predicts a continuation of the decrease (Figure 2). At this time, only less than one-third of the forest area with Norway spruce stands with more than 30% spruces is climatically suitable for the species, i.e., the cultivation of spruce is not secure (from a climatic point of view) in two-thirds of the area (second map of Figure 2).



Figure 2. Distribution of categories of climatic suitability for the cultivation of Norway spruce for stands with more than 30% of Norway spruce in the assessed periods.

The distribution of the climatically suitable area for spruce moves to higher and higher altitudes. Only a small part of the highlands and uplands will be climatically suitable for spruce in the period 2021–2040. In the period 2041–2060, suitable conditions will be restricted to the border mountains (Figure 2).

3.2. Comparison of Outputs of Evaluating Climatic Suitability with Tree Cover Loss in 2001–2020

The annual tree cover loss in areas with more than 30% of *Picea abies* fluctuated between 1.5 kha (2001) and 13.7 kha (2011) in 2001–2015. The last five years exceeded these values—the cover loss was 15.0 kha in 2016, 18.1 kha in 2017, 27.9 kha in 2018, 55.1 kha in the 2019, and 82.3 kha in 2020 (Figure 3). In total, the cover loss affected 309.4 kha (19.5% of area with more than 30% of Norway spruce) from 2001 to 2020.



Figure 3. The area with tree cover loss in stands with more than 30% of *Picea abies*—2001–2020.

For the following analysis, we combined the categories "unsuitable" and "suitable to 1990", representing areas that were unsuitable in the period from 2001 (with analyzed tree loss cover data). The categories "suitable to 2040" and "suitable in all periods" were also combined as areas climatically suitable in the assessed period 2001–2020. The tree cover loss was detected above all in areas climatically unsuitable in all the assessed periods (Figures 3 and 4). Until 2015, the share of the area with tree cover loss was comparable in stands with climatically suitable conditions for spruce and with unsuitable conditions. In the last five years (2016–2020), the share has been markedly greater in the area classified as unsuitable in these years (unsuitable, suitable to 1990, suitable to 2014) than in the climatically suitable areas (Figure 5a). We compared the tree cover loss data (Figure 5a) with reported felling data collected by the Czech Statistical Office [40] (Figure 5b). The percentage of the area with tree cover loss (from the total area of the climatically suitable category) positively correlated with the percentage of felling caused by insects (from total roundwood removals) (Table 2). A positive correlation was also found between the intercategory differences in the percentage of area with tree cover loss and the percentage of salvage logging caused by insects (Table 3). The higher the percentage of salvage logging caused by insects, the greater the inter-category differences in the percentage of the area with tree cover.

Table 2. Pearson correlation between the percentage of area with tree cover loss (from the total area of the climatically suitable category) in stands with more than 30% of *Picea abies* (Figure 5a) and the percentage of reported categories of salvage logging (Figure 5b). Natural disaster = wind, ice, and snow. Significant values of the Pearson correlation coefficient are given in bold, significance level: p < 0.05.

Category of Logging	Suitable to 2040 + Suitable in All Periods	Suitable to 2014	Unsuitable + Suitable to 1990
Natural disasters	0.083	-0.112	-0.184
Insects	0.622	0.918	0.923
Other salvage logging	0.154	0.393	0.285



Figure 4. Detected tree cover loss 2001–2020 (colored areas) differentiated according to combined categories of climatic suitability.



Figure 5. The percentage of area with tree cover loss (from the total area of the climatically suitable category) in stands with more than 30% of *Picea abies*—2001–2020 (**a**) and the percentage of reported categories of felling (from total roundwood removals) according to data from the Czech Statistical Office (CSO) in the same period [48] (**b**). Natural disaster = wind, ice, and snow.

Table 3. Pearson correlation between the inter-category differences in the percentage of area with tree cover loss (Figure 5a) and the percentage of reported categories of salvage logging (Figure 5b). The inter-category differences were calculated for categories "suitable to 2014" and "unsuitable + suitable to 1990" as the difference between the percentage of the category and the percentage of "suitable to 2040 + suitable in all periods". Natural disaster = wind, ice, and snow. Significant values of the Pearson correlation coefficient are given in bold, significance level: p < 0.05.

Category of Logging	Suitable to 2014	Unsuitable + Suitable to 1990
Natural disasters	-0.241	-0.245
Insects	0.871	0.927
Other salvage logging	0.460	0.292

4. Discussion

4.1. Relationships between Climatic Suitability and Tree Cover Loss in 2001–2020 and their Consequences for Forest Management

Our evaluations and predictions involved only climatic suitability, i.e., only climatic variables were included in the suitability modeling. However, the comparison with felling data from the CSO inventory (Figure 5b) and the results of previous research enable us to make some interpretations.

We supposed that the portion of regular and salvage logging and the prevailing cause of the felling influence the tree loss cover distribution. The salvage logging prevailed over intentional logging in 2007–2008 and 2015–2020 (Figure 5b) in the Czech Republic. The main causes of the salvage logging were natural disasters (wind, snow, and ice) in 2007–2008 and 2015 and insects (above all bark beetles) in 2016–2020. The observed high tree cover loss in climatically unsuitable areas for the cultivation of Norway spruce during bark beetle calamity in 2016–2020 (Figures 3 and 5) was expected. In general, a high temperature during the growth season and related high transpiration rates of Norway spruce (by reason of the high vapor pressure deficit), together with a relatively low precipitation sum and precipitation inequality, are characteristic of climatically unsuitable areas, especially during 2016–2020. The increasing summer rainfall deficit and warm temperatures leading to an increase of stand transpiration deficits proved to raise the probability of bark beetle outbreak [49]. The stand transpiration deficit was identified as an important driver of bark beetle attacks in warmer and drier areas by Netherer et al. [26]. The bark beetles have profited from warmer spring and summer, enabling more generations during the growing season, and at the same time, the precipitation deficits have led to a weakening of the spruce defense system (resin flow decreases or even stops during severe water deficiency) [26,50,51]. Especially in situations when the extensive breeding material provided by storm damage is also available in stands, the risk of a bark beetle outbreak is very high [50]. We can assume that the winter storms with ice and snow damage (2015) and windthrows (2017, 2018) contributed to the start and acceleration of the bark beetle calamity in the Czech Republic (Figure 5b).

The observed differences in the relationship between the salvage logging category and tree cover loss in climatically suitable and unsuitable areas (Figure 5, Tables 2 and 3) can be explained by differences in their modes of action and their driving factors. If the major causes of salvage logging are wind, snow, and ice (felling category natural disaster), many factors affect the distribution of tree cover loss, and mid-term and long-term climate conditions are only indirect factors. There is a completely different situation during the longer dry, warm period. McDowell et al. [52] hypothesized that three mechanisms of mortality can work during warm and drought periods: hydraulic failure, carbon starvation, and changes in biotic agent demographics. The climate situation drives changes in the demographics of mortality agents—increases the number of pest generations per year (see above) and decreases over-winter mortality (through the higher winter minimum temperatures). Biotic agents may amplify, or be amplified by, plant physiological stress. The bark beetles are getting the key contributing stress factors [53] in the longer-term stress situation of Norway spruce, i.e., bark beetle outbreak is triggered by climate conditions, and areas with the greatest climatic discomfort are the most severely affected.

Central Europe was predicted as an area with an increasing risk of drought-induced mortality of Norway spruce [12,14,15], as well as an area with a high risk of bark beetle outbreaks on Norway spruce [54–56]. Climate change only amplifies the difference between monospecific and species-diverse forests in their sensitivity to disturbance impacts [57]. The predictions correspond well with observed damage outbreaks [18,19,58].

The climatically suitable area for the cultivation of Norway spruce has markedly decreased since the climate normal period 1961–1990, and it will probably dynamically decrease also in 2021–2040 (Figure 2). We predicted that only 16.1% of current stands with more than 30% of spruce will grow in climatically suitable conditions (conditions enabling relatively secure cultivation) in the Czech Republic by 2040. This is a very complicated situation for Czech forestry because the highly probable result of cultivation in the habitat unsuitable areas will be a continuation of bigger disturbances in the relatively large area of the forests. The continuing destabilization of the managed forest will complicate the implementation of the changes needed in forest management—part of new approaches and measures, which can lead to changes in forest composition and structure, are not applicable in very disturbed forests. The need for marked changes in species composition and structure of Czech forests has been repeatedly identified [5,15,59,60] in the last 25 years. The proportion of Norway spruce in Czech forests decreased from 55.0% in 1990 to 50.2% in 2019; the proportion in reforestation decrease the risk of big forest disturbances.

In this context, the need to convert secondary Norway spruce forests into more diverse mixed-species forests or deciduous forests is very urgent. However, such a conversion is only reluctantly accepted by foresters. The reasons given are that mixed-species stands are often less productive than pure Norway spruce stands (if the trees are healthy) and that the industry specifically demands timber from Norway spruce for technological reasons [16]. The current calamity situation is very complicated for the forestry sector. The plentiful supply of beetle-infested timber is reducing wood prices, and forests are not meeting policy expectations for a viable bioeconomy [58]. National and regional predictions of climatic suitability/unsuitability for the main tree species can help support the argument for converting secondary Norway spruce forests into more stable and less risky forests. Such predictions are necessary for correctly planning tree species composition as a basic framework for realizing the conversion.

4.2. Planning Tree Species Composition in the Light of Climate Change

Planning tree compositions in the Czech Republic is currently carried out based on the mapping of habitat conditions and knowing the requirements of tree species. The specification of tree compositions according to habitats has been taking place in our country since the mid-1950s, when systematic typological research and mapping according to the methodological procedures of Mezera, Mráz, Samek [61] and Zlatník [62,63] began. The results of typological mapping (a methodology according to Plíva [64]) are mainly the characteristics of mapped habitats and the definition of natural and target tree compositions. A reconstructed woody composition is a natural species composition, which would have developed in the given natural conditions without human intervention. On the contrary, the target species composition is related to the period when the stand is in the so-called "felling age"; optimal provision of production and non-production functions of the forest are assumed. Proposals for recommended target compositions are currently regulated by legislation [65] reflected in the framework management guidelines, which are part of the forest management plans of forest owners.

Until the current period of large-scale calamities in the region, it may have seemed that Norway spruce (and Scots pine and European larch) was a woody plant that grew practically everywhere in the conditions of the Czech Republic. In addition, spruce is best suited for large-area restoration systems in clearings, is easy to handle, grows well in open areas, and is very economical. It seemed that the simplicity of its cultivation did not even require forestry education, and the habitat differentiation on which the planning of woody compositions is currently based also seemed unnecessary. Especially in the case of spruce and the planning of its share in woody compositions in specific habitats, there is a fundamental difference between the amount of its representation in the natural and target composition. The mentioned difference increases when we realize that the goals of management have been considered essential for its determination so far rather than habitat conditions [66]. The current legislative measure only partially eliminates this fact by stating that the cultivation of Norway spruce as a basic target tree is risky with regard to possible climate change in the habitats of the fourth forest vegetation zone (FVZ) and, in the habitats of the third FVZ, is very risky [65]. At present, the cultivation of Norway spruce is not expected in the habitats of the first and second FVZ, although by 2012, it was represented in the first FVZ 0.4%, in the second FVZ 2.6%, in the third FVZ 9.3%, and in the fourth FVZ 9.1% of the total forest area of the Czech Republic, resp. 6.7%, 24.4%, 39.4%, and 51.2% relative to a given FVZ [67].

All that remains is to mark the current method of planning woody compositions based primarily on typological mapping as static. Only the static classification of habitats into units of the typological classification system is assumed, but without knowledge of the behavior of woody plants for the ongoing climate change. We, therefore, assume that this planning could be enriched by the dynamic approach that was used and described in this paper—an approach based on climate data, emission scenarios, and a global circulation model. The 500 \times 500 m grid could, of course, be enlarged as needed.

4.3. Driving Factors of Tree Cover Loss—Recapitulation

We detected that a considerable part of tree cover loss observed in Czech Norway spruce stands in the last five years (2016–2020) was in areas evaluated as climatically unsuitable for the cultivation of Norway spruce (Figures 3 and 4). The main damaging factor was insects, above all bark beetles (Figure 5b), in the same period. The situation is similar in a large part of Europe. Norway spruce was the tree species most affected (52%) by forest dieback over the period 2018–2019, according to EUSTAFOR data. The main factor was the bark beetle, followed by storms and droughts [68]. The driving factors of the bark beetle outbreak were described and discussed in Section 4.1. The main factors are warmer spring and summer and related water stress. These climatic driving factors of bark beetle dynamics correspond to the most significant climatic variables determined by our modeling of climatic suitability using Random Forest—annual temperature, temperature in the spring months from March to June, global radiation in the spring months, and the number of days with temperatures above 10 °C.

Our evaluation and prediction of the climatic suitability for the cultivation of Norway spruce clearly demonstrate the speed and extent of changes of climatic conditions for spruce growth as a result of ongoing climate changes. Long-term forest management planning usually works with time horizons of 20 years or longer. In dynamically changing conditions, the recommendations of the plans become inadequate in the course planning period. Therefore, long-term forest management planning should also be flexible, as for example, with the evaluation and revision of recommendations during the feasible planning period of 10 years [15]. Using the approach described in Section 4.2., the forest owners and authorities can reflect in their plans the dynamics of climate change and thus predict the suitability of growing individual species and mixtures of woody plants, which we consider very desirable in the future. The implementation of the approach must be an integral part of forest adaptation strategies.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3 390/f12121687/s1, Table S1. Global climate models from the CMIP5 ensemble used in the study Figure 1, Table S2. Classification matrix of observed and predicted values for spruce suitability in the number of pixels (0—unsuitable, 1—suitable), Table S3. Classification matrix of observed and predicted values for spruce suitability in percentage (0—unsuitable, 1—suitable).

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Data Availability Statement: Data contained within the article are available on request from the corresponding author.

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