UNIVERSITY OF SZEGED
DOCTORAL SCHOOL OF GEOSCIENCES

APPLYING CORRELATIVE BIOME MODELS TO ADDRESS CERTAIN PHYTOGEOGRAPHICAL ISSUES OVER DIFFERENT SPACE AND TIME WINDOWS

Theses of the PhD dissertation

ZOLTÁN SZELEPCSÉNYI

Supervisor:
PROF. PÁL SÜMEGI DSC
full professor
Department of Geology and Palaeontology
University of Szeged

Co-Supervisor:
NÁNDOR FODOR PHD
senior research fellow
Agricultural Institute
Eötvös Loránd Research Network

External Consultant:
HAJNALKA BREUER PHD
assistant professor
Department of Meteorology
Eötvös Loránd University

UNIVERSITY OF SZEGED
FACULTY OF SCIENCE AND INFORMATICS
DEPARTMENT OF GEOLOGY AND PALAEONTOLOGY

SZEGED
2022

1 Introduction

Bioclimatic classification methods (BCMs) are tools used to transform a set of climate and soil variables into an index-class that can be directly related to biome-level vegetation units. Although the BCMs have been developed for discovering regional differences in climate and potential vegetation, the access to projections of future climate change led necessarily to investigations using these tools for assessing the potential effects of climate change on vegetation. In the mid-1980s, Emanuel et al. (1985) were the first to apply one of the simplest BCMs, called Holdridge life zone (HLZ) system, to the simulated temperature alterations under unchanged precipitation patterns, demonstrating that climate change can induce large shifts in vegetation distribution at high latitudes. A decade later, the hypothesis of warming-driven range shift of woody plants was already supported by long-term observations from both mountain and lowland regions.

By the early 2000s, a large body of evidence had accumulated that climate change is forcing the flora to react, at levels from individuals to communities. This decade has seen a surge in studies linking species distribution data to contemporary climate data in order to extrapolate this link to future climates. In this algorithm, called species distribution modelling, besides topographic and soil variables, various bioclimatic variables derived from monthly climatologies (multi-year averages) for temperature and precipitation are usually used as environmental predictors. In the 2000s, this approach began to be used in large numbers in conservation biology for both teaching and practical purposes, due to the easier access datasets related to species occurrence and climatic conditions.

In the second half of the 2000s, a number of coordinated research projects have undertaken to provide fine-scale climate data for impact studies, by means of dynamical downscaling of climate fields derived from global climate models (GCMs). Access to outputs of regional climate model (RCM) and GCM simulations derived from, among others, these projects laid the groundwork for those distribution modelling studies whose main goal was to assess possible responses of main forest-forming tree species to estimated climate change, in Hungary and Serbia. Regional studies of beech in Hungary and Serbia using various species distribution models have reached similar conclusions: towards the end of the twenty-first century, a significant proportion of beech stands might be outside of the climatically suitable habitat for this species. As a climatic predictor, the vast majority of these studies used also the Forestry Aridity Index, which has been basically developed to delineate different climate categories applied in forestry practice. The classification system in question, however, included the community type “forest-steppe” without a lower xeric limit, which was eventually introduced in the context of assessing the effects of future climate change. This simple modification fixed a major shortcoming of the classification system, considering that the transitional zone between forests and grasslands must also be taken into account when mapping the vegetation of Hungary (see Varga et al. 2000).

Given that most BCMs optimized at a global scale are not able to capture the spatial variability of climate within a relatively small domain (see Szelepcsényi et al. 2009), there are relatively few studies that have evaluated the projected changes in spatial patterns of bioclimatic classes, at a regional or national level in the Carpathian Region. The few examples found show, however, that by applying these classification methods to sufficiently high-resolution climate data, the marginal biome types of the region, such as the tundra both in the Tatra Mountains of the Carpathians (Skalák et al. 2018) and in the Prokletije Mountains of the Dinaric Alps (Mihailović et al. 2015), can also be identified. In addition to an assessment of recent conditions in Serbia, Mihailović et al. (2015) have applied one of the best-known BCM, the Köppen scheme, to bias-corrected climate outputs of RCM simulations forced by two different emission scenarios. It has been found that in the future, the coverage of climate categories reflecting warmer and drier conditions could significantly increase, while the type “tundra” may totally disappear from the country, regardless of the emission scenario used. To evaluate future changes in spatial distribution of Köppen climate classification zones within Central Europe, Skalák et al. (2018) have used bias-adjusted climate simulations generated using two different RCMs under one emission scenario. It has been concluded that although the type Cfb (temperate climate with no dry season and warm summer) will remain the dominant type in the region, it will shift toward higher altitudes and replace types reflecting cooler conditions, which will practically vanish by the end of the century. The results from the above-mentioned two studies therefore show that the temperature signal simulated by the RCMs is large enough to cause transitions between classes within the region in question, so there is no need to rule out the use of BCMs in this study configuration.

In addition, the Köppen scheme is still being used to this day in so-called paleo data–model comparisons, in order to convert outputs from paleoclimate simulations into the distribution patterns of vegetation. Comparative studies of this kind use (raw) climate simulation data and proxy archives such as fossil pollen records in a common framework. The first global data–model comparisons, also carried out as part of a coordinated research project, the Cooperative Holocene Mapping Project (COHMAP), were primarily aimed at evaluating the capabilities of climate models, and providing feedback on areas needing improvement. A data–model comparison using pollen data can be made basically in two ways, either by collating pollen-inferred climate with that simulated by climate models, or by comparing biome distribution estimated using paleoclimate model outputs with plant communities reconstructed from pollen assemblages. The key step in these comparisons is thus to make the climate model outputs and paleo data directly comparable to each other by some transformation procedures.

To translate climate model outputs into biome distribution patterns, comparisons focusing on the Late Quaternary climates carried out within the COHMAP have used the BIOME model which has been developed as a diagnostic tool for mapping the potential natural vegetation (PNV) and land cover features, basically in the context of the future climate change. In terms of the implementation logic, the BIOME model shows a similarity with the model developed by Box (1981) for predictive vegetation modelling, which builds on two important ecological insights: (i) vegetation responds to changes in climatic conditions at the species level rather than at the biome level, and (ii) species can be grouped based on their physiognomic characteristics. These findings are already important because they have provided the theoretical basis for defining the so-called plant functional type (PFT), i.e., the basic unit of calculation used in most global vegetation models. (The PFT is a group of plants assumed to have similar functional characteristics and reactions to environmental alterations.)

However, despite the structural similarity, there are two major differences between the two above-mentioned predictive vegetation models:

- In the Box model, each plant type is characterized by lower and upper limits of each of the selected bioclimatic indices, based on the “current” observed correlations between vegetation and climate. In contrast, when developing the BIOME model, threshold values were assigned to each PFT only in cases where a known or hypothesized physiological response had been identified.
- In the Box model, to describe moisture conditions, the ratio of the annual precipitation to the annual potential evapotranspiration, i.e., the moisture index (*MI*) is used. However, the value of *MI* does not directly reflect the drought stress inhibiting plant growth, thus to account for the plant-available moisture, the BIOME model uses the Priestley–Taylor coefficient, which is computed as the ratio of actual to equilibrium evapotranspiration at an annual time scale. These water balance components are estimated using a process-based simulation model. For this reason, the use of the BIOME model, in contrast to the Box model and the BCMs, besides temperature and precipitation data, requires also a meteorological variable directly related to radiation, and optionally soil parameters. The initial version of the model uses

monthly mean daily values of the relative sunshine duration (*RSD*) for estimating the components of the net radiation.

Thus, the BIOME model represents an important step in the development from totally statistical models to more physiologically grounded models, the so-called dynamic global vegetation models (DGVMs). However, this topic is beyond the scope of the present dissertation.

To transform fossil pollen assemblages into biome types, comparisons focusing on the Late Quaternary climates carried out within the COHMAP have used a vegetation reconstruction approach, the so-called biomization scheme. This reconstruction method, given that it was specifically developed to create a common language for data–model comparisons, builds on the PFT concept used in the BIOME model. The essence of the approach in question is to assign pollen types (taxa) to one or more PFTs (considering the climatic tolerances and requirements of taxa), and then describe a set of biomes based on their PFT compositions. In practice, each taxon in the pollen sample is taken into account based on its relative abundance value (i.e., the percentage of individuals for the given species within the community) in the calculation of biome scores, and the procedure ends with the selection of the biome type with the highest score. The biomization approach was inherently designed to reconstruct the PNV using pollen data, but over time on the basis of this classification technique, an additional algorithm has also been developed to reconstruct anthropogenic land use changes.

In consideration of the literature discussed above, this dissertation investigates the following research questions:

1. Can the impacts of recent climate change in the Carpathian Region be properly assessed using the HLZ system or not? How did the spatial and altitudinal distribution patterns of HLZ types alter in the Carpathian Region in the last century? (These questions are discussed in Chapter 2.)
2. Does a modified version of the HLZ system, which is based on theoretical considerations, have the ability to identify the potential distribution of forest-steppe ecotone (i.e., a boundary zone between closed forests and treeless steppes) in the Carpathian region or not? What is the degree of agreement between climate-derived vegetation maps generated by different versions of the HLZ system and an expert-based PNV map? (These questions are discussed in Chapter 2.)
3. What changes are expected in the distribution of HLZ types in the Carpathian Region in the future? Is there a significant trend in the projected shifts in the mean centres of HLZ types or not? How are altitudinal ranges of HLZ types likely to change in the future? What conclusions can we draw if the HLZ system is combined with an ensemble of bias-corrected regional climate model outputs? What is the uncertainty of the predicted changes

considering the inter-model variability? (Chapter 3 is dedicated to answering these questions.)

4. Is the spatial distribution of biomes able to be properly simulated using only monthly climatologies of temperature and precipitation, and location data? Can values of *RSD* required to run more sophisticated biome models be estimated with sufficient accuracy from commonly available meteorological variables or not? How does the quality of estimates change as a result of proposed modifications of the approach which are justified by its applicability in paleoenvironmental studies? (These issues are investigated in Chapter 4.)

5. Is a high-resolution biome map of the Greater Alpine Region (GAR) generated using only monthly temperature and precipitation data (and digital elevation models) consistent with a vegetation map generated by ecological experts using field surveys and other sources, or not? What conclusions can we draw from a comparison of climate- and pollen-inferred biome types of the GAR, in this highly heterogeneous and human-modified landscape? What is the effect of refining the evaluation methodology (e.g., considering near-misses, i.e., assignments to a biome type with similar PFT composition) on the comparison result? (Chapter 5 is devoted to these issues.)

2 Research methods

The research methodologies used in the studies on which the dissertation is based on are summarised as follows.

Study 1: <u>Climate of the Carpathian Region in the twentieth century based on various versions of the Holdridge life zone system</u> (Szelepcsényi et al. 2014a)

Using monthly temperature and precipitation data provided by the CRU TS 1.2 database, I calculated climatologies for five 20-year time periods of the twentieth century (P1: 1901–1920, P2: 1921–1940, P3: 1941–1960, P4: 1961–1980, P5: 1981–2000), focusing on the Carpathian Region. The HLZ system was applied to these data, in order to track the temporal evolution of the spatial and altitudinal distribution patterns of HLZ types.

Based on theoretical considerations and my own previous experience (Szelepcsényi et al. 2009), I proposed a modification to the HLZ system: both the core and transitional HLZ types were determined as separate classes. The modified model was also used to the above climatologies.

As a validation, I compared the HLZ maps generated by both the original and modified models for the period 1901–1920 to an expert-based vegetation map, and determined the degree of agreement between them using the Kappa statistic (κ).

I assessed the temporal changes in the relative coverage, the mean centre and the mean distributional altitude (MDA) for each HLZ type in order to map the ecological impacts of the recent climate change in the Carpathian Region.

Study 2: <u>Assessment of projected climate change in the Carpathian Region using the Holdridge life zone system</u> (Szelepcsényi et al. 2018)

I applied the HLZ system to bias-corrected temperature and precipitation fields of 11 RCM simulations provided by the ENSEMBLES project in order to evaluate the magnitude and uncertainty of the possible ecological impacts of the projected climate change in the Carpathian Region. Climatologies – and thus the spatial and altitudinal distribution patterns of HLZ types – were determined for three 30-year (T1: 1961–1990, T2: 2021–2050, T3: 2061–2090) and also 28 10-year (D1: 1951–1960, D2: 1956–1965, D3: 1961–1970, etc.) time periods.

In my assessment, the distribution patterns of HLZ types were characterized by the relative extent, the mean centre and the altitudinal range (i.e., the lower and upper altitudinal limits and also the altitudinal midpoint). I used the modified Mann-Kendall trend test to these spreading parameters generated using 10-year climatologies, in order to assess the expected temporal evolution of them, i.e., the direction and uncertainty of their predicted changes.

Using values of κ, I selected simulations, which provide the maximal and minimal distributional changes. The results for these simulations and the ensemble mean were presented in detail.

Study 3: <u>Estimating relative sunshine duration from commonly available meteorological variables for simulating biome distribution in the Carpathian Region</u> (Szelepcsényi et al. 2022)

Applying the regression model of Yin (1999) to monthly temperature and precipitation data from the CarpatClim dataset, I estimated the monthly time series of *RSD* for each year of the period 1961–2010. Then, in each grid cell, values of the root mean square error normalized by the mean value of observed data (*RRMSE*) were computed between the observed and estimated 50-year time series of *RSD*, separately for each month.

To test the applicability of the estimation scheme to paleoclimate datasets, I calculated *RSD* values for the period 1981–2010 in two ways: (a) by averaging the time series estimated using the initial scheme for each year, and (b) by applying the scheme to 30-year averages. The estimated results were compared with the averages of the measured values over the study period.

I assessed the sensitivity of the BIOME model for estimating the spatial distribution of potential vegetation to changes in various configuration settings. The simulations were performed using climate data for the period 1981–2010. Here, I only evaluated the effects of the choice of the method used to generate the quasi-daily values and of the source of the *RSD* data on the results. With respect to the former, I performed the simulations in two ways: (a) monthly means were assumed constant over each day of the month, and (b) different mean-preserving interpolation techniques were applied.

Study 4: <u>Comparing climate- and pollen-inferred vegetation in the Greater Alpine Region</u> (Szelepcsényi et al. in review)

Using simple statistical assumptions, I re-gridded the monthly temperature and precipitation fields derived from the HISTALP database for each year of the period 1800–1980 to a 0.5 arc-min grid of the Global 30 Arc-Second Elevation Dataset (GTOPO30). Applying the regression model of Yin (1999) to these downscaled meteorological fields, I estimated the monthly time series of *RSD* for each year within the study period. Then, I computed the mean field separately for each of the three relevant meteorological variables. Finally, I used these data to drive the BIOME model in order to simulate the distribution pattern of biomes in the GAR.

I applied a refined version of the biomization procedure to 770 of the most recent fossil pollen assemblages derived from the European Pollen Database. In the next step, I calculated the relative biome scores (RBSs) obtained from the biomization for the involved 86 pollen sequences, and the type of dominant vegetation was ultimately determined for each profile.

Using a pointwise approach, I compared the vegetation simulated by the BIOME model with the vegetation reconstructed on the basis of the RBSs characterizing the pollen sequence. To assess the effects of near-misses on the comparison of climate- and pollen-based biome reconstructions, I determined the values of the area expansion and definition expansion required for matching (AEm and DEm) for each pollen profile, and aggregated these values for subgroups formed from the sequences, by using various landscape characteristics.

3 Results and conclusions

The main findings and conclusions of this dissertation are summarized and discussed as follows.

Study 1: <u>Climate of the Carpathian Region in the twentieth century based on various versions of the Holdridge life zone system</u> (Szelepcsényi et al. 2014a)

T1 Using the selected variants of the HLZ system, I demonstrated the effects of recent climate change on the potential vegetation in the Carpathian Region. Consistent with the recently observed shifts of the natural ecosystems, I showed northward and/or upward shifts of the HLZ types.

a. During the last century, the mean centres of those HLZ types which were not related to mountains shifted northward.

b. From the period 1901–1920 to the period 1941–1960, the value of MDA increased for all HLZ types, apart from one exception, whereas from the period 1941–1960 to the period 1961–1980, a decrease in this parameter can be registered for all HLZ types. The reason for this is the fact that the climate in the period 1961–1980 was slightly rainier and cooler than in the former period. All in all, for the five most abundant HLZ types, the value of MDA increased during the last century.

T2 Based on theoretical considerations, I proposed a modification to the HLZ system. By applying the proposed modification, I circumscribed the potential distribution range of the forest-steppe ecotone in the Carpathian Region.

a. Due to the introduction of transitional HLZ types, the spatial pattern of vegetation classes is significantly rearranged: (a) the first in the coverage ranking is the core HLZ type "cool temperate moist forest", with an areal proportion of 50–60% (depending on the study period), whereas (b) the second most abundant vegetation class is the transitional HLZ type "cool temperate subhumid forest-steppe", covering a significant part of the lowland areas.

b. Comparing the distribution pattern of this transitional HLZ type in the period 1981–2000 and the potential areas of the forest-steppe ecotone (see Varga et al. 2000), a big overlap can be found between them.

Study 2: <u>Assessment of projected climate change in the Carpathian Region using the Holdridge life zone system</u> (Szelepcsényi et al. 2018)

T3 **Using the HLZ system, I demonstrated that under a moderate emission scenario, the spatial patterns of potential vegetation types may change significantly by the end of the twenty-first century in the Carpathian Region, regardless of RCM simulations used.**

a. The boreal HLZ types are estimated to disappear from the region, whereas the types “warm temperate thorn steppe” and “subtropical dry forest” can appear, which can be found nowadays, for example, in Spain and Turkey.

b. By the end of the twenty-first century, the relative extent of humid and perhumid HLZ types is projected to decrease by 41 ± 12 and 58 ± 13%, respectively. The relative coverage of warm temperate HLZ types at the end of the century can be estimated to be 10 times as much as at present, while in the case of cool temperate HLZ types, the same value can be reduced by one or two thirds, in the same time frame.

T4 **I showed that the recently detected increasing temperature trend is likely to continue in the future in the Carpathian Region, for which as a response, northward and/or upward shifts of biome types are projected.**

a. The altitudinal ranges of potential vegetation types may expand in the future. The lower and upper altitudinal limits and also the altitudinal midpoint of HLZ types are likely to move to higher altitudes.

b. A northward shift is expected for most HLZ types, and the magnitudes of these shifts can even be several times greater than those observed in the last century.

T5 **I pointed out that there is a considerable uncertainty in the predicted evolution of precipitation patterns in the Carpathian Region, which weakens the reliability of projections of potential vegetation distribution.**

a. The expected change in the coverage of the type “cool temperate steppe” is extremely uncertain because there is no consensus among the projections even in terms of the sign of the change (high inter-model variability).

b. A significant trend in the westward/eastward shift is simulated just for some HLZ types (high temporal variability).

Study 3: Estimating relative sunshine duration from commonly available meteorological variables for simulating biome distribution in the Carpathian Region (Szelepcsényi et al. 2022)

T6 I showed that in the most important period for evapotranspiration processes, the monthly time series of *RSD* can be estimated with reasonable accuracy by applying the procedure proposed by Yin (1999) to single-year time series, under varied topographic conditions.

a. From May to August, the *RRMSE* between the estimated and measured *RSD* values in more than 90% of the study area does not exceed the threshold of 20% below which the model performance can be considered excellent.
b. In the period from April to October, in nearly 99% of the grid cells with elevation smaller than 500 m a.s.l., the value of *RRMSE* is less than 40%, which is the limit of the model performance still considered acceptable.
c. In the summer months, the *RRMSE* value in almost 90% of the lower regions (elevation < 500 m a.s.l.) does not even exceed the threshold of 15%.

T7 I demonstrated that in a data poor modelling environment, *RSD* data can be adequately replaced by using a novel modelling framework based on the procedure proposed by Yin (1999), in which the data processing steps are reversed and the estimation scheme is fine-tuned.

a. For the *RSD* climatologies estimated for the period 1981–2010 with the new modelling framework, from April to September (with one exception), the value of *RRMSE* calculated for the whole study area does not exceed the threshold of 10%, which indicates a very good quality of the estimates.

T8 I showed that the BIOME model is insensitive to the configuration settings assessed here (i.e., the choice of the method used to generate the quasi-daily values and of the source of the *RSD* data).

a. The choice of source for the monthly time series of *RSD* has no effect on the biome distribution under given space and time conditions: comparing the simulation using measured *RSD* values to both simulations driven by estimated *RSD* values, no differences between the biome maps were found.
b. All biome maps generated using interpolated daily values are consistent with each other. Comparing them to the reference map, only a slight mismatch can be found. For only 0.4% of grid cells, there is a disagreement between biome maps derived using different daily weather data. In all cases, this mismatch could be explained by the discrepancy in the spatial distribution of growing degree-days above a 5 °C base (GDD_5).

Study 4: <u>Comparing climate- and pollen-inferred vegetation in the Greater Alpine Region</u> (Szelepcsényi et al. in review)

T9 Using only monthly temperature and precipitation data (and digital elevation models), I generated a very high-resolution distribution map of biomes for the GAR in a modelling framework where *RSD* data required to run more sophisticated biome models were estimated using the model of Yin (1999).

a. In the GAR, the main vegetation formations determined by vegetation scientists can be properly detected by applying the BIOME model with the configuration used here. Comparing distribution patterns of the tundra biome type simulated here and that represented by the subunit alpine vegetation (B.2) on the map of Bohn et al. (2003), there is a large overlap between them. The same conclusion holds for the following pairs: (a) the subunit fir and spruce forests (D.4) in the map of Bohn et al. (2003) and the aggregate represented by the types “taiga” and “cool conifer forest” on the biome map generated here, and (b) the subunit beech and mixed beech forests (F.5) in the expert-based vegetation map and the type “cool mixed forest” simulated here.

b. In valleys characterized by less harsh conditions, where the value of GDD_5 exceeds the threshold of 1200 °C day, the types “temperate deciduous forest” and “cool mixed forest” usually appear, depending on whether the mean temperature of the coldest month is above −2 °C or not. In the GAR, these types occur only marginally at altitudes above 1500 m a.s.l. On the slopes, the types “cool conifer forest” and “taiga” become dominant, replacing the “warmer” forests. Where the value of GDD_5 does not exceed the threshold of 350 °C day, woody PFTs cannot activate. Here, this is mostly the case in areas at altitudes above 2000 m a.s.l., making the type “tundra” dominant. The altitudinal zonation of biomes simulated using climate data is consistent with the position of vegetation belts revealed by phytogeographical analysis (see e.g., Fauquette et al. 2018).

T10 I re-assessed discrepancies between climate- and pollen-inferred biome types in the Alpine region detected by initial validation experiments of the biomization approach, making active use of improvements made in the relevant research fields over the past 25 years.

a. The vegetation type estimated by the biomization scheme is only consistent with the climate-based vegetation type in 35 of the 86 pollen sequences, representing a matching rate of only 41%.

b. The following statement is true in about 76% of the sequences used here: the climate-inferred biome type is the same as one of the three types with the highest RBSs.

T11 By taking into account both the impeding factors and the near-misses, I further nuanced the picture that emerged from comparing climate- and pollen-inferred vegetation types in the GAR. I pointed out that the discrepancies are not necessarily due to the inappropriateness of the biomization procedure but rather due to human impacts on the landscape.

a. Considering near-misses, for example, it was found that in the case of low altitude pollen sites (elevation < 1000 m a.s.l.), even a small expansion of the definition significantly increases the matching percentage: if sites with DEm below 4 are identified as a match, this rate increases from 43 to 74%. This may suggest that although climate is currently not a major determinant of biome distribution in the GAR, at many sites in this region, ancient woodlands have only been partially altered by human activities (e.g., establishment of forest plantations, eradication of certain species).

b. For high altitude sites (elevation ≥ 1000 m a.s.l.), the expansion of the search window increases the matching ratio because if sites with AEm below 4 are accepted as a match, the matching percentage increases from 39 to 77%. However, this observation can even be explained by the simultaneous presence of several effects: (a) the terrain ruggedness, (b) the anthropogenic landscape alteration (e.g., opening of the closed vegetation), and/or (c) the transitional nature of the vegetation (see forest-tundra ecotone).

c. Overall, the above results suggest that the fact that the classification schemes used here do not take into account either ecotones or anthromes (i.e., intensive land-use biomes) significantly impedes comparisons.

4 Összefoglaló

Doktori kutatásom során két különböző korrelatív biom modellt alkalmaztam annak érdekében, hogy változatos növényföldrajzi kérdések értékelése számára biztosítsam a potenciális vegetáció (PV) szimulált elterjedési mintáit. Megmutattam például, hogy a Holdridge-féle életzóna (HLZ) rendszer elméleti megfontolások alapján történő módosítása révén körülhatárolható az erdőssztyepp ökoton (azaz a zárt erdők és a fátlan sztyeppék közötti határzóna) potenciális elterjedése a Kárpát-régióban (CR-ban). A HLZ rendszert egy megfigyelési klímaadatbázisra alkalmaztam. Így a természetes ökoszisztémák múlt században megfigyelt eltolódásaival összhangban kimutattam a CR-ban a PV-típusok északi irányú és/vagy felfelé irányuló eltolódásait. A HLZ rendszert hibakorrigált regionális klímamodell (RCM) outputok egy csoportjára alkalmazva megállapítottam, hogy mérsékelt kibocsátási forgatókönyv esetén az alkalmazott RCM szimulációtól függetlenül jelentősen megváltozhat a XXI. század végére a PV-típusok elterjedése a CR-ban. Eredményeim arra engednek következtetni, hogy a prediktált hőmérsékleti jel hatására a PV-típusoknak a korábbiakénál nagyobb sebességű északi irányú és/vagy felfelé irányuló eltolódása várható. Ellenben úgy találtam, hogy a vizsgált terület csapadékmintázatának a várható alakulása jelentős mértékben bizonytalan, ami gyengíti a PV eloszlására vonatkozó előrejelzések megbízhatóságát. Vizsgálatokat végeztem egy folyamat-alapú vegetáció modellel, a BIOME modellel is, amely a klimatikus vízmérleg szezonális meneteinek szimulációja miatt a relatív napfénytartam (RSD) havi idősorainak ismeretét is igényli. Emiatt kiértékeltem a Yin (1999) által a havi RSD-adatok becslésére javasolt regressziós modellnek a teljesítményét a CR példáján keresztül. Az eredeti verzió mellett teszteltem egy módosítottat is, amelyet a módszer paleoklimatológiai adatkészletekre való alkalmazhatósága indokolt. Úgy találtam, hogy mind az eredeti, mind a módosított séma megfelelően teljesít a párolgás szempontjából legfontosabb időszakban. Bebizonyítottam, hogy az általam leírt modellezési keretrendszerben a folyamat-alapú vegetáció modellek megfelelően összekapcsolhatóak olyan paleoklimatológiai adatkészletekkel is, amelyek kizárólag hőmérséklet- és csapadékadatokat tartalmaznak. A hőmérséklet- és csapadékmezők térbeli leskálázása és az RSD-adatoknak a fent javasolt módszerrel történő pótlása révén előállítottam a BIOME modell segítségével a PV egy olyan rendkívül nagy felbontású elterjedési térképét, amely összhangban van Európa vegetáció-szakértők által elkészített PV-térképével. Ezt a klímaadatok alapján generált biom-térképet végül az egyik legelterjedtebb pollen-alapú vegetációrekonstrukciós módszernek, a biomizációnak a teljesítmény-értékeléséhez használtam fel.

References

Bohn U, Neuhäusl R, with contributions by Gollub G, Hettwer C, Neuhäuslová Z, Raus Th, Schlüter H, Weber H (2003) Map of the Natural Vegetation of Europe. Scale 1:2 500 000. Federal Agency for Nature Conservation, Bonn, Germany

Box EO (1981) Macroclimate and Plant Forms: An Introduction to Predictive Modeling in Phytogeography. Springer Netherlands, The Hague, The Netherlands. DOI: 10.1007/978-94-009-8680-0

Emanuel WR, Shugart HH, Stevenson MP (1985) Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. Clim Chang 7(1):29–43. DOI: 10.1007/BF00139439

Fauquette S, Suc J-P, Médail F, Muller SD, Jiménez-Moreno G, Bertini A, Martinetto E, Popescu S-M, Zheng Z, de Beaulieu J-L (2018) The Alps: A Geological, Climatic and Human Perspective on Vegetation History and Modern Plant Diversity. In: Hoorn C, Perrigo A, Antonelli A (eds) Mountains, Climate, and Biodiversity. First Edition. Wiley-Blackwell, Oxford, UK, pp. 413–428

Mihailović DT, Lalić B, Drešković N, Mimić G, Djurdjević V, Jančić M (2015) Climate change effects on crop yields in Serbia and related shifts of Köppen climate zones under the SRES-A1B and SRES-A2. Int J Climatol 35(11):3320–3334. DOI: 10.1002/joc.4209

Skalák P, Farda A, Zahradníček P, Trnka M, Hlásny T, Štěpánek P (2018) Projected shift of Köppen–Geiger zones in the central Europe: a first insight into the implications for ecosystems and the society. Int J Climatol 38(9):3595–3606. DOI: 10.1002/joc.5520

Szelepcsényi Z, Breuer H, Ács F, Kozma I (2009) Biofizikai klímaklasszifikációk. 2. rész: magyarországi alkalmazások (Bioclimatic classification methods. Part 2: Hungarian applications). Légkör 54(4):18–23 (in Hungarian)

Varga Z, Borhidi A, Fekete G, Debreczy Zs, Bartha D, Bölöni J, Molnár A, Kun A, Molnár Zs, Lendvai G, Szodfridt I, Rédei T, Facsar G, Sümegi P, Kósa G, Király G (2000) Az erdőssztyepp fogalma, típusai és jellemzésük (Concept and types of forest-steppe and their characterization). In: Molnár Zs, Kun A (eds) Alföldi erdőssztyepp-maradványok Magyarországon (Forest-steppe remnants in Hungary). WWF Magyarország, Budapest, Hungary, pp 7–19 (in Hungarian)

Yin X (1999) Bright Sunshine Duration in Relation to Precipitation, Air Temperature and Geographic Location. Theor Appl Climatol 64(1–2):61–68. DOI: 10.1007/s007040050111

Publications related to the topic of the thesis

Szelepcsényi, Z., Breuer, H., Fodor, N., Sümegi, P. (in review): Comparing climate- and pollen-inferred vegetation in the Greater Alpine Region. Quaternary Research

Szelepcsényi, Z., Breuer, H., Fodor, N. (2022): Estimating relative sunshine duration from commonly available meteorological variables for simulating biome distribution in the Carpathian Region. Hungarian Geographical Bulletin, **71/1**, 3–19. DOI: 10.15201/hungeobull.71.1.1

Szelepcsényi, Z., Breuer, H., Kis, A., Pongrácz, R., Sümegi, P. (2018): Assessment of projected climate change in the Carpathian Region using the Holdridge life zone system. Theoretical and Applied Climatology, **131/1–2**, 593–610. DOI: 10.1007/s00704-016-1987-3

Szelepcsényi, Z., Breuer, H., Sümegi, P. (2014a): The climate of Carpathian Region in the 20th century based on the original and modified Holdridge life zone system. Central European Journal of Geosciences, **6/3**, 293–307. DOI: 10.2478/s13533-012-0189-5

Szelepcsényi, Z., Breuer, H., Sümegi, P. (2014b): Hogyan változtak a Kárpát-medence régiójának életzónái a múlt században? In: Sümegi, P. (szerk.): Környezetföldtani és környezettörténeti kutatások a dunai Alföldön. GeoLitera, Szeged, 163–171.

Szelepcsényi, Z., Breuer, H., Sümegi, P. (2014c): A Kárpát-medence régiójára várható éghajlatváltozás elemzése Holdridge életzóna rendszere alapján. In: Mesterházy, B. (szerk.): XIII. Természet-, Műszaki és Gazdaságtudományok Alkalmazása Nemzetközi Konferencia – Előadások. Nyugat-magyarországi Egyetem, Szombathely, 76–83.

Szelepcsényi, Z., Breuer, H., Sümegi, P. (2014d): Analysis of projected climate change in the Carpathian Basin region based on Holdridge life zone system. Geophysical Research Abstracts, **16**, 13642.

Szelepcsényi, Z., Kis, A., Skarbit, N., Breuer, H. (2014e): Életzóna-térképek alkalmazása az éghajlatváltozás vizualizációjára. Légkör, **59/3**, 111–116.

Szelepcsényi, Z., Breuer, H., Sümegi, P. (2013): A Kárpát-medencében, múlt században lezajlott éghajlatváltozás Holdridge életzóna rendszere alapján. In: Mesterházy, B. (szerk.): XII. Természet-, Műszaki és Gazdaságtudományok Alkalmazása Nemzetközi Konferencia – Előadások. Nyugat-magyarországi Egyetem, Szombathely, 24–32.

Ács, F., Breuer, H., Skarbit, N., Szelepcsényi, Z. (2012): A biofizikai éghajlat-osztályozások alkalmazása Magyarországon. In: Pongrácz, R., Mészáros, R., Dobor, L., Kelemen, F. (szerk.): Meteorológiai kutatások és oktatás hazai felsőoktatási intézményekben – A Meteorológus TDK 2012. évi nyári iskola előadásainak összefoglalói. ELTE Meteorológiai Tanszék, Budapest, 30–36.

Szelepcsényi, Z., Breuer, H., Ács, F., Kozma, I. (2009a): Biofizikai klímaklasszifikációk (1. rész: a módszerek bemutatása). Légkör, **54/3**, 21–26.

Szelepcsényi, Z., Breuer, H., Ács, F., Kozma, I. (2009b): Biofizikai klímaklasszifikációk (2. rész: magyarországi alkalmazások). Légkör, **54/4**, 18–23.