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Key Points:

- More than half of central European land categorized as highly productive in a long-term context has lost this status due to drought
- Central European agroclimate is projected to move beyond the conditions of the past 2,000 years in upcoming decades
- Three previous cases of poor agroclimate conditions have been associated with major societal downturns

Supporting Information:

Supporting Information may be found in the online version of this article.

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Past and Future Climate-Driven Changes of Agricultural Land in Central Europe

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Abstract Europe is expected to experience major climatic shifts during the 21st century but the impact on agricultural productivity from such changes is uncertain. Here, we combine proxy, instrumental, and model data to assess interannual to multi-centennial changes in central European agroclimate over the past 2,000 years and projections into the near future. Whereas early 21st century conditions are rare but not fully unprecedented, more than half of the area that was considered highly productive throughout the Common Era in central Europe currently falls outside of that definition. This trend will likely continue as even the most conservative climate projections push central Europe outside the range of past natural variability of changes to agroclimatic zones. Reconstructed extremes prior to the instrumental record align well with contemporary documentary records of societal upheaval. Forecasted changes to the main agroclimatic drivers require substantial adaptation in land use and agricultural management strategies of considerable costs.

Plain Language Summary Climate variability has a direct impact on agricultural productivity in Europe. However, to fully understand how this relationship may impact society in the future, we need long-term records that encompass many different scenarios. We combine stable isotopes from tree rings, instrumental weather data, and climate projections for the future to study the changes occurring within the system over a period of 2,100 years. Periods in the past that experienced harsher agroclimate conditions coincide with societal change or events. The climate projections indicate that more than half of the high-productivity land within the study region will experience worse conditions in the near future.

1. Introduction

The global food demand is expected to increase by 31%–56% from 2010 to 2050 (van Dik et al., 2021), increasing pressures on the agricultural sector to feed a growing global population (FAO, 2023; Godfray et al., 2010). Simultaneously, there is a rising demand for sustainability in farming (Seufert et al., 2012), as agriculture is considered the biggest driver of many of the global environmental challenges (Campbell et al., 2017). These combined challenges require a range of interventions, which include technological advances (Herrero et al., 2021), expansion of cropland (Potapov et al., 2022), crop breeding (Guarin et al., 2022), and maximizing yields under existing natural conditions (Drewer et al., 2014; Richter et al., 2023). Weather and climate play an important role in determining agricultural productivity (Lesk et al., 2022; Parry & Carter, 1985) and the spatial extent of crops (Elsegaard et al., 2012) and thus our understanding of the natural variability of climate is crucial for addressing the needs for enhancing agricultural outputs.

Future changes to temperature and precipitation are expected to have considerable impacts on agricultural productivity (Olesen et al., 2011; Ray et al., 2015; Rezaei et al., 2023), with severe consequences for global market prices and food security (Wheeler & von Braun, 2013; Brás et al., 2021). However, the relationship between climate and agricultural yields is complex as many climatic factors can influence agricultural productivity in different ways depending on timing and duration (e.g., growing-season length, maximum temperatures, droughts, and floods). Short-term weather events can have devastating impacts on agricultural systems (Christian et al., 2021; He et al., 2022; Trnka et al., 2014), and ongoing changes to climate are documented to increase the frequency of extreme warm temperatures and enhance hydroclimatic variability (Robinson et al., 2021; Russo et al., 2014).

Climate change is projected to impact traditional cropping systems and, in some cases, current agroclimatic zones may shift their geographical boundaries (Anderson et al., 2023; Ceglar et al., 2019). Although many adaptation options are being considered (Zhao et al., 2022), the difficulty to predict extreme events and variability may greatly hamper effective strategies (Trnka et al., 2015). Although climate model projections show high agreement on the increase in temperature across Europe, the uncertainty in estimated changes in precipitation totals remains large across models (Coppola et al., 2020; Ritzhaupt & Maraun, 2023). Therefore, future climate change effects on shifts of agroclimatic zones and central European agriculture are difficult to predict. Furthermore, the instrumental record, on which many climate projections are based, may not contain the full variability of the natural system (Büntgen et al., 2021). Assessing potential changes in agroclimatic patterns without considering pre-observational variability is therefore at risk of underestimating the true range of relevant conditions that could occur under natural climatic variability.

2. Materials and Methods

2.1. Study Area and Agroclimatic Zone Calculation

Observed daily temperature, precipitation, wind-speed, relative humidity, and sunshine duration hours data starting in 1961 were homogenized. The climate of the data selected region has been represented by in total 194 climatological stations (108 in Czech Republic, 50 in Slovakia, and 36 in Austria). The sum of daily temperatures during days with main daily temperatures above 10°C was calculated (TS) for each of the stations. Similarly, the sum of daily potential evapotranspiration for the growing season peak (June-August) has been estimated and subtracted from the precipitation accumulated over the same period to estimate JJA water balance (WB). While TS is a good proxy of the growing season duration, summer WB provides an integrated overview of precipitation and potential evapotranspiration during the summer months. The calculation of potential evapotranspiration was performed on a daily scale based on the Penman-Monteith method (Allen et al., 2005) using the SoilClim model (Hlavinka et al., 2011). Based on the daily inputs, the values of WB and TS were determined for each year during the 1961–2018 evaluation period. The agroclimatic zoning scheme is based on the work of Němec (2001), here modified from a simplified approach (Trnka, Balek, Brázdil, et al., 2021). A zone represents the general climatic conditions for which a group of crops produces the highest yields. Additional zones were added as the instrumental period does not cover all conditions recorded by the reconstructions (Torbenson et al., 2023), and the zone naming scheme proposed here (Table 1) is not based on the representative crop, as it may add confusion when applied to the full period of analysis. The WD and VWD zonings indicate agroclimatic conditions that require substantial irrigation to sustain field crops.

2.2. Reconstructed Temperature Sum and Water Balance

Annually resolved measurements of tree-ring stable isotopes from 147 increment cores and disc samples from living, historical/archeological, and subfossil oaks (*Quercus* sp.) represent the predictors of the TS and WB reconstructions (Torbenson et al., 2023). Six different trees (minimum) make up the average chronology value of each calendar year (Büntgen et al., 2021). The $\delta^{13}C$ chronology represents the proxy for WB and $\delta^{18}O$ represents the proxy of TS. Each predictor was entered into a linear regression. Model calibrations were performed for the longest overlap of instrumental data (1961–2018), with a region-wide interpolation of WB/TS serving as the predictand of the models. The WB reconstruction explains 31.3% of the variance of the instrumental target during the calibration period, and the TS reconstruction explains 48.7%. Several validation analyses were performed, including on monthly instrumental temperature and precipitation data prior to 1961. The reconstructions display statistically significant correlations with independent field reconstructions of precipitation and mean summer temperatures for 1500–1900, as well as documentary records of extreme dry and wet events for 1090–1499.

The reconstructions were extrapolated across cadaster units, based on the relationship of the regional average and the individual areas for the 1961–2020 period of instrumental data. The agreement of agroclimatic classification for reconstructed versus instrumental data is >98% of cadasters. The full reconstructions were then used to estimate agroclimatic zone for each year of the period 75 BCE-2018 CE. Mean zone for 25-year blocks were calculated for all cadaster units. Cadasters with a mean zone of HPd or HPh for the full reconstruction period were

Table 1
Climate Variable Thresholds and Characteristics of the Agroclimatic Zones Calculated on the 1961–2020 Baseline Period (Trnka, Balek, Brázdil, et al., 2021)

	Agroclimatic zone	Approximate summer WB range (mm)	Approximate TS range (°C)	Characterization of agricultural activities under the present climate	Examples of present day crops
InPc	Insufficiently productive - cool and dry	< −30	<2,100	Not suitable for primary field crops with lack of water affecting the productivity in combination with low temperatures.	Potatoes, oat, rye, flax, hay
InPd	Insufficiently productive - cool	> −30	<1,850	Only marginally suitable for arable crops with pastures and grasslands being affected by low temperatures and short growing season.	Potatoes, oat, rye, flax, hay
InPw	Insuficiently productive - warm	> −30	1,850–2,150	Not suitable for primary field crops but can accommodate spring and winter cereals; production is quite low due to low temperatures.	Potatoes, oat, spring barley, rye, flax, hay
SuPc	Sufficiently productive - cool	+120 to −30	2,100–2,400	Suitable for cold tolerant cereals; lower temperatures occur regularly; frequently used also for pastures and fodder production.	Wheat, potatoes, other cereals, clover
SuPw	Sufficiently productive - warm	+120 to −30	2,400–2,700	Suitable for most cold tolerant cereals; in some years highly productive but in other years production is limited by soil workability and field access.	Wheat, oil seed rape, other cereals, clover
HPh	Highly productive - humid	−30 to −100	2,550–2,950	Suitable for cereals and most other field crops; rarely limited by water availability and cereals as wheat and barley in general reach the highest yields, Irrigation in general not needed.	Sugar beet, High quality barley, High quality wheat, oil seed rape, alfa-alfa, hops
HPd	Highly productive - dry	−100 to −180	2,700–3,100	Suitable for cereals and other field crops with some years limited by water availability, irrigation can increase productivity of most crops.	Grape vine, fruit trees, grain maize, sunflower, high quality wheat, high quality barley, alfa-alfa, hops
WD	Warm and dry	−140 to −200	2,950–3,200	Suitable for horticulture crops; lack of water limits field crop production. Production can still be high in cases of irrigation and/or high levels of groundwater. Temperature extremes and arid season occur occasionally.	Warm/dry climate vine varieties, apricots, peaches, sunflower, sorghum, millet, maize, wheat
VWD	Very warm and dry	< −200	>3,200	High temperatures and lack of water limits field production with part of the land likely being used as extensive pastures. Production can still be high in cases of irrigation and/or high levels of groundwater. Temperature extremes and arid season occur regularly.	Warm/dry climate vine varieties, sunflower, sorghum, millet, maize, wheat

Note. WB = June-to-August water balance, TS = temperature sum (>10°C).

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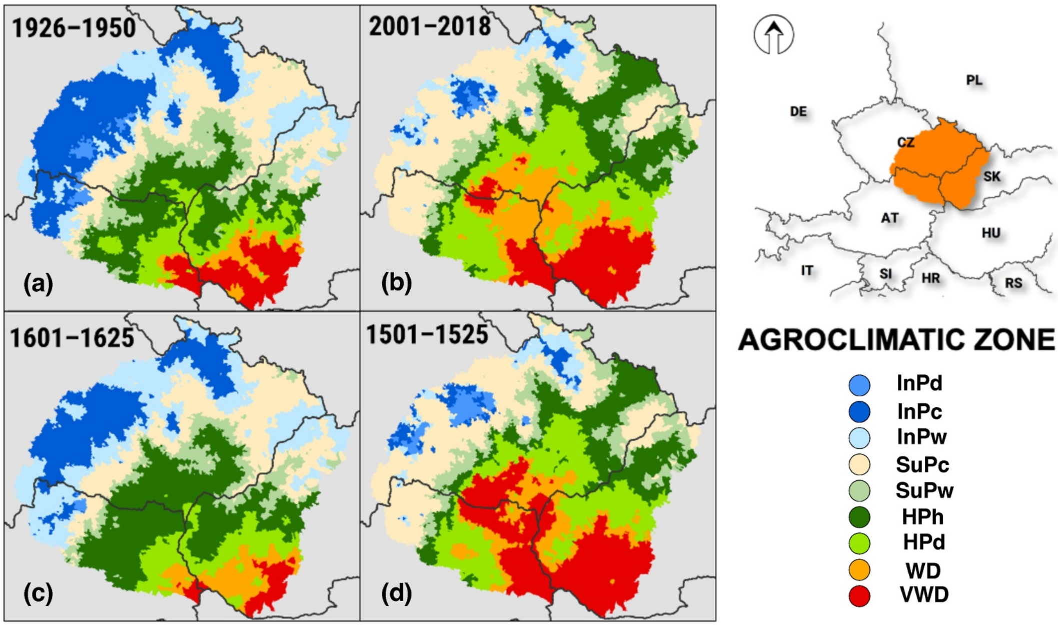

Figure 1. Spatial variability of nine modern agroclimatic zones in central Europe during the 20th and 21st centuries (a) and (b), and pre-instrumental analogs (c) and (d).

considered as long-term highly productive land, and the (areal) percentage of the study region falling within this definition used to estimate fluctuations of agricultural suitability.

2.3. Projected Scenarios

Six ensemble members (Danabasoglu et al., 2020; Döscher et al., 2022; Dunne et al., 2020; Lee et al., 2020; Mauritsen et al., 2019; Yukimoto et al., 2019) of CMIP6 were used for future climate conditions (Table S1 in Supporting Information S1) of central Europe. The same agroclimatic zoning scheme as for instrumental and reconstructed data was applied for 30-year windows of model projections. While the ensemble of six global circulation models (GCMs) represents the inter-model uncertainty of future climate estimates, the uncertainty arising from future greenhouse gases concentration is defined by four pathways: SSP1-2.6; SSP2-4.5; SSP3-7.0; and SSP5-8.5. The parameters of future conditions have been estimated through the advanced delta method (Kraaijenbrink, 2013; Navarro-Racines et al., 2020) for each of the climate station and interpolated data.

3. Results and Discussion

3.1. Reconstructing Agroclimatic Conditions

Here we apply 2,000-year long reconstructions of growing season temperature sums and June-to-August water balance—variables that have been identified as the main climatic determinants of agricultural productivity for central Europe (Figure 1)—to a modified scheme of agroclimatic zones (Trnka, Balek, Brázdil, et al., 2021, Table 1). Although other climatic variables are important to European agriculture (Ceglar et al., 2019), many of these act on temporal resolutions finer (Brás et al., 2021) than what is typically captured by paleoclimate proxy records. The reconstructions are based on annually resolved tree-ring stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotopes and have previously been quantitatively and qualitatively verified against instrumental data and documentary evidence of their respective targets for the last millennium (Torbenson et al., 2023). The paleoclimatic records show long-term trend but most of the resulting agroclimatic zones display no statistically significant increases/decreases in the study region over the reconstruction period (Figure 2). Only the warm and dry zones are the exceptions, with general increases in area since around the start of the second millennium CE.

Our results show large variations in prevailing agroclimatic conditions, with known periods of upheaval in European society coinciding with cooler conditions (and an increase in the area of insufficiently productive agroclimatic zones), such as the early fifth and eighth century CE (Helema et al., 2017; Hakenbeck &

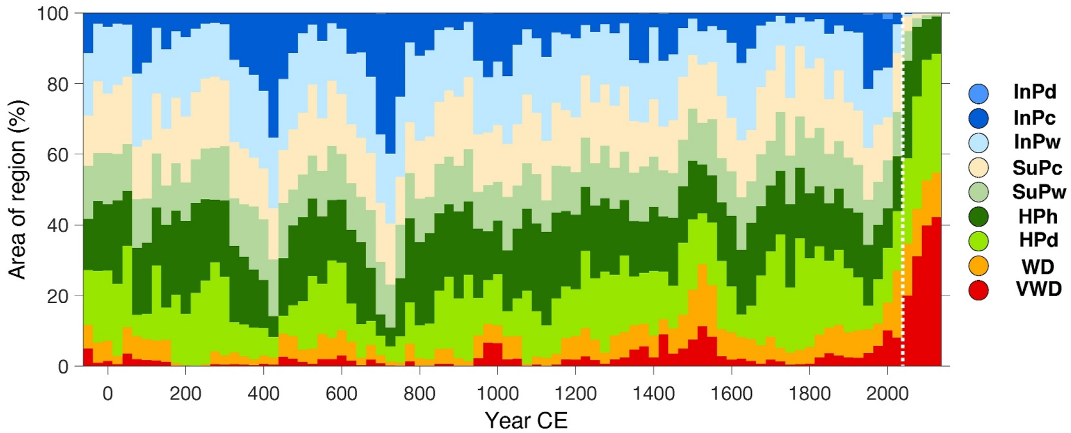

Figure 2. Reconstruction of changing mean areal percentage of agroclimatic zones across the study region during the past two millennia for 25-year periods. Dotted white line indicates the boundary between reconstructed and projected climate data. The projected data represent the mean of the six CMIP6 models considering SSP2-4.5 scenarios.

Büntgen, 2022, Figure 2; Figure S1 in Supporting Information S1). Other, shorter, periods for which the agroclimatic zone reconstruction suggest extremely poor conditions include consecutive extreme values in the 1270s to early 1280s and the early 1430s (with both extreme warm and cold-driven anomalies). Although the historical record is fragmented prior to 1500 CE, both periods have been described as the earliest documented famines in the Czech Lands (Brázdil et al., 2018). Our reconstruction of changes to agroclimatic zones can also provide an alternative record for comparison with archeological data of periods without documentary evidence.

Conversely, the early 16th century CE is characterized by the highest areal proportion of warmer productivity zones (Figure 1d), followed by a sharp increase in lower-rated agroclimatic conditions, with much of the Czech highlands unsuitable for field crops. The 1500–1510 and 1530s were described by contemporary records as an exceptional time for regional wines (Brázdil et al., 2008) but followed by a period of such poor grape harvests from the 1580s that the high social classes in Vienna turned from wine to beer (Pfister & Brázdil, 1999). The late 16th century and early 17th century display the lowest area classified as highly productive for the past 500 years (Figure 1c; Figure 2), with the closest modern comparison being 1926–1950 (Figure 1a).

Such periods of high agreement with documentary evidence of food production serve as further verification of the robustness of the pre-instrumental agroclimatic zone estimates, beyond that of the underlying reconstructions. Farming practices, agricultural inputs, crop varieties, population sizes, and even crop types have changed significantly over the study period (Grigg, 1982), and therefore, we cannot make definite inferences about yields in the distant past from the proxy reconstructions alone. However, the relationship between climate and potential productivity is very likely to have been of a similar nature over the past 2,000 years. We therefore argue that the estimates of past changes in agroclimatic conditions can contain valuable information also for historical and archeological contexts, even if only for describing general patterns.

3.2. Natural Variability of Changes in Agroclimatic Zones

No clear shifts in variance appear in the underlying TS and WB reconstructions (Torbenson et al., 2023), but the optimum agroclimatic zones display varying magnitudes of change over the Common Era. The most recent 50 years display an uptick in change that includes large areal percentages of zones shifting both down (1976–2000) and up (2001–2018), with the latter period representing the largest two-zone upshift over the past 2,000 years (Figure 3a). This unprecedented change may indicate that anthropogenic forcings have already impacted agroclimatic variability in central Europe. The percentage of the study region that falls within the high productivity potential zones (HPh and HPd per Table 1) has varied over time (most notably low points during the 5th and 8th centuries), but no clear trend is evident (Figure 3b). This percentage is, however, of limited practical importance when studying the land currently used for agriculture—as more than half of the region falls outside the high productivity zone (which represents 34.5% of the study region for the full reconstructed period; Figure 3b).

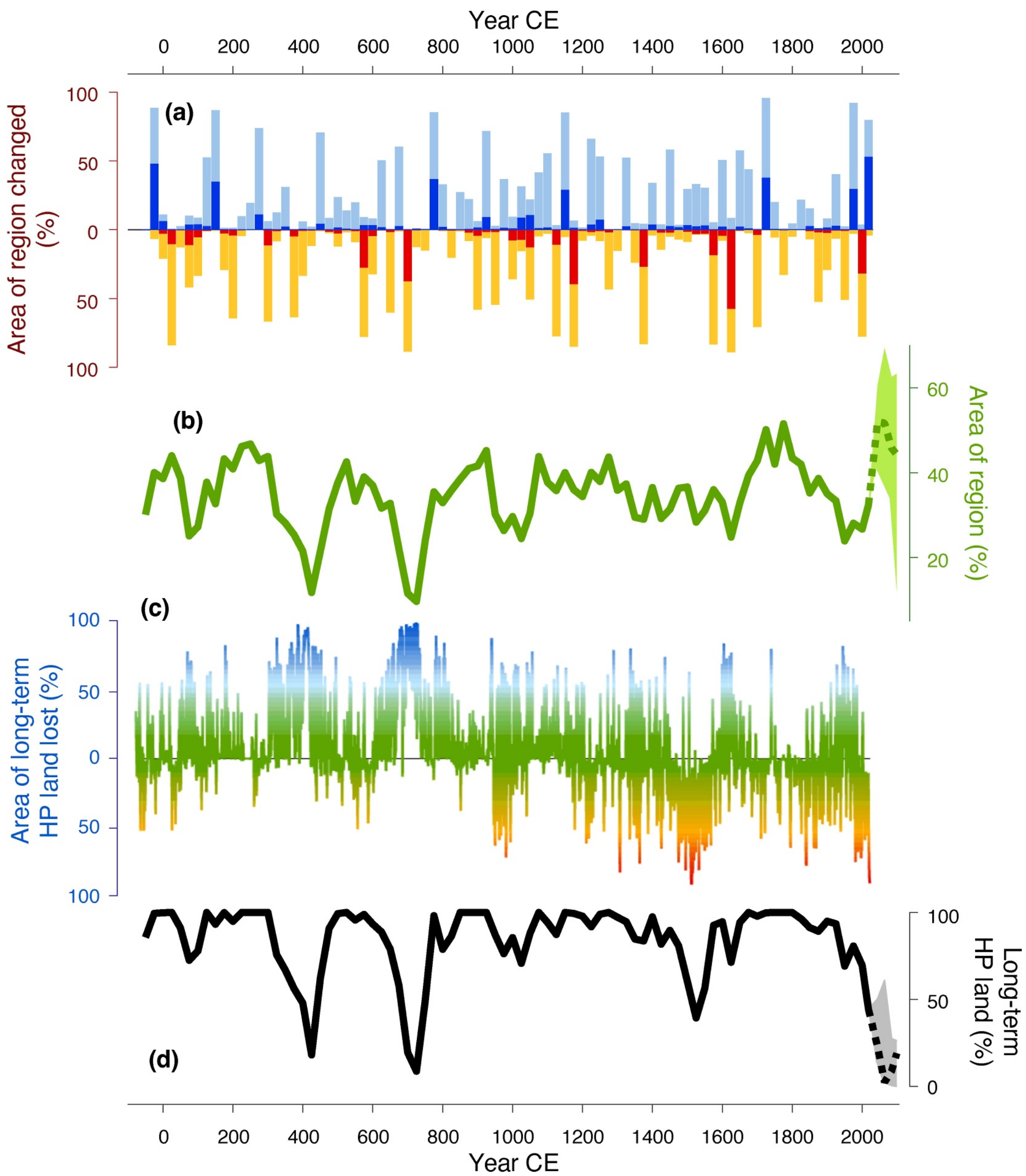

Figure 3. Changes over time in area agroclimatic zone. (a) Percentage of the study region for which the 25-year mode changed by one (light colors) and two (dark colors) zones compared to the previous 25-year period, and the direction of change (yellow/red toward drier and warmer zones; blue toward cooler). (b) Percentage of the study region that is classified as highly productive-humid (HPh) or dry (HPd). Light green spread indicates the range of changes for the six CMIP6 models considering SSP2-4.5, with the dotted line representing the mean of projected change. (c) Annual changes to the area of long-term HP land, with direction of change. (d) Percentage of long-term HP land that is classified as such for the 25-year periods over the full study period (75 BCE to 2099 CE). Gray spread indicates the range of the models, dotted line the mean.

When only considering land that displays mean agroclimatic conditions that fall within the most productive zones for the full period (Figures 3c and 3d), the 18th century stands out as the period with the highest productivity potential and it is the most stable such period over the past 2,000 years (Figure 2). The 21st century does not appear to fall outside of the range of natural variability in terms of long-term highly productive land, with the most analogous period of the past again being the early 16th century (Figures 3c and 3d). Some uncertainty exists, especially pertaining to the low-frequency variability of temperature, which differs between many previous reconstructions for central Europe (Corona et al., 2010). Regardless, recent decades must be considered extreme, as

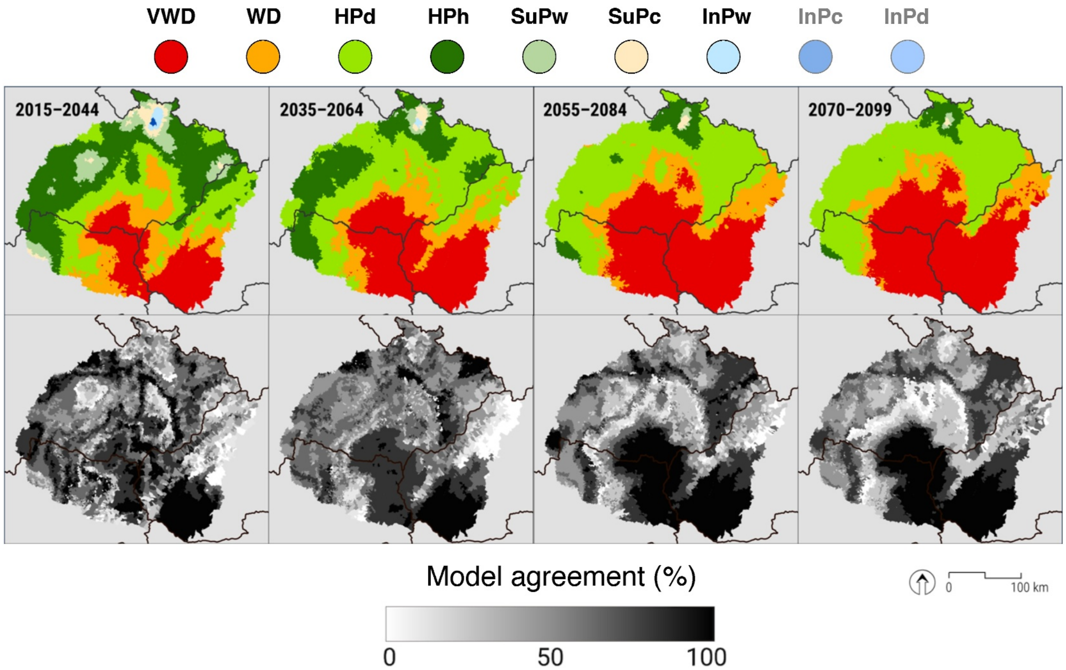

Figure 4. Agroclimatic zone projections (top) Four panels showing the distribution of mean agroclimatic zones during overlapping 30-year periods until 2099 CE considering the SSP2-4.5 climate scenario applied to six CMIP6 models (bottom) Agreement between the mean (as shown in top row) and the six models for each 30-year period.

only three other episodes with less than half of long-term highly productive land were identified (Figure 3d)—and only the period around 1500 CE was driven by warmer and drier conditions (Figure 3c).

3.3. Projections of Agroclimatic Zones in Central Europe

To assess future scenarios of agroclimatic conditions for individual Shared Socio-Economic Pathways (SSP) according to the IPCC (IPCC, 2021), output from six CMIP6 (Eyring et al., 2016) ensemble members were used (Table S1 in Supporting Information S1). There is considerable spread in the areal percentage of agroclimatic zone designation for the different models and scenarios, however, the area of the insufficiently productive zones decreases significantly in all periods (Figure 4) and in all scenarios (Figures S2–S5 in Supporting Information S1). Five of the six models project increases in the high productive zones throughout the 21st century for SSP2-4.5. The exception is the sharp decline toward the end of the century when using output from the TAIESM1 model, responsible for the wide range in model conditions (Figure 3b). The greatest expansion of the warmest zones occurs in the first half of the projected period (2015–2044 and 2035–2064). For SSP3-7 and SSP5-8.5, the models display higher disagreement. The most extreme scenario is recorded in TAIESM1 for SSP5-8.5, with more than 98% of the region seeing conditions that have not been experienced for the majority of the Czech portion of the study region for more than short episodes in the instrumental or reconstructed period (Figure S5 in Supporting Information S1).

Further impact of the projected temperature and precipitation changes on agroclimatic zones is evident when only considering the portion of the area that is considered of long-term high productivity (Figure 3d). By the end of the 21st century, all six SSP2-4.5 models indicate that less than a quarter of highly productive area will fall within the same agroclimatic zone as the Common Era average. In all cases, the changes will mean warmer and drier conditions (WD and VWD). Even for SSP1-1.6, the long-term highly productive areas continue to decline and although there is a small recovery toward the end of the 21st century, the region does not return to pre-21st century levels (Figure 4; Figure S2–S5 in Supporting Information S1). These results are in line with previous studies on future shifts of Köppen-Geiger climatic zones (Skalák et al., 2018) as well as agroclimatic zones (Trnka, Balek, Brázdil, et al., 2021) in central Europe, with increasing temperatures expected to improve conditions for grapevine cultivation in northeastern Austria and the Czech Republic (Ashenfelter & Storchmann, 2016; Petriashvili et al., 2023). Our results could be seen as part of a longer trend over the past 1,000+ years, in which a progressively larger fraction of the study region is becoming suitable for wine production. The European grapevine, for which the center of our study region represents the northeastern extent of current cultivation (Tscholl et al., 2024), should be considered an indicator species, but other crops are projected to be affected as well (Alexandrov et al., 2002). Increases in temperature will likely lead to less favorable conditions for hop production (Možný et al., 2023). Major increases in adverse weather events are also likely to impact the production of cereals, including wheat (Trnka et al., 2014), and perhaps even more so grassland (Trnka, Balek, Semenov, et al., 2021). The projected changes can be seen in the context of long-term trend since the sixteenth century when cold/drought resilient rye was progressively replaced by wheat suited for warmer climate, culminating in a state of wheat dominance in the early 21st century and spring cereals replacing winter types (Možný et al., 2012).

3.4. Connecting Past, Present, and Projected Conditions

The impact on agricultural productivity potential from anthropogenic climate change may already be experienced (Heino et al., 2023; Howden et al., 2007; Praveen & Sharma, 2019). The late 15th and early 16th centuries CE offer an analogue for central Europe in terms of current mean conditions; however, these earlier periods appear to have lasted longer than what we have experienced so far, despite warmer temperatures in recent decades (Luterbacher et al., 2016). This comparable period occurred without any anthropogenic forcing and therefore, if the current conditions are (at least partly) anthropogenic, it is likely that the projections underestimate the magnitude of potential future changes. Likewise, conditions like those recorded for the early 17th century may mitigate or mask some of the changes that may occur in decades to come.

Globally, the impacts of changing climatic conditions on agriculture differ across space (Ceglar et al., 2019; Challinor et al., 2014), and this is also true at a finer spatial scale. The projected changes indicate that areas falling within the highest productivity zones may increase, however, much of the study region will need to readjust the crops grown to optimize yield and productivity. The Czech highlands will be more productive under current projections, assuming appropriate and corresponding changes to agricultural practices. The projected agroclimate suggest that a negligible area of the study region will be classified as insufficiently productive by the second half of the 21st century. In the southern parts of the study region, future temperatures and precipitation totals will promote the growing of crops such as maize and grapevine. However, adaptation strategies must consider that shifts in agroclimatic zones are not always simple in practice and such adaptations have limits (Anderson et al., 2020; Petriashvili et al., 2023), even for single cultivars (Duchêne et al., 2011). Much of the lands currently considered as low productivity are forested and large-scale changes to land-use are unlikely a feasible strategy (Lorencová et al., 2013). It should be noted that the agroclimatic zones do not consider soil and slope, and many of the regions for which other crops could be cultivated must take this into account, as well as the complex logistical components of on-the-ground adjustment in farming structure and management practices (Rickards & Howden, 2012). The latter includes water resources demands, which already have been flagged as an issue in our study region (Potopová et al., 2022). Furthermore, the rate of agroclimatic change represents a source of uncertainty for adaptation strategies (Moore & Lobell, 2014), and the temporal scales studied here for agroclimatic zone shifts may be too coarse for some adaptation approaches (Rickards & Howden, 2012).

4. Conclusions

Here, we connect paleoclimatic records to pressing issues of practical importance, combining data sources with different strengths and weaknesses to provide a holistic perspective on the stability and suitability of climate for agricultural systems. The approach presented is possible in part because of the exceptional proxies that the tree-ring stable isotope records from the Czech Republic represent. It should be noted that there are many more places in Europe and beyond for which both temperature and hydroclimate variables have separately been reconstructed. Such regions hold high potential for understanding the natural variability of climatic forcing on agriculture, not only in absolute terms but also in changes to optimal conditions for crop cultivation. In tandem with climate model outputs, which give crucial information on projected change but may lack robust inter-annual variability, it is possible to establish baselines for future agroclimatic conditions.

Our results show that our study region in central Europe is amid a paradigm shift in terms of how the landscape functions as a producer of agricultural goods. We describe the co-occurrence of downwards and upwards shifts in agroclimatic zones, for which the overall region is increasing its potential productivity, but the conditions in land traditionally farmed for such crops are deteriorating. The region has in the past 50 years experienced shifts toward warmer and drier agroclimate, of a magnitude that rivals anything previously seen in the Common Era. Although there is considerable spread in conditions from the different climate model outputs, most of the land will in upcoming decades fall into agroclimatic zones that do not have precedence in the past 2,000 years even under the most favorable climate projections. For a considerable part of the region, rainfed agriculture will cease to be a viable option. Adaptation measures will only be able to mitigate a portion of these changes.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The annually resolved reconstructions of TS and WB, as well as annually resolved region-wide mean zone and areal percentages of each zone, are available through Torbenson (2024). The underlying tree-ring stable isotope data are available through the International Tree-Ring Data Bank (https://ncei.noaa.gov/products/paleoclimatology/tree-ring).

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