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Consequences of climate change for the soil climate in Central Europe and the central plains of the United States

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Abstract

This study aims to evaluate soil climate quantitatively under present and projected climatic conditions across Central Europe (12.1°–18.9° E and 46.8°–51.1° N) and the U.S. Central Plains (90°–104° W and 37°–49° N), with a special focus on soil temperature, hydric regime, drought risk and potential productivity (assessed as a period suitable for crop growth). The analysis was completed for the baselines (1961–1990 for Europe and 1985–2005 for the U.S.) and time horizons of 2025, 2050 and 2100 based on the outputs of three global circulation models using two levels of climate sensitivity. The results indicate that the soil climate (soil temperature and hydric soil regimes) will change dramatically in both regions, with significant consequences for soil genesis. However, the predicted changes of the pathways are very uncertain because of the range of future climate systems predicted by climate models. Nevertheless, our findings suggest that the risk of unfavorable dry years will increase, resulting in greater risk of soil erosion and lower productivity. The projected increase in the variability of dry and wet events combined with the uncertainty (particularly in the U.S.) poses a challenge for selecting the most appropriate adaptation strategies and for setting adequate policies. The results also suggest that the soil resources are likely be under increased pressure from changes in climate.

1. Introduction

Soils continuously form and change at different rates and along different pathways. Thus, they are never static for more than short periods of time (Schaetzl and Anderson *2005*). The influence of climate on soil formation was first recognized in the late 19th century when Dokučhaev (*1883*) and Hilgard (Fanning and Fanning *1989*) independently formulated the main soil-forming factors (climate, plants and organisms, parent material and time). Jenny (*1941*, *1961*) investigated the factors of soil formation (including climate) and formulated the state factor equation in which ecosystem properties are determined by determined by fluxes (energy or matter) driven by potentials, which could be climate (e.g. precipitation), parent material, relief (e.g. slope), organisms (e.g. vegetation) and others. The results of Gray et al. (*2009*) support the state factor model (on the global level), in which climate and parent material have a dominant influence on the distribution of numerous soil properties. It is also clear that biological processes in the soil are largely controlled by soil temperature and moisture (e.g., Orchard and Cook *1983*). Soil temperature and moisture affect the soil carbon (C) and nitrogen (N) balance through influence on the rate of N-mineralization and also the emission of greenhouse gases from soils. Within limits, temperature controls suitability of an area for plant growth and soil formation (e.g., Ellenberg *1974*; Larcher *2003*), while soil fauna and flora have temperature requirements for their activity levels and survival (USDA-NRCS *1999*).

Surprisingly, a limited number of reports have focused on the impact of climate change on soils and the ecosystem services that they provide. A comprehensive review was conducted by Rounsevell et al. (*1999*), who found that processes with relatively short response timescales (e.g., nitrogen/carbon dynamics, erosion) are better represented in the literature than long-term processes (e.g., pedogenesis), which are inherently difficult to investigate. A recent review by Jones et al. (*2009*) focuses on the effects of climate change on soil carbon, soil erosion by water and water retention, but offers few quantitative assessments. The Millennium Ecosystem Assessment (Hassan et al. *2005*) and the IPCC's 4th Assessment Report (FAR) (Solomon et al. *2007*) shed some light on the potential effects of climate change on soils in certain regions, particularly drylands and polar regions. However, few studies have addressed soil climate and its change per se, despite their importance in key processes, such as carbon sequestration, nutrient cycling and food production. The main objective of the presented study is therefore to evaluate soil climate under both present and projected climate-change conditions over Central Europe and the U.S. Central Plains (Figure 1) with special focus on changes in soil temperature and hydric regimes. Changes in drought risk and potential productivity (assessed as a period of length suitable for crop growth) as well as the wider implications of estimated changes in soil climate for the soil properties are also discussed.

2. Material and methods

2.1 Estimating soil climate characteristics

Two interconnected attributes of soil climate regimes are the hydric (moisture) soil regime and the thermic (temperature) regime. The hydric soil regime describes the presence or absence of soil water held at a tension of <1,500 kPa (or between the field capacity and permanent wilting point) in specific horizons during a defined period of the year (USDA-NRCS *1975*, *1999*; Waltman et al. *1997*). According to Waltman et al. (*2003*):

- hydric soil regimes are derived from the water content in the moisture control sections (MCSs).
- MCS I is defined as a soil layer with 75 mm of maximum soil water holding capacity (MSWHC) from the surface.
- MCS II is the layer between MCS I and the lower boundary of the soil profile.
- The soil water content (AV) is expressed as a percentage of the soil saturation between the wilting point (AV = 0 %) and field capacity (AV = 100 %)
- If AVMCS I is higher than 37.5 %, then MCS I is considered moist. If AVMCS II is greater than 35.0 %, then MCS II is considered moist, and if both layers are moist on the same day, then the day is considered moist.
- If the AVMCS I < 5.0 % and the AVMCS II < 35.0 %, then MCSs I and II are defined as dry and when MCSs I and II are considered dry, the day is considered dry.

These thresholds were set to follow the original model of Van Wambeke et al. (*1992*). The soil hydric regime is determined by the amount of time that soil layers are moist or dry. At the same time, the classification must consider the occurrence of prolonged episodes of drought and climatological water balance (the difference between precipitation and ref-

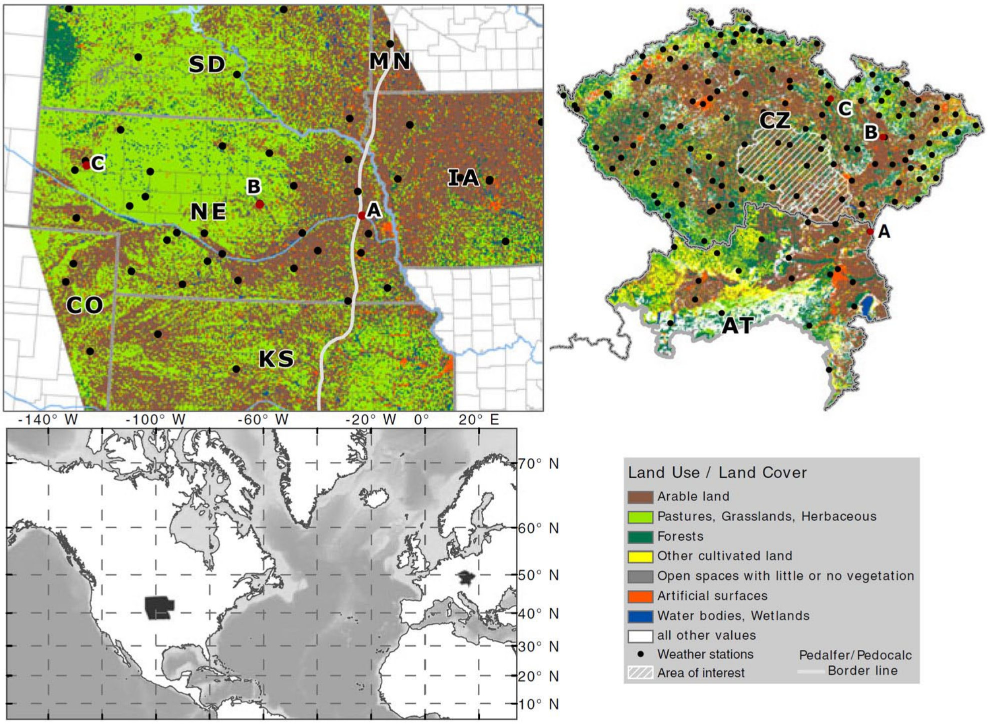

Figure 1. Overview of the study regions in Central Europe (1) and the U.S. Central Plains (2), including present land use and information on the location of the climate stations used in this study. The red-marked stations are used for more detailed analyses (Figure I in Online Resource 2): A. Hohenau (155 m asl), B. Olomouc (210 m asl) and C. Červená (750 m asl) in Central Europe; and A. Ames (309 m asl), B. Ord (625 m asl) and C. Alliance West (1,213 m asl) in the U.S. Central Plains. The countries in Central Europe include Austria (AT) and the Czech Republic (CZ) and the states in the U.S. Central Plains include Colorado (CO), Iowa (IA), Kansas (KS), Nebraska (NE), Minnesota (MN) and South Dakota (SD).

erence evapotranspiration, ETr) during the warmest months (June–August) and the entire year. Because the biological processes in the soils depend not only on available water but also temperature, it is important to assess soil moisture availability during parts of the year when biological activity in the soil is possible. Consequently, the hydric soil regime classification is divided into a sequence of 12 steps using 8 soil moisture indicators combined with information on soil temperature (Table I, Supplement 1).

The SoilClim model (Hlavinka et al. *2011*) was specifically designed and validated to describe soil climate and was applied in this study. The key water balance components of SoilClim are based on the concept and model formulation in FAO Irrigation and Drainage paper No. 56 (Allen et al. *1998*). It also considers snow cover, runoff, deep percolation, simplified macropore water flow (modifying the cascade principle used by Allen et al. (*1998*)), dynamically simulated vegetation cover (including changes in root depth, water withdrawal rates, crop height and leaf area index) and multiple vegetation cover types (e.g., spring and winter field crops, permanent grasslands, evergreen and deciduous temperate forests). The water content calculation does not account for the capillary rise from deeper layers (the groundwater table).

One of the most studied problems in soil science is the feasibility of growing different plants in a given soil and the cultural practices for their cultivation (USDA-NRCS *1999*). From the range of SoilClim outputs, in addition to using the soil hydric regime itself, we

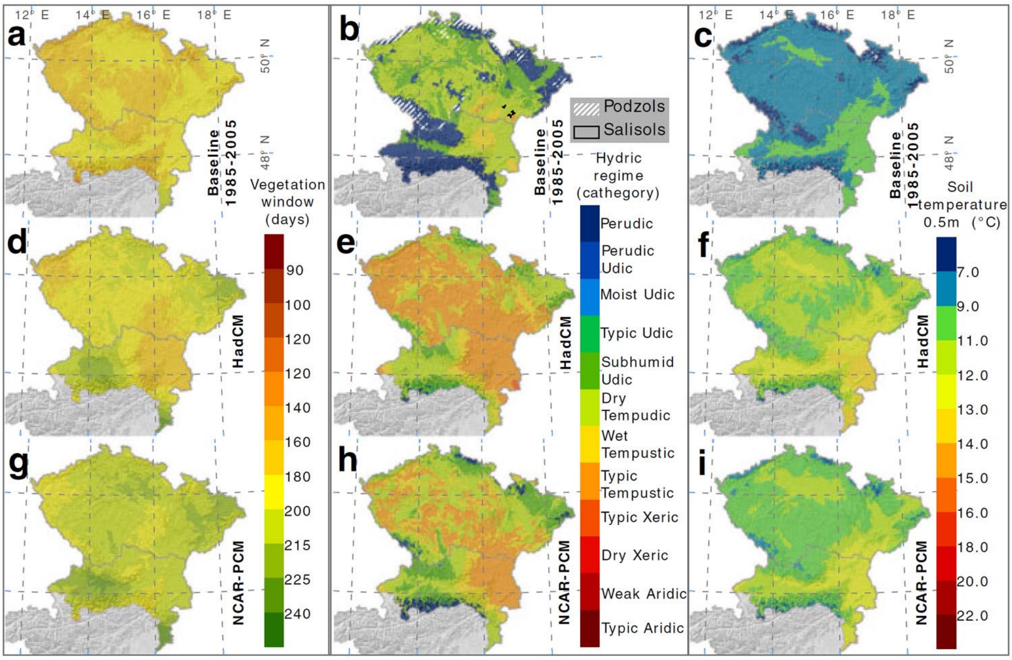

Figure 2. Length of the biological window (a, d, g); the hydric soil regime (b, e, h) and mean annual soil temperature at a 50 cm depth (c, f, i) in the Central European domain. The maps a–c represent the climate baseline (1961–1990), while the conditions expected in 2100 are depicted for HadCM (d–f) and NCAR-PCM (g–i). Maps assume moderate sensitivity of the climatic system (i.e., 2.5 °C increase in global mean temperature per doubling of CO_2 concentration). The present occurrence of Podzolic soils (associated with "wet" soil climate regimes) and soils with high salinity levels (made possible by a relatively dry soil climate regime) are depicted in plate b. Note: biological window is defined as the number of days when the soil temperature at a 50 cm depth is above 8 °C and the soil profile is at least partly moist.

also used soil temperature at a depth of 0.5 m and the length of the biological window (i.e., the period during which at least part of the soil profile is moist and the soil temperature is above 8 °C (see Figs. 2 and 3)).

2.2 Set-up of the case studies

To demonstrate the effects of climate change on the soils in different parts of the world, two case study regions in the temperate zone, with a variety of land covers, were selected (Figure 1).

In the Central European region under investigation, altitude ranges from 109 m asl to 2,566 m asl (mean of 467 m asl) and the area covers 114,438 km^2. There are 145 weather stations (Figure 1) from which the Czech Hydrometeorological Institute and the Austrian Weather Service have provided data for the period 1961–2000. The period 1961–1990 was used as the baseline in this case study, as this period has been used throughout the climate change related studies in Central Europe during the past two decades and reflects the period for which the main soil surveys were conducted in the region (i.e., 1970s and 1980s).

In the U.S. Central Plains, altitude ranges from 151 m asl to 2,115 m asl (mean of 623 m asl) and the region covers a total of 989,756 km^2. The weather data were kindly provided by the High Plains Regional Climate Center from 60 sites in their Automated Weather Data Network (AWDN). Because of the later start of the observation period, 1985–2005 was used as the baseline in this case study to provide sufficient data for the training of the weather

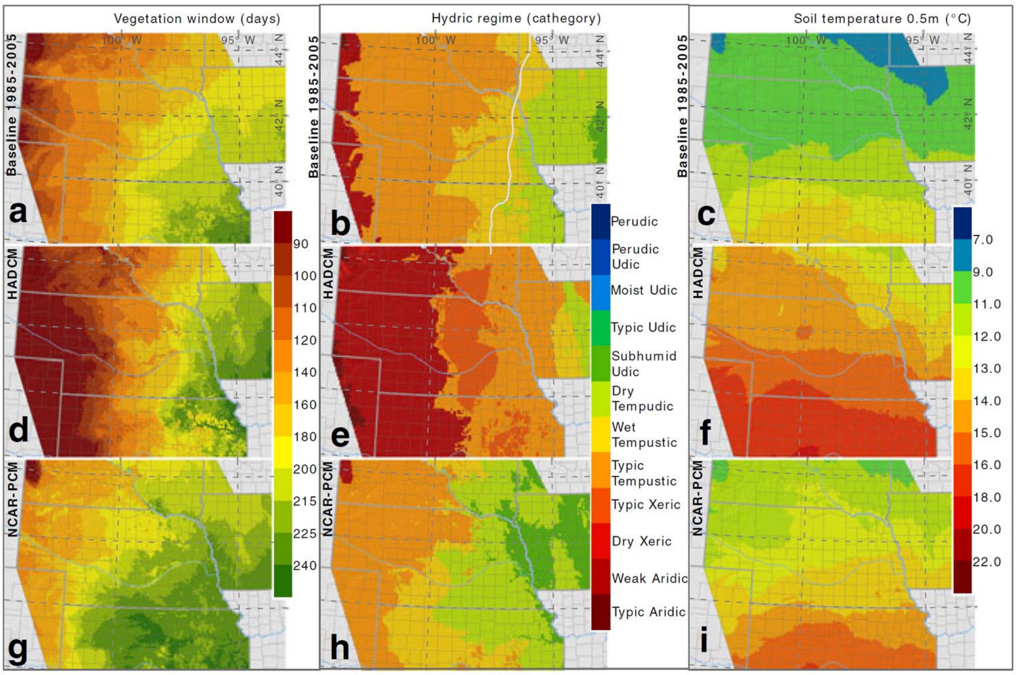

Figure 3. Length of the biological window (a, d, g); hydric soil regime (b, e, h) and mean annual soil temperature at a 50 cm depth (c, f, i) in the U.S. Central Plains. The maps a-c represent the baseline climate (1985–2005), while the conditions expected in 2100 are depicted for HadCM (d–f) and NCAR-PCM (g–i), assuming a moderate sensitivity of the climatic system (i.e., 2.5 °C increase in global mean temperature per doubling of CO_2 concentrations).

generator. The use of different baseline periods in both study areas affects the estimates of soil climate under present conditions but has no influence on the estimate of the soil climate estimated for the latter part of the 21st century.

The climate data were subjected to quality control and then homogenized. Gaps in the measurements were filled using the ProClimDB and AnClim programs (http://www.climahom.eu, last accessed July 2011). Because the aim of the study was to explore the long-term characteristics of soil climatology, a large number of annual series was required. Therefore, observed data were used to train the stochastic weather generator Mandrfi (Dubrovský et al. *2004*), and for each site, a 600-year stochastic weather series of the daily sum of global radiation, maximum and minimum temperatures, gross precipitation, daily mean air humidity and wind speed was prepared. The SoilClim model was then run for a continuous period of 600 years, with the first 100 years used to "spin up" and initialize the model. The soil, terrain and land-cover information used for both regions are summarized in Table 1.

The SoilClim model was used to calculate 8 soil climate indicators (Table I in Supplement 2) at all weather stations and for all soil classes (Figure 1). The results were interpolated using a co-kriging method (ArcGIS™ 9.3) into an appropriate grid mesh (1 km resolution in Central Europe and 2.5 km in the U.S. Central Plains) and then visualized according to the soil conditions found within the individual grid cell. Winter C_3 crop (winter wheat) was considered the cover crop in the Central European domain, while C_4 crop (grain maize) was considered the cover crop in the United States. These divisions were considered the best approximation of the prevailing land uses (arable land and grassland) for both regions when future land use is not known.

Table 1. The sources of soil, land-cover and terrain information for calculations in Central Europe and the U.S. Central Plains (depicted in Figure 1). The soil water holding capacity values were compared for consistency between the study regions using the Harmonized World Soil Database (FAO et al. 2008)[a]. When discrepancies occurred between the soil parameter sources, the value with the highest soil water holding capacity was selected for the given grid.

Region	Soil properties	Land cover	Terrain
Central Europe grid resolution: 1 km	1:500,000 Soil map of the Czech Republic (Tomášek 2007) combined with 1,000 soil profiles from a 1970s complex soil survey 500 m gridded dataset of the soil water-holding capacity of agriculture soils in the Czech Republic (Research Institute for Soil and Water Conservation, v.v.i.,) 1:25,000 Soil map of Austria (Murer et al. 2004) Harmonized World Soil Database (FAO et al. 2008)	Corine land cover CLC2000-9/2007 (EEA, Copenhagen, 2007)[b]	Digital elevation model derived from the Shuttle Radar Topography Mission (Farr et al. 2007)
U.S. Central Plains grid resolution: 2.5 km	1:250,000 Conus-Soil database (Miller and White 1998) Harmonized World Soil Database (FAO et al. 2008)[a]	National Land Cover Dataset (NLCD) 2001 (Homer et al. 2004)	

a. FAO/IIASA/ISRIC/ISS-CAS/JRC, 2008. Harmonized World Soil Database (version 1.0). FAO, Rome, Italy and IIASA, Laxenburg, Austria at http://www.fao.org/nr/water/docs/Harm-World-Soil-DBv7cv.pdf

b. http://www.eea.europa.eu

In addition to the maps in both regions, 3 sites were selected to represent prevailing gradients (Figure 1). In Central Europe, the southernmost station is the warmest and driest, while within the U.S. Central Plains, the sites follow a climate gradient of precipitation totals decreasing westward.

2.3 Climate change scenarios

The climate change scenarios in this study were developed via a "pattern-scaling" technique (Santer et al. *1990*; Mitchell *2003*; Dubrovský et al. *2005*) and then applied to modify the parameters of the weather generator as used in Trnka et al. (*2004*) wherein the parameters were modified according to the climate change scenarios developed from the output of the Global Circulation Models (GCMs). The pattern-scaling technique defines a climate change scenario by the product of the standardized scenario and the change in global mean temperature. The standardized scenarios, which relate the responses of climatic characteristics to a 1 °C rise in global mean temperature (ΔTG), were determined by applying a regression method (Dubrovský et al. *2005*) to the 2000–2099 period, which was obtained from three GCMs run with the SRES-A2 emission scenario from the AR4 (Solomon et al. *2007*). The 3 GCMs utilized include the ECHAM5/MPI-OM, HadCM3 and NCAR-PCM, hereafter referred to as ECHAM, HadCM and NCAR, respectively. The projected changes in global mean surface air temperature (ΔTG) for three years (2025, 2050 and 2100) were calculated via a simple climate model, MAGICC (Harvey et al. *1997*; Hulme et al. *2000*), assuming the SRES-A2 emission scenario and moderate (3 °C) and high (4.5 °C) climate sensitivities (i.e., an equilibrium change in ΔTG following a doubling of the atmospheric equivalent CO2 concentration). Table III (Supplement 1) shows that the selection of 3 GCMs accurately represented the temperature and precipitation ranges expected based on the ensemble of 17 available GCM projections for both regions during warm and cold seasons. Only the situation that included a significant precipitation drop was not captured fully by the three selected GCMs. When calculating evapotranspiration, an adjustment for atmospheric CO2 concentration was made using the method proposed by Kruijt et al. (*2008*), and the CO2 ambient air concentrations listed in Table II (Supplement 1) were used.

3. Results

3.1 Central Europe

The effect of predicted warming would cause a significant prolongation of the biological window in all three assessed periods (2025, 2050 and 2100). In the lowlands, the effect would be mixed because of changes in water availability. The NCAR (Figure 2d) results indicate lengthening of the vegetation season, while those from HadCM (Figure 2g) and ECHAM (not shown) tend to indicate a decrease across the most fertile agricultural regions. The return probability functions (RPFs) presented in Figure I (Supplement 2) confirm the Figure 2 conclusions in general, with decreases in the length of the biological window in the lowland sites and increases in the highlands. However, regardless of the altitude, the interannual variability of this parameter increases markedly (Figure I, Supplement 2). In particular, the southernmost site is strongly affected. The prolongation of the biological window is associated with sharp increases in the soil temperature in most places. The expected increase in the mean annual soil temperature at 50 cm expected by the end of the 21st century is between 3 and 6 °C. Soil temperatures are predicted to increase more under the HadCM scenarios (Figure 2f) than under the NCAR scenarios (Figure 2i), while the distribution and overall amount of precipitation is much more favorable under the NCAR-based scenarios, leading to enhancement of the biological window. However, even under the comparably wetter and cooler NCAR-based scenarios, increased interseasonal variability and a noticeable increase in the number of days with completely dry soil profiles is to be expected across Central Europe (Figure I in Supplement 2). In all situations, the number of dry days increases significantly above the present levels.

Under the present climate conditions (Figure 2b), the region is dominated by rather wet hydric regimes, including Dry Tempudic (42.5 %), Subhumid Udic (22.7 %) and Perudic (30.3 %). Perudic areas are dominated by evergreen forests and permanent grasslands, while arable land is the primary type of land in Dry Tempudic and Subhumid Udic areas. Despite the pronounced differences between the scenarios, there is very good agreement in terms of future hydric regimes (Figure 2e and h). While the Perudic regime is retreating over the 21st century, the relatively dry Typic Tempustic regime begins to dominate the soil climate in the region in 2050 and 2100 in particular. Assuming the present land use patterns, in the future, most of the arable land would be situated in a Dry Tempustic soil climate regime that would likely require irrigation to achieve the full production potential of the site. Under HadCM-High, almost one-third of the arable soils would belong to a Xeric regime that does not allow for cultivation without irrigation during the summer. Similarly, areas covered by evergreen forests (mostly spruce) would experience shifts from Perudic and Dry Tempudic regimes to Tempustic and even Xeric soil climate regimes, with obvious consequences.

The altered climate will inevitably affect the probability of Xeric years from 2025 (i.e., years when soil is dry during most of the summer throughout the profile). Under the present climatic conditions, the probability is less than 1 % across most of the study region, with the driest regions showing less than a 10 % probability (Figure II, Supplement 2). The results show a clear increase in the probability of Xeric events from “very rare” to events occurring at least once every 10 years by 2100. In addition, Arid years (i.e., years during which the soil profile remains mostly dry) will become increasingly common in the southeast part of the region, according to HadCM-High.

3.2 U.S. Central Plains

Under the present climate, the U.S. Central Plains are sandwiched between semiarid and arid regions adjacent to the Rocky Mountains and relatively humid regions to the east, which is reflected in an east/west gradient of soil climate parameters. The effect of climate change depends strongly on the applied GCM. The realization of the NCAR-based projections would lead to a rather dramatic prolongation of the biological window during the 21st century across the entire region and a reduction in the east–west soil moisture gradient (Figure 3g). However, according to the HadCM scenarios (Figure 3d), the length of the biological window would increase in the east (especially across Iowa and eastern Nebraska) but would shorten across much of the western two-thirds of the region. For the east, both GCMs predicted lengthening of the window and thus an improvement in the potential productivity in the transition zone and dry western regions, where the GCM outputs are most uncertain and where the length of the biological window depends most on the chosen GCM. Even in the east, the altered climate might lead to severe problems in agricultural production because under the HadCM scenario, the mean value of the biological window increases but also becomes more variable (Figure III, Supplement 2). The NCAR-based projections show lower interannual variability than the present values in the east and central sites (Figure III, Supplement 2). The realization of the HadCM scenario would result in a severe decline in the biological window (because of decreases in water availability), with 5 % of the seasons being completely dry throughout the entire rooting zone by 2100.

Although the spatial patterns and south-to-north soil temperature gradient will not change, there are significant differences between individual scenarios. HadCM-HI shows a possible increase of more than 10 °C in soil temperature, which surpasses the estimated increase in the air temperature, mainly because of the much shorter duration of snow cover and more intensive insolation.

Hydric soil regimes in the U.S. Central Plains are governed by an east–west precipitation gradient (Figure 3b), with the east dominated by the Dry Tempudic and Tempustic regimes prevalent across most of the area (73.8 %) and with the western part containing a Weak Aridic soil climate. The dominant land use in the Tempudic and Wet Tempustic areas is arable land, while under the Dry Tempudic regime, grasslands prevail over arable land. The estimated effect of climate change depends on the GCM employed (Figure 3e, h) because the HadCM model indicates a tendency for a soil climate shift toward a drier climate, with Aridic regimes dominant in the west and Xeric together with Tempustic dominating the central part of the domain (Figure IV, Supplement 2). Only central Iowa would remain in a relatively wet Tempudic zone. However, the realization of the NCAR-based projections would mean an overall shift in the wetter climate regimes toward the west (Figure 3h), with diminished Aridic regimes and Subhumid Udic regimes occurring in eastern Nebraska.

According to the projections based on the NCAR-PCM global circulation model, the water availability in the U.S. Central Plains may improve, which translates to a longer biological window across almost the entire region. This lengthening should be accompanied by only a moderate increase in soil temperature and a shift in the hydric soil regimes toward wetter categories. The HadCM-based projections show a very different pattern, indicating significant drying in the western part of the U.S. Central Plains, with the eastern part remaining relatively wet.

4. Discussion

4.1 Hydric soil regimes under the present climate

SoilClim enables long-term continuous simulations to determine the long-term effects of changing climate on the soil climate parameters. However, because it assumes unchanged management practices, the resulting hydric soil regimes reflect a model situation in which only the climate conditions change. Human activities affect soil properties, including hydric soil regimes, and this fact has been known since the 1920s (e.g., Lang *1920*; Novák *1921*).

Another key assumption made in our study concerned the properties of vegetation cover, which were kept constant over both target areas. We analyzed the influence of uniform vegetation cover type on soil water extraction and the ratio between plant transpiration and soil evaporation compared to various crop cover types, including C_3 and C_4 plants. We noted (especially during some seasons) significant differences between the onset of the drought stress or reduced soil water content. However, when we compared hydric soil regimes for individual grids for all crop covers available within SoilClim, we found only minor differences between the baseline climate runs.

The spatial distribution of the hydric soil regime assumed by our modelling approach could be partially verified in the U.S. Central Plains using studies by Marbut (*1928*, *1935*) and more recent studies by Waltman et al. (*2003*) and in the location of the boundary known as the “Pedocal-Pedalfer” line (Figure 1), which is the zero point at which the mean annual precipitation and evapotranspiration are equal (Marbut *1935*; Jenny *1941*). The location of pedocals/pedalfers could be approximated by a boundary between the Ustic and Udic hydric regimes (Figure 3b). Compared to Marbut (*1935*), as depicted in Figure 1a, the boundary approximated by SoilClim is located closer to the east (by approximately 50–100 km). The difference could be explained by the fact that our study is based on climate data collected between 1985 and 2005, while Marbut (*1928*) and Waltman et al. (*2003*) used early 20th century and 1961–1990 datasets, respectively (i.e., from comparatively cooler and wetter periods).

In Central Europe, the chernozems are typically attributed to drier hydric conditions, as typical steppe soils with their pedogenesis are dominated by humus accumulation because of the dry continental climate and steppe vegetation. Soils with high salt accumulation are typical for a drier soil climate, something that would not be possible under more humid conditions. While Eckmeier et al. (*2007*) found only poor correlations between classified chernozems and climatic and topographic conditions in Central Europe (likely caused by other factors affecting pedogenesis), virtually all soils with a naturally high salt content in the Czech Republic are found within Tempustic (i.e., drier) zones (Figure 2b). In contrast, Podzols require a humid climate with a positive water balance to reach a stage of acidification that allows for iron and aluminum transport. Under present climate conditions, we find Podzols within the Czech Republic predominantly within Perudic areas (Figure 2b).

4.2 Consequences of changes in water availability and hydric soil regimes

Changes in the soil moisture distribution (which we see in both study areas) could influence regional and potentially global atmospheric circulation (Sivakumar and Stefanski

2006). Summer precipitation in the continental mid-latitudes is significantly influenced by water returning to the atmosphere through evapotranspiration, which is reduced under low soil moisture availability. This feedback tends to lock summer soil moisture in either a "dry" or a "wet" state, while intermediate conditions have a low probability of occurrence (D´Odorico and Porporato *2004*). Recent studies by Hirschi et al. (*2010*) and Seneviratne et al. (*2006*) have shown a relationship between the soil-moisture deficit and summer heat extremes (heat waves) in southeastern Europe. Munson et al. (*2011*) concluded that increased temperature and aridity (as assumed by HadCM in our study) might increase the likelihood of dust production from wind erosion in the future, as was the case during the "Dust Bowl" of the 1930s in North America. The U.S. Central Plains are also characterized by a strong soil moisture-evapotranspiration (and photosynthesis) coupling (Seneviratne et al. *2010*). According to Teuling et al. (*2009*), the coupling is much weaker, but still present, in Central Europe. The risk of decreased rainfed crop productivity (mostly from increased probability of drought during growing season) estimated for parts of Central Europe and the U.S. Central Plains agrees quite well with findings of Fischer et al. (*2002*) concerning rainfed cereal production.

4.3 Long-term prospects

Figure V (Supplement 2) shows an example of an altitudinal transect study (over the Central European region highlighted in Figure 1) with the likely vectors of change in various soil properties that could be expected during the 21st century. The original values come from a detailed survey of forest soils carried out during the 1960s by Pelíšek (*1966*). Increases in alkalinity and changes in carbon content (expressed in terms of litter and humus here) are likely to be substantial because the soil temperature and moisture regimes will change significantly (Figure 2 and Supplement 2). While the quality of humus at higher altitudes is likely to increase, the total carbon storage in the soils will be thus reduced. A larger amount of available nitrogen will be available to plants/crops and for leaching, while the total amount of nitrogen in the soil will probably decrease. Clearly, the soil moisture and temperature regimes will change dramatically within the transect, as shown in Figure Vc (Supplement 2).

In general, changes toward warmer and drier conditions carry the risk of increasing the salinity on the predisposed (Várallyay *1994*) and/or inadequately irrigated soils. A decrease of already low organic matter content of the farmed soils is more likely under expected soil climate conditions, if the soil management is not adapted accordingly. Potentially drier conditions also contribute to slower decomposition, which can result in increasing carbon content, as was historically the case for chernozems forming in the warmer and drier "pannonium" climate. However, this direction of pedogenesis would be possible only if other parameters that allowed for the accumulation of biomass and management practices did not interfere with the process. It should be stressed that our study did not consider other potent factors (beyond climate), such as soil type, vegetation succession and soil management, that could influence the carbon dynamics and pedogenesis.

One of the most notable findings of the study is the uncertainty range provided by the set of GCMs used and the climate system sensitivity toward increased ambient CO_2 concentrations. Increased variability in the length of the biological window and the likelihood of far more intensive droughts is observable in Central Europe and, to a lesser degree, within the U.S. Central Plains (Supplement 2).

Despite the fact that the soil is an essential component of many impact models used in climate change studies, the results of these models are rarely made available. At the same time, studies identifying key threats for soils do not typically quantify the risks associated with climate change. For example, the Soil Atlas of Europe (*2005*) stated that "climate change presents an overarching but as yet uncertain factor linked to degradation processes."

5. Conclusions

The study included a range of potential pathways using a representative subsample of available global circulation projections, which sometimes led to opposing results for the same region in terms of hydric regime or drought trends. Based on the evidence provided here, the soil climate will change dramatically in both the U.S. Central Plains and Central Europe, with significant consequences for soil genesis. Our findings suggest an increased risk of extremely unfavorable dry years, resulting in an increased soil erosion risk or lower productivity, especially in Central Europe but potentially in the U.S. Central Plains as well. The projected increase in the variability of dry/wet events should lead to the establishment of appropriate agricultural and soil conservation policies; this action should be conducted with greater urgency in Central Europe, where the uncertainty is lower. Soil resources will most likely be under unprecedented pressure from changes in climate forcing that occur much faster than in previous centuries. The selected ensemble of GCMs excluded those predicting the largest shortfalls in precipitation and highest increases in temperature. Given that soil is one of the most critical and vulnerable resources for producing food and raw materials, more attention should be paid to studying the impacts of climate change on soil climate and, in particular, toward designing proper responses for a broad range of scenarios. The results also highlight the potential shortcomings of using only one GCM as an adaptation strategy based on one particular scenario, as this method might prove to be ill-advised, especially in the case of the U.S. Central Plains.

Failing to identify the risks associated with changing soil climate regimes for soil processes carries the risk of deteriorating soil fertility and a subsequent decrease in productivity. The analysis presented here might serve as a precursor to more ambitious studies on different scales to better reflect how specific regions may be affected both now and under changing climate conditions.

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Supplementary material — The supplementary material is presented following the References.

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Title: CONSEQUENCES OF CLIMATE CHANGE FOR THE SOIL CLIMATE IN CENTRAL EUROPE AND THE CENTRAL UNITED STATES

Running title: Climate change and the soil climate in Central Europe and the central United States

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Table I: List of indicators used to assign the hydric soil regime to the given grid. The regime was determined in a step-wise fashion: if the grid did not fall into the no. 1 regime, the iteration continued to the no. 2 regime, etc. (ns – "not specified," i.e., not used to determine the given hydric regime).

Order of the regime iteration	Hydric regime	$MS_{June\text{-}August}$ [1] [mm]	$MCS_{year\ moist\ days}$ [2] [days]	MS_{Year} [3] [mm]	sMd_{max} [4] [days]	dB_{5ratio} [5] [unitless]	B_{8m} [6] [days]	wM_{wmax} [7] [days]	$4sM_{wmax}$ [8] [days]	Order of the regime according dryness [9]
1	Perudic	>0	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	**1**
2	Perudic Udic	< 0	>330	>575	*ns*	*ns*	*ns*	*ns*	*ns*	**2**
3	Moist Udic	< 0	>330	450-575	*ns*	*ns*	*ns*	*ns*	*ns*	**3**
4	Typic Udic	< 0	>330	175-450	*ns*	*ns*	*ns*	*ns*	*ns*	**4**
5	Subhumid Udic	< 0	>330	<175	*ns*	*ns*	*ns*	*ns*	*ns*	**5**
6	Dry Tempudic	< 0	271-329	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	**6**
7	Dry Xeric	< 0	≤270	*ns*	≥ 90	*ns*	*ns*	*ns*	*ns*	**9**
8	Weak Aridic	< 0	≤270	*ns*	< 90	≥ 0.5	>45	*ns*	*ns*	**11**
9	Typic Aridic	< 0	≤270	*ns*	< 90	≥ 0.5	≤45	*ns*	*ns*	**12**
10	Typic Xeric	< 0	≤270	*ns*	*ns*	*ns*	45-89	≥ 45	*ns*	**10**
11	Typic Tempustic	< 0	≤270	*ns*	*ns*	< 0.5	*ns*	*ns*	≤ 45	**8**
12	Wet Tempustic	< 0	≤270	*ns*	*ns*	< 0.5	*ns*	*ns*	>45	**7**

Notes: 1) MS$_{June\text{-}August}$ *- difference between the precipitation and reference evapotranpsiration during June-August;* ***2) MCS***$_{year\ moist\ days}$ *- number of days during the year when both layers of the soil profile were considered moist;* ***3) MS***$_{Year}$ *- difference between the sum of annual precipitation and reference evapotranpsiration;* ***4) sMd***$_{max}$ *- the highest number of consecutive dry days after the summer solstice (21st June);* ***5) dB***$_{5ratio}$ *- ratio of dry days with soil temperature above 5°C and total number of days with soil temperature 5°C;* ***6) B***$_{8m}$ *- number of days with soil temperature higher than 8°C during which soil was moist at least in some parts;* ***7) wM***$_{wmax}$ *- the highest number of consecutive wet days after the winter solstice (21st December);* ***8) 4sM***$_{wmax}$ *- defined as the number of MCS wet days during a period of 4 months after the summer solstice (between June 21 and October 21););* ***9)*** *provides an order according to soil moisture availability over the long term, with 1 reserved for the wettest and 12 for the driest of the hydric soil regimes.*

Table II: Overview of the scenarios considered in this study and their associated CO_2 and global mean temperature values.

Target year	Medium sensitivity		High Sensitivity	
	Ambient CO_2 concentration [ppm]	Δ mean global temperature [ºC]	Ambient CO_2 concentration [ppm]	Δ mean global temperature [ºC]
2025	435	+ 0.80	435	~ +1.10
2050	536	+ 1.48	538	~ + 2.08
2100	857	+ 3.00	866	~ + 4.29

Table III. Estimated changes of the mean temperature and precipitation per 1°C increase of global mean temperature over the case study areas for three GCMs used in the study compared with an ensemble of 14 GCM runs for which A2-SRES runs were available (see notes for more details). The expected climate conditions are obtained after multiplying the Table 3b values by the assumed change of global mean temperature listed in Table 3a. Both areas are also split into two parts to account for increasing continentality. The Central Europe study area (Czech Republic and northeast Austria) is divided by the 15°E meridian, with the western area experiencing a stronger oceanic influence. The Central Plains are divided by the 98°W meridian, with the eastern part generally experiencing a stronger oceanic influence and increased precipitation.

	Mean Δ of temperature April-September [°C]						Mean Δ of precipitation April-September [%]						Mean Δ of temperature October-March [°C]						Mean Δ of precipitation October-March [%]					
Environmental Zone	Models used in the study			17 GCM with SRES-A2 run			Models used in the study			17 GCM with SRES-A2 run			Models used in the study			17 GCM with SRES-A2 run			Models used in the study			17 GCM with SRES-A2 run		
	H	E	N	min	avg	max	H	E	N	min	avg	max	H	E	N	min	avg	max	H	E	N	min	avg	max
Central E. (whole)	1.5	1.1	1.0	1.0	1.2	1.5	-6.6	-6.5	2.1	-15.0	-4.7	3.3	1.2	1.3	1.2	1.0	1.2	1.5	3.1	3.3	1.7	-1.5	2.0	5.5
Central E. (west)	1.4	1.1	1.0	0.9	1.2	1.5	-6.0	-5.9	2.6	-12.9	-4.3	3.5	1.2	1.2	1.2	1.0	1.2	1.4	3.2	3.8	1.7	-1.7	2.1	5.3
Central E. (east)	1.5	1.1	1.0	1.0	1.3	1.5	-7.1	-7.1	1.6	-16.9	-5.0	3.1	1.2	1.3	1.2	1.0	1.2	1.5	3.1	2.8	1.7	-1.3	1.9	5.6
H. Plains (whole)	2.0	1.2	1.0	1.0	1.6	2.3	-4.5	2.2	3.5	-13.1	-2.3	5.8	1.4	1.3	1.1	1.1	1.4	1.9	3.0	5.5	5.7	-2.8	2.2	7.6
H. Plains (east)	2.0	1.2	1.1	1.1	1.6	2.4	-3.7	3.0	2.4	-14.0	-2.1	6.5	1.5	1.2	1.2	1.1	1.5	1.9	2.4	6.0	5.4	-3.3	2.4	7.2
H. Plains (west)	2.0	1.2	1.0	1.0	1.6	2.2	-5.1	1.5	4.0	-13.2	-2.5	5.4	1.4	1.3	1.1	1.1	1.4	1.9	3.5	5.1	6.0	-2.8	2.0	8.0

Notes:

1) ECHAM (E), HadCM (H) and NCAR (N)

2) 17 GCM models used to develop the ranges of GCM projections included BCM2.0 (Bjerknes Centre for Climate Research, Norway), CGMR (Canadian Center for Climate Modeling and Analysis, Canada), CNCM3 (Centre National de Recherches Meteorologiques, France), CSMK3 (Australia's Commonwealth Scientific and Industrial Research Organization, Australia), MPEH5 (Max-Planck-Institut for Meteorology, Germany), ECHOG (Meteorological Institute University Bonn, Germany + Meteorological Research Institute, Korea + Model and Data Group at Max-Planck-Institut for Meteorology, Germany), GFCM20 and GFCM21 (Geophysical Fluid Dynamics Laboratory, USA), INCM3 (Institute for Numerical Mathematics, Russia), MIMR (National Institute for Environmental Studies, Japan), MRCGCM (Meteorological Research Institute, Japan), PCM and NCCCSM (National Center for Atmospheric Research, USA), HADCM3 and HADGEM (UK Met. Office, UK), IPCM4 (Institut Pierre Simon Laplace, France), GIER (Goddard Institute for Space Studies, USA) and data were downloaded from http://www.mad.zmaw.de/IPCC_DDC/html/SRES_AR4/index.htm

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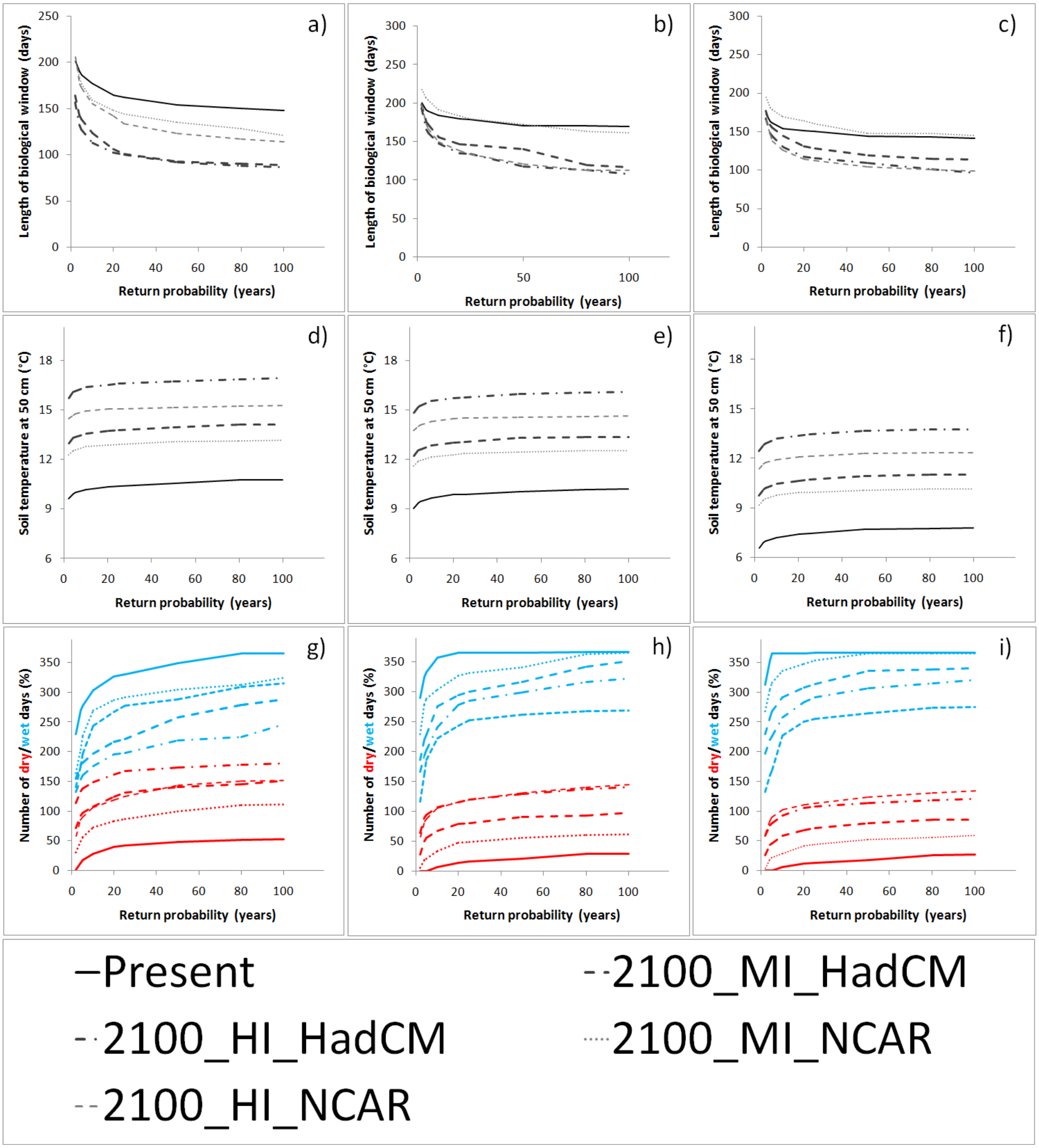

Figure I: Return probability functions for the length of the biological window (a, b, c), mean annual soil temperature at 50 cm depth (d, e, f) and number of days with a completely dry and at least partly wet soil profile (g, h, i) over three sites located in Central Europe (Fig. 1). These sites are located along the same meridian, with the southern area (A. Hohenau) being the driest and warmest (left column), the center (B. Olomouc) being relatively humid and warm and the northern area (C. Červená) being humid and cool (right column). The RPFs were calculated for the present climate (1961-1990) and those expected in 2100 based on outputs of the HadCM and NCAR-PCM global circulation models and two sets of climate sensitivities (HI = high, assuming a 4.5°C increase per doubling of CO_2 concentrations; MID = medium, assuming a 2.5°C increase).

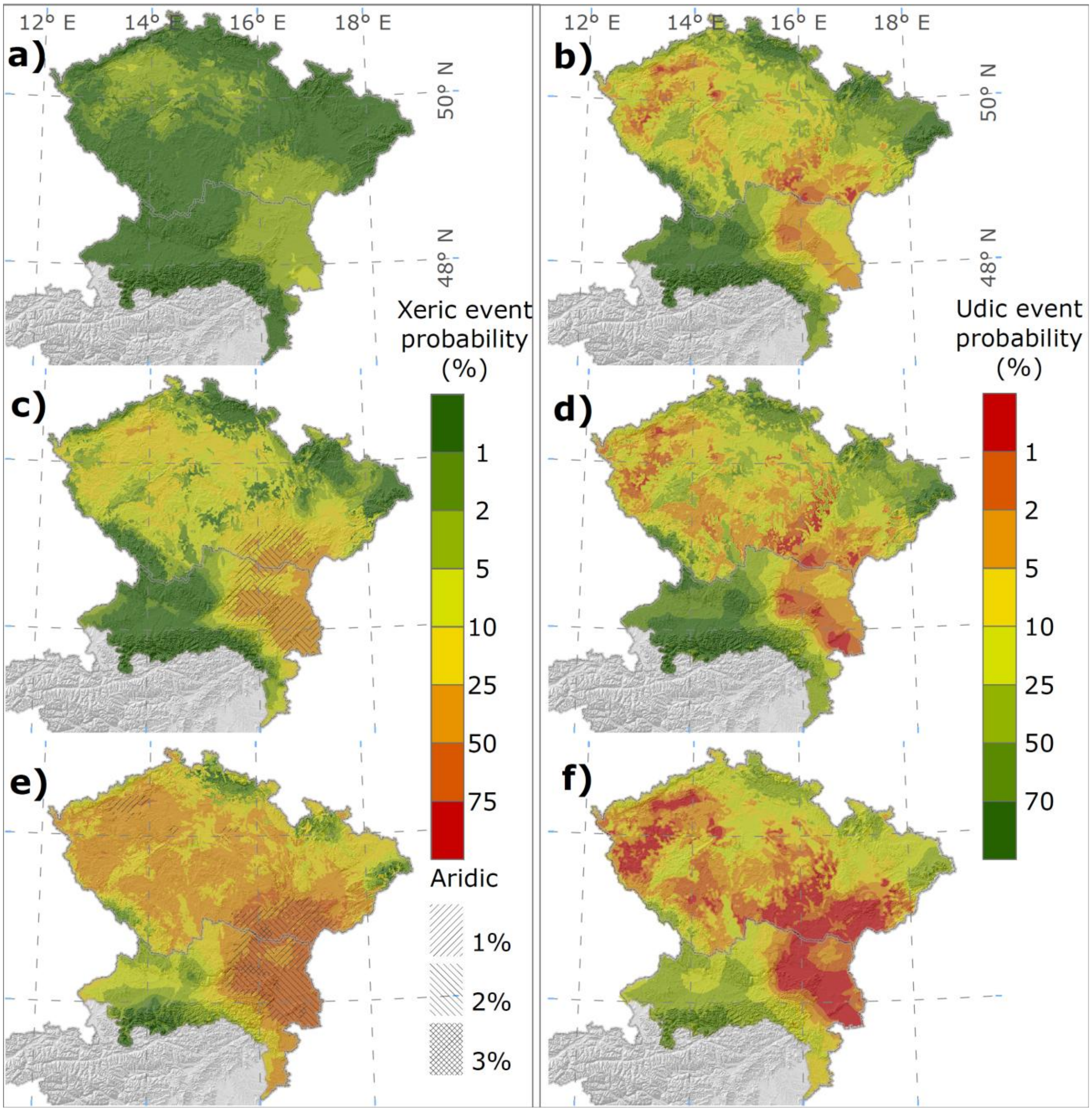

Figure II: a, c, e: Probabilities of an Xeric season (i.e., a year with an extremely dry summer season) over the Central European study area under the present climate conditions (1961-1990) and those expected in 2100 based on outputs of the HadCM global circulation model and two sets of climate sensitivities (HI = high, assuming a 4.5°C increase per doubling of CO_2 concentrations; MID = medium, assuming a 2.5°C increase); Under the changed climate (c, e), the probability of Aridic years (i.e., those having an almost completely dry soil profile) is also given. b, d, f: The same as above for the case of a Udic season (i.e., a very wet year with an at least partly moist profile for the entire year).

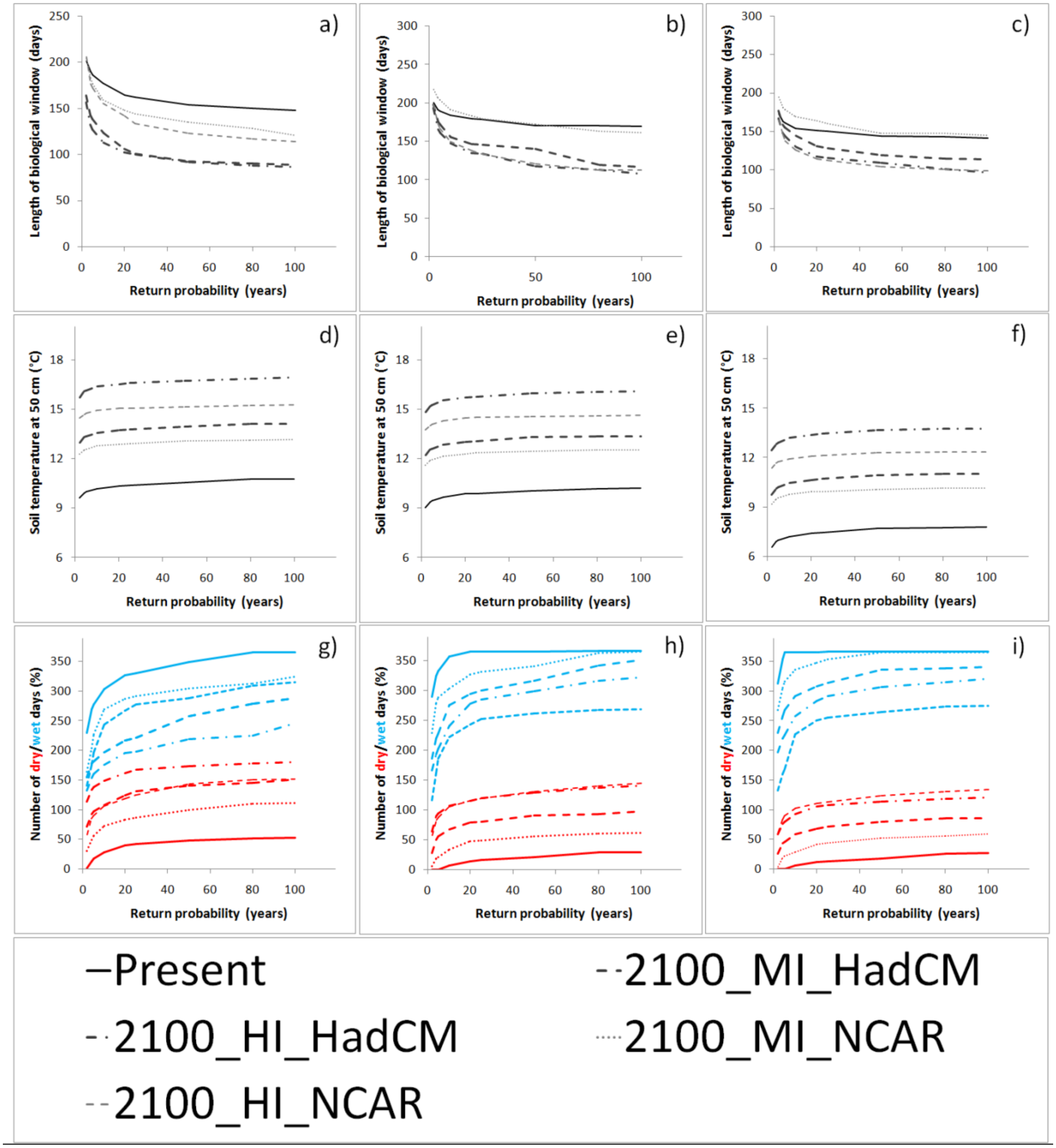

Figure III: Return probability functions for the length of the biological window (a, b, c), mean annual soil temperature at 50 cm depth (d, e, f) and number of days with a completely dry and at least partly wet soil profile (g, h, i) over three sites in the central Central Plains along the same parallel (Fig. 1). The eastern area (A. Ames) is the most humid (left column), the center is semi-arid (B. Ord), and the western area is arid (C. Alliance West) (right column). The RPFs were calculated for the present climate (1985-2005) and those expected in 2100 based on outputs of HadCM and NCAR-PCM global circulation models and two sets of climate sensitivities (HI = high, assuming a 4.5°C increase per doubling of CO_2 concentrations; MID = medium, assuming a 2.5°C increase).

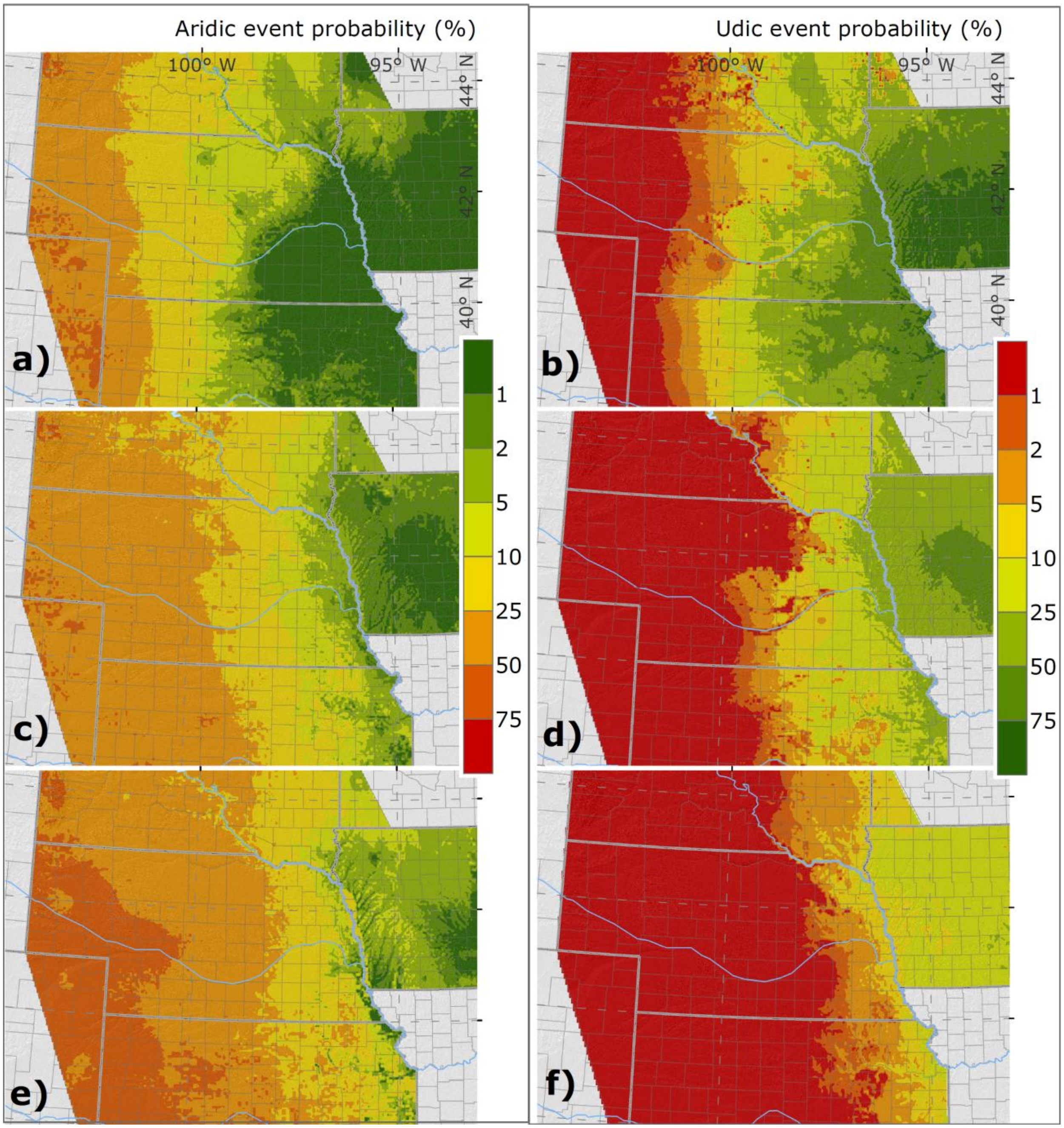

Figure IV: a,c,e: Probabilities of an Aridic season (i.e., an extremely dry year with completely dry soil profile) over the Central Plains study area under present climate conditions (1985-2005) and those expected in 2100 based on the outputs of HadCM global circulation model and two sets of climate sensitivities (HI = high, assuming a 4.5°C increase per doubling of CO_2 concentration; MID = medium, assuming a 2.5°C increase). b, d, f: The same as above for the case of a Udic season (i.e., a very wet year with an at least partly moist profile over the entire year).

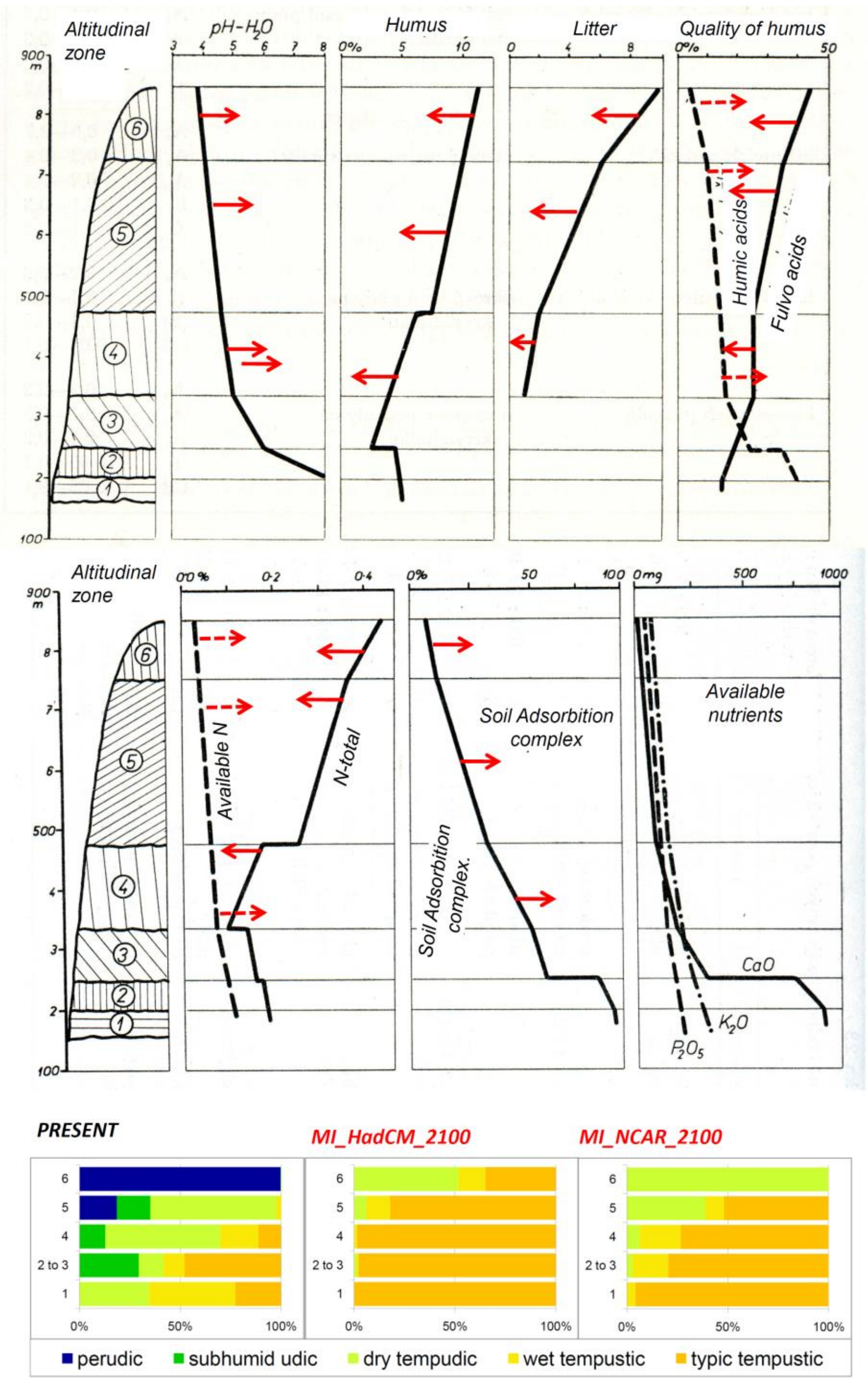

Figure V: Relationship between the altitudinal zone and key soil properties of forestry soils within the study sub-region (marked by white on the Fig. 1b) based on the experimental datasets of Pelíšek (1966), indicating the (a) altitudinal dependence of pH and organic matter and (b) nutrient availability. The arrows within (a) and (b) show the anticipated trends. The proportion of individual hydric regimes within each zone under the present climate conditions and those expected in 2100 using HadCM- and NCAR-based projections is shown in (c). Note: Altitudinal zones include the following: (1) gleyic soils (180-200 m), (2-3) chernozems and dark brown soils (200-350 m), (4) lowland podzolic soils (350-500 m), (5) brown soils (500-750 mm) and (6) humid podzols (above 750 m).