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Research Article

Changes to Land Area Used for Grain Maize Production in Central Europe due to Predicted Climate Change

Petr Pavlik,[1] Veronika Vlckova,[2] and Ivo Machar [1]

[1] *Department of Development and Environmental Studies, Faculty of Science, Palacky University, Olomouc 771 46, Czech Republic*
[2] *Department of Transportation Telematics, Faculty of Transportation Sciences, Czech Technical University in Prague, Prague 110 00, Czech Republic*

Correspondence should be addressed to Ivo Machar; ivo.machar@upol.cz

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Regional biogeographical models are considered to be important tools for supporting decisions relating to sustainable agricultural planning for climate change. These models are useful for a better understanding of the impact of climate change on individual crop species due to their sensitivity to regional ecological conditions. This paper deals with the application of a regional biogeographical model in order to predict the impact of climate change on growing conditions for grain maize in Central Europe. The model is based on a detailed knowledge of the relationships between the climatic characteristics of vegetation zones in landscapes with ecological growing conditions suitable for grain maize in the region under study. The results gained from using the model indicate a substantial increase in the total area suitable for growing of grain maize in the study region. By 2070, this area is expected to be triple the size it is today. Special maps are used to visualize prediction scenarios in order to support decision-making in regional planning in the study region, where grain maize is an important agricultural crop. This biogeographical model can be used in other European regions, where basic data related to vegetation zones are available.

1. Introduction

Increasing average global temperatures and changing precipitation patterns over the past 100 years have induced vegetation change and caused disruption to ecosystems all over the world [1]. Modelling global vegetation change using general circulation models [2] has been useful in obtaining an overview of global changes in the distribution of vegetation [3]. However, global vegetation models cannot simulate all species and theories concerning the impact of climate change on vegetation and thus cannot incorporate species-level migration and succession processes [4]. It is best to study these processes on a regional scale [5]. A regional scale is also convenient for a better understanding of climate variations and change and is essential in assessing the climate's sensitivity to a variety of factors, both human and natural [6]. Moreover, climate change tends to affect certain ecosystems in a given geographic region in synergy with other specific regional impacts, such as landscape fragmentation [7]. On a regional scale, the impact of climate change on ecosystems manifests itself as a shift of vegetation zones, both northwards and to higher elevations [8]. Thus, regional models of changes to vegetation are considered fundamental for an understanding of the impact of climate change on ecosystems [9].

In the temperate zone of Europe, studies on the shift of vegetation zones tend to be limited to individual countries, and most focus on countries in the Alpine region [10]. Published regional studies concerning the impact of climate change on vegetation shift in Central Europe are still rare. Of those, one study [11] report an upward shift of the tree line in the Tatra Mts (Slovakia) and another [12] predicts an upward shift of vegetation belts in the forest ecosystems in Slovenia. Based on the differentiation of vegetation zones in the Czech Republic, we have published a prediction on the impact of climate change on the future climatic growth conditions of sugar beet [13]. In this study, we used a regional biogeographical prediction model to create an algorithm of the defined climate requirements for specific species affected by the predicted shift in the climate conditions under different scenarios of climate change [14]. This model [15] provides predictions of future changes in climate conditions affecting a range of species on a regional level. This biogeographical model is particularly suitable for the modelling of crops, as their ecological requirements for climate conditions are well established [16].

It is known that predicted changes in climate conditions may potentially have a considerable impact on both the quantity and quality of agricultural production [17]. That is why close attention has been paid to the study of the possible impacts of climate change on agriculture over the past 25 years [18]. More frequent drought episodes combined with higher temperatures have increased the risk of decreased crop yields and threaten the overall stability of agricultural production, as was seen in the year 2000 in the temperate zone of Western and Central Europe [19]. Yet, it is assumed that the technologically well-secured agricultural systems of Western and Central Europe will be relatively well adjusted to resist climate change [20]. Model estimates of future yields of what are currently the main crops of Central Europe (wheat and barley) may indicate an increase in yields due to higher photosynthetic efficiency caused by higher CO_2 concentrations; yet, a change in climate conditions as such will lead to a slump in yields (best-case scenario) and a lower yield stability than today (according to the most realistic scenario) [17]. A comparison of yield stability and its relation to climate conditions in the late 19th century and the late 20th century confirms these scenarios, as today's European agrosystems (affected by increased temperatures and more frequent droughts) are as dependent on weather in a given growing season as was the case in the late 19th century. It is estimated that, in the next 50 to 100 years, the climate could experience the most massive shift in agroclimatic conditions since the beginning of farming, which is beyond our historical experience [21].

The combination of increased air temperature and changes in the total and annual cycle of precipitation predicted for the next decades will induce a significant shift in the size and location of individual agroclimatic zones [22]. In all cases, the size of the cereal- and potato-growing areas, as well as the forage and grassland zones, will be reduced greatly by 2050 and will be replaced by sugar beet and grain maize-growing zones. Similar claims were made by a study [23] which analysed the expansion of the area suitable for grain maize production in Central and Northern Europe under climate change projections. But a serious knowledge gap still exists in relation to the future regional consequences of climate change for maize production in many agricultural areas around the world. This can limit the application of conservation agriculture cropping systems, which have emerged as potentially successful means of sustainably maintaining and increasing grain maize production [24]. Thus, it seems very important to study geographical scenarios concerning the future impact of climate change on maize production areas in different agricultural regions. In this paper, we aim at assessing future changes in the climate conditions for growing grain maize (*Zea mays* L.) in the study area of the Czech Republic (Central Europe). The production of grain maize in the study area is currently expected to be more important in the next years because of long-term declining trend of other grain crops (wheat, barley, and oat). Total grain harvest (excluding grain maize) was in 2017, 13.2 percent lower, when compared to the year 2016 according to the latest estimates of the Czech Statistical Office. Similarly, rapeseed harvest in 2017 has declined by 11.8 percent in comparison with 2016 year. The major reason for the decreased production is lowered yield, as the total sowing area in 2017 was almost identical to the one in 2016. Yields dropped in all basic grains (excluding grain maize) and rapeseed because of unfavorable weather conditions. Frost in January 2017 reduced winter crops, and in May and June 2017, the crops were negatively impacted by drought. Despite it, grain maize harvest in the study area indicates a stable long-term trend in the yield. The production of grain maize in 2017 in the study area reached an amount of 533 thousand tonnes of grain. The area under grain maize of 84 thousand hectares in 2017 slightly dropped compared to the last-year harvested area (−3.1%). Total grain maize consumption in the Czech Republic was (in 2017) estimated by the Czech Ministry of Agriculture at 493,000 MT, out of which, 830,000 MT will be used in the feed industry and approximately 80,000 as feedstock for bioethanol production. These indicate high economical potential of grain maize production in the study area.

The expected climate changes in European agriculture indicate unprecedented changes in crop production [25]; thus, we can establish the hypotheses that grain maize production areas will increase on a geographical scale in Central Europe. This hypothesis is tested in this paper through the application of the biogeographical regional model.

2. Materials and Methods

Vegetation zones [26] reflect the altitudinal gradients of climatic conditions in the landscape scale [27]. Climate change can induce the vegetation zone altitudinal shifts. Thus, vegetation zones changes can be used as a basis for applying the biogeographical modelling to predictions of climate change impacts on the growing conditions of agriculture crops on a regional scale [28, 29]. In this study, we applied a process-based biogeographical model [30] based on the equilibrium responses of vegetation to climate change [31, 32]. The model is based on the idea that the general ecological relationship between climate conditions and vegetation zoning will be maintained in the future [33].

The input climatological data for the model used the validated database of the Czech Hydrometeorological Institute (annual precipitation, mean annual relative air humidity, average daily global radiation, mean annual air temperature, and mean annual wind speed). This database is calculated for the selected regional emissions scenario RCP8.5. This scenario predicted the most significant climate change and corresponded to natural climate variability. It indicated the highest precision of standardized climate change scenarios for a global temperature increase of 1°C. Based on the standardized scenario, the biogeographical model was derived climatological values for future time horizons. The climatological data are closely related to a regular trapezoid network of 131 points evenly distributed in the Czech Republic.

The input geobiocoenological data for vegetation zonation come from the database called Register of Biogeography (RB). This database describes a precise range of vegetation zoning in the Czech Republic in order to creation of the National Ecological Network [34]. RB contains a vegetation zonation, trophic series, and hydric series of soils. It is in accordance with the 13,000 cadastre polygons as spatial units of the administrative territorial classification in the Czech Republic. The cadastre territorial system originated in the 19th century and the cadastre polygons are bordered by natural vectors formations in the landscape (streams, forest edges, etc.).

The biogeographical model applies a specific software applications (using FORTRAN programming language) and GIS application (see scheme of the model in Figure 1). Climatological characteristics for the cadastre polygons were derived using an analytical-geometric method by constructing a network of points with a fine resolution of 250 m. The climate data of these new points are calculated using the gradient method, from the climatic variable of their four closest neighbors in the original climatological input database. The predicted climatological data for defining points corresponded to defined vegetation zones in the model algorithms for the target agricultural crop (i.e., grain maize). The algorithms used the Lang's rainfall factor as the relationship coefficient (combining total annual precipitation and average annual temperature into one value) via the method of spatiotemporal analogies. Following an analysis of the existing ecological conditions in the maize-growing regions of the Czech Republic (Table 1), the model algorithmized the present conditions for maize production into vegetation zones and geobiocoenological characteristics of hydric and trophic series of soils. The climate framework for grain maize-growing conditions was divided into three categories: "unsuitable conditions," "medium-optimal conditions," and "optimal conditions." This classification was visualized on maps. The model revealed a regional scenario of predicted future climate conditions for grain maize production.

3. Results and Discussion

The results of the conducted algorithmization of the present conditions for the growing of grain maize into vegetation zones and the geobiocoenological characteristics of hydric and trophic series are shown in Figure 2 as a baseline scenario. The definition of areas with unsuitable climate conditions for grain maize encompasses those vegetation zones and trophic and hydric series (e.g., hydric soils in river alluvia) which are entirely unsuitable for the grain maize growing requirements of today.

The map in Figure 3 illustrates the range of areas suitable for grain maize growing in the period 2011–2030 and Figure 4 shows the same in the period 2031–2050. Figures 5 and 6 clearly indicate the temporal trend towards a significant expansion of areas suitable for grain maize. By the period of 2051–2070, the total area of sites suitable for growing maize in the Czech Republic should be triple the size it is today (Figure 5). This trend remains for the prediction period 2071–2090 (Figure 6). This finding indicates that the predicted climate change may have a positive impact on the agricultural production of thermophilic crops such as grain maize in the area studied (increase in the total production area).

Detailed model predictions of the temporal and spatial trends in the development of areas climatically suitable for the future growing of grain maize in the Czech Republic are shown in graphs in Figure 7 (in relative units) and Figure 8 (in absolute units). Both graphs correspond to the cartographic depiction of development trends in Figures 2–6. The defined hypothesis concerning the increasing area of grain maize production has been confirmed—the results of the biogeographical model indicate that the total area suitable for grain maize production in the study area is expected to triple by 2070.

The graphs (Figures 7 and 8) demonstrate the potential of the model used with the time horizon of 2090, which is the limit value of its prediction scope as determined by the input climatological prediction data. However, the model-related data which exceed the time horizon of 2050 must be considered purely indicative, as they are subject to a high degree of climatological prediction uncertainty.

Climate influences the geographical distribution of organisms within ecosystems, as well as human activities such as agriculture. For practical reasons of agricultural planning on a regional scale, models are being sought which predict scenarios concerning the impact of climate change on the growing conditions of crops. Grain maize is one of the oldest crops in the world [35], and its production is extremely important in the global context [36]. A number of studies have indicated that grain maize yield is negatively affected by climate change on a global scale. Close attention is also paid to regional perspectives relating to the impact of global changes on grain maize yields, e.g., in Switzerland, China, and Africa [37]. Ecosystem production in agricultural landscapes is highly sensitive to climate change. Long-term analyses of mean temperature trends in Europe indicate an increase in mean temperatures of 1.2°C during the 20th century [38]. The average number of summer days in Europe doubled during the 20th century, while the number of tropical days tripled [39]. Clearly, this has had a significant impact on European agriculture and the formulation of agricultural priorities in Europe. Similarly, long-term climatological measurements conducted in the territory of the Czech Republic [40] have revealed significant increases in mean temperatures as well as a sharp rise in the occurrence of weather externalities—the numbers of tropical and summer days and nights are increasing, while the numbers of frosty and icy days are decreasing. An analysis of the stability and diversity of agricultural production in the Czech Republic over the last 75 years have shown that climate change has a positive impact on the production of

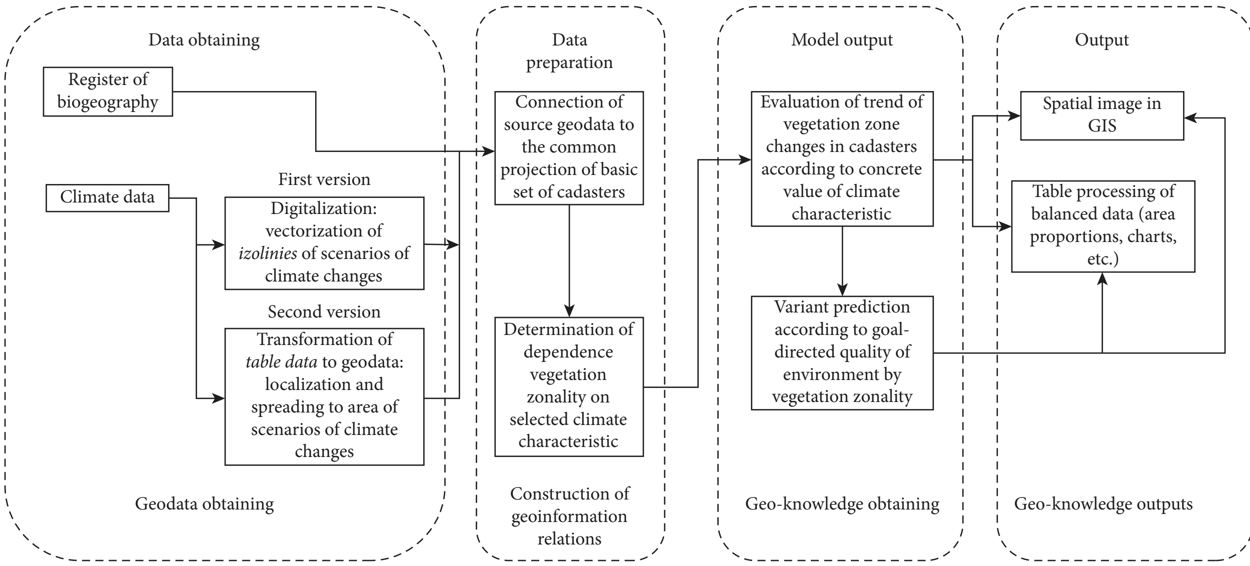

Figure 1: Scheme of biogeographical model processing.

Table 1: Climate conditions for grain maize planting in the Czech Republic.

	Temperature annual sum (°C)	Annual precipitation sum (mm)
Value range	9-10	500–600

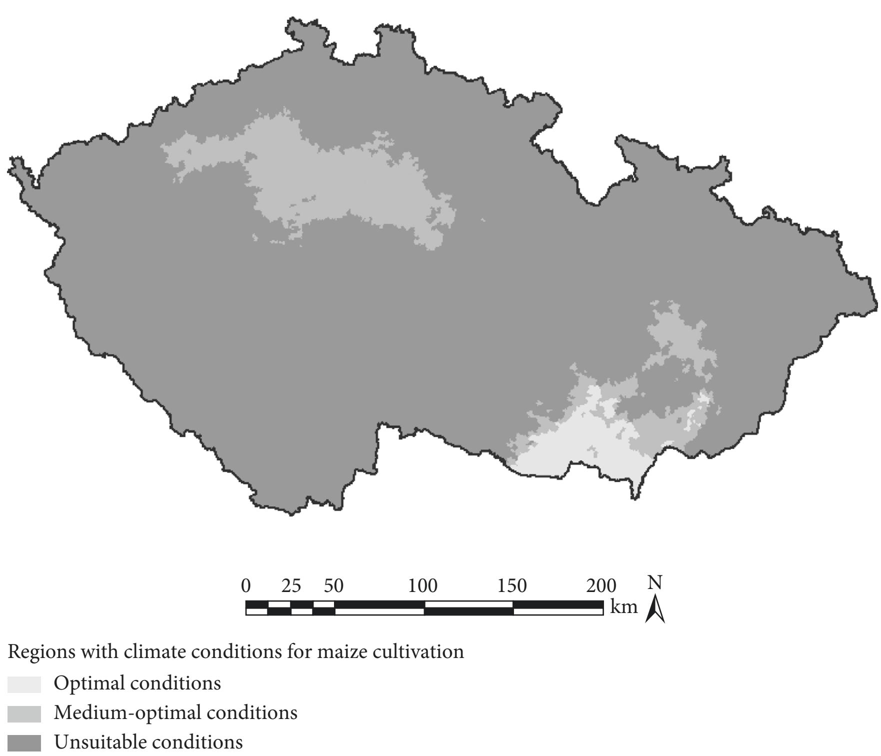

Figure 2: Climate conditions for grain maize growing in the study region of the Czech Republic in 2010.

some crops (higher yield). Linear trends in regional temperature and rainfall totals in the Czech Republic (i.e., modified values from the overall processing of station network data which takes into account the position of individual meteorological stations) confirm increasing mean temperatures, decreasing overall precipitation in all seasons except winter, and a dramatic increase in extreme weather events. This climate development may be linked to adverse

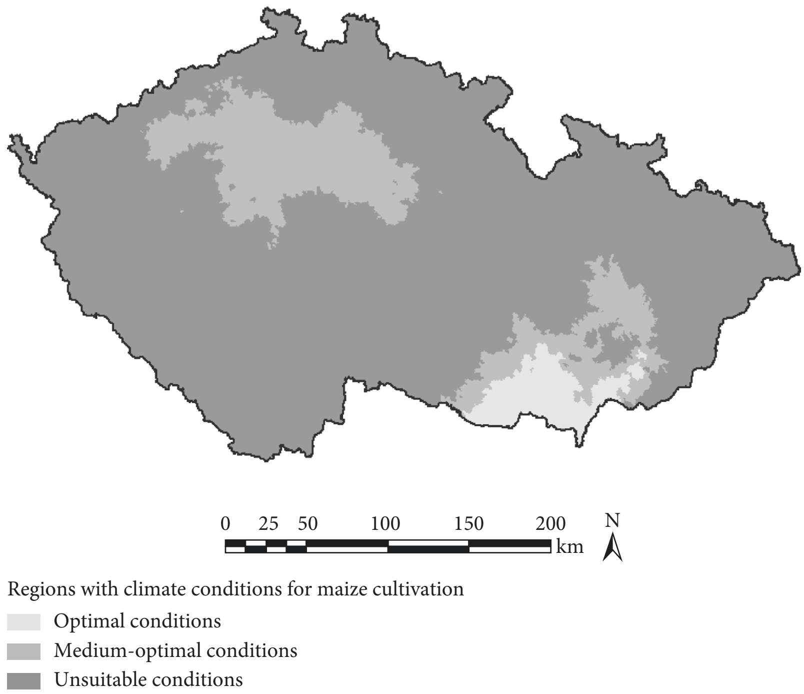

Figure 3: Prediction scenario of climate conditions for grain maize growing in the study region of the Czech Republic in the period 2011–2030, based on the regional biogeographical model.

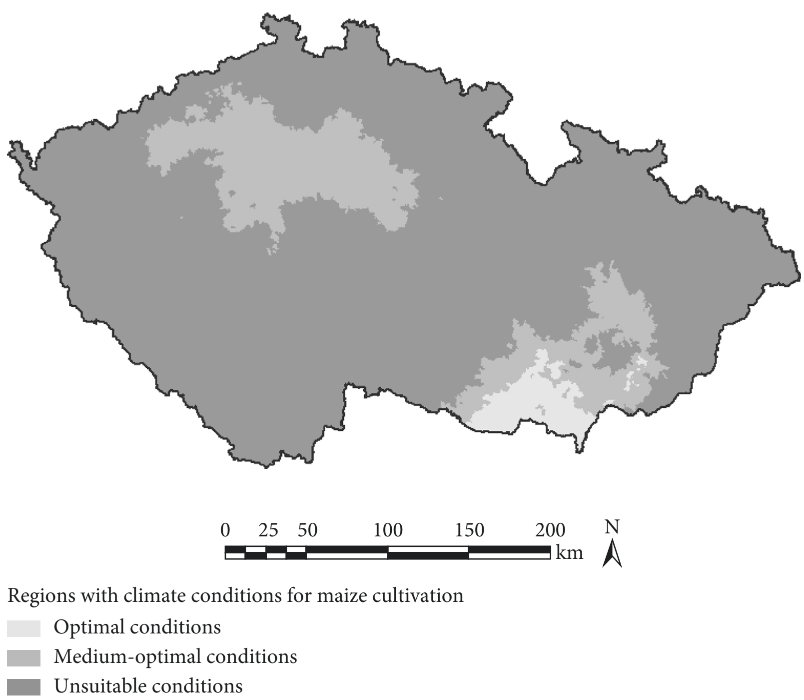

Figure 4: Prediction scenario of climate conditions for grain maize growing in the study region of the Czech Republic in the period 2031–2050, based on the regional biogeographical model.

effects on agricultural production [41]. The results of a broad-based survey conducted among agroclimatic and agronomy experts from 26 European countries also show a surprisingly high proportion of negative expectations concerning the impacts of climate change on crops and crop production throughout Europe.

The impact of climate change on crops and their growth conditions can be estimated using two different methods: (1) crop models and (2) experimental and biogeographical models. The proposed adaptive measures for climate change in the landscape developed on the basis of crop models focus predominantly on adjustments in agroclimatic terms and

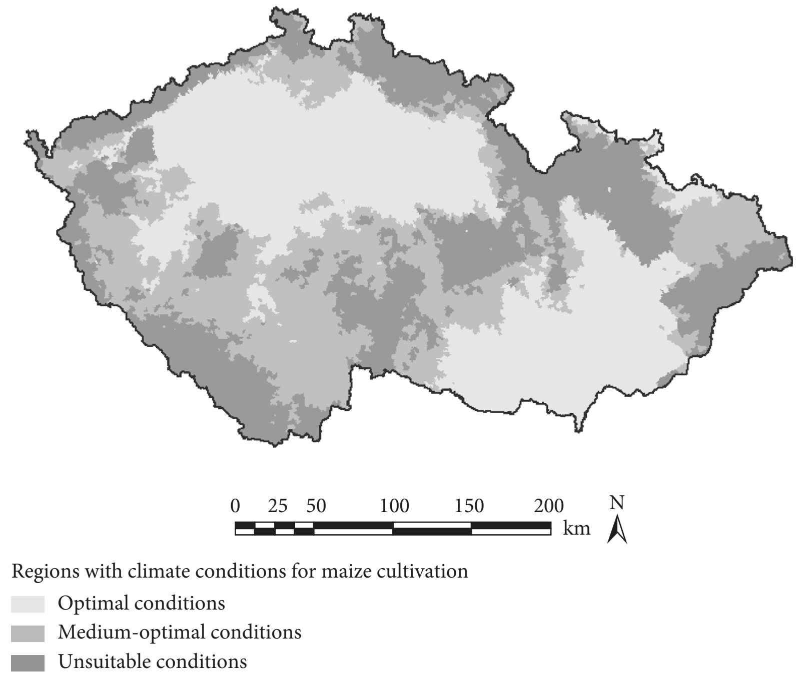

Figure 5: Prediction scenario of climate conditions for grain maize growing in the study region of the Czech Republic in the period 2051–2070, based on the regional biogeographical model.

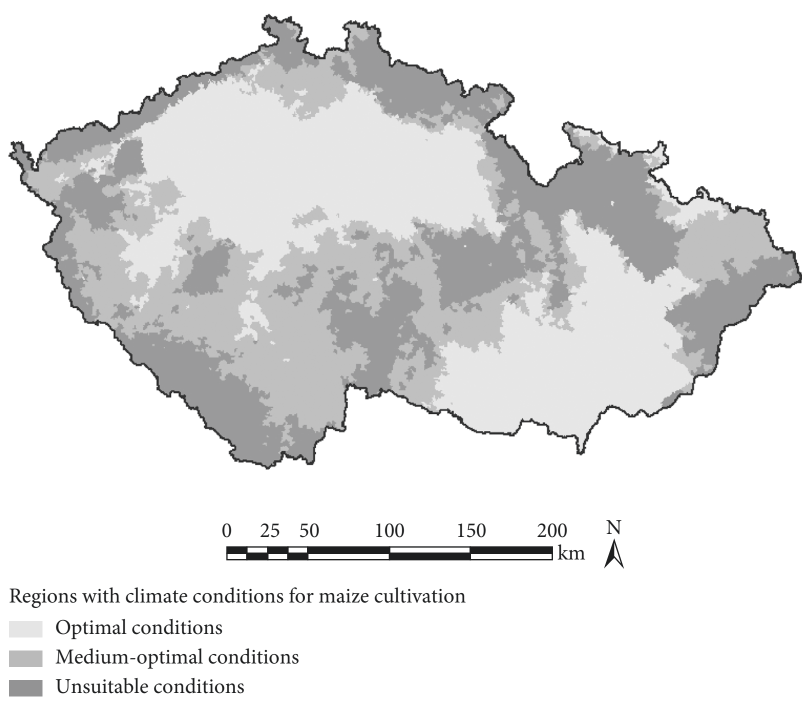

Figure 6: Prediction scenario of climate conditions for grain maize growing in the study region of the Czech Republic in the period 2071–2090, based on the regional biogeographical model.

changes in agrotechnics. In contrast, biogeographical models tend to stress the importance of predicting extend of estimated changes in the growing conditions of crops and forest tree species. Biogeographical models may also help clarify the issue of the potential shift to higher altitudes of the growing conditions for crops and forest tree species [42].

When interpreting mathematical models of the impact of climate change on biota, one needs to consider the fact that the models are not predictions of future developments. They enhance forecasts but must be interpreted sensitively, based on profound knowledge of the biology and ecology of the organisms being modelled.

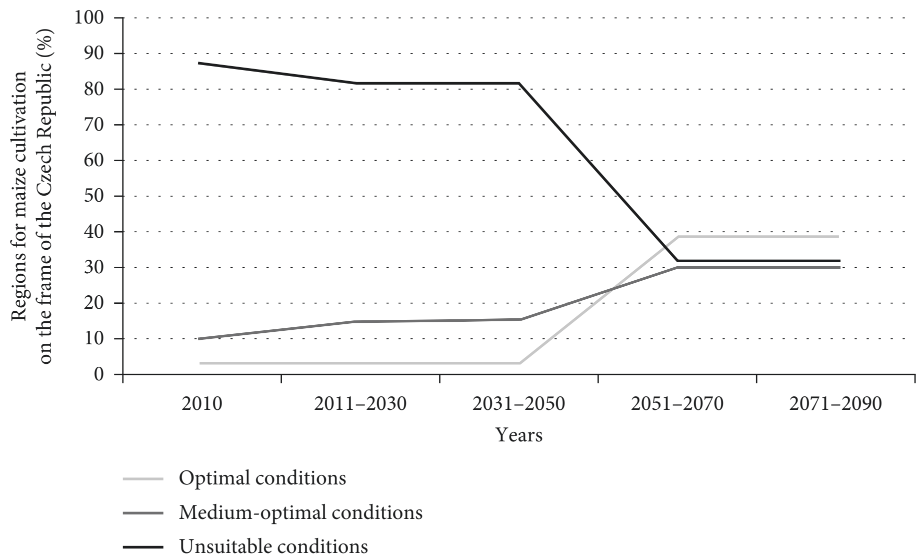

Figure 7: Relative time changes in areas with different climate conditions for grain maize growing in the study region of the Czech Republic based on the regional biogeographical model.

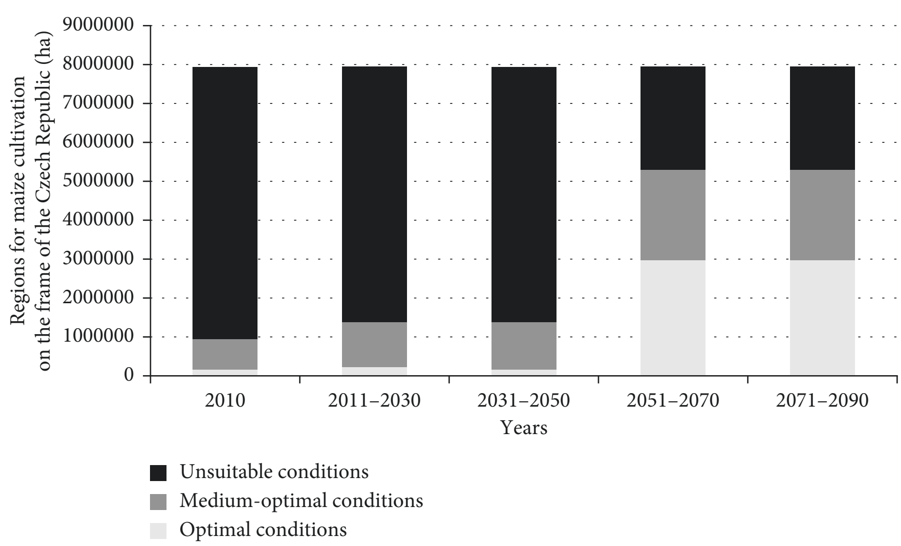

Figure 8: Scenario of changes in areas (hectares) with different climate conditions for grain maize growing in the study region of the Czech Republic based on the regional biogeographical model.

A vast majority of the so-far designed models are correlational, based on the mutual dependence (of a function or an algorithm) among certain bioclimatic variables in the environment (most commonly mean temperature and precipitation) and the present range of a species or the characteristics of a species' ecological niche [43]. If predictions based on climate scenarios show how the climate can change in the future, the corresponding biological species and their communities are assigned to the changed variables. This process is commonly referred to as bioclimatic envelope modelling. For instance, a prediction model of climate change impact on the growing conditions of sugar beet in Slovakia drew on the evaluation of the present production potential of agricultural soils, expressed by classified soil-ecological units, to which ecological growth requirements and production parameters of sugar beet were assigned [44].

The biogeographical model used in this study looks at the long-term effects on vegetation caused by changes in altitude and elevation, defined by both the average and extreme air temperatures and the amount and distribution of atmospheric precipitation (including horizontal precipitation). The present vegetation zoning in the territory of the Czech Republic stabilized in the older subatlantic between approximately 800–500 B.C., and since that time, shifts in vegetation zones have accurately reflected the course of climate change [45]. The present vegetation zoning therefore represents a suitable basic framework for the modelling of climate impacts on the production and growth conditions of vegetation in the Czech Republic. We have applied this modelling in the Czech Republic for grapevine [28] and European beech [31]. But these prior studies were based on former climatological scenarios SRES, which are not developing currently. In this study, we apply a new climatological regional scenario RCP8.5, which today reveals a more precise data for assessment of climate change impacts in agriculture.

Simulations of the redistribution of vegetation in biogeographical models represent an essentially static (equilibrium) perspective of the analysed issue, by modelling a given level of carbon dioxide concentration at a certain point in the future (although they do not take into account the more realistic accumulation of carbon dioxide over time). Statistical/equilibrium biogeographical models provide useful "images" of terrestrial ecosystems in equilibrium with certain climate conditions. They are limited in that they fail to simulate the internal factors of vegetation dynamics (competition, mortality, physiological factors, etc.). To overcome these limitations, new dynamic global vegetation models which integrate vegetation dynamics and ecosystem functions are being developed, although they are not yet applicable at a regional level [46].

4. Conclusions

This case study from the Czech Republic (Central Europe) focuses on the impact of predicted climate change on future opportunities for the growing of grain maize. The paper is intended to contribute to the ongoing discussions about the impact of climate change on agriculture. The results of the model presented concerning the shifts of vegetation zones due to predicted climate change indicate a significant expansion of sites in the study area that are climatically suitable for grain maize. The results of the model designed for the Czech Republic are in line with existing assumptions about the future impact of climate change on viticulture. However, data from the model presented for the territory of the Czech Republic past the horizon of 2050 must be considered only indicative and subject to a great degree of uncertainty depending on the uncertainties related to the input of climatological predictions in the given time period.

Data Availability

The biogeographical data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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