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forests

Article

Modelling of Climate Conditions in Forest Vegetation Zones as a Support Tool for Forest Management Strategy in European Beech Dominated Forests

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Abstract: The regional effects of climate change on forest ecosystems in the temperate climate zone of Europe can be modelled as shifts of forest vegetation zones in the landscape, northward and to higher elevations. This study applies a biogeographical model of climate conditions in the forest vegetation zones of the Central European landscape, in order to predict the impact of future climate change on the most widespread tree species in European deciduous forests—the European beech (*Fagus sylvatica* L.). The biogeographical model is supported by a suite of software applications in the GIS environment. The model outputs are defined as a set of conditions - climate scenario A1B by the Special Report on Emission Scenarios (SRES) for a forecast period, for a specified geographical area and with ecological conditions appropriate for the European beech, which provide regional scenarios for predicted future climatic conditions in the context of the European beech's environmental requirements. These predicted changes can be graphically visualized. The results of the model scenarios for regional climate change show that in the Czech Republic from 2070 onwards, optimal growing conditions for the European beech will only exist in some parts of those areas where it currently occurs naturally. Based on these results, it is highly recommended that the national strategy for sustainable forest management in the Czech Republic be partly re-evaluated. Thus, the presented biogeographical model of climate conditions in forest vegetation zones can be applied, not only to generate regional scenarios of climate change in the landscape, but also as a support tool for the development of a sustainable forest management strategy.

Keywords: biogeographical model; climate change scenarios; *Fagus sylvatica*; sustainable forest management

1. Introduction

Increasingly, severe and more frequent drought events are expected to become a major risk for forest ecosystems under predicted climate change [1]. The changes in climate conditions are expected to result in changes in the forest structure [2]. We know that the current form of forest management in Central Europe, with its preference for conifer monocultures, will not be sustainable in the future [3,4]. A substantial increase in air temperature, along with a simultaneous reduction in precipitation during the growing season in Central and Southern Europe, will increase the likelihood of long and intensive summer droughts, which may have severe effects on vegetation in natural and managed ecosystems [5]. Timber production from these ecosystems also needs to be maintained because timber is a renewable material and, as such, it represents an environmentally viable material option. In the face of change and uncertainty [6], a forester needs to know the types of forests that will be most suitable under future climatic conditions. However, forests develop slowly, and during periods of rapid climate change they are likely to be in disequilibrium with the environment, leading to changed competition and possibly mortality [7]. Conversions to more drought-adapted forest types have been recommended in order to prevent climate change-induced forest dieback, and this should be the aim of any adaptive management, especially in areas where monocultures of drought-sensitive Norway spruce (*Picea abies* L. Karst) were promoted in the past. Although a complete forest conversion takes up to 120 years [8], a gradual process of introducing drought-tolerant species into drought-sensitive conifer monocultures provides immediate benefits, with the short-term enhancement of biodiversity, and the maintenance of timber production. This process includes planning for future long-term conditions.

The European beech (*Fagus sylvatica* L.) is the dominant tree species of the potential natural vegetation, from planar to montane vegetation zones in temperate Central Europe [9], and it has a key role in the European forest transition and adaptation strategies [10]. In the future, the European beech may occupy a larger area of the lower uplands and mountains, while its area in the lowlands and lower uplands may be restricted due to higher competitive pressure from the oak [11]. European beech distribution has been at equilibrium with the climate on its north-eastern leading edge, but not on its north-western leading edge [12]. The annual gross primary production of European beech is primarily affected by spring temperatures and, more irregularly, by summer water stress [13]. Based on climate change scenarios, by 2100, we can expect an expansion of climatically suitable habitats for the European beech towards northeastern Europe and higher elevations, especially in the Alps and the Pyrenees. At the same time, a sharp decline in suitable areas for the European beech in Western Europe can be expected [14]. The changing climate may also affect the European beech's life history. In the next few decades, the European beech's maximum lifespan could be shortened at higher elevations in Central Europe because of its faster growth, and in the Mediterranean mountains (e.g., Apennines) due to drought-induced mortality [15]. Several studies of European beech forests point to particular sensitivities to meteorological summer drought conditions [16–20], indicating that the growing season's precipitation totals, which are often used to characterize the local growing conditions of stands of trees, are only subordinate determinants to above-ground productivity in European beech forests. Sensitivity to drought can also be reduced with an appropriate thinning strategy [21]. However, some studies show that European beech dominated forests are not severely prone to negative functional climate change effects and, therefore, their key functions, such as welfare and recreation, can be maintained [22].

In lowland areas, the European beech is often associated with the oak (*Quercus* sp.). Each of these species have different ecological requirements and the dominance of the European beech has begun to decline in locations where the mean annual temperature exceeds 11.2 °C and the annual precipitation drops below 510 mm [23]. It is predicted that in Serbia (the European beech's most southeastern occurrence in Europe), by the end of the 21st century, approximately 90% of the current European beech forests will be outside their 20th century bioclimatic niche, and approximately 50% of European beech forests will be in a bioclimatic niche where mass European beech mortality has been recorded [24].

Although the European beech shows sensitivity to drought in forests where it is mixed with the Norway spruce, it can mitigate this limitation, as became evident during the extremely dry years of 1976 and 2003 in Central Europe [25,26]. The European beech trees near their distribution limit have already adapted to extreme conditions, while we have to expect changes in the growth patterns of the beech under mesic conditions [27]. In addition, according to [28], the sensitivity of the European beech to environmental constraints depends on neighborhood identity. Therefore, a systematic formation of mixed stands tends to be an appropriate sylvicultural measure in order to mitigate the effects of global warming and droughts on European beech growth patterns. However, management practices in the area of nature conservation strategies have not been substantially affected by scientific recommendations for forest management, and de [29] cites that 'Pure' science cannot solve the big uncertainties that surround climate change.

In forest ecosystems, the effects of climate change on a regional scale are most evident in the shift of forest vegetation zonation to higher elevations [30,31]. Nevertheless, disturbances, interspecific competition, different phenotype plasticity and various adaptations of dominant species to a particular ecosystem can all introduce considerable uncertainties into regional models of shifts in forest vegetation zones [32]. The growth response to climate change is manifest in long-term horizons [33], and the best recent records are probably in the shifts of the tree line in European mountains [34], although one of the most important drivers for upper tree line shift in the past was the management of alpine areas (e.g., grazing).

An understanding of the ongoing and potential shifts in vegetation zones is important for the development of strategies of sustainable forest management in the context of climate change [35]. The forest vegetation zones represent the regional fundamental frames of climatic conditions for the growth of forest tree species in commercial forests [36], which dominate in the European temperate zone. However, previously published studies of vegetation zone shifts are limited to a few countries dominated by Alpine regions [37–39]. Aside from the Alpine region, Svajda et al. [40] studied the altitudinal shift of the Dwarf mountain's pine vegetation at the upper forest limit in the High Tatras (Slovakia)and Kutnar et al. [41] published predictions concerning the changes in the vegetation zones under climate changes in Slovenia. Predictions concerning the influence of the shift of the vegetation zones on tree species in Poland were elaborated on by [42], and the impact of terrain and vegetation structure on the tree line dynamic in the Sudeten region in central Europe was studied by [43].

Regional studies conducted in several countries, with the aim of predicting which forests would be more suitable for future conditions, have come up with similar recommendations concerning reductions in spruce monocultures, and giving preference to mixed forests with a higher proportion of deciduous tree species, particularly the European beech [44–46].

Our study aims to apply the forest vegetation zonation for modelling to future changes in climate conditions for the European beech, which is currently one of the most important deciduous tree species in European forests [47] (EUFORGEN 2011). The main aim of this article is to show how predicted changes in climate conditions in forest vegetation zones, as related to regional climate scenarios, can influence the European beech's growth in the Central European landscape. Modelling climate condition changes in relation to the European beech can provide support for the development of strategies of adaptation measures in forest stands dominated by the species. They also provide a science-based rationale for forest management decisions [48] based on the adaptation approach to forest ecosystems [49]. Forest management adaptation strategies [50] aimed at sustainability must take into account a range of economic [51] and social aspects [52–54]. There are many uncertainties concerning the impact of climate change on European forests [6], so another goal of this study is to highlight the importance of the somewhat neglected biogeographical models, rooted in the concept of the forest vegetation zones. This article presents the results of the biogeographical model applications for the European beech in the cultural landscape of the Czech Republic for the forecast period 2030–2090.

2. Materials and Methods

This biogeographical model of climate conditions in the forest vegetation zones of the Czech Republic (hereinafter, model) is based on the relationship between the present climate and the distribution of vegetation zones in the landscape [55]. The model (Figure 1) is based on fundamental assumptions: (i) that the general ecological relationship between climate conditions and vegetation zonation will be maintained in the future [56,57]; (ii) that predicted climate change will be manifested into modified climate conditions in the present vegetation zones at the regional level; and (iii) that this process can be predicted [58]. It does not imply that the present vegetation zones within the cultural landscape will shift to higher elevations. The model outlines projections of changes in climate conditions to vegetation zonation, not changes in the vegetation zones as such. This fact is an important basic principle of the model. The model uses the forest vegetation zones as a reference framework for climate predictions of particular growing conditions for the European beech, for which the optimal climate conditions in the Czech Republic are unambiguously defined [59]. The current representation of the European beech in the forests of the Czech Republic is only 7.7%, which is considerably less than the expected representation (40.2%) in the potential natural vegetation [60].

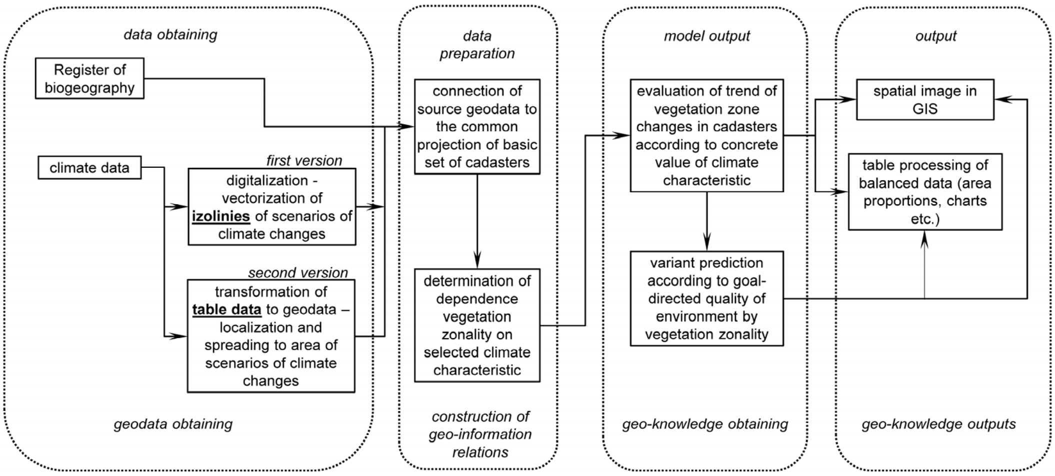

Figure 1. Flowchart of biogeographic envelope for a regional model of climate conditions in vegetation zones of the Czech Republic

The forest vegetation zones of the Czech Republic (Table 1) were defined using the method of bio-indication in the fundamental study by [61], and are widely applied in forest management practice. The detailed characteristics of the natural conditions of forest ecosystems in the forest vegetation zones of the Czech Republic [62] can easily be converted to the European forest, agricultural and protection typology systems related to habitats (e.g., in the NATURA 2000 European Network). Detailed climate characteristics of the vegetation zones are based on Macků [63].

A predictive climate database from the Czech Hydrometeorological Institute (CHMI), known as CLIMDATA, is the source of climate data for the model. It assigns the climate data to the set of 131 points regularly distributed throughout the Czech Republic in the form of the regular trapezia network. It contains a large validated database of climate parameters calculated by the model ALADIN-CLIMATE.CZ for the period 2010–2100 [64], for the scenario SRES A1B [65].

The Register of Biogeography [66] is an ecological database which includes geographical and site information, and it is the source of biogeographical data used in the model. It contains the detailed ecosystem characteristics of the Czech Republic's landscape (i.e., vegetation zonation, soil types and soil conditions the so-called trophic and hydric series, the predominant type of topography) matched with individual cadaster areas. The Czech Republic consists of 13,000 cadasters (polygons with an average area of 6 km^2). The register was created as a component of the Area Integral Information

System (AIIS) [67]. The cadaster was selected as a basic spatial unit for the Register because it enables the evaluation of changes in the landscape, and utilizes periodically updated databases from the AIIS which characterize the current state of, and anthropogenic pressure on, the landscape. Census data and the utilization of soil resources are of particular interest, and they both use the cadaster as a basic unit. Cadasters are historic landscape units, originally established to document land tenure and estates, and as such they are not homogeneous in their natural conditions. Nevertheless, on the regional scale (all of the Czech Republic), the cadaster polygons capture the heterogeneity of the natural conditions in the whole country, because the original cadaster system, in existence without many changes since the 18th century, used natural boundaries such as streams, forest edges, and major geomorphological formations in the landscape to delineate its units [68].

Table 1. Current extent and future areas with projected climatic characteristics corresponding to the respective forest vegetation zones of the Czech Republic.

Forest Vegetation Zone		Extent of Climate Conditions for Vegetation Zones in				
		2010	2030	2050	2070	2090
		% from the Area of the Czech Republic				
1.	Oak	3.46	3.98	12.78	38.41	40.82
2.	Beech-oak	12.06	14.29	5.49	38.51	38.51
3.	Oak-beech	18.21	20.14	20.14	16.41	16.41
4.a	Beech	39.62	46.22	54.91	5.60	3.98
4.b	Oak-coniferous variety of the fourth vegetation belt	3.62	8.69	0.00	0.00	0.00
5.	Fir-beech	19.40	5.60	5.60	1.07	0.28
6.	Spruce-fir-beech	2.53	0.80	0.80	0.00	0.00
7.	Spruce	1.00	0.28	0.28	0.00	0.00
8.	Dwarf pine subalpine	0.10	0.00	0.00	0.00	0.00

The biogeographical model of changes to climatic conditions in the vegetation zones is a suite of specific software applications (FORTRAN programming language, IBM, New York, NY, USA) and a GIS application of Esri products (ArcGIS, Prague, Czech Republic). This is a static model that does not enable prediction of the rate of vegetation change. Climate characteristics were assigned to the points of the Register of Biogeography using an analytical-geometric method, which involved the construction of a network of points with a fine resolution of 250 m. The climatic data from these new points were calculated with a gradient method [69] and taken from the climatic variable of their four closest neighbors in the original climatic database CLIDATA. The predicted climate characteristics of defining points, their corresponding potential vegetation zone and the characteristics of natural climate conditions are expressed in the model algorithms. The algorithms were developed using the method of spatio-temporal analogies, with Lang's Rainfall Factor used as the relationship coefficient (combining total annual precipitation and average annual temperature in one value) [70]. The climate growing conditions for the European beech in the Czech Republic were divided into four categories: "unsuitable climate conditions", "moderately suitable climate conditions", "suitable climate conditions", and "optimal climate conditions" (related to climate conditions for different vegetation zones). These divisions in predicted climate conditions enable a clear visualization of the model outputs. The model outputs for the defined scenario combinations (time period, climate scenario, geographic area, ecological conditions for the European beech) provided a regional scenario of predicted future climate conditions for the European beech in the forecast period 2030–2090.

3. Results

3.1. Regional Scenario of Changes in Climate Conditions of Vegetation Zonation in the Czech Republic

The regional scenario of the changes in climate conditions for vegetation zonation in the Czech Republic for the forecast period 2030–2090 (regional scenario) clearly identifies three main predicted trends (Table 1): (i) a gradual increase in area for regions with climate conditions of the lower forest vegetation zones (1–3); (ii) a relatively stable area with climate conditions of the fourth forest vegetation zone, which remains the vegetation zone with the largest representation (55%) on the landscape in the Czech Republic, in both predicted periods; and (iii) a significant and very fast decrease in area for regions with climate conditions of the higher forest vegetation zones (5–8).

3.2. Application of the Regional Scenario for Sustainable Management of Beech-Dominated Forests

Good and optimal growing conditions for the European beech currently prevail in two thirds of the Czech Republic (Table 2), and cover an area from the second to the sixth forest vegetation zones (Figure 2).

Table 2. Current state and prediction of the climate conditions for European beech in the Czech Republic (forecast period 2030, 2050, 2070, and 2090 year).

Climate Conditions	**2010**	**2030**	**2050**	**2070**	**2090**
			km^2		
Unsuitable climate	2144.86	2728.52	2144.86	30,281.86	30,281.86
Moderately suitable climate	10,624.10	18,522.57	12,258.37	23,510.92	24,781.26
Suitable climate	30,883.58	23,772.25	23,027.48	22,092.23	21,281.24
Optimum climate	35,182.71	33,811.91	41,404.54	2950.25	2490.89

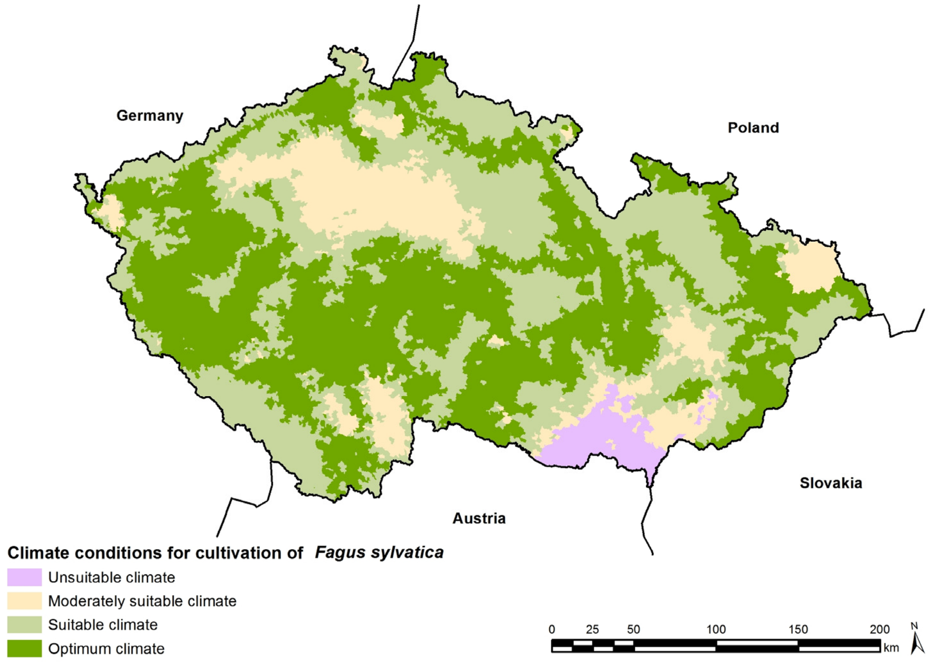

Figure 2. Present status (2010) of climate conditions for European beech in the Czech Republic.

The visualization of the regional scenario for the year 2030 (Figure 3) shows a decrease in areas with optimal climate conditions for the European beech in the lower uplands and, instead, a slight enlargement of the area with mediocre climate conditions in this terrain. In the prediction period for 2050, the trend is reversed (Figure 4) and the area with the optimal climate conditions for the growth of European beech is 10% larger than today, according to the regional scenario (Table 2). However, the regional scenario predicts a relatively dramatic deterioration in the growing conditions for the European beech between the years 2070 and 2090. In 2070, in connection with an elevational shift of climate conditions in the forest vegetation zones to higher elevations (Figure S1), the optimal climate for the growth of the European beech will move to the highest mountain areas of the Czech Republic (higher than 1000 m above sea level) and a good climate for growing the European beech will remain in and above the area of the present fifth forest vegetation zone. The proportion of the good and excellent climate conditions will decrease to less than 10% of the whole area of the Czech Republic (Table 2). This trend will remain the same for the year 2090. The predicted trend in the changes in climatic growing conditions for the European beech in the Czech Republic forecasts a significant deterioration of its silviculture in the future. Following the regional scenarios, a strategy of sustainable forest management in the Czech Republic should take into consideration potential future threats likely to affect the European beech, which is now the major economic deciduous tree species in the forest sector in the Czech Republic. The predicted shift in the good and optimal climatic growing conditions for the European beech to the highest mountain areas in the Czech Republic will most likely affect the biodiversity associated with the present vegetation belts. In particular cadasters, according to the regional scenario, from 2070 onwards, the good and optimal climatic growing conditions for European beech dominated forests will only be found in parts of the areas currently occupied by natural European beech, from the fifth to the eighth forest vegetation zones (Figures 5 and 6). Based on the regional scenario results, the national strategy of sustainable forest management in the Czech Republic (National Forest Program) should pay more attention to plans for alternative tree species composition in future planning, with regard to the predicted deterioration of climatic growing conditions for the European beech from the year 2070 (Table 2, Figures 5 and 6).

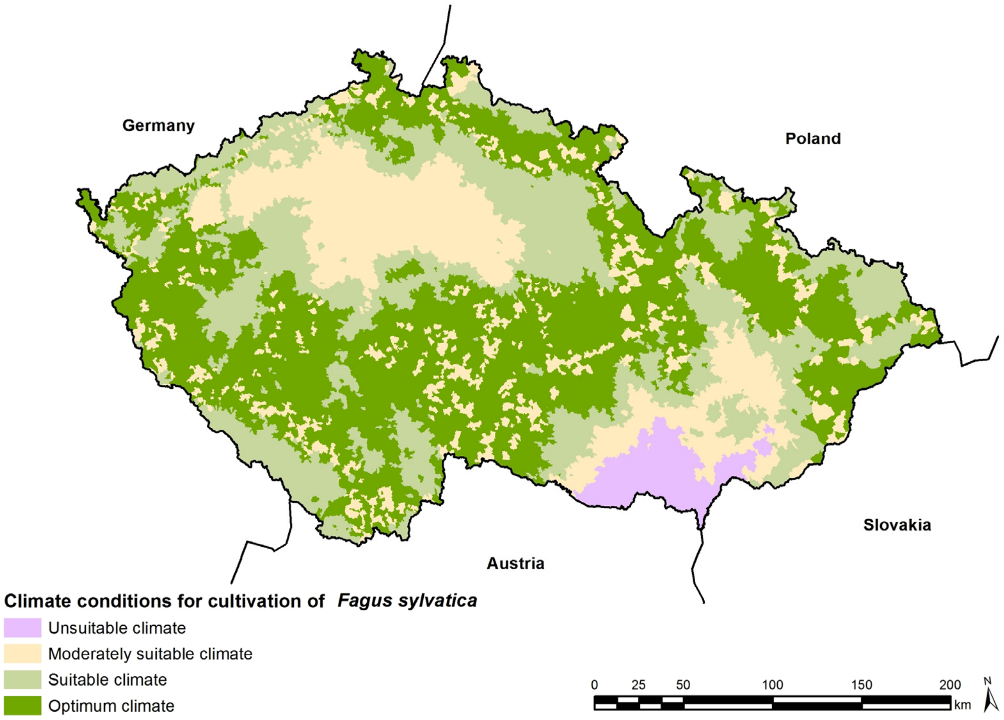

Figure 3. Visualization of predicted distribution of climate conditions for the European beech in the Czech Republic in 2030.

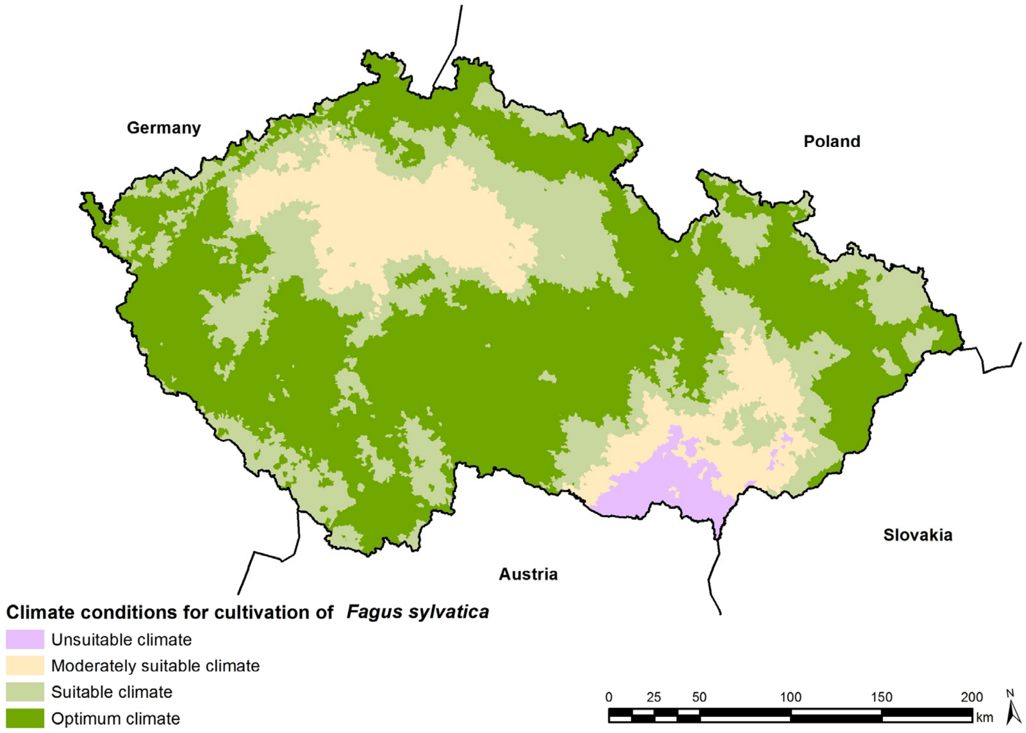

Figure 4. Visualization of predicted distribution of climate conditions for the European beech in the Czech Republic in 2050.

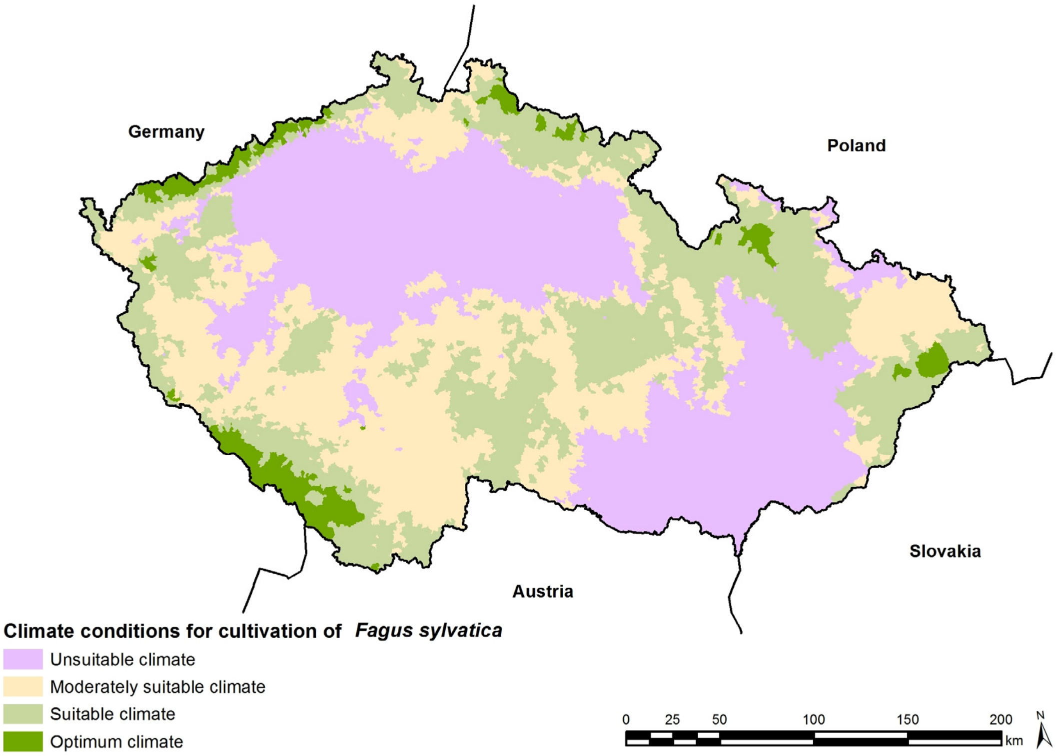

Figure 5. Visualization of predicted distribution of climate conditions for the European beech in the Czech Republic in 2070.

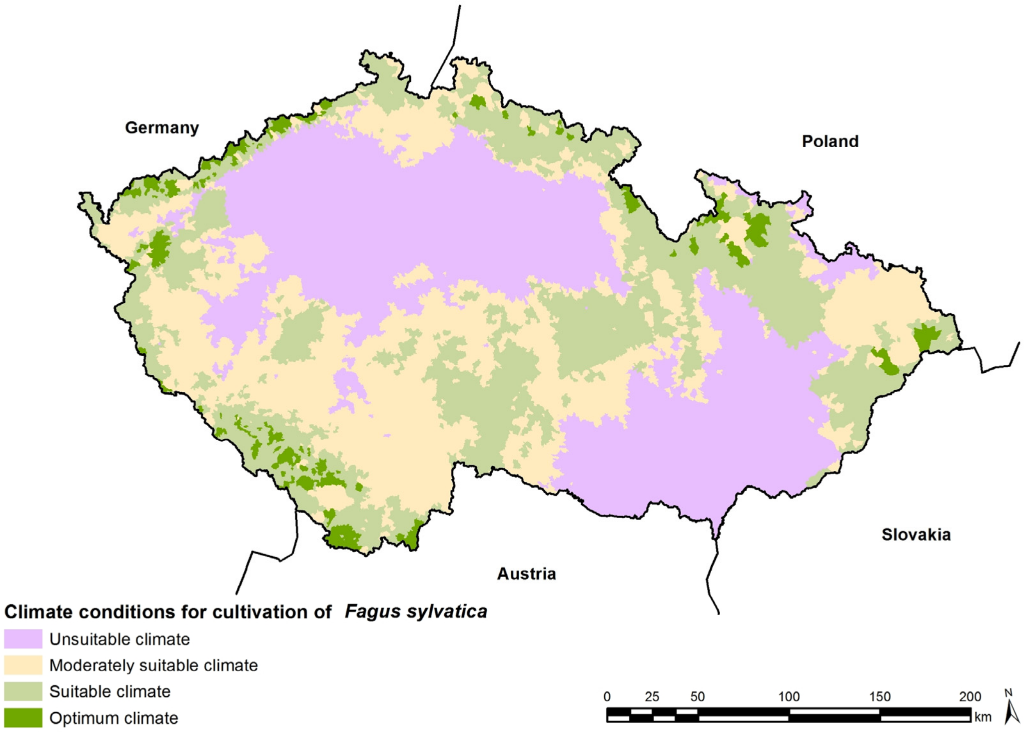

Figure 6. Visualization of predicted distribution of climate conditions for the European beech in the Czech Republic in 2090.

4. Discussion

Global Climate Envelope Models [71], also referred to as Ecological Niche Models or Species Distribution Models, are statistical predictive tools applied in ecological research to estimate the distribution of species, biological communities and habitats [72], and may not always correspond to specific local conditions [73]. This applies to the European beech, which grows in central Europe under fairly specific climate conditions [74], with a natural elevational distribution from 350 m to 990 m.a.s.l. [75], tested the influence of climate and tree-specific traits on inter and intra-site variability in the drought responses of three common European temperate forest tree species in southern Germany and Alpine Austria: Norway spruce, Silver fir and European beech. General patterns of tolerance indicated the high vulnerability of the Norway spruce in comparison to the Silver fir and the European beech, and the strong influence of bioclimatic conditions on the drought responses of all three species. Consequently, drought events led to heterogeneous and variable response patterns in forests stands. These findings support the idea of deliberately using spontaneous selection and adaptation effects as a passive strategy in forest management under climate change conditions. This supports the importance of natural reserves; areas left to natural development without human intervention, where selection processes can take place. Such areas should be an integral part of a broad set of adaptation measures in temperate forests in Europe [76].

The results of the regional modelling of the impact of climate change on European Beech in the Czech Republic are consistent with the main phenomena related to vegetation changes induced by climate change in European beech-dominated forests. These include movement of montane forests dominated by deciduous trees towards a higher elevation, shift of montane beech-fir communities to beech communities and replacement of beech-dominated forests in highland areas by oak-hornbeam forests (especially in the northern Alps) [31]. The results of the biogeography model used in this article suggest that the strategy of sustainable forest management in the lower forest vegetation zones (1st–3rd) of the Czech Republic should focus on adjusting the tree species' composition in commercial forests (plantations) in favour of native broadleaved species, which may be less profitable but more ecologically suitable in these vegetation zones. The area of the fourth vegetation zone (with optimal climate conditions for the growth of the European beech) will continue to dominate the landscape of the Czech Republic in the context of the predicted climate changes. In forest management, the scenario indicates a stable area with optimal climate conditions for European beech (*Fagus sylvatica* L.). Sustainable forest management strategies in the fourth vegetation zone should thus favour such forest systems, which support beech as the dominant tree species. This can be done using the shelter wood system, and with the support of the European beech's natural regeneration, etc. The commercial beech forests located in the fourth vegetation zone, in the northern area of the Bílé Karpaty Mountains in the eastern part of the Czech Republic, are where the European beech currently has its Central European ecological optimum [21]. The conditions suitable for the oak-coniferous variety of the fourth vegetation zone will disappear from the landscape, according to the scenario for 2050 (Figure 4). In comparison to the climate of the zonal variety in the fourth vegetation zone (beech zone), the climate of the oak-coniferous variety is characterized by higher continentality, frequent temperature inversions, late frosts and cooler soil profiles during the growing season which are caused by a higher water content in the soil. Ecosystems associated with these specific climate conditions, possessing the characteristics of the so-called central European taiga [77], will be adversely affected by future climate change, according to the model scenario for 2050 (Figure 3). The area with the conditions of the fifth vegetation zone (fir-beech) will decrease by 14% compared to its present state (Figures 2–6). Overall, the shift in the climate conditions of vegetation zones toward higher altitudes will affect forest management strategies in the mountainous areas of the Czech Republic. The scenario for 2070 and 2090 indicate changes towards less favourable climate conditions for European beech, which can enhance a risk of biotic and abiotic disturbances and stressors. Strategies for sustainable forest management should aim to enhance the static stability of the present forest stands and, most importantly, convert the current spruce monoculture stands to mixed forests of European beech and Silver fir (*Abies alba* Mill), where a minor proportion of Norway spruce occur in moist and wet habitats (on pseudogleyed soils).

Projected changes in climate conditions for beech planting linked with forest vegetation zones, correspond to the expected trends in vegetation development in Europe concerning climate changes in the model of European vegetation EUROMOVE [78]. The main trends in the changes are also in line with observed trends in the distribution of wild animals, also explained by climate change, such as certain butterfly species [79] expanding their range to higher elevations. Reference [80] showed that the trend in ongoing changes in bird population sizes and the shifts in nesting areas in the Czech Republic, in the context of climate change, are caused by a decline in species adapted to colder climates in mountainous areas, and an increase in the ranges of lower-elevation species. This confirms the regional scenario of climate characteristics for the beech planting in our study.

Increasing average global temperatures and changes in precipitation over the last 100 years have induced movements in the vegetation zonation of ecosystems around the entire world [81]. The modelling of global vegetation changes using the General Circulation Model [82] clearly shows the effect of global changes on the distribution of vegetation formations. However, assessments of climate parameters vary among global climate models, mainly for the most recent decades [83]. Moreover, global vegetation models cannot take into consideration individual plant species, and the theoretical bases for those models neglect the migration characteristics of individual species and the succession processes occurring at the level of particular ecosystems [84]. The regional scale appears to be the most appropriate for addressing the influences of climate change, species distribution and the succession processes at the level of the ecosystem [85]. In addition, climate change in a particular geographical region often affects certain ecosystems in synergy with other regional influences, such as with landscape fragmentation [86]. Therefore, regional models may provide a fundamental understanding of the significance of climate change for specific target ecosystems [87].

The Fifth Assessment Report for the Intergovernmental Panel on Climate Change (IPCC) defined a set of four new scenarios, known as Representative Concentration Pathways (RCP). Predictive regional climate data for these scenarios are not yet available for the Czech Republic. Therefore, in our model, we had to apply the scenario SRES A1B, based on a validated regional climate database. One of the most important current research projects modelling regional climate change and its effect on organisms is the CORDEX project [88], with its Europe-specific section EURO-CORDEX [89]. The outputs of the regional modelling CORDEX, suitable for regional adaptation studies, should be available in the 500 × 500 m grid in the future.

The modelling of the spatial aspects of occurrence and its development, and the implications for vegetation zonation generate material for further research activities. Refs. [90,91] assessed the impact of elevation and terrain on various species of alpine herbaceous assemblages in the area of Picos de Europa in Spain by modelling on a 15 × 15 m grid. Elevation has the biggest effect on the overall floristic diversity of the community, supporting the close association between elevational climate and vegetation belts. However, the occurrence of individual species was influenced more strongly by slope aspect, topographic index, soil water content and the sun's radiation. The existing models for the future distribution of flora and fauna mostly concentrate on individual target species or groups of species, whereas organisms interact in the ecosystem processes within their ecological niches, and thus the responses of biota to climate change are more likely to be identified at the level of ecosystem diversity [92]. The biogeographical regional models are particularly useful from this point of view [93].

The biogeographical model of changes in climatic conditions for the European beech, as caused by the predicted climate change, is one of a group of process-based biogeographical models used to predict the equilibrium reactions of vegetation to potential climate change on the regional scale [94]. This model type identifies the ecological limitations in the distribution of vegetation formations' (vegetation zones) different equilibrium climate conditions [95]. The majority of proposed models are correlational models based on the mutual dependence among certain environmental bioclimatic variables (average temperature and total precipitation) and the present area of species distribution, or characteristics of species ecological niches [96]. When predictions based on climate scenarios show how the climate can change in the future, the corresponding biological species or their communities with zonal distribution are assigned to the new parameters, whereas, in our study, the vegetation zones were assigned as the new parameters. The biogeographical model used in our study utilizes the dependence of the vegetation belts on the long-term impacts of elevation and aspects characterized by average and extreme temperatures, and their dependence on the amount and distribution of precipitation [97]. The specifications for the present forest vegetation zones in the Czech Republic [98] were updated to a higher precision during the establishment of forest habitat typology [62], which laid the groundwork for silviculture based on ecological conditions [99].

The simulations of vegetation redistribution using biogeographical models are essentially static (equilibrium) views of the analyzed problem, as those models represent modelling based on a certain concentration of atmospheric carbon dioxide in the future. The static models provide a useful "picture" of the terrestrial ecosystems in equilibrium with particular climate conditions at a given time [100]. However, the application of these models is limited by the fact that the models do not simulate all known internal factors of vegetation dynamics, such as interspecies competition, natality and mortality of populations or physiological factors. Dynamic global vegetation models that integrate vegetation dynamics and ecosystem functions have been developed to overcome these limitations [101], but they cannot be used on a regional scale [102]. Some uncertainties in the prediction models arising from insufficient data on the autecology of a particular species can be partly eliminated by using species-specific models. However, these are few and far between and mostly applicable on a continental scale [103], only providing rough guidelines for regional applications. In addition, when interpreting mathematical models of the impact of climate change on biota, we must take into consideration that models do not provide a perfect prognosis of future development [104]. The models based on sophisticated analyses contribute significantly to the prognosis (by providing synthetic scenarios), but their sensitive application must be based on a good knowledge of the biology and ecology of the organisms being modelled [105].

The important benefit of biogeographical models is their potential application for strategies of adaptation and mitigation in the landscape in the context of ecosystem services [106]. The vegetation belts are also important with respect to ecological growing conditions for forest tree species (the European beech currently has optimal growing conditions in the Czech Republic, in the fourth vegetation belt). The first study, which analyzed the continual fluctuations in agro-climatic conditions over the last 200 years, as well as expected shifts in future decades [107], showed an expansion of warmer and drier agro-climatic conditions in the most fertile regions. The development of the climate in Europe can lead to the largest shift in agro-climatic conditions since the onset of agricultural activity long before our historical experience [108]. The same consideration is undoubtedly also valid in forestry [109,110]. Therefore, in forestry, the predictions concerning climate conditions and the analyses of their impact on the forest ecosystem must be considered as crucial initial inputs into the formation of strategies in sustainable forest management [111,112]. In relation to the strategies for the lower uplands and mountain forest vegetation zones in the European temperate zone [113], the European beech has been very intensively researched [114–116]. The high stability of old-growth European beech forests under natural conditions can contribute to the overall stability of managed forests in Central Europe [117].

5. Conclusions

In conclusion, based on the results of the regional models, we recommend that focus is placed on the sustainable forest management strategy of the Czech Republic, and on developing target tree species whose compositions take into consideration the climatic deterioration of growing conditions for the European beech from the year 2070 onwards.

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