

FUTURE CLIMATIC SUITABILITY OF KEY AGRICULTURAL AND FOREST LAND COVER TYPES IN THE MIDDLE DANUBE BASIN UNDER SSP5-8.5

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Trájer, A. J. (2025): Future climatic suitability of key agricultural and forest land cover types in the Middle Danube Basin under SSP5-8.5. – *Studia bot. hung.* 56(1): 169–190.

Abstract: Climate change is projected to cause substantial shifts in the distribution and climatic suitability of both natural and cultivated vegetation types across Central Europe, with the Middle Danube Basin being particularly sensitive. This study applies climate envelope modelling to assess future suitability for non-irrigated arable lands, broadleaf forests, olive groves, and Mediterranean sclerophyllous vegetation under the high-emission SSP5-8.5 scenario, using CMCC-ESM2 climate data for the period 2021–2100. Six bioclimatic variables (bio1, bio10, bio11, bio12, bio18, bio19) were used to define suitability thresholds based on Boolean logic and 5–95% percentile cuts from current conditions. The results reveal a marked decline in the climatic suitability of non-irrigated arable lands, mainly due to intensifying drought and increasing temperature variability. Broadleaf forests are expected to retreat northward, with most lowland and upland areas becoming unsuitable by the end of the century, except for some riparian gallery forests. Olive groves will likely remain climatically unstable due to persistent continental winters. However, sclerophyllous vegetation may establish in localized areas by late century as Mediterranean-like conditions emerge. These findings highlight the need for forward-looking land use and conservation strategies to support ecological resilience in this climate-sensitive region.

Key words: agriculture, bioclimatic modelling, climate change, Middle Danube, SSP5-8.5, vegetation shift

INTRODUCTION

Climate change is one of the most pressing environmental challenges of the 21st century, with sweeping implications for terrestrial ecosystems, land use patterns, and socio-economic sustainability (FOLEY *et al.* 2011, IPCC 2022, LEGG 2021). As the global climate system warms, changes in temperature regimes, precipitation seasonality, and the frequency of extreme events are expected to reshape the ecological viability and distribution of both natural vegetation zones and cultivated landscapes (FOLEY *et al.* 2011; IPBES, Weltbiodiversitätsrat, 2019, KOCSIS *et al.* 2024). One of the most important outcomes of these changes is the decline of forested ecosystems particularly in current subhumid regions (ALLEN

et al. 2010, SEIDL *et al.* 2017). Particularly in Southern and Central Europe, these climatic changes may result in significant biome shifts (GIORGI and LIONELLO 2008, SCHRÖTER *et al.* 2005), threatening agricultural productivity, forest stability, and the ecological coherence of semi-natural landscapes (MARTINEZ DEL CASTILLO *et al.* 2022).

In the agricultural sector, non-irrigated arable lands are especially exposed to climate variability due to their dependence on rainfall and their typically shallow root systems (BROWN *et al.* 2013, LOBELL *et al.* 2011, TRNKA *et al.* 2014). Declining summer rainfall and increasing evapotranspiration can lead to reduced soil moisture availability, crop failure, and long-term degradation of land quality (KIS *et al.* 2023, TRNKA *et al.* 2014.). Conversely, certain perennial systems, such as olive groves and Mediterranean sclerophyllous vegetation, show higher tolerance to heat and drought stress (LO GULLO and SALLEO 1988, RICO *et al.* 2024, VICENTE-SERRANO *et al.* 2025). However, these systems have their own bioclimatic limits and may face northward migration or regional contraction under high-emission scenarios (KAHILUOTO *et al.* 2019). At the same time, climate change could undermine the persistence of olive trees in their historical Mediterranean homeland (FRAGA *et al.* 2020).

Broadleaf deciduous forests, characteristic of temperate and sub-Mediterranean zones, are also at risk of climatic unsuitability. Forest types dominated by *Quercus robur*, *Fagus sylvatica*, or *Carpinus betulus* require specific temperature and humidity ranges, and are highly sensitive to drought-induced mortality, pest outbreaks, and phenological mismatches (BERÉNYI *et al.* 2023, HANEWINKEL *et al.* 2013, ZIMMERMANN *et al.* 2009). As warming continues, these forests are expected to retreat to higher elevations or northern latitudes, while their southern edges may be replaced by more drought-adapted formations, such as sclerophyllous scrub or sparse oak-pine mosaics (SCHRÖTER *et al.* 2005).

Europe's vegetation and land-use systems are already undergoing climatic and biogeographical transitions, driven by a combination of direct climate effects and indirect socio-economic responses (SEIFOLLAHI-AGHMIUNI *et al.* 2015). In Central and Southeastern Europe, this process is often framed through the Köppen-Geiger climate classification, where scenarios such as CMCC-ESM2 under SSP5-8.5 suggest a shift from humid continental (Dfb) climates toward humid subtropical (Cfa) or even semi-arid (Bsk) conditions by the end of the 21st century (BECK *et al.* 2018, LEŠČEŠEN 2025). Such shifts alter the bioclimatic envelopes within which different land cover types can persist, ultimately forcing reorganization of both natural vegetation and agricultural suitability zones (SABLJIC *et al.* 2023, SOARES *et al.* 2025).

Research gap and aims

Despite the growing number of climate impact assessments in Europe, relatively few studies have addressed the combined climatic suitability of both cultivated and natural vegetation types within the Middle Danube Basin, a region that is particularly vulnerable due to its transitional climatic position. Previous research has mainly focused either on agricultural land or on forest ecosystems (e.g., BAYER *et al.* 2021, CHATTERJEE *et al.* 2018, ROBERTSON *et al.* 2023, XIAO *et al.* 2023), but an integrated analysis across different land cover categories under consistent climatic scenarios is still lacking.

MATERIALS AND METHODS

Background

To fill the aforementioned gap, the present study applies climate envelope modelling to assess future climatic suitability of four key land cover types under the high-emission SSP5-8.5 scenario. The specific aim is to identify the direction and magnitude of suitability shifts throughout the 21st century, thereby providing a scientific basis for forward-looking land use planning and conservation strategies in this climate-sensitive region.

In a methodological sense, the potential impacts of climate change on different vegetation types in Central Europe are investigated under future climate conditions using a correlative ecological modelling approach. The applied methodology integrates high-resolution land use data, bioclimatic variables derived from Earth system model outputs, and spatial modelling techniques grounded in ecological niche theory. The key components of the methodology are described in detail below.

This research applies the Climate Envelope Modelling (CEM) approach to project changes in bioclimatic suitability for the land cover types using high-resolution climate projections (CMCC-ESM2 ssp585, 2021–2100, LOVATO *et al.* 2022). CEM was chosen because, although simpler than more advanced correlative approaches (e.g., MaxEnt, Random Forest, or ensemble modelling), it offers a transparent and easily interpretable framework for identifying climatic thresholds of vegetation suitability (RAMAMPIANDRA *et al.* 2023, WARREN and SEIFERT 2011). This clarity is advantageous when projecting land-use related suitability, where stakeholders and policymakers require unambiguous results (KAKY *et al.* 2020, WILTSHIRE and TANNER 2020). CEM is particularly suitable for Mediterranean and Central European vegetation types, where land use is strongly influenced by climatic extremes and management practices, allowing

for straightforward assessment of suitability shifts under future climate scenarios (BEDAIR *et al.* 2025, MACHAR *et al.* 2017).

Environmental predictors include key temperature and precipitation variables (bio1, bio10, bio11, bio12, bio18, bio19), which represent annual means, seasonal extremes, and biologically relevant thresholds for vegetation growth and phenology. The model operates on a Boolean algebra framework, incorporating percentile-based suitability thresholds (5–95% cuts from the observed environmental extremes) to define the climatic space where each vegetation type currently exists and where it may persist or shift in the future.

The outcomes of such projections are essential not only for understanding ecological vulnerability but also for informed land-use planning, biodiversity conservation, and agricultural adaptation strategies. Anticipating areas of gain or loss in climatic suitability allows stakeholders and policymakers to proactively address future challenges in land management, food security, and habitat conservation.

Logical framework of the study

This study focuses on assessing the climatic suitability of four key land cover types under projected future climate conditions: non-irrigated arable lands (CLC code 2.1.1), broadleaf forests (CLC code 3.1.1), (Mediterranean) sclerophyllous vegetation (CLC code 3.2.3), and olive groves (CLC code 2.2.3). These categories represent a spectrum from intensive agroecosystems to natural and semi-natural vegetation types, and all are integral to the ecological, cultural, and economic identity of the Mediterranean and continental regions of Europe (EEA, 2017; FAO, 2020). However, these systems are particularly sensitive to climate-driven stressors, such as prolonged droughts, heatwaves, and shifts in precipitation patterns, which may alter their spatial distribution, productivity, and long-term sustainability (CEGLAR *et al.* 2017).

The logical steps of the study were as follows:

1. Selection of the study region, which is the Middle Danube Region in this study.
2. Selection of land cover categories from CLC 2018.
3. Selection of future projections.
4. Extraction of current climatic envelopes (six bioclimatic variables, 5–95% percentiles).
5. Application of Boolean algebra to define suitability masks.
6. Projection of suitability masks under future climate scenarios (CMCC-ESM2 SSP5-8.5).
7. Comparison of suitability changes across four time periods (2021–2040, 2041–2060, 2061–2080, 2081–2100).

To facilitate understanding, a workflow figure was prepared that illustrates the methodological steps. This figure reflects all four land cover types modelled independently and clarifies the sequence of analyses (Fig. 1).

Climate model and scenario selection

CMIP6 downscaled future climate projections were obtained from the WorldClim v2.1 dataset in 2.5 minutes spatial resolution (FICK and HIJMAN 2017). The primary source of future climatic data used in this analysis is the CMCC-ESM2 global Earth system model, operated under the SSP5-8.5 (Shared Socioeconomic Pathway 5 – Representative Concentration Pathway 8.5) scenario, for the period 2021–2100 (including the periods of 2021–2040, 2041–2060, 2061–2080, and 2081–2100). The SSP5-8.5 pathway represents a high-emissions future characterized by continued fossil fuel use, rapid economic growth, and minimal climate mitigation policies, often referred to as a “business-as-usual” trajectory. CMCC-ESM2 was selected due to its advanced representation of coupled atmosphere–ocean dynamics and land processes, making it suitable for regional assessments of climate-driven environmental change.

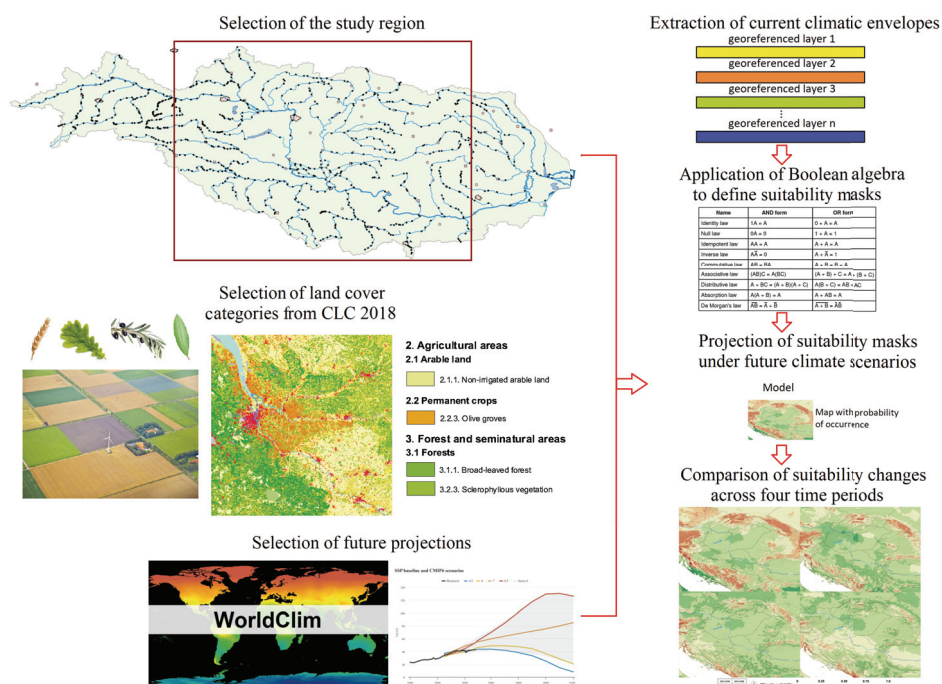


Fig. 1. Workflow of the study.

As was described, in the present study, the SSP5–8.5 (Shared Socioeconomic Pathway 5 – Representative Concentration Pathway 8.5) scenario was selected as the primary basis for modelling future climatic suitability. This high-emission scenario represents a fossil fuel-intensive development pathway, characterized by rapid economic growth, globalized markets, and a continued reliance on carbon-intensive energy sources (O’NEILL *et al.* 2016). While SSP5–8.5 was initially regarded as a “worst-case” or less probable trajectory, recent analyses have shown that current global emission trends and energy policies are still largely aligned with this pathway, especially in the near- to mid-term (HAUSFATHER and PETERS 2020, SCHWALM *et al.* 2020). Despite growing climate policy commitments, greenhouse gas emissions continue to rise globally, and fossil fuels remain dominant in many national energy portfolios.

Using SSP5–8.5 in ecological and land-use modelling allows researchers to assess the upper bounds of potential climatic impacts on ecosystems, agriculture, and biodiversity. This scenario provides a critical benchmark for understanding how extreme climate conditions may affect the viability of existing vegetation zones and agroecosystems if emissions remain unchecked. For climatic envelope modelling, which is sensitive to temperature and precipitation thresholds, SSP5–8.5 ensures a robust exploration of worst-case spatial shifts in habitat and land cover suitability, enabling stakeholders and policymakers to prepare for high-risk outcomes that cannot be excluded under current global trajectories (RIAHI *et al.* 2017).

In addition, selecting SSP5–8.5 is particularly relevant for long-term horizon projections (e.g., 2081–2100), as many near-term mitigation effects are unlikely to fully materialize within this timeframe due to climate inertia and cumulative emissions. Therefore, applying this scenario not only enhances the precautionary dimension of the modelling framework but also contributes to the urgency of proactive adaptation strategies, especially in vulnerable regions such as the Mediterranean Basin and Central Europe, which are projected to become climate change hotspots (GIORGI and LIONELLO 2008).

The model outputs were used to derive a series of bioclimatic variables, which provide biologically meaningful summaries of temperature and precipitation patterns across temporal and spatial gradients. These bioclimatic indices are widely used in ecological modelling due to their direct relevance to species and land-use suitability.

Land use data

To spatially define the target habitat – non-irrigated arable lands – the CORINE Land Cover dataset was employed, which offers standardized land cover classifications across Europe. In this study, the CLC 2018 version was

used, which provides updated and harmonized coverage of the European landscape. CORINE (Coordination of Information on the Environment) provides pan-European land use data at high spatial resolution, updated regularly to reflect land cover dynamics.

The extracted polygons were classified as non-irrigated arable land (CORINE Code: 211), which include areas primarily used for crop cultivation that rely solely on natural precipitation rather than artificial irrigation. These areas represent a key agricultural resource that is particularly sensitive to climatic fluctuations, especially under future conditions of intensified drought and temperature extremes. It should be clarified that these polygons were not manually digitized or cut out from raster layers but obtained by a database query for the relevant CLC code.

As was mentioned before, in addition to non-irrigated arable lands, three further land cover categories were modelled: broadleaf forests, olive groves, and (Mediterranean) sclerophyllous vegetation. These were processed with the same CEM framework, using CLC 2018 polygons to define their current climatic ranges. Each category was treated as a distinct land cover class, with independent climatic envelopes established from the six selected bioclimatic variables. Thus, their future suitability projections were obtained separately, allowing for a comparative assessment across natural and cultivated vegetation types.

Modelling approach

To assess future climate suitability for the selected target land cover types, CEM approach was used. CEM is a correlative, rule-based method that identifies suitable climatic conditions for a given land use or species based on current bioclimatic parameters, and projects these conditions onto future climatic landscapes.

Rather than relying on species presence-absence data, CEM uses defined environmental thresholds derived from observed climatic envelopes – ranges of climatic variables within which the land cover type is currently found. This method is particularly effective for land-use suitability projections because it allows for clear and interpretable delineation of suitable versus unsuitable areas under changing climatic conditions and has been applied successfully in land-use and vegetation studies where transparent rules were necessary to guide planning decisions.

Selected bioclimatic variables

A subset of six bioclimatic variables was selected for the modelling process, chosen for their relevance to crop growth, phenological development, and water availability:

- bio1 – annual mean temperature
- bio10 – mean temperature of warmest quarter

- bio11 – mean temperature of coldest quarter
- bio12 – annual precipitation
- bio18 – precipitation of warmest quarter
- bio19 – precipitation of coldest quarter

These variables capture both annual trends and seasonal extremes in temperature and precipitation, which are critical for assessing the suitability of non-irrigated agricultural systems. The selection of these six variables follows established ecological rationale and previous studies demonstrating their strong influence on vegetation growth, phenology, and water availability (CEGLAR *et al.* 2017, FAO 2020).

As these variables are partly correlated (temperature and precipitation components often show collinearity), it is important to acknowledge that CEM does not explicitly correct for multicollinearity. Since the model is rule-based and threshold-oriented, it is less sensitive to collinearity compared to regression-type models; nevertheless, the risk remains. By integrating both thermal and hydrological dimensions of the climate, this variable set provides a comprehensive basis for determining climatic thresholds.

Mathematical framework: Boolean algebra and thresholding

The suitability classification was implemented using Boolean algebra, a logical framework that allows the construction of composite suitability rules based on individual variable thresholds. Each bioclimatic variable was processed to define a binary suitability mask: suitable (1) or unsuitable (0), based on threshold ranges derived from the current climate distribution of the target land cover types.

To establish these thresholds, the 5th and 95th percentiles (i.e., 5–5% percent cuts from the extrema) of each variable were calculated within the current CORINE-defined areas corresponding to the studied land cover classes. The distribution of each variable was checked to ensure that extreme skewness would not bias the percentile-based thresholds. Although the Boolean method does not require normal distributions, trimming the outer 5% values reduces the influence of non-normal tails and ensures ecological robustness. This percentile-based trimming method reduces the influence of outliers and ensures that the derived climatic envelope reflects the core range of suitable conditions, avoiding marginal extremes that may not be ecologically robust under future scenarios.

For each V variable, an x pixel was classified as suitable if:

$$V_{5\%} \leq x \leq V_{95\%}$$

where:

$V_{5\%}$ is the 5th percentile of the variable over current target land cover types

$V_{95\%}$ is the 95th percentile of the variable over current target land cover types

All six variables were processed this way, and their suitability masks were then combined using Boolean intersection (logical AND operation). Thus, a location was considered climatically suitable under future scenarios only if it met the threshold conditions for all six variables simultaneously:

$$S(x) = V_1(x) \wedge V_{10}(x) \wedge V_{11}(x) \wedge V_{12}(x) \wedge V_{18}(x) \wedge V_{19}(x)$$

where $S(x)=1$ indicates a suitable location, and $S(x)=0$ indicates an unsuitable one.

In addition to the strict Boolean mask, the individual binary maps were also summed:

$$\sum x = \sum_{i=1}^6 V_i(x)$$

This additive suitability score (ranging from 0 to 6) reflects the number of climatic variables for which a given pixel satisfies the suitability criterion. While $S(x)$ represents strict climatic suitability (all variables must meet the thresholds), $\Sigma(x)$ provides a gradient of climatic compatibility, highlighting areas that partially meet the climatic envelope. The cumulative suitability scores (0–6) were subsequently normalized to a continuous 0–1 scale to facilitate comparative spatial analysis and visualization.

The result of this modelling approach is a spatial binary raster indicating climatically suitable versus unsuitable areas for the selected target land cover types under the CMCC-ESM2 SSP5-8.5 scenario for the late 21st century. This map highlights regions that are likely to retain climatic suitability, those that are projected to lose suitability, and potentially novel areas that may emerge as suitable due to shifting climate envelopes.

This framework provides a conservative yet ecologically meaningful estimate of land use vulnerability, grounded in present-day climatic tolerances and robust percentile filtering. It allows for spatially explicit risk assessments and supports decision-making regarding agricultural adaptation, land management, and regional climate resilience planning.

Table 1 shows the climatic constraints applied in the modelling.

RESULTS

The modelling results reveal significant spatial and temporal transformations in the climatic suitability of key plantation and vegetation types in the Middle Danube region under the influence of ongoing climate change. These projected changes, derived from the CMCC-ESM2 model under the high-emis-

Table 1. The climatic constraints applied in the modelling.

Broadleaf forest (CLC 3.1.1)			
Abbreviation	Bioclimatic variable	Lower limit	Upper limit
bio1	annual mean temperature	0.54 °C	14.41 °C
bio10	mean temperature of warmest quarter	10.35 °C	22.47 °C
bio11	mean temperature of coldest quarter	7.59 °C	7.67 °C
bio12	annual precipitation	498 mm	1563 mm
bio18	precipitation of warmest quarter	76 mm	355 mm
bio19	precipitation of coldest quarter	98 mm	490 mm
Non irrigated arable land (CLC 2.1.1)			
Abbreviation	bioclimatic variable	Lower limit	Upper limit
bio1	annual mean temperature	5.99 °C	15.29 °C
bio10	mean temperature of warmest quarter	14.82 °C	23.40 °C
bio11	mean temperature of coldest quarter	−4.28 °C	7.95 °C
bio12	annual precipitation	434 mm	1008 mm
bio18	precipitation of warmest quarter	51 mm	273 mm
bio19	precipitation of coldest quarter	82 mm	289 mm
Olive grove (CLC 2.2.3)			
Abbreviation	bioclimatic variable	Lower limit	Upper limit
bio1	annual mean temperature	13.11 °C	17.47 °C
bio10	mean temperature of warmest quarter	20.72 °C	25.70 °C
bio11	mean temperature of coldest quarter	5.08 °C	10.10 °C
bio12	annual precipitation	403 mm	1451 mm
bio18	precipitation of warmest quarter	29 mm	168 mm
bio19	precipitation of coldest quarter	127 mm	632 mm
Sclerophyllous vegetation (CLC 3.2.3)			
Abbreviation	bioclimatic variable	Lower limit	Upper limit
bio1	annual mean temperature	10.45 °C	17.73 °C
bio10	mean temperature of warmest quarter	18.51 °C	25.45 °C
bio11	mean temperature of coldest quarter	2.17 °C	11.37 °C
bio12	annual precipitation	384 mm	872 mm
bio18	precipitation of warmest quarter	11 mm	134 mm
bio19	precipitation of coldest quarter	78 mm	338 mm

sions SSP5-8.5 scenario, indicate a marked reorganization of ecological conditions, with both regressive and progressive trends observed across vegetation categories. The following subsections detail the results according to modelled plantation and vegetation types.

Altering climatic suitability patterns of non-irrigated arable lands

The CEM indicates a progressive decline in the climatic suitability of non-irrigated arable lands throughout the Middle Danube region across the 21st century. This pattern becomes increasingly evident after 2050, coinciding with the intensification of aridification and the rise in mean temperatures. By the late 21st century, a significant proportion of currently suitable areas will fall outside the derived climatic envelope, particularly in the southern and central portions of the region. These areas will increasingly experience seasonal temperature extremes and precipitation deficits, especially during the warmest and coldest quarters (bio10, bio11, bio18, and bio19), exceeding the biologically sustainable thresholds for rain-fed agriculture. The retreat of suitable zones is most pronounced in lowland basins and floodplain fringes, where soil moisture deficits will become more acute. In contrast, limited areas in the northwestern margin of the region may retain marginal suitability, suggesting a potential geographic contraction rather than complete disappearance (Fig. 2).

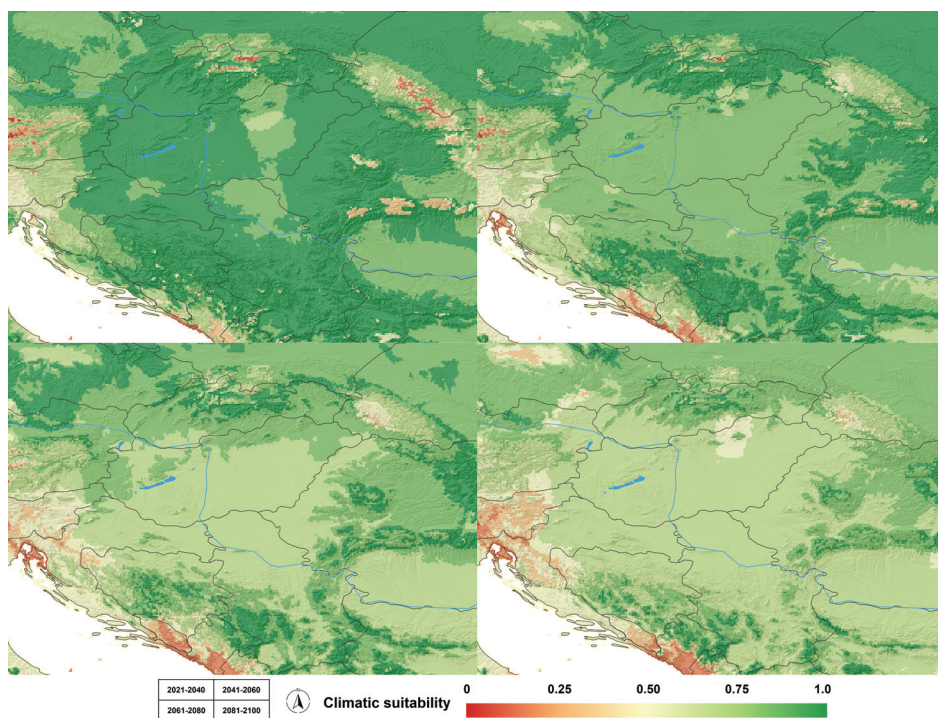


Fig. 2. Spatial distribution of projected climatic suitability for non-irrigated arable lands in the Middle Danube Region across four time slices: 2021–2040 (upper left), 2041–2060 (upper right), 2061–2080 (lower left), and 2081–2100 (lower right). Suitability values range from 0 (unsuitable, red) to 1 (highly suitable, dark green). Blue lines indicate major rivers and lakes.

Retreat of broadleaf forests due to climate change

The model projects a clear and sustained northward retreat of broadleaf forests, which currently dominate the temperate lowlands and lower hills of the Middle Danube basin. Under increasing thermal stress and declining precipitation, especially during the coldest and driest months, broadleaf forests – except for gallery forests that benefit from localized riverine microclimates – are unlikely to persist in much of their present range by the end of the century. The decline in climatic suitability is especially severe in areas where the shift from humid continental to continental steppe climate is most advanced. These areas are projected to exceed the upper thermal limits (bio1, bio10) and fall below critical precipitation thresholds (bio12, bio18) that support deciduous forest species. Consequently, vast tracts of broadleaf woodland in southern Transdanubia and along the Great Hungarian Plain may face conversion to open shrublands, steppe-like grasslands, or mixed transitional systems dominated by drought-tolerant vegetation types (Fig. 3).

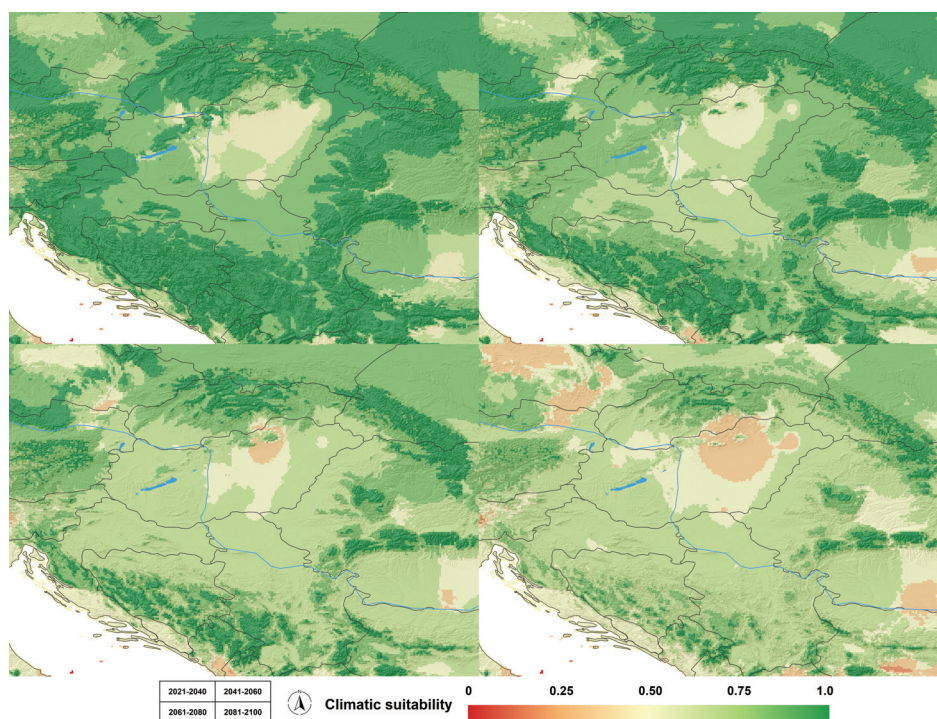


Fig. 3. Spatial distribution of projected climatic suitability for broadleaf forests in the Middle Danube Region across four time slices: 2021–2040 (upper left), 2041–2060 (upper right), 2061–2080 (lower left), and 2081–2100 (lower right). Suitability values range from 0 (unsuitable, red) to 1 (highly suitable, dark green). Blue lines indicate major rivers and lakes.

Changing climatic constraints on the plantation of olive groves

While the warming climate may suggest an expansion of thermophilic crop types, the developed model indicates that olive groves are unlikely to become climatically stable in the Middle Danube region during the 21st century. Despite moderate improvements in temperature-related variables (bio1, bio10, bio11) that fall within the olive tree's optimal range, the seasonal precipitation deficits and intra-annual variability (especially bio18 and bio19) render the region unsuitable for long-term, climate-resilient olive cultivation. The erratic precipitation and potential for winter cold extremes in early-century decades continue to constrain olive viability. Even by the late 21st century, when some southern subregions may approach the climatic limits necessary for olive grove establishment, the suitability remains spatially fragmented and climatically unstable. The persistence of frost events and unreliable summer rainfall preclude robust and sustainable plantation strategies for olives in the region (Fig. 4).

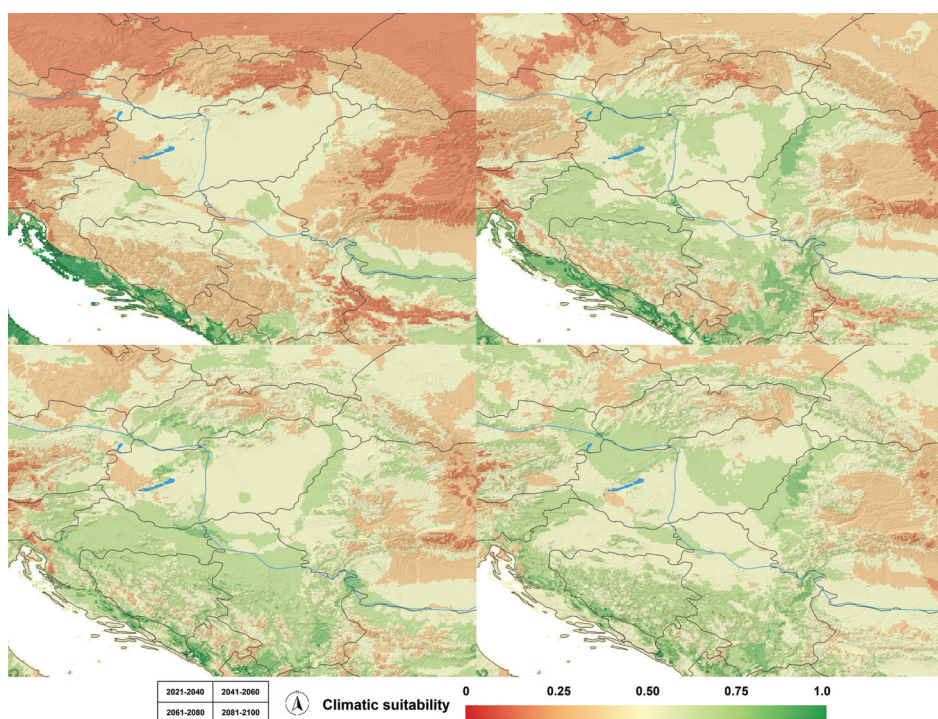


Fig. 4. Spatial distribution of projected climatic suitability for olive groves arable lands in the Middle Danube Region across four time slices: 2021–2040 (upper left), 2041–2060 (upper right), 2061–2080 (lower left), and 2081–2100 (lower right). Suitability values range from 0 (unsuitable, red) to 1 (highly suitable, dark green). Blue lines indicate major rivers and lakes.

Altering climatic suitability patterns of sclerophyllous vegetation

In contrast to the regressive trends observed for temperate ecosystems, the model reveals a gradual increase in climatic suitability for sclerophyllous vegetation, which is characteristic of the Mediterranean biome. By the second half of the 21st century, particularly after 2070, patches of the Middle Danube region begin to fall within the climatic envelope that supports evergreen, drought-tolerant vegetation types such as holm oak and Mediterranean shrubs. These areas, primarily located on south-facing slopes and dry lowland plateaus, exhibit increased alignment with the temperature and precipitation regimes (bio1, bio10, bio18) associated with sclerophyllous growth. However, this transition does not occur uniformly across the region, and the stability of these vegetation types becomes plausible only in select microclimatic niches where summer precipitation deficits are not too severe. It is projected that by the late 21st century, small but climatically stable zones could support Mediterranean-

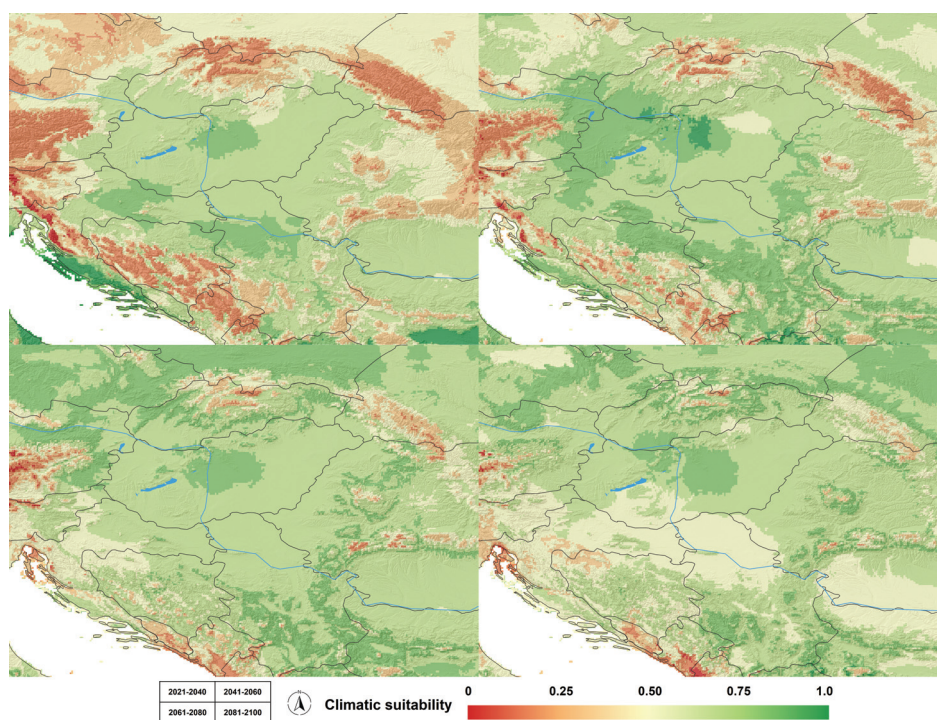


Fig. 5. Spatial distribution of projected climatic suitability for sclerophyllous vegetation in the Middle Danube Region across four time slices: 2021–2040 (upper left), 2041–2060 (upper right), 2061–2080 (lower left), and 2081–2100 (lower right). Suitability values range from 0 (unsuitable, red) to 1 (highly suitable, dark green). Blue lines indicate major rivers and lakes.

type vegetation, heralding a biome transition under prolonged warming scenarios. Nonetheless, these occurrences remain spatially constrained and highly sensitive to interannual climate variability (Fig. 5).

DISCUSSION

The results of this model experiment study align with and expand upon a growing body of literature highlighting the profound ecological consequences of climate change in Central Europe, particularly within the Middle Danube region. The gained projections, derived from the CMCC-ESM2 Earth system model under the high-emission SSP5-8.5 scenario, illustrate substantial shifts in climatic suitability for both natural and cultivated vegetation types. These findings are consistent with broader predictions of biome restructuring, land use vulnerability, and ecosystem stress across Europe in the coming decades (e.g., BECK *et al.* 2018, THUILLER *et al.* 2011).

The modelled decline in the climatic suitability of non-irrigated arable lands is in line with prior studies that have identified Central Europe as a future hotspot of agricultural stress due to increasing summer drought and higher temperatures (TRNKA *et al.* 2014, ZAJAC *et al.* 2022). The projections suggest a retreat of suitable zones from the southern and central lowlands of the Middle Danube basin, mirroring patterns seen in climate impact models for major cereal crops, including wheat and maize, which are particularly sensitive to water deficits during reproductive phases (ZHAO *et al.* 2017).

The anticipated increase in extreme weather variability, particularly during critical growing seasons, threatens the viability of rain-fed agriculture (SALEEM *et al.* 2024). This is further exacerbated by the limited adaptive capacity of many traditional farming systems in this region, where irrigation infrastructure is scarce and economically unfeasible on large scales. As such, these results underscore the urgent need for adaptive agricultural strategies, including drought-resilient crop varieties, agroforestry integration, and the reconsideration of crop calendars (WANG *et al.* 2022).

The findings on the northward retreat of broadleaf forests are strongly supported by existing ecological and dendroclimatological research. Numerous studies have indicated that temperate deciduous forests across Central and Southeastern Europe are likely to suffer from increasing summer aridity and warming-induced physiological stress (e.g., HANEWINKEL *et al.* 2013, MÁTYÁS *et al.* 2010). Species such as *Q. robur*, *F. sylvatica*, and *C. betulus* have narrow tolerance ranges for drought and thermal extremes and are predicted to lose competitive dominance in favour of more xeric-adapted assemblages.

Notably, gallery forests – linear, riparian woodland ecosystems – may exhibit greater resilience due to their hydrological connection to rivers and groundwater (DINCA *et al.* 2025). These localized refugia may temporarily buffer against regional climatic stress, but even these systems are vulnerable in the long term to reduced river discharge and groundwater decline (JUNK *et al.* 2013). This study confirms that while gallery forests may persist, upland and non-riparian deciduous woodlands could face widespread contraction or transformation into mixed woodland–steppe mosaics.

The projection that olive groves will remain climatically unstable in the Middle Danube region throughout the 21st century challenges common assumptions about the northward shift of Mediterranean crops. While warming trends may superficially suggest potential for olive expansion into Central Europe, the results highlight the importance of multifactorial climatic constraints, particularly winter cold events and summer drought extremes, which olive trees are highly sensitive to (e.g., GRATSEA *et al.* 2022, PONTI *et al.* 2014).

Despite rising annual mean temperatures (bio1), the persistence of frost events in the coldest quarter (bio11) and inconsistent summer rainfall (bio18) are major limiting factors. Even small climatic anomalies during critical phenological periods can result in crop failure or long-term damage to perennial systems like olive plantations. This confirms the findings of regional agricultural models which suggest that the climatic envelope for olives in Europe remains largely restricted to the Mediterranean basin under current and near-future scenarios (FRAGA *et al.* 2019).

Conversely, the identification of limited, climatically stable patches for Mediterranean-type sclerophyllous vegetation by the end of the century offers a compelling glimpse into the potential biome-level reorganization within the Middle Danube region. This aligns with projections from biogeographic models indicating that Mediterranean vegetation types, including evergreen oaks and shrubland species (*Quercus ilex*, *Pistacia lentiscus*), could expand into Central Europe as summer aridity and high temperatures become more common (THUILLER *et al.* 2005). In addition, under projected climate scenarios, sclerophyllous vegetation is expected to experience increasing thermal stress and reduced precipitation, potentially affecting their spatial distribution (GIORGI and LIONELLO 2008).

The emergence of such vegetation types in the region, however, is conditional upon not only climate suitability but also dispersal limitations, soil compatibility, land use, and disturbance regimes (GIADROSSICH and SCOTTI 2025). Fire dynamics will play a critical role in shaping the viability of sclerophyllous systems in novel environments (ROCHE *et al.* 2024). While the model identifies climatically favourable zones, actual vegetation transition may lag due to ecological inertia and anthropogenic landscape fragmentation.

The overall pattern revealed by the modelling framework is one of ecological reorganization marked by the decline of mesic, temperate ecosystems and the incipient rise of thermophilic and drought-tolerant assemblages. This is broadly consistent with Europe-wide climate-biodiversity projections, which point to substantial turnover in vegetation communities, with implications for biodiversity, ecosystem services, and land-based carbon storage (LEGG 2021).

These transitions are not uniform but heterogeneous in space and nonlinear in time, requiring fine-scale, region-specific assessment to guide adaptation strategies. The Middle Danube region, positioned at the crossroads of temperate and Pannonian bioclimatic zones, is especially vulnerable to these changes due to its climatic marginality and historical land use intensity.

The results of this study reinforce the urgency of integrating climate adaptation into agricultural, forestry, and conservation planning, emphasizing the need for flexible land-use frameworks, the promotion of climate-resilient species and varieties, and the preservation of ecological corridors to facilitate species movement.

CONCLUSIONS

The modelling results reveal that climate change will profoundly reshape land-use and vegetation patterns in the Middle Danube region. Traditional systems such as non-irrigated arable land and broadleaf forests are projected to decline in climatic suitability, particularly after mid-century, as rising temperatures and increasing aridity push these ecosystems beyond sustainable thresholds. These highlight growing risks for agriculture and forestry that depend on temperate climatic conditions. At the same time, the projections suggest limited but notable opportunities for Mediterranean-type vegetation. Olive groves remain climatically unstable due to frost risk and erratic rainfall, but sclerophyllous vegetation shows a gradual increase in suitability, especially in microclimatic niches such as south-facing slopes and dry plateaus. These shifts point toward a potential biome transition in localized areas by the end of the century. For policymakers and land managers, the results underline the urgency of developing adaptive strategies. Declining suitability for temperate crops and forests will require forward-looking planning, while the possible emergence of drought-tolerant Mediterranean systems highlights the need to balance agricultural productivity, ecosystem resilience, and conservation priorities in a rapidly changing climate.

* * *

Acknowledgement – This study was supported by A DANube WETlands REStoration (DaWet-Rest) Lighthouse project.

Összefoglaló: A klímaváltozás a 21. században alapjaiban alakíthatja át Közép-Európa növény-takaróját. A különösen érzékeny Közép-Duna-medencében már a század közepére megváltozhatnak az ökológiai feltételek, befolyásolva a mezőgazdaságot, az erdőboritottságot és a tájhasználatot. A tanulmány éghajlati burkológörbe modellezéssel vizsgálta a nem öntözött szántók, lombos erdők, olaj-faültetvények és mediterrán cserjések jövőbeli klimatikus megfelelőségét a CMCC-ESM2 modell SSP5-8.5 forgatókönyve alapján (2021–2100). Az elemzés hat bioklimatikus változót és a jelenlegi európai elterjedés 5–95% percentilis határait használta. A nem öntözött szántók és lombos erdők klimatikus megfelelősége várhatóan fokozatosan csökken az aszályosodás és hőmérsékleti szélsőségek miatt, különösen az alföldi területeken. A lombos erdők a század végére főként a hegyvidékekre szorulhatnak vissza, míg sík vidéken szárazságtűrő vegetáció váltja fel őket. Az olajfaültetvények telepíthetőségének feltételei javulhatnak, de a hideg telek és nyári szárazság miatt stabil termesztés nem várható. A mediterrán cserjések számára viszont 2070 után kedvezőbbé válhat az éghajlat, és megjelenhetnek déli kitétséggű lejtőkön. Az eredmények jelentős ökológiai átrendeződést jeleznek, ami hangsúlyozza a klímaadaptív tájhasználat és természetvédelem fontosságát.

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(submitted: 30.07.2025; accepted: 04.10.2025)