ARTICLE IN PRESS

Agricultural Water Management xxx (xxxx) xxx

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Projection of 21st century irrigation water requirements for sensitive agricultural crop commodities across the Czech Republic

V. Potopová[a,b,*,1], M. Trnka[b], A. Vizina[c,e], D. Semerádová[b], J. Balek[b], M.R.A. Chawdhery[a], M. Musiolková[a], P. Pavlík[c,e], M. Možný[a,b], P. Štěpánek[b], B. Clothier[d]

[a] Czech University of Life Sciences Prague, Department of Agroecology and Crop Production (Meteorological Section), Czech Republic
[b] Global Change Research Institute of the Czech Academy of Sciences, Brno, Czech Republic
[c] TGM v.v.i. T.G. Masaryk Water Research Institute, p.r.i., Czech Republic
[d] The New Zealand Institute for Plant and Food Research Limited, New Zealand
[e] Czech University of Life Sciences Prague, Department of Water Resources and Environmental Modeling, Czech Republic

ARTICLE INFO

Handling Editor - Xiying Zhang

Keywords:
Crop water consumption
Crop-specific irrigation requirements
Water use indicators
Orchards
Vineyards
Hop gardens
Vegetables
Fodder

ABSTRACT

This study quantified the crop water consumption, crop-specific irrigation requirements, and availability of water resources to catchments under climate change in the Czech Republic (CZ). Within the SoilClim model and BILAN-WATERES hydrological water balance modeling process, we tried to answer the question of whether there are at least theoretical water resources in the individual catchments of the CZ that could cover possible higher demands for irrigation. An ensemble of five global climate models under the moderate representative concentration pathway (RCP4.5) from the EURO-CORDEX initiative was chosen to project the future water use indicators. The irrigation water requirement indicators for the growing season (GS) of vineyards, hop gardens, orchards, vegetables, and fodder crops were calculated in 1143 catchments for two periods, 2031–2050 (Sc1) and 2061–2080 (Sc2), compared to the observed period 1961–2020 (Obs). To project irrigation scenarios in agricultural water management, the following water use indicators were quantified: relative soil moisture at 0–40 cm (*AWR1*) and 0–100 cm (*AWR*), crop water balance (*Rain-ET$_a$*), irrigation water requirement (*Irrig*), and the ratio of actual and reference evapotranspiration (ET_{ratio}). To assess areas with a critically low water supply and quantify the frequency of water deficit during the GS of each crop, we calculated the number of days with extreme values of water use indicators. Quantification of the extreme irrigation characteristics reflected the highest depletion of soil moisture and the highest water demands, i.e., when the assessed indicators reached the 25th percentiles. For highly marketable vegetables, the largest deficit in *Rain-ET$_a$* during the GS for Sc1 was projected. If current vegetable growing areas and cropping systems remain unchanged, *Irrig* will increase by 10.2% by the end of the 21st century under RCP4.5. Although current potato planting areas have soils with a high available water capacity, they will become controlled by the water deficit over the next few decades. The accumulated vineyard water required suggests that 15% and 25% of irrigation water will be lost by evaporation from the soil surface during the 2030s and 2080s, respectively. However, changes in future hopyard irrigation extent and amounts may have important implications in largely cropped irrigation hotspots. In the main traditional hop region for the 2030s, we project a 25% depletion of soil moisture and an increase of $ET_{ratio} < 0.4$ by up to 5.3%. The projection of a high frequency of days with an $ET_{ratio} < 0.4$ and $AWR1 < 30\%$ for fodder crops was related to the most risk-prone areas with an extreme lack of moisture in the regions with the most developed animal production. Thus, there will be insufficient fodder supply to the livestock sector due to any water stress during the production season under climate change conditions.

* Correspondence to: Department of Agroecology and Crop Production (Meteorological Section), Czech University of Life Sciences Prague, Prague, Czech Republic.
E-mail address: potop@af.czu.cz (V. Potopová).
[1] https://home.czu.cz/en/potop/home.

https://doi.org/10.1016/j.agwat.2021.107337
Received 28 July 2021; Received in revised form 3 November 2021; Accepted 6 November 2021

Please cite this article as: V. Potopová, *Agricultural Water Management*, https://doi.org/10.1016/j.agwat.2021.107337

1. Introduction

Irrigation is a crucial activity for global food production and regional economies (Thiery et al., 2017) and is responsible for 40% of the world's food supply (Cody, 2018). Approximately 70% of global water consumption is used for irrigation of crops (Wisser et al., 2008), and harmonization of water requirements with limited water resources is a significant political dilemma (Grafton et al., 2018). Water-saving irrigation has benefits for climate change mitigation and adaptation as well as for sustainable economic development (Zou et al., 2013; Thiery et al., 2020). Irrigation water demand has increased in recent decades (Drastig et al., 2016; Wang et al., 2019) in connection with anthropogenic climate change. Water requirements for crop irrigation are likely to increase with considerable regional variation, and irrigation requirements might increase to such an extent that established regional agricultural practices might be challenging to retain in some regions (Riediger et al., 2016; Wang et al., 2016). Excessive irrigation leads to drainage problems, so reduced irrigation strategies need to be implemented to protect water resources (Mondaca-Duarte et al., 2020). For example, the Mediterranean region could save 35% of water by implementing more efficient irrigation and conveyance systems (Fader et al., 2016). At the same time, irrigation influences many land components; it modulates the terrestrial water budget (Shah et al., 2019) and affects local hydrological and energy cycles (de Vrese et al., 2016) as well as weather and climate conditions (Chen et al., 2018; Cook et al., 2015), especially hot extremes (Thiery et al., 2020; Potopová et al., 2021a, 2021b). While global warming increases the likelihood of hot extremes almost globally, irrigation can regionally cancel or even reverse the effects of all other forcing combined (Cook et al., 2015; Chen et al., 2018). It seems likely that demand and supply can be brought into a sustainable balance only by changing and moderating the pattern of requirements, by introducing new sources of supply, or both (Cody, 2018).

Earlier studies (Dusenge et al., 2019) have already described the effect of elevated CO_2 on plant growth as a result of climate change, but the effects on crop water use and water use efficiency are less studied (Lenka et al., 2020, 2021). Few studies have projected future impacts of climate change, land-use change, and changes in water consumption on water resources for the European continent (Schaldach et al., 2012; Bisselink et al., 2020). Wriedt et al. (2009) simulated irrigation water requirements in Europe, taking into account the spatial distribution of crops, soil conditions, climate, and crop management. Riediger et al. (2016) modeled a generally increasing water demand with increasing temperatures in the Northern German Plain that is most likely of equal relevance for central European regions. Southern European countries are projected to face decreasing water availability (Sordo-Ward et al., 2019; Potopová et al., 2019, 2020). Central and Northern European countries show increasing annual water availability (van Vliet et al., 2015), but projected temperature and precipitation changes show large subannual variability (Trnka et al., 2015a, 2015b, 2020; Žalud et al., 2017; Zahradníček et al., 2020). Therefore, a seasonal assessment of both water availability and demand should be undertaken for farmland management (Pfister et al., 2020). Regional implications of global climate change will likely affect evapotranspiration, which is an important aspect of crop cultivation and the most important influence on irrigation requirements for central European regions. Even today, compound climate events and less-developed irrigation systems are significant issues in the agriculture of the Czech Republic (Trnka et al., 2014; Duffková et al., 2019; Potopová et al., 2021a, 2021b; Balvín et al., 2021). The required amount of irrigation water depends on how much water the cultivation of a particular crop type requires and how much water is available from local sources (El-Naggar et al., 2020). Therefore, irrigation requirements estimated by independent modeling approaches will be useful to assist in irrigation planning and water management at high spatial resolution with large geographical coverage. Recently improved detail in water use scenarios (Nadal and Flexas, 2019), which foreshadow possible future water consumption in Europe (Bisselink et al., 2020), further open new opportunities for an integrated assessment of water resources (Machlica et al., 2012; Hanel et al., 2014; Melišová et al., 2020; Vyskoč et al., 2021).

Large-scale irrigation modeling to investigate water availability has made significant progress in recent years (e.g., Perea et al., 2018; Dang et al., 2020), and there is still a need to better assess future crop water consumption. Two different modeling frameworks have been applied to analyze their suitability for simulating time series of crop-specific irrigation requirements. The first framework refers to soft-coupling a dynamic vegetation model with a land-use model (Yalew et al., 2018), whereas the second framework relies on conceptual modeling of crop evapotranspiration (Zhao et al., 2019). Bastiaanssen et al. (2007) provide a comprehensive overview of the state-of-the-art of irrigation modeling by many methods. Direct observations are often used for comparison of measured temperatures and precipitation within different areas or seasons and evaluation of spatial-temporal changes (e.g., Fowler and Helvey, 1974) or an assessment of crop yields (Kresovic et al., 2014). Models and simulations are commonly used to study the influence of different parameters on complex systems (de Vrese and Hagemann, 2018). For example, the effect of irrigation on hydrology (Sorooshian et al., 2014), the effects of climate change, climatic variability, and water trade on irrigation operations (King et al., 2019), the influence of heatwaves on vegetation (Boeck et al., 2016), irrigation water requirements (Döll and Siebert, 2002) and crop coefficients (Mahmoud and Gan, 2019) can all be studied by different types of models. The results of these analyses can be used, for example, for planning and management of sustainable water use in different regions (Mahmoud and Gan, 2019) or for adopting policy responses to reduce climate change impacts (Wang et al., 2016). The influence of irrigation on vegetation health and land surface temperature (Ambika and Mishra, 2019) or the spatial and temporal distribution of evapotranspiration (Mahmoud and Gan, 2019) can also be studied by remote sensing methods.

The effect of the management system on irrigation efficiency largely depends on the socioeconomic factors of the country. In the Czech Republic (CZ), the water management system is marked by intensive agriculture, large settlement, and intensive human activities as well as by extensive artificial modifications of watercourses and floodplains. Although there are 76,000 km of watercourses in total, of which approximately 15,300 km is important for the management of water resources and approximately 60,700 km of other small watercourses, the majority of watercourses drain into neighboring states. Moreover, the long-term fluctuations in climatic variables are reflected in the variabilities of river streamflow and water level that have relatively short residence times. Therefore, **our hypothesis** assumes that the current and future available water resources are not sufficient for optimal crop growth with the highest water requirements according to their water demand in the CZ. The main aim was to project the water demands and irrigation strategies for vineyards, hop gardens, orchards, areas with vegetables and fodder crops under climate change at the catchment level. The objectives of this study were (i) to project water needs to cover the moisture deficit and water need to ensure stable yields of fodder, orchards/vineyards, hop gardens, and vegetables for two periods, 2031–2050 (Sc1) and 2061–2080 (Sc2), compared to the observed period 1961–2020 (Obs), (ii) to identify deficit areas and distribution of water needs for the growing season (GS) of 15 crops, (iii) to quantify the extreme irrigation characteristics to reflect the highest depletion of soil moisture, the most negative water balance and the highest water demands for the Obs, Sc1 and Sc2 periods, and (iv) to quantify the availability of water resources to catchments and the contribution of the use of irrigation systems to mitigate the effects of drought.

2. Target area and their irrigation system

The target area of this study is the CZ, a dry-warming country in central Europe with a less developed irrigation system. Alterations in water deficit and water excess events are becoming common, even during the same year (e.g., 2020), and the balance between water supply and demand is becoming fragile. According to the predictions of the models under RCP4.5, the lowest precipitation totals for various recurrence intervals of 5 yr were 170 mm for the 2041–2060 period, whereas the highest precipitation totals for 100 yr were 311 mm for the 2021–2040 period (Dolák et al., 2017). The improvement of drainage and irrigation systems, the conservation of water, and the use of water-saving technologies seem to be crucial for farmers' adaptation measures. Therefore, we aim to provide new results about interactions between irrigation and farming systems for the current and future climate over the CZ. Approximately 160,000 ha of irrigation is built in the fertile and driest areas of the country, of which 88,000 ha is in Czech lands and 72,000 ha is in Moravia. The national irrigation system is usually limited to crops that cannot be grown without irrigation or that gain more value through irrigation (vegetables, early potatoes, hops, orchards, and vineyards). The sprinkler irrigation system dominates, but approximately 4000 ha of drip irrigation is applied for vegetable crops. Most of the irrigation systems (approximately 127,000 ha) were privatized in 1997 and 1998. At present, approximately 40% of the original extent of irrigation systems is in use while the remaining portion is not operated. The water demand was evaluated in the irrigated grid area for the following crops: potatoes, garlic, onion, carrot, peppers, cucumbers, cauliflower, cabbage, apple trees, peaches, cherries, apricots, alfalfa for hay and hop. The GS of crop growth when an adequate supply of water is critical for high-quality production is shown in Table 1, where we have also classified crop irrigation needs. This selection covers highly water-demanding crops with high economic returns per unit of land and thus offers promising prospects regarding income. The study used a catchment area (UPOV) as a basic water management unit. The UPOV areas belong to medium-sized catchments (100–1000 km^2). Integration of crop water requirements, water supply, and specific cropland use under the present and future climates was aggregated for 1143 catchments. Information regarding the land cover relies on the Corine land cover 2015–2020 dataset.

3. Data and methods

The entire study was based on a cascade of models (Fig. 1a,b) that utilized a carefully compiled, quality controlled, and homogenized dataset of daily meteorological data from 268 climatological and 787 rain gauge stations of the Czech Hydrometeorological Institute for the period 1961–2020. These data combine all key weather variables, including daily mean, 2 pm, maximum and minimum temperatures [°C]; daily mean air relative humidity [%]; precipitation [mm day^{-1}]; global solar radiation [MJ-m^{-2} day^{-1}] and wind speed [m s^{-1}], as they are used in the national drought monitoring system (CZ: last accessed 15 October 2021), covering the whole CZ with daily weather inputs interpolated to 500 × 500 m grids. For each gridpoint, land use was considered and data on slope and land exposure were taken into account in radiation and energy balance calculations. For each gridpoint, data on retention capacity in the individual layers, soil depth, and possible impact of groundwater were also available. Meteorological and grid-specific data were used in the SoilClim model to estimate soil moisture and irrigation requirements on a 500 m grid. These were then aggregated for each UPOV and used as input for the BILAN-WATERES hydrological models, which in turn estimated the water available for irrigation.

The final procedure required to generate water requirements at the catchment level for the present and future climate is captured in Fig. 1a, b. To estimate the potential of irrigation water needs at the UPOV level, the following items are required: (i) knowledge of the crop composition, which will be irrigated ideally to the level of the soil block or at least at the level of the catchment area; (ii) the optimal composition and distribution of crops in individual catchments and soil blocks; and/or (iii) the optimal use of available water resources; however, in that case, it is necessary to allocate moisture water for individual river basins or set priorities for its distribution (e.g., the lowest catchment areas have the highest priority).

The following daily series of irrigation water requirements indicators were calculated for 1143 catchments: reference evapotranspiration (ET_o, mm), actual evapotranspiration (ET_a, mm), growth coefficient (K_c), relative soil moisture 0–40 cm (AWR1, %), and 0–100 cm (AWR, %), crop water balance (Rain-ET_a, mm), irrigation water requirement (Irrig, mm), and the ratio of actual and reference evapotranspiration (ET_{ratio}). The indicators used here were the average values from all catchments at the median and 5th, 10th, 25th, 75th, 90th, and 95th percentiles for 1961–2100, Obs, Sc1, and Sc2. Future trend magnitudes of water use indicators were estimated by a nonparametric Mann-Kendall trend ($p\ value < 0.05$, same hereafter). We averaged the magnitude of changes across a range of ensemble models to reduce the effect of natural variability.

3.1. Quantification of crop water balance under irrigated areas

To evaluate differences between the crop water availability and the atmospheric water demand for each crop, we applied the SoilClim tool (Hlavinka et al., 2011). The SoilClim model is based on one of the most frequently used approaches to irrigation scheduling by Allen et al. (1998), which has been adopted for Czech conditions with some additional features, e.g., snow cover model, modification of bucket approach, phenologically dependent K_c and root depth values added (e.g., Hlavinka et al., 2011; Trnka et al., 2020). Similar to the original work by Allen et al. (1998), in this study: (i) ET_o was calculated by the Penman-Monteith method, (ii) daily ET_a for each crop was calculated by multiplying K_c and ET_o, and (iii) differences between daily precipitation and ET_a were used to calculate crop water balance (Rain-ET_a).

To determine the period of the highest crop water consumption (Table 1), ET_a was expressed as follows:

$$ET_a = ET_{a1} + ET_{a2} \quad (1)$$

$$ET_a1 = ET_o \cdot K_c \cdot K_s1 \cdot Ratio1 \quad (2)$$

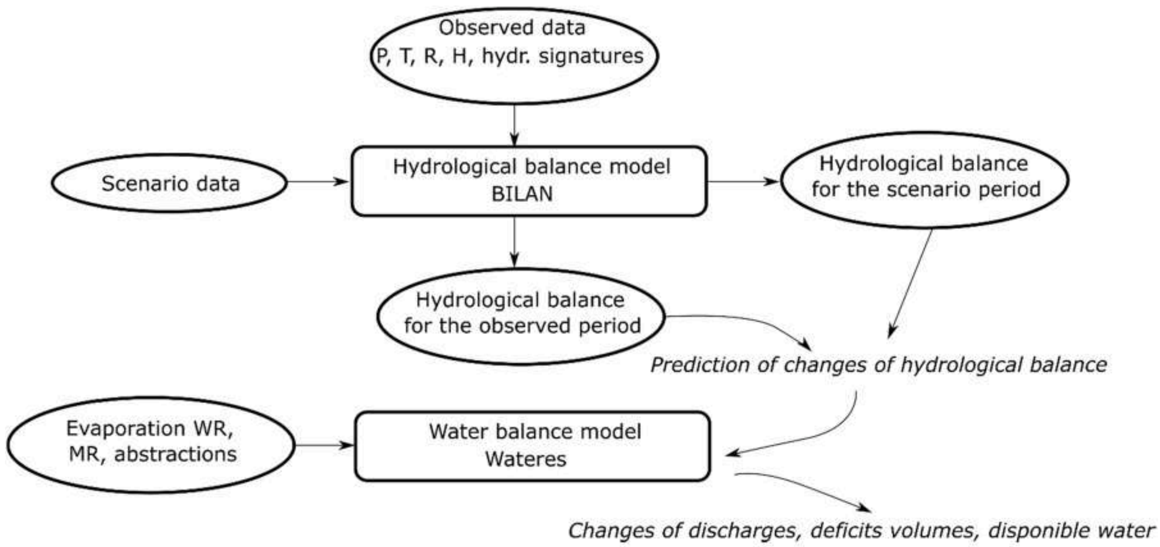
$$ET_a2 = ET_o \cdot K_c \cdot K_s2 \cdot Ratio2 \quad (3)$$

where ET_a1 and ET_a2 are the values of actual evapotranspiration from the top layer and rootzone layer; ET_o is the value of reference evapotranspiration; K_c is the coefficient describing the properties of the crop canopy and its phenological stage (i.e., crop height and the leaf area

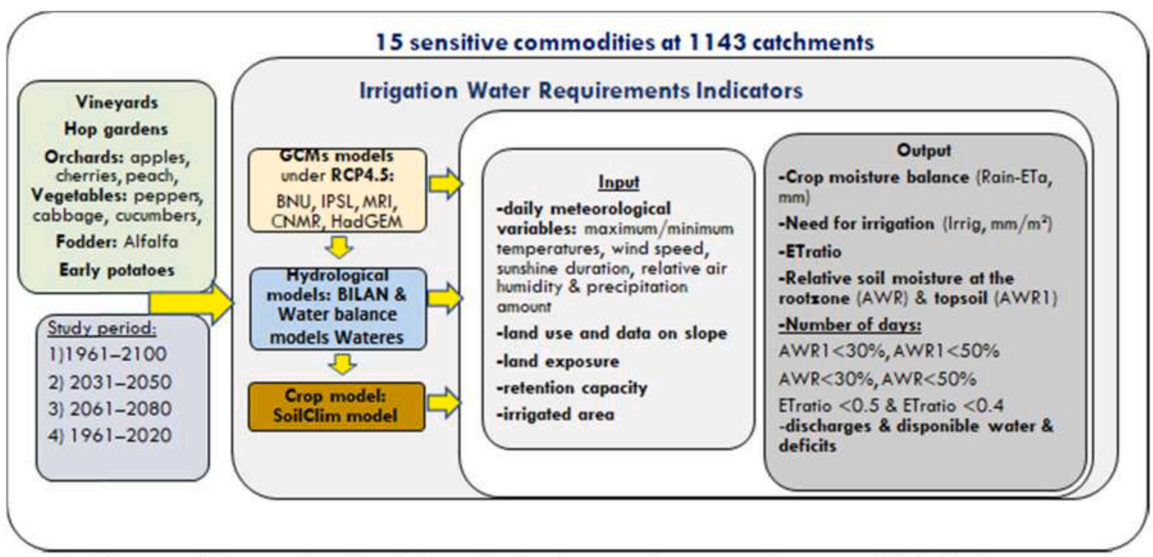
Table 1
The beginning and end of the growing season (GS) of crops and their water requirements.

Crop types		GS Start Day	GS End Day	Water requirement [m^3/ha][a]
1. Early potatoes	*Solanum tuberosum* L.	105	250	2000
2. Garlic	*Allium sativum* L.	304	196	2000
3. Onion	*Allium cepa* L.	70	240	2000
4. Carrot	*Daucus carota* L.	75	225	2900
5. Peppers	*Capsicum annuum* L.	135	260	3000
6. Cucumbers	*Cucumis sativus* L.	120	225	4000
7. Cauliflower	*Brassica oleracea* L.	110	220	3600
8. Cabbage	*Brassica oleracea* L. convar. *capitata*	105	250	3200
9. Apples	*Malus domestica* L.	70	310	5000
10. Cherries	*Prunus avium* L.	70	310	4000
11. Apricots	*Prunus armeniaca* L.	70	310	3500
12. Peach	*Prunus persica* L.	70	310	5000
13. Alfalfa for hay	*Medicago sativa* L.	100	265	3800
14. Vineyard	*Vitis vinifera* L.	100	310	3200
15. Hop yard	*Humulus lupulus* L.	100	255	3500

[a] Water requirement values.



a Scheme of hydrology modeling Bilan (P - precipitation, T - temperature, R - runoff, H - humidity) and water balance modeling Wateres (WR - water reservoir, MR - manipulation rules).



b. Diagram of the cascade of models used in the framework concept of crop-specific irrigation requirements.

Fig. 1. (a) Scheme of hydrology modeling Bilan (P - precipitation, T - temperature, R - runoff, H - humidity) and water balance modeling Wateres (W*R* - water reservoir, MR - manipulation rules). (b) Diagram of the cascade of models used in the framework concept of crop-specific irrigation requirements.

index) concerning reference grassland; K_s is the soil water stress coefficient expressed as K_s1 and K_s2 according to the availability of soil water for evapotranspiration topsoil layer and subsoil layers; and Ratio1 and Ratio2 are the shares of water absorption from the topsoil and subsoil layers (according to the relevant crop root depth).

The crop coefficient K_c was defined based on the crop coefficient approach with possible modifications as a function of growing degree days (GDD). The crop coefficient K_c was formulated by the following Eq. (4):

$$K_c = K_{c(tab)} + [0.04\ (u_2 - 2) - 0.004\ (RH_{min} - 45)]\ (\tfrac{h}{3})^{0.3} \tag{4}$$

where $K_{c(tab)}$ was the value of $K_{c,ini}$, $K_{c,mid}$ or $K_{c,end}$; RH_{min} was the mean daily minimum relative humidity (%) for both mid-season or late stages; and h was the mean crop height (m) during the growing stages (in mid-season and late season).

The soil water stress coefficient K_s was estimated in SoilClim (Hlavinka et al., 2011) using the FAO-56 (1998) approach. The K_s standard equation is given below:

$$K_s = 1 \text{ for } \Theta i > RAW \tag{5}$$

$$Ks = \frac{TAW - D}{TAW - RAW} = \frac{TAW - D}{(1-)TAW} \quad \text{for} \quad \Theta i < RAW \tag{6}$$

where TAW (Θ_{fc}-Θ_{wp}) was the total available soil water; RAW (p TAW) was the readily available soil water; D (Θ_{fc}- Θ_i) was the soil water depletion; p was the fractional part of the soil water that could be absorbed by the crop without any water stress (soil water depletion fraction for no stress); Θ_{fc} ($m^3\ m^{-3}$) and Θ_{wp} ($m^3\ m^{-3}$) were the soil water content at the field capacity and the permanent wilting point, respectively; and Θi ($m^3\ m^{-3}$) was the actual soil water content. The p has been derived during calibration of the SoilClim model and set at 0.3 for top layer and 0.2 for the lower soil layer based on the experimentally data driven SoilClim model calibration runs (Hlavinka et al., 2011).

The Ratio1 and Ratio2 were based on the experimental data collected by SoilClim team (Hlavinka, pers. comm) and accounting for available studies (e.g. Fan et al., 2016). The ratio for the crops and non-perennials differed based on the phenological development, while it has been held constant for perennial cultures (e.g. orchards, grape-wine).

SoilClim dynamically simulates the vegetation cover and considers changes in its parameters in daily time steps (e.g., changing the rooting depth or crop height in the case of crops or the presence/absence of leaves in the case of deciduous trees). The changes are driven by the GDD and vernalization requirements (depending on the crop cover type). Therefore, the crop parameter K_c (Allen et al., 1998) and the root growth dynamics vary for individual vegetation covers throughout the year (or the vegetation season). For instance, the values for K_c in Fig. S1 are values for nonstressed crops cultivated under excellent agronomic and water management conditions and achieving maximum crop yield. The establishment of individual K_c parameters as well as water requirements in this study followed obligatory technical standards (Czech State Standard, 1994), which are mandatory, e.g., for irrigation project building permits or water-withdrawal permit requests (Tables 2, 3).

The Rain-ET_a in the SoilClim model was calculated for each grid with a resolution of 0.5 km x 0.5 km throughout the CZ. Then, the results were aggregated into cadaster units, which represent the smallest administrative area in the CZ. The calculation was limited to grids with agricultural land or irrigable grids for the GS of each crop as well as the time series of *Rain-ET_a* for individual years under optimal growth conditions (*Rain-ET_{a50}*) and drought conditions (*Rain-ET_{a10}* and *Rain-ET_{a20}*) for the current and future climates.

3.2. Quantification of irrigation water requirement

We quantified the potential *Irrig* (mm/m^2) for each crop GS for the current and future climates. All calculations of *Irrig* were performed at the level of individual grids in a daily step, and an irrigation dose was applied whenever the saturation of the current root layer fell below 30% retention capacity, i.e., the lower limit was reached. Subsequently, from the area of selected grids with irrigation, we calculated the sum of water that must be supplied in the topsoil (0–40 cm; AWR1) and rootzone (0–100 cm; AWR) layers. The abbreviation AWR stands for the relative content of plant-available water and is expressed in % where 0% is reached at the wilting point and 100% at field capacity. The root depth during GS was dynamically simulated by a crop growth model that was incorporated into SoilClim. The soil moisture available to plants was calculated as the difference between soil moisture at field capacity and wilting point multiplied by layer depth. The indicators of AWR1 $\geq$ 50% and AWR $\geq$ 50% were calculated as "productive" irrigation, while AWR1 $\geq$ 30% and AWR $\geq$ 30% were calculated as "maintenance" irrigation, i.e., ensuring the survival of the commodity. A special regime was used for weeks when the value of the irrigation efficiency factor taken from the Czech State Standard (1994, Table S1) for a given week and a given crop indicated an efficiency factor higher than 40 (which means a significant effect of irrigation on economic yield). This means that the AWR1 and AWR for the whole GS are always greater than 0.3, and if the irrigation efficiency is greater than 40 mm each week, the soil moisture level is kept at a level equal to or greater than 0.5. In these cases, the saturation of the root layer was maintained at least 50%. Irrigation designed in this way would be relatively very effective. The frequency of soil dry days is defined as AWR1/AWR $< 50\%$.

Table 2
Overview of the Kc parameters as reference values used in the SoilClim model.

Crop type	Kc ini	Kc mid	Kc end	Height at MID (m)	Height at END (m)
Apricots / peaches / cherries	0.45	0.90	0.65	3.0	3.0
Apples	0.45	0.95	0.70	4.0	4.0
Vineyards	0.30	0.70	0.45	1.8	1.8
Hopyards	0.30	1.05	0.85	5.0	5.0
Alfalfa	0.40	1.20	0.90	0.7	0.2
Carrot	0.70	1.05	0.95	0.3	0.0
Sweet peppers (bell)	0.60	1.05	0.90	0.7	0.0
Cucumbers	0.60	1.00	0.75	0.3	0.0
Cabbage / cauliflower	0.70	1.05	0.95	0.4	0.0
Garlic	0.40	1.00	0.70	0.4	0.1
Potatoes	0.50	1.15	0.75	0.6	0.0
Onion	0.20	1.05	0.70	0.4	0.1

Table 3
The shares (%) of water absorption from the 0–40 cm soil layer used in the SoilClim model according to the kind of crop root depth.

Crop type	Ini (%)	Mid (%)	End (%)	Interim (%)	Depth of roots (m) in Mid growth phase Allen et al. (1998)
Apricots / peaches / cherries	0.60	0.60	0.60	0.60	1.0–2.0
Apples	0.60	0.60	0.60	0.60	1.0–2.0
Vineyards	0.99	0.60	0.90	0.99	1.0–2.0
Hopyards	0.99	0.80	0.90	0.99	1.0–1.2
Alfalfa	0.90	0.80	0.80	0.90	1.0–2.0
Carrot	0.99	0.90	0.99	0.99	0.5–1.0
Sweet peppers (bell)	0.99	0.85	0.99	0.99	0.5–1.0
Cucumbers	0.99	0.80	0.95	0.99	0.7–1.2
Cabbage / cauliflower	0.99	0.90	0.99	0.99	0.5–0.8 / 0.4–0.7
Garlic	0.99	0.95	0.99	0.99	0.3–0.5
Potatoes	0.99	0.90	0.99	0.99	0.4–0.6
Onion	0.99	0.90	0.99	0.99	0.3–0.6

3.3. Quantification of the ratio of actual and reference evapotranspiration

The ratio of actual and reference evapotranspiration (*ET_{ratio}*) provided basic information on the potential water deficit and its course within the GS for the entire territory of the CZ. We focused on the quantification of *ET_{ratio}* for each crop during current and future climates. We calculated the long-term time series for individual years, normal years, and 5-yr and 10-yr droughts, i.e., in the sense of the highest water demands.

3.4. Estimating the number of days with required irrigation

To quantify the frequency of water deficit during GS that may result in drought, the number of days where ET_{ratio}, AWR1, and AWR met specific threshold criteria was calculated. The number of days with an $ET_{ratio} < 0.4$ was chosen as the indicator of drought stress, i.e., a state where we can assume a significant lack of moisture in the root layer and the soil moisture content is below the point of reduced availability; therefore, plant growth is beginning to be limited by water. To express the available soil moisture for each crop in the root layer of the soil, the number of days with AWR1 $<$ 30%, AWR1 $<$ 50%, and AWR $<$ 30%/ AWR $<$ 50% was calculated. To assess areas with critically low water supply, GIS-based high-resolution mapping of the spatiotemporal dynamics of the number of days for AWR1 $<$ 30%, AWR1 $<$ 50%, AWR $<$ 30%, and AWR $<$ 50% was applied. The results were processed as average overall catchments as the 10th and 25th percentiles for Obs, Sc1, and Sc2 (*$AWR1_{10} < 30\%$, $AWR1_{10} < 50\%$, $AWR_{25} < 30\%$,* and *AWR25 <50%,* in the sense of the highest depletion of soil moisture).

3.5. Estimating the availability of water resources to catchments

This section describes the stepwise iterative calculation of irrigable areas for selected commodities. The available water sources were estimated daily based on the BILAN-WATERES hydrological models (Vizina et al., 2015; Melišová et al., 2020). This model runs in daily steps with precipitation, mean temperatures, and humidity as necessary inputs. Time series of total runoff (direct runoff plus baseflow), actual evapotranspiration, soil moisture and groundwater storage are among the outputs. A more in-depth description of the model can be seen in Melišova (2020). The site-specific outputs are routed using Muskingum-Cunge and dam operational rules in Wateres. The process flowchart is shown in Fig. 1a. The calculations considered the impact of both the water management system and real extractions and discharges. Compatibility between BILAN-WATERES and SoilClim parameters (e.g., available water in the soil) was ensured by common input parameters aggregated to the UPOV level. The BILAN model corresponds very well with soil profile moisture from the SoilClim model to a depth of 1 m. For better interpretability, the management of water resources and their availability were analyzed both at the level of individual catchments (i. e., each catchment manages only its resources) and at the level of systems (i.e., each UPOV has water resources obtained by optimized management within the water system). Areas with the highest quality soil will be selected as a priority for the implementation of irrigation. The available water in each catchment was divided into individual grids, and water was initially distributed to irrigable grids by the creditworthiness of the soil. If the water in the given catchment basin was sufficient to cover the requirements of all irrigable grids, the moisture was subsequently distributed to other grids according to the soil quality. Twenty percent of this available amount was subtracted to cover losses during the transport of water to irrigated land. Finally, the output of the calculation was a potentially irrigable area. The calculation for the sources of available water in each UPOV and subsequently at the eight subbasins (Upper and middle Labe (Elbe), Berounka, Upper Vltava, Lower Vltava, Lower Labe (Elbe) and Ohře, Odra (Oder), Morava and Dyje (Thaya)) was compared. The suitability of chosen crop cultivation in the given catchment area was not considered in the calculations.

3.6. *Estimating irrigation characteristics for 15 sensitive commodities under the future climate*

All future climate estimates were based on RCP4.5, which describes possible future changes under radiative forcing changing by 4.5 Wm^{-2} by 2100. Based on the validation of the individual global climate models (GCMs) from the CMIP5 database and regional climate from the EURO-CORDEX (Giorgi and Gutowski, 2015) initiative, the GCMs were found to better represent the climate projection uncertainty. Instead of using daily data from GCMs directly, the delta approach method (for more details, see Trnka et al., 2016) was used to obtain daily climate data for each 500 × 500 m grid for the 2031–2050 and 2061–2080 periods. The differences (deltas) between the control period and future projections of individual GCMs were used to modify the observed weather data series. This was done according to the methodology described by Dubrovsky et al. (2014). The RCP4.5 and climatic sensitivity of 3.0 °C were used. Out of the CMIP 5 database (Taylor et al., 2011) of 40 global circulation models, only five GCMs were used. The IPSL (Institute of Pierre Simone Laplace, France) was found to best represent the centroid of the future temperature and precipitation values over the territory of the CZ. The four remaining models were found through Dubrovsky et al.'s (2014) methodology to best capture the variability in the expected changes in precipitation and temperature (BNU – Beijing Normal University, China; MRI – Meteorological Research Institute, Japan; CNMR – National Centre for Meteorological Research, France and HadGEM – Hadley Center Global Environment Model, UK).

4. Results

4.1. *Patterns of crop water consumption and irrigation requirements under future climate change scenarios*

Changes in crop water consumption and irrigation water requirements under optimal growth conditions and drought stress in the Sc1 and Sc2 periods of the 21st century relative to the Obs period are averaged in Tables 4–6. The largest change in projected water use indicators for some commodities can be seen in Sc1, while the smallest change is seen in Sc2. Models project minor changes in the future soil moisture at the rootzone and topsoil across the country due to differences in climatic factors, soil properties, and crop types. Moreover, models tend to project a nonnegligible reduction in the relative soil moisture indicators in topsoil in drought years (Table 4). The AWR1 decreased for orchards, vineyards, hopyards, and fodder crops under mid-century conditions. Even in potato planting areas, the AWR1 was generally higher, yet the deficit of *Rain-*ET_a was higher than that of fodder crops. The frequency of days with a lack of soil moisture differs significantly among crops, with the highest for orchards and fodder crops (Fig. S2a–f). AWR1 < 50% ranged from 15 to 30 days in the Obs, 28–42 days for Sc1, and 32–48 days for Sc2 for orchards in the mean GS. The spatiotemporal distribution of crop water consumption (Fig. 2a–c) and irrigation water requirements (Fig. 2d–f) were also determined. The future water consumption of hopyards, apples, and vineyards was predominantly negative, which means that within the overall growing season, the *Rain-*ET_a was not sufficiently met and the assessed crops were exposed to water stress. Broadly similar anomalies with the highest frequency of drought stress days with $ET_{ratio} < 0.4$ (Fig. S3a–c) and $ET_{ratio} < 0.5$ (Fig. S3d–f) occurred for hopyards and vineyards, while the lowest number of days with drought stress occurred for vegetable commodities. Compared to nonirrigated crops, cherries, or apples, however, the water content in the deeper layers of the soil after irrigated vegetables is still higher due to the shorter growth time and shallower root system. Irrespective of scenario, onion (−50 mm) and cauliflower (−50 mm) presented greater water demand than the other vegetables. In the case of garlic, there was a reduction in water demands for both scenarios. The moisture deficit of carrots increases in traditional cultivated areas, which indicates that carrots have one of the highest water demands among the root vegetables (6500 m^3 ha^{-1}) and are susceptible to water shortages during the early development stages.

Positive values of *Irrig* indicate an increase in irrigation demands for the majority of the crops throughout the century (Tables 5, 6). Averaged results from five GCMs for orchards show that *Irrig* would increase by 14.5% in the 2030s (average for Sc1) and 10.2% in the 2080s (average for Sc2) relative to the observed period. *Irrig* for vineyards will increase by 8.2% in the 2030s and 4.4% in the 2080s. For hopyards, *Irrig* would change by 25% under Sc1, which is 2.2–3.5% more water than for vineyards. Over the 2030s, the increased *Irrig* under drought conditions would be larger in the hopyards, which is 2.2% more water than the observed period. For 2031–2050, there is a 50% chance that the extreme *Irrig* for vineyards will become 1.0–1.5 times that of Obs. Moreover, the required amount of *Irrig* was increased by 20% for losses in water transport by the valid Czech State Standard (1994).

4.2. *Trends of projection water use indicators*

The changes in trend magnitudes of water use indicators were comparatively higher during the 2030s than during the 2080s (Figs. 3, 4; Figs. S4–7). However, the results for some commodities were related to initially small decreasing trends (Sc1) followed later by large increasing trends (Sc2) in water use indicators. For an observed period, the trends of soil moisture at the topsoil of sensitive commodities were already decreased by up to 15%. However, there are significant differences between the magnitude of trends of individual commodities in the projection *AWR1* and *AWR* indicators. A statistically significant decrease in the trend of *AWR1* and *AWR* (−3.9 to −6.3%/10 yr) was detected during the GS of each crop by the 25th percentiles during the 2030s. The magnitude of the changes for the two future periods for the number of days with $AWR_{50} < 50\%$, $AWR_{25} < 50\%$, $AWR1_{50} < 50\%$, and $AWR1_{25} < 50\%$ exhibited an increase of up to 17%, which was linked to the steep decline in soil moisture (Fig. S6). Such behavior is closely

Table 4
Changes (%) in the relative soil moisture indicators at the topsoil (AWR1) and rootzone (AWR) under normal and drought conditions for the growing seasons of vegetables and potatoes for 2031–2050 (Sc1) and 2060–2080 (Sc2).

	Potatoes	Garlic	Onion	Carrot	Peppers	Cucumbers	Cauliflower	Cabbage
AWR1/AWR – median								
Sc1	- 2.0/– 1.3	+ 3.8/+ 2.6	- 3.9/– 2.2	- 2.0/– 0.7	- 1.4/– 1.2	- 1.4/– 0.4	- 0.2/– 0.2	- 1.5/– 0.6
Sc2	+ 1.1/+ 1.0	+ 1.5/+ 1.9	+ 1.3/+ 1.3	+ 1.0/+ 1.7	- 2.7/– 1.8	+ 2.6/0.4	+ 1.2/+ 0.2	2.7/0.2
AWR1/AWR – 25th percentile								
Sc1	- 5.5/– 2.4	+ 2.9/+ 1.2	- 6.7/– 6.3	- 2.9/– 1.5	- 1.8/– 1.3	- 2.6/– 1.9	- 1.7/– 0.7	- 2.7/– 1.6
Sc2	- 2.0/– 1.0	+ 1.8/+ 1.6	- 1.3/– 1.3	- 1.0/– 0.9	- 1.1/– 0.8	- 1.1/– 0.4	- 1.2/– 0.2	- 1.5/– 0.8
AWR_{50} < 50% / $AWR1_{50}$ < 50% – median								
Sc1	- 3.8/– 1.8	+ 1.6/+ 0.9	- 3.8/– 2.6	- 2.4/– 1.5	- 3.8/– 2.9	- 2.4/– 1.2	- 0.7/– 0.7	- 3.5/– 2.9
Sc2	- 1.7/– 1.2	+ 1.3/+ 0.4	- 1.9/– 2.0	+ 2.0/+ 1.5	+ 1.2/+ 1.6	+ 2.6/+ 1.8	+ 2.2/+ 2.0	+ 2.7/+ 0.2
AWR_{25} < 50% / $AWR1_{25}$ < 50% – 25th percentile								
Sc1	- 7.5/– 5.5	+ 0.9/+ 0.2	- 7.7/– 6.8	- 3.0/– 2.2	- 3.2/– 2.6	- 2.4/– 1.9	- 2.2/– 1.2	- 8.5/– 7.0
Sc2	- 3.2./– 2.0	+ 0.3/+ 0.3	- 3.3/– 2.5	- 1.8/– 1.5	- 1.6/– 1.6	- 1.5/– 1.4	- 1.2/– 0.2	- 1.7/– 1.2

Table 5
Changes (%) in the crop water balance (Rain-ET_a, mm) and irrigation water requirement (Irrig) under normal and drought conditions for the growing season of vegetables and potatoes during 2031–2050 (Sc1) and 2060–2080 (Sc2).

	Potatoes	Garlic	Onion	Carrot	Peppers	Cucumbers	Cauliflower	Cabbage
Rain-ET_a – median								
Sc1	-1.9	+ 4.1	-7.8	-2.5	-4.2	-5.6	-5.3	-8.5
Sc2	+ 0.6	+ 0.8	-2.8	-1.1	-0.5	-1.5	-1.3	-2.4
Rain-ET_a – 25th percentile								
Sc1	-11.1	-1.2	-15.0	-5.9	-6.9	-7.7	-6.8	-15.0
Sc2	-2.2	-0.1	-3.4	-2.3	-2.3	-2.4	-2.4	-3.3
Irrig – median								
Sc1	+ 1.0	-15.0	+ 1.8	+ 2.3	+ 0.6	+ 2.2	+ 2.0	+ 2.9
Sc2	+ 0.1	-0.5	-0.8	-0.5	+ 0.9	+ 1.0	+ 1.2	+ 0.5
Irrig – 75th percentile								
Sc1	+ 6.7	-2.1	+ 16.0	+ 4.6	+ 0.5	+ 5.5	6.6	+ 20.0
Sc2	+ 5.5	-0.8	+ 2.6	+ 1.9	+ 0.1	+ 1.6	+ 1.6	+ 1.8

Table 6
Changes (%) in the crop water balance (Rain-ET_a, mm) and irrigation water requirement (Irrig) under normal and drought conditions for the growing season of orchards (apples, peaches, cherries, and apricots), alfalfa, vineyard, and hopyard during 2031–2050 (Sc1) and 2060–2080 (Sc2).

	Apple	Cherries	Apricots	Peaches	Alfalfa	Vineyard	Hopyard
Rain-ET_a – median							
Sc1	-3.9	-1.1	-2.8	-2.5	-4.2	-1.6	-2.3
Sc2	-0.6	+ 1.1	+ 1.3	+ 1.6	-0.5	-0.5	-0.6
Rain-ET_a – 25th percentile							
Sc1	-18.1	-3.2	-4.8	-2.5	-6.8	-6.2	-9.8
Sc2	-2.0	-0.8	-1.3	-1.0	-2.3	-2.4	-2.4
Irrig – median							
Sc1	+ 3.0	+ 2.1	+ 2.0	+ 1.3	+ 2.6	+ 2.9	+ 3.0
Sc2	+ 1.3	+ 0.5	+ 0.9	+ 0.5	+ 1.3	+ 1.0	+ 1.2
Irrig – 75th percentile							
Sc1	+ 15.0	+ 3.1	+ 5.8	+ 2.6	+ 5.2	+ 7.5	+ 10.0
Sc2	+ 5.5	+ 1.2	+ 2.6	+ 1.9	+ 1.5	+ 2.6	+ 6.6

related to the increasing trends of warming (0.51–0.99 °C/decade) in daily soil temperature series at all depths and in all seasons in the CZ (Potopová et al., 2021a, 2021b), which was also linked to the sharp decline in soil moisture. Similar results have been found for trends of $ET_{ratio50}$ under optimal growth conditions and drought years with values of $ET_{ratio25}$.

Further water use indicators also identified a prevalence of moisture deficit (*Rain-ET_a*) under drought years by -20.0 mm and − 50.0 mm for orchards and vineyards, respectively, and by − 5.3 mm and − 40.0 mm for vegetables, respectively, for the 2030s compared to the observed period (Fig. 4a,b). The averaged results for apples, apricots, and peaches show that the magnitudes of *Irrig* trends in the mid-21st century would increase by 30 mm/decade. Comparing the *Irrig* results among crops, we identified two patterns (Fig. 4a,b). First, there is a generally stronger increase in irrigation water requirements for orchards, fodder, and hopyards than for vegetable and potato commodities due to longer GS lengths to fulfill the respective crop production goals. Second, analyzing each irrigation indicator separately, this *Irrig* trend is strengthened by the climate impact on soil-atmosphere drought conditions, which leads to increasing demand for the irrigated area.

4.3. *Spatiotemporal distributions of crop irrigation water requirements for sensitive commodities*

Key results of irrigation water requirements for 15 crops are mapped in Figs. 5–7. Using the multimodel mean, time series of irrigation characteristics of vegetables (garlic, onion, carrot, pepper, cucumber, cauliflower, and cabbage) for 1961–2020, 2031–2050, and 2061–2080 are mapped (Fig. 5a–f). Here, projected irrigation water requirements range from 10 mm per irrigated grid cell in the brassicas (cauliflower and cabbage) and root-producing (carrot) regions to 100 mm per irrigated grid cell in the fruiting-vegetable-producing region (pepper,

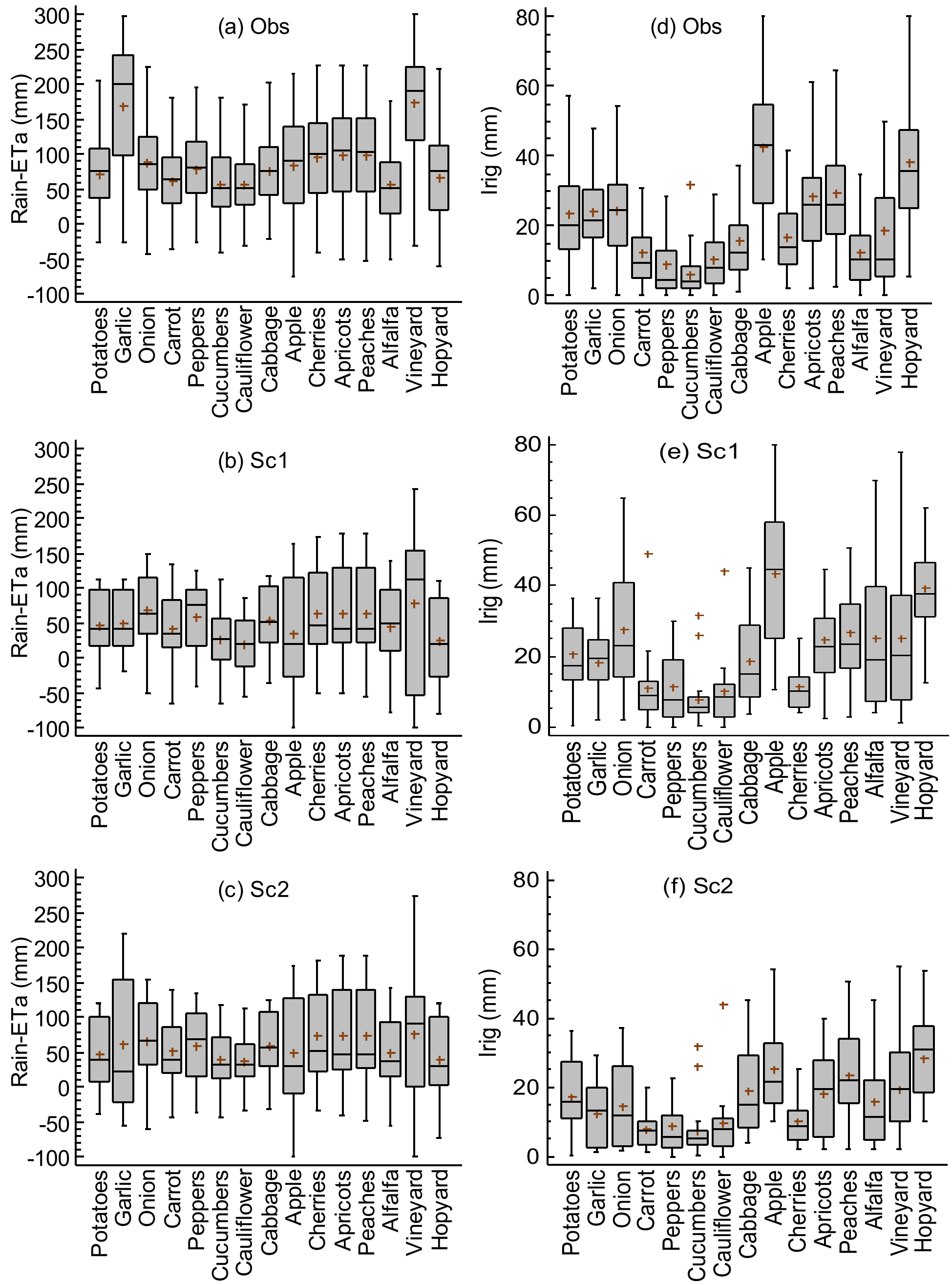


Fig. 2. The ranges of the crop water balance (Rain-ET$_a$) and irrigation water requirement (Irrig) for the growing season of each crop overall planting area for 1961–2020 (Obs), 2031–2050 (Sc1), and 2060–2080 (Sc2).

cucumber), which can be attributed to the spatial heterogeneity of climate parameters. We find that the potential irrigation areas increase in the brassicas and root-producing regions for 2031–2050. A more significant increase in $Irrig_{50}$ of the bulb vegetables was expected in all the cultivated regions, especially for garlic and onion, which reflects the predominantly rain-fed system of cultivation. The lowest ET_{ratio} was found to be the dominant type of adverse event for pepper and cucumber production regions due to its effect on increased soil water demand, which increased transpiration rates (Potopová et al., 2017), whereas changes in irrigation water requirements were associated with minimal increases (due to short growing season). Cauliflower and cabbage vegetables are widely irrigated, but irrigation does not fully mitigate drought effects; hence, $Rain\text{-}ET_{a50}$ variability largely controls crop production in growing catchments.

Although current potato planting areas have soils with high available water capacity, as apparent from Fig. 6a, early potatoes will become controlled by the water deficit over the next few decades. These changes will be driven by an increase in ET_{ratio} combined with low values of *AWR1* and *AWR*. A higher potato potential water deficit area was detected in the Berounka, Lower Vltava, Odra, Lower Labe, and Ohře River subbasins when $Rain\text{-}ET_a$ affected most potato production regions. The area of potatoes with a suboptimal soil moisture regime increased threefold to 25% in the 2031–2050 period, while the area of potatoes on soils with high available water capacity decreased.

Fig. 6b illustrates the spatial patterns of the most risk-prone areas for each of these irrigation indicators over vineyard production regions. For the mid-century, the greatest increases would occur in critical thresholds of the $Rain\text{-}ET_a$, ET_{ratio}, and *AWR1* for catchments of the middle and lower Labe, Berounka, the Ohře River, Odra River, Morava, and Dyje River basins. The results of $Rain\text{-}ET_a$ and ET_{ratio} are influenced by growth

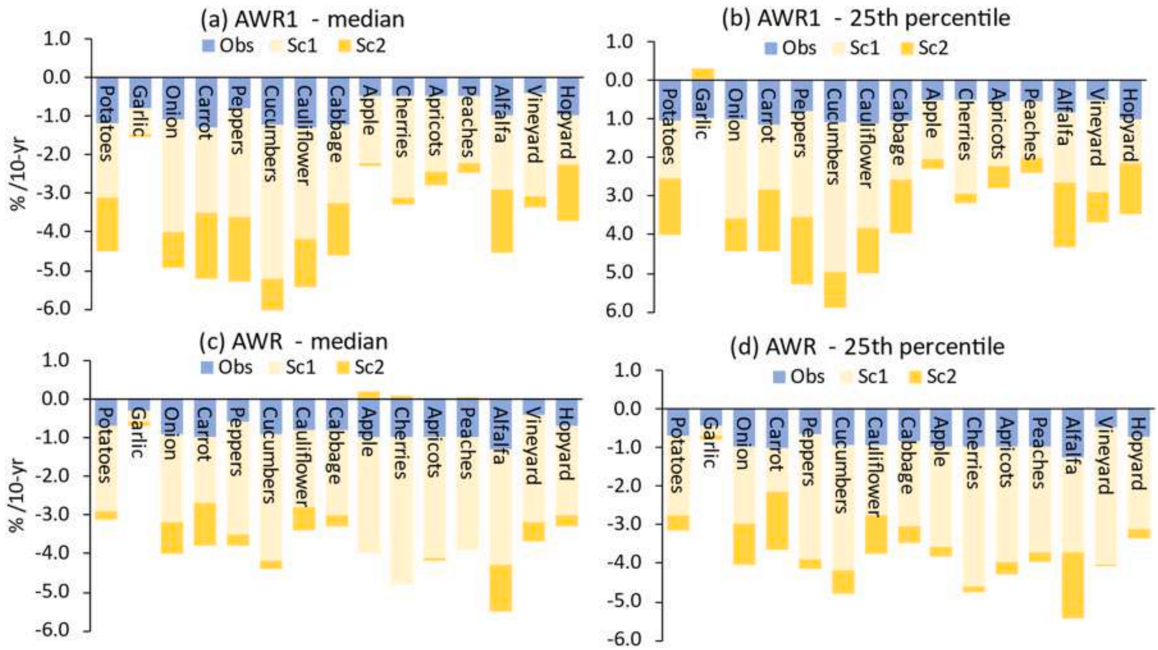


Fig. 3. The linear trends (%/10 yr) of the relative soil moisture in the topsoil when reaching the value of the median (a; AWR1) and 25th percentile (b; AWR1). The relative soil moisture at the rootzone of each crop when reaching the value of the median (c; AWR) and 25th percentile (d; AWR). Trends refer to the 1961–2020 (Obs), 2031–2050 (Sc1), and 2060–2080 (Sc2) periods.

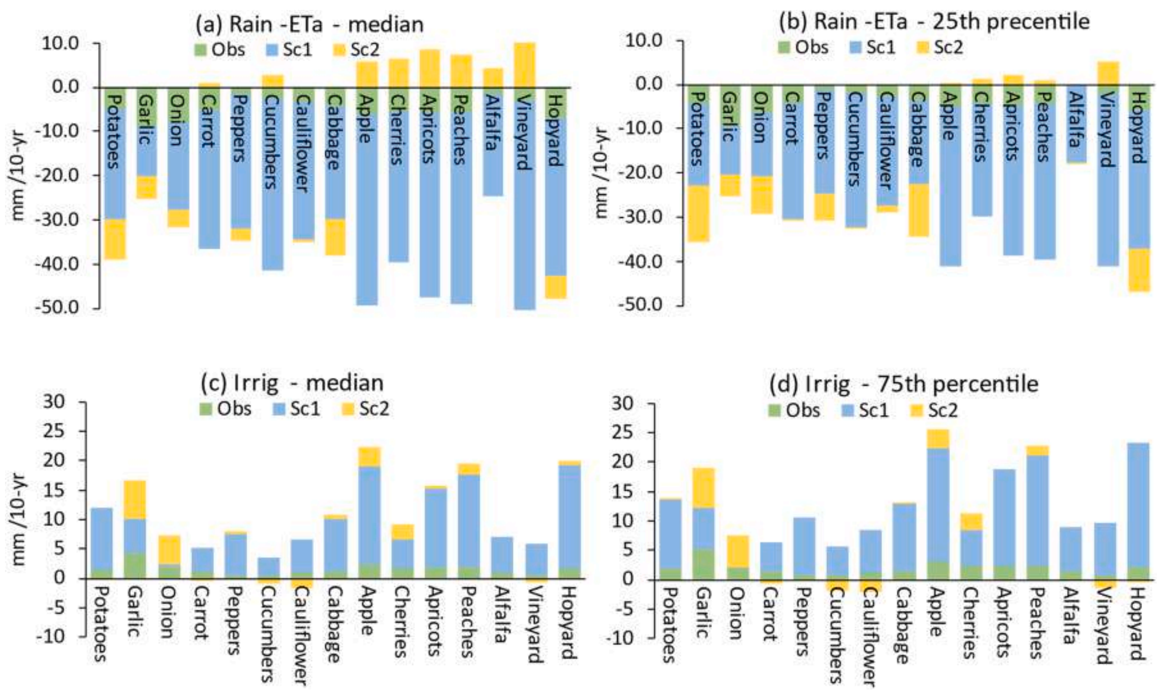


Fig. 4. The linear trends (mm/10 yr) of crop water balance when reaching the value of the median (a) and 25th percentile (b). The irrigation water requirement (mm/10 yr) when reaching the value of the median (c) and 75th percentile (d). Trends refer to the periods 1961–2020 (Obs), 2031–2050 (Sc1), and 2060–2080 (Sc2).

dynamics and the different onset of phenological phases but also by differences in the ability of the soil to retain water. Therefore, 15% and 25% of irrigation water will be lost by evaporation from the soil surface in the Morava and Dyje River basins during the 2030s and 2080s, respectively. For the end century, the increasing rate of ET_a exceeds that of precipitation across the grapevine production region, which will inevitably aggravate *AWR1 and AWR*. However, the ET_a and *AWR* in the rootzone tend to show a reduced *Irrig* due to decreases in transpiration and increases in water use efficiency.

Fig. 6c documents the median irrigation during hop GS for Obs and two future periods under RCP4.5. For the 2030s, in Žatec – the main traditional hop region, we project the highest depletion of soil moisture values of *AWR1* to decrease by 25%, and in Tršice and Úštěcko hop regions to decrease by 5% and 9%, respectively. This means that summer irrigation is essential for maintaining adequate soil moisture levels.

Fig. 6d documents the median irrigation characteristics during the

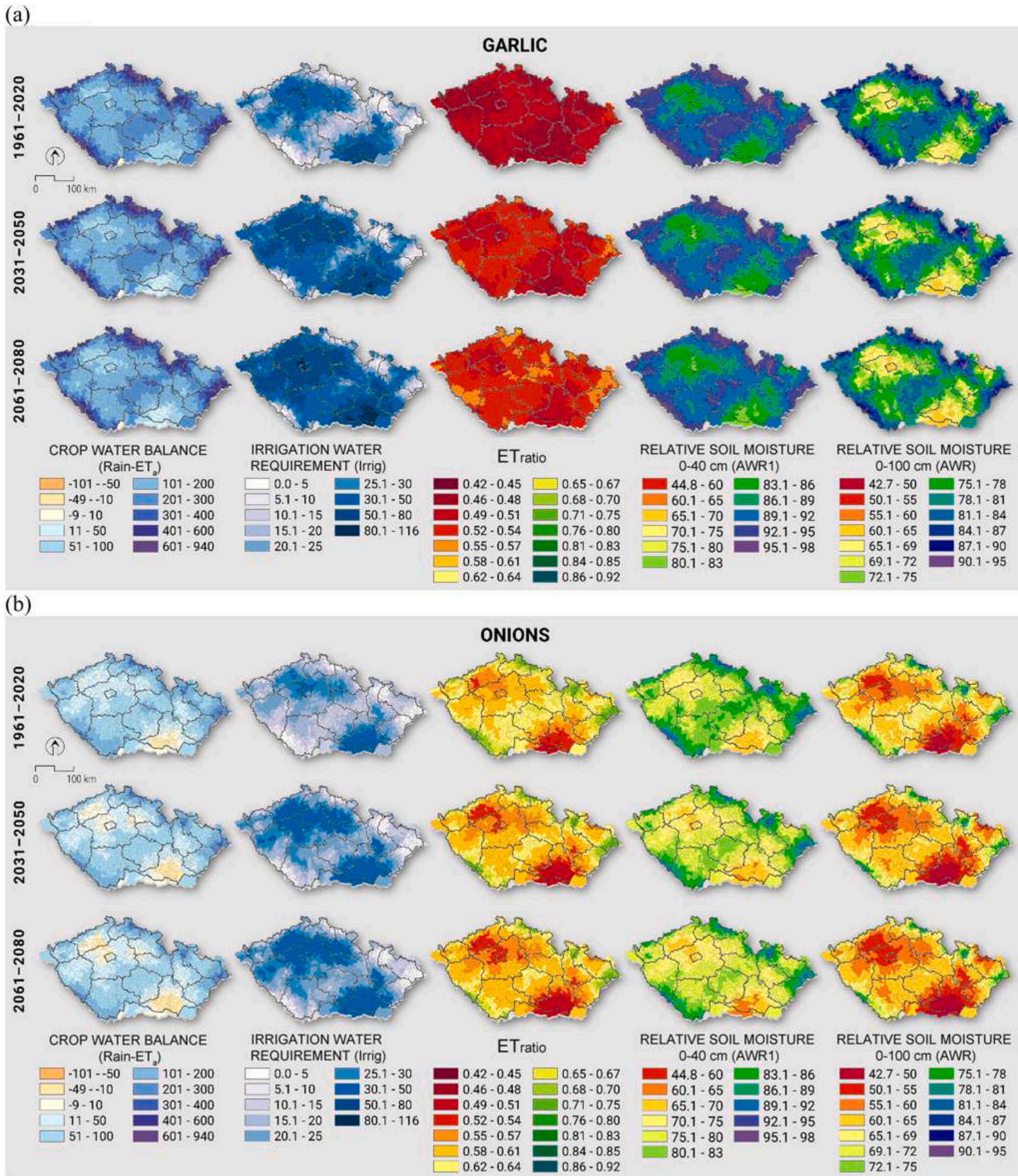


Fig. 5. (a–f) Maps of the water use indicators during GS of vegetables (garlic, onion, carrot, pepper, cucumber, cauliflower, and cabbage) for the observed period (1961–2020) and two future periods under RCP 4.5 (2031–2050 and 2061–2080).

GS of alfalfa for hay in forage production regions under the current and future climates. The lowest values of *Rain-ET$_a$* (11–50 mm), ET$_{ratio}$ (0.62–0.64), AWR (75.1–80%), and AWR1 (60.1–65%) occurred frequently throughout the grassland regions during both scenarios. However, the highest irrigation water demand for the same period ranged from 15.1 to 25 mm. This change consequently led to water deficits and could result in yield depressions for productive grasslands, which were indeed observed, e.g., during the 2015 summer drought (Žalud et al., 2017).

Fig. 7a–d demonstrates the magnitude of the difference in irrigable area between trees. Here, the lowest values of *Rain-ET$_a$* (−101 to −50 mm), ET$_{ratio}$ (0.42–0.45), AWR (44.8–60%), and AWR1

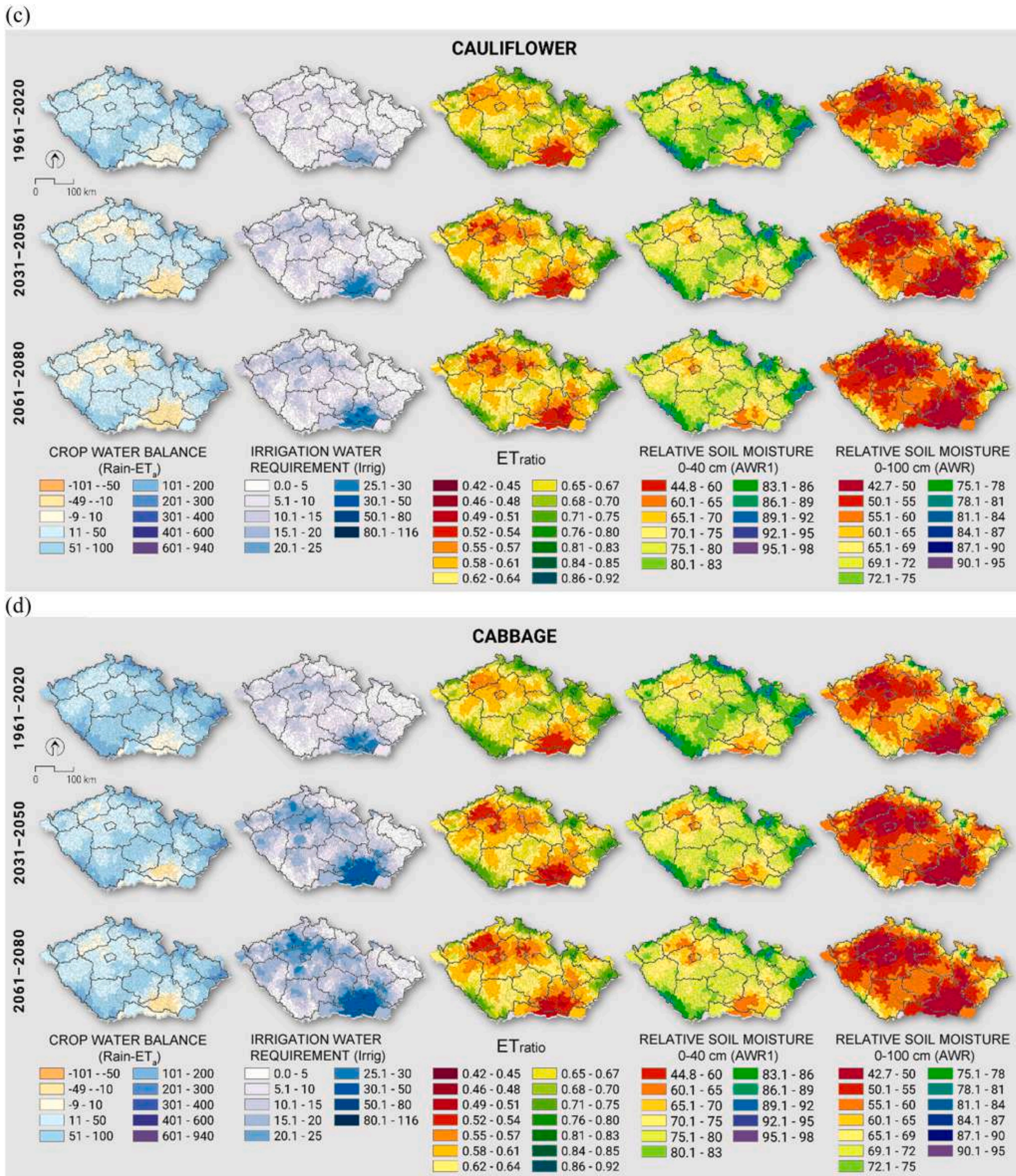


Fig. 5. (*continued*).

(42.7–50%) occurred mainly throughout the orchard regions in future scenarios. Conversely, the highest irrigation water demand ranged from 80.1 to 116 mm. These results indicate that the functions of water use indicators within fruit trees can adapt to high depletion of soil moisture if the trees are sufficiently irrigated. The higher water consumption in the case of apple trees compared to other crops is due to their long vegetation and relatively high irrigation efficiency at a time when water resources are generally insufficient (Table S1).

4.4. *Mapping the extreme water requirement indicators*

The maps of the extreme irrigation characteristics that reflect the highest depletion of soil moisture and the highest water demands are shown in Fig. 8a–f (Fig. S8). The results of this section were not to determine the real irrigation needs but to outline the area with the potential highest water requirement in over-irrigation hotspots. The higher risk areas for orchards and vineyards are widespread, covering more

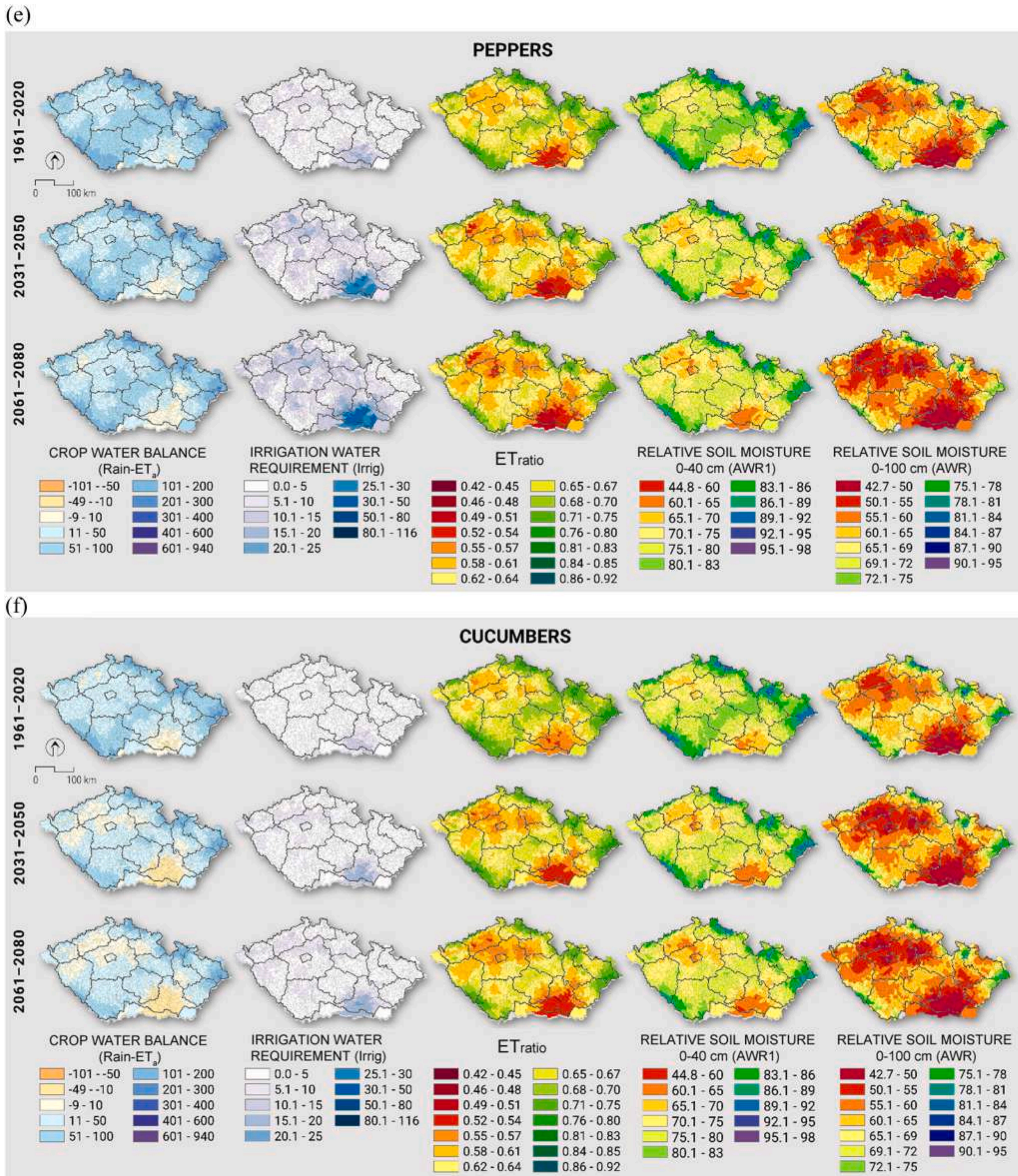
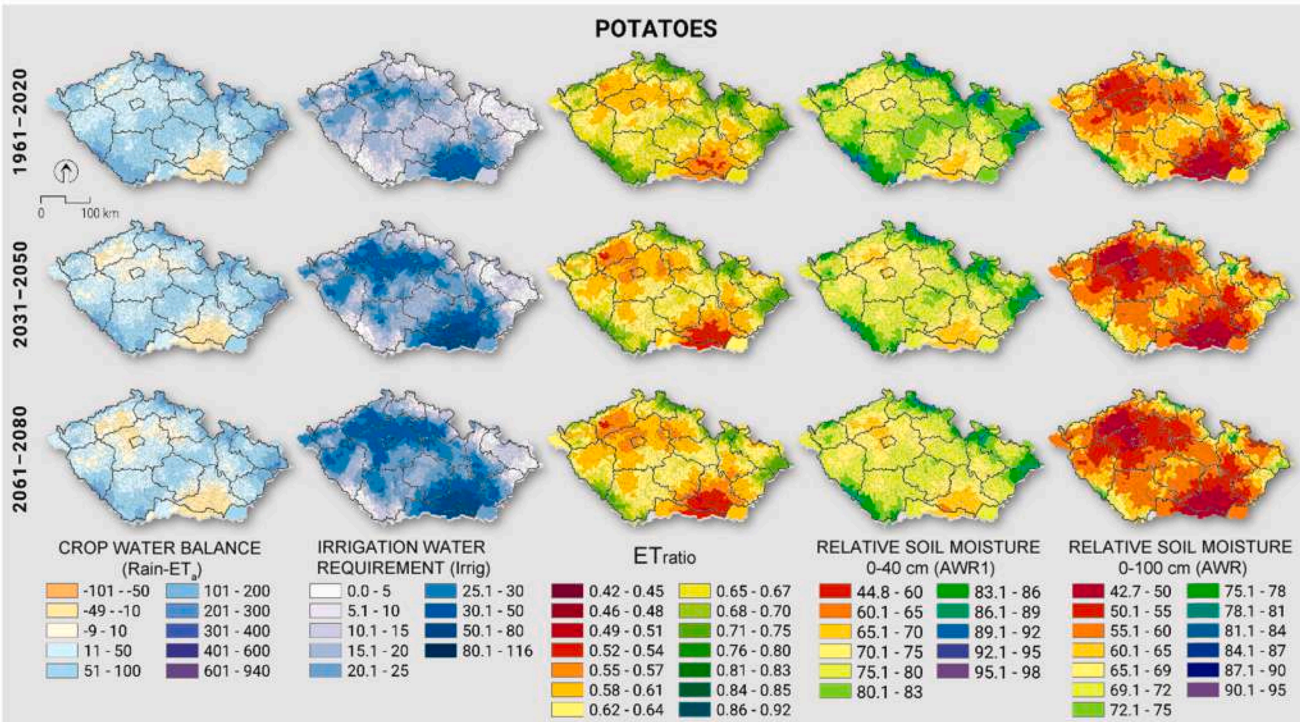


Fig. 5. (*continued*).

than 25% of the country due to exceedance of thresholds for both high depletion of soil moisture and water demands in most catchments, while risk areas where $ET_{ratio} < 0.4$ exceeds the threshold are found mainly in hopyards.

Maps from Fig. 8a (Fig. S8) illustrate spatial patterns of the most risk-prone areas for each of these indicators, which have varied relevance across a range of vegetables, and overlay observed and future periods. Growing vegetables with supplemental irrigation would be presumed on 33% of UPOVs. Toward the middle of the century, the sharp increase in areas with days $ET_{ratio} < 0.4$ and $AWR1 < 50$ (extremely limited water availability) has been most apparent for onion in the catchments of the Lower Labe and Ohře, the middle Labe, Lower Vltava, Morava, and Dyje. Overall, the results suggest that onion conditions are generally likely to become less favorable without irrigation. The current suitable cultivated proportion of brassicas-producing regions will be reduced by the 2050s due to large water deficits. By the end of the century, 28.2% of UPOVs

(a)



(b)

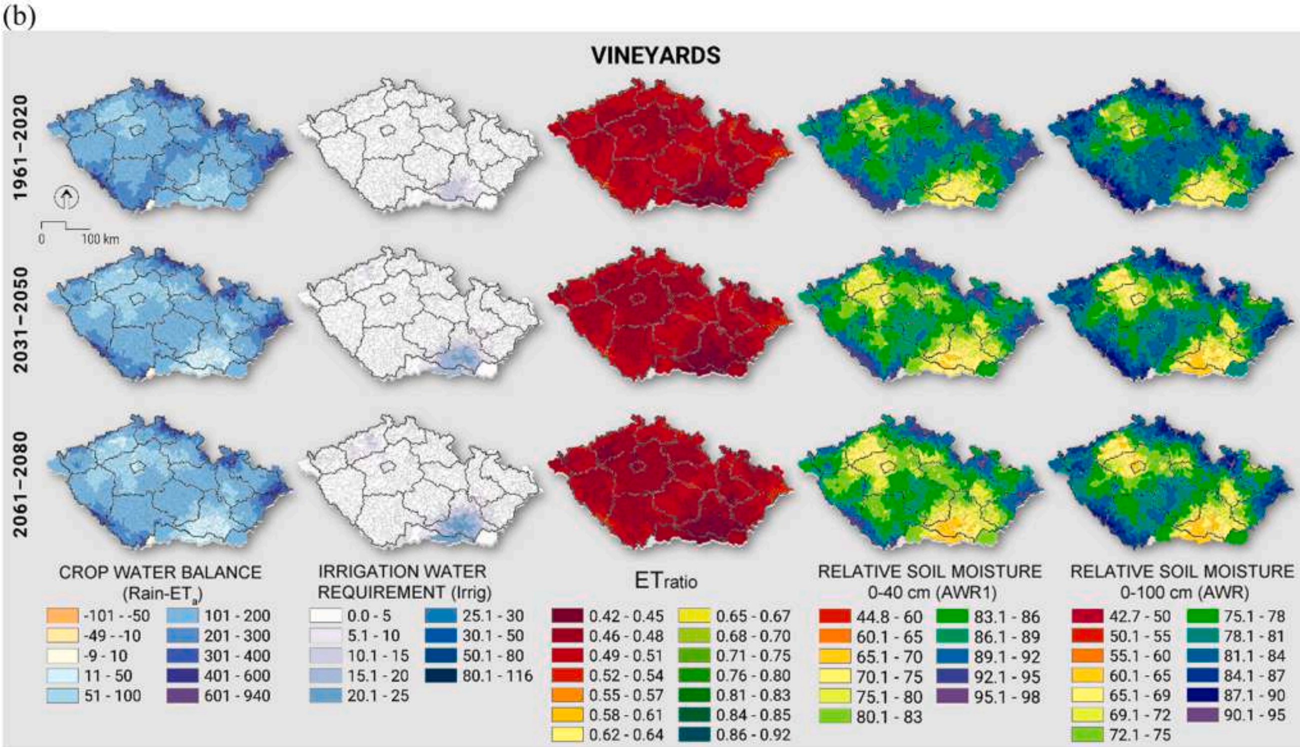


Fig. 6. (a–d) Maps of the water use indicators during GS of early potatoes (a), vineyards (b), hopyards (c) and alfalfa for hay(d) for the observed period (1961–2020) and two future periods under RCP4.5 (2031–2050 and 2061–2080).

increased the number of days with the highest depletion of topsoil moisture (*AWR1* < *30%* and *AWR1* < *50%*) for late cabbage and cauliflower (160 m^2 ha^{-1} per tonne yield). The high numbers of days with ET_{ratio} < 0.4 resulted in cucumber and pepper fruit qualities (150 m^2 ha^{-1} per tonne yield) that were more sensitive to short drought stress during the fruit setting stage in all producing regions. We find a relatively similar but more pronounced result for potato water requirement indicators (Fig. 8b). The projected future anomalies of the

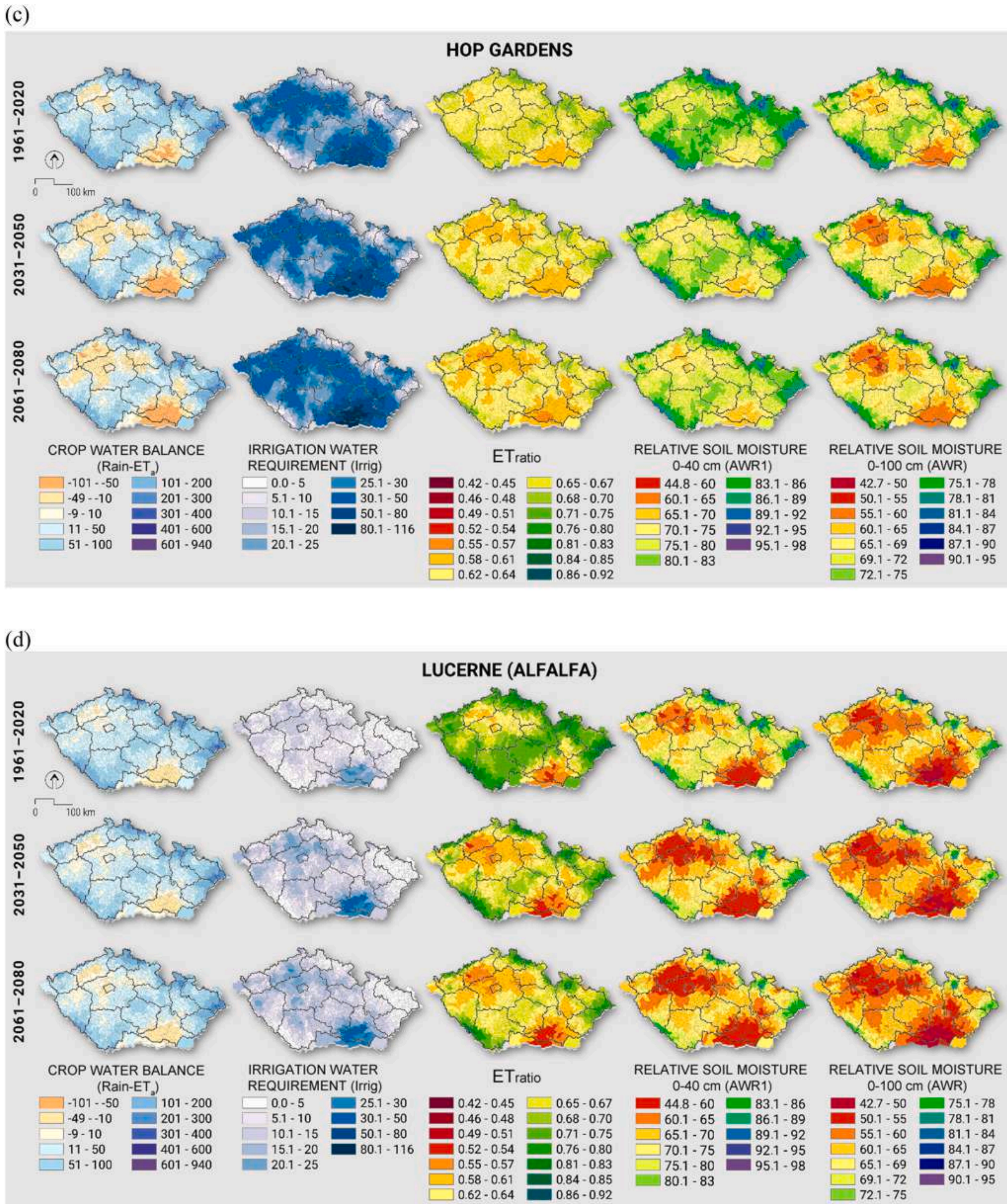


Fig. 6. (*continued*).

number of days with the highest depletion of soil moisture will increase at approximately two-thirds of the UPOVs in the topsoil layer (*AWR1* $<30\%$, *AWR1* $<50\%$) by the end of the 21st century compared to the Obs.

The number of days with water deficit ($ET_{ratio} < 0.4$) for vineyards was projected to increase with deficit irrigation and would require supplemental irrigation up to 22% (Fig. 8c). The number of expected days with the highest depletion of topsoil moisture for vineyards will be approximately 27% of UPOVs for the period 2031–2050 and 15% of UPOVs for 2061–2080. This increase in soil water stress will harm sunburn risks and will be strongly related to vintage quality (sugar, color, and aroma). These findings agree with those of Trnka et al. (2021), who reported that the extent of grapevine production regions is considerable, as is the massive increase in the warmer and drier regional

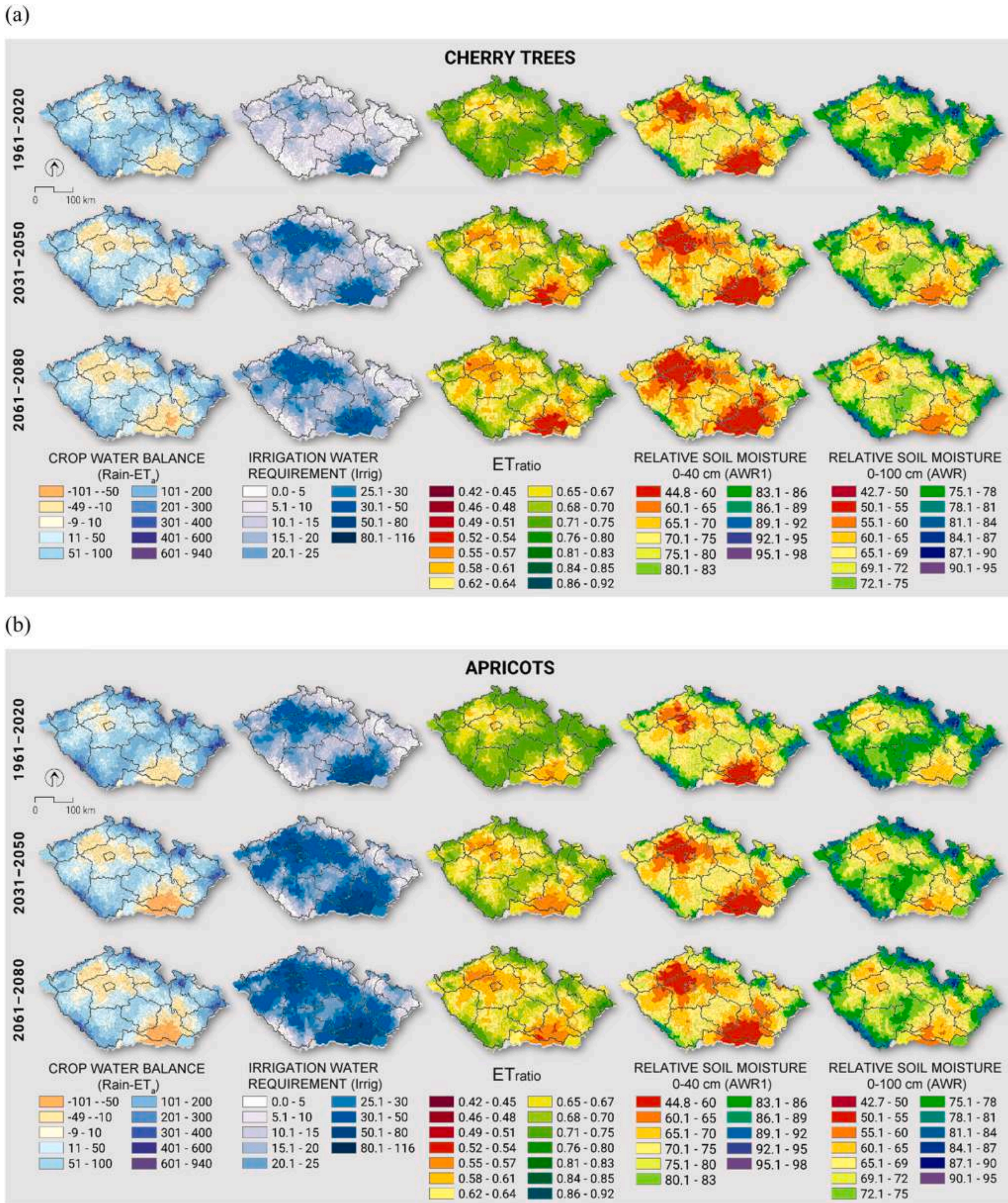
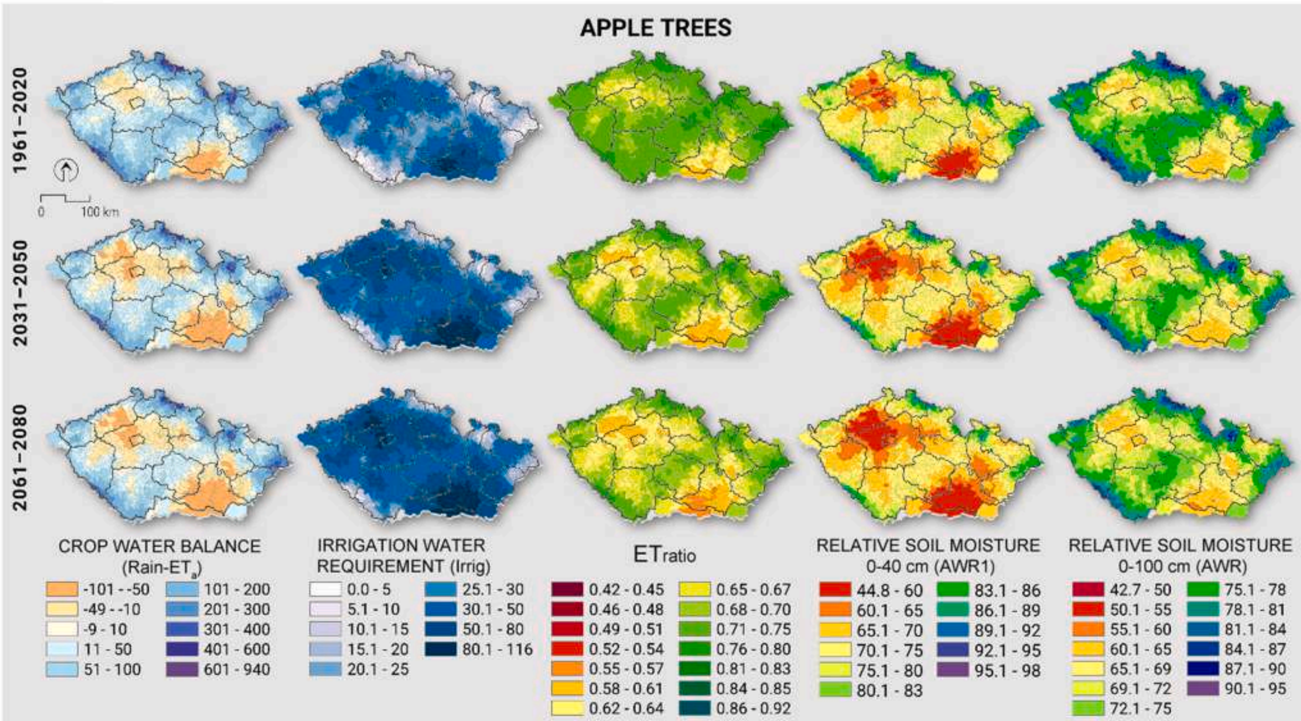


Fig. 7. (a–d) Maps of the water use indicators during orchards GS for (a) apples, (b) peaches, (c) cherries, (d) apricots for the observed period (1961–2020) and two future periods under RCP4.5 (2031–2050 and 2061–2080).

conditions of grapevines.

Maps of the number of days with water use indicators of hopyards for the observed and two future periods are shown in Fig. 8d. Changes in future hopyard irrigation extent and amounts may have important implications in largely cropped irrigation hotspots. Approximately 22% of the hilly catchment areas would require supplemental irrigation, while in the lowland catchment areas these percentages reached 28–35%. We determined that days with water deficit occurred 1–3 times per GS in the observed period, while in the 2031–2050 and 2061–2080 periods, days with water deficit occurred more than 2–4 times. Even with the modest

(c)



(d)

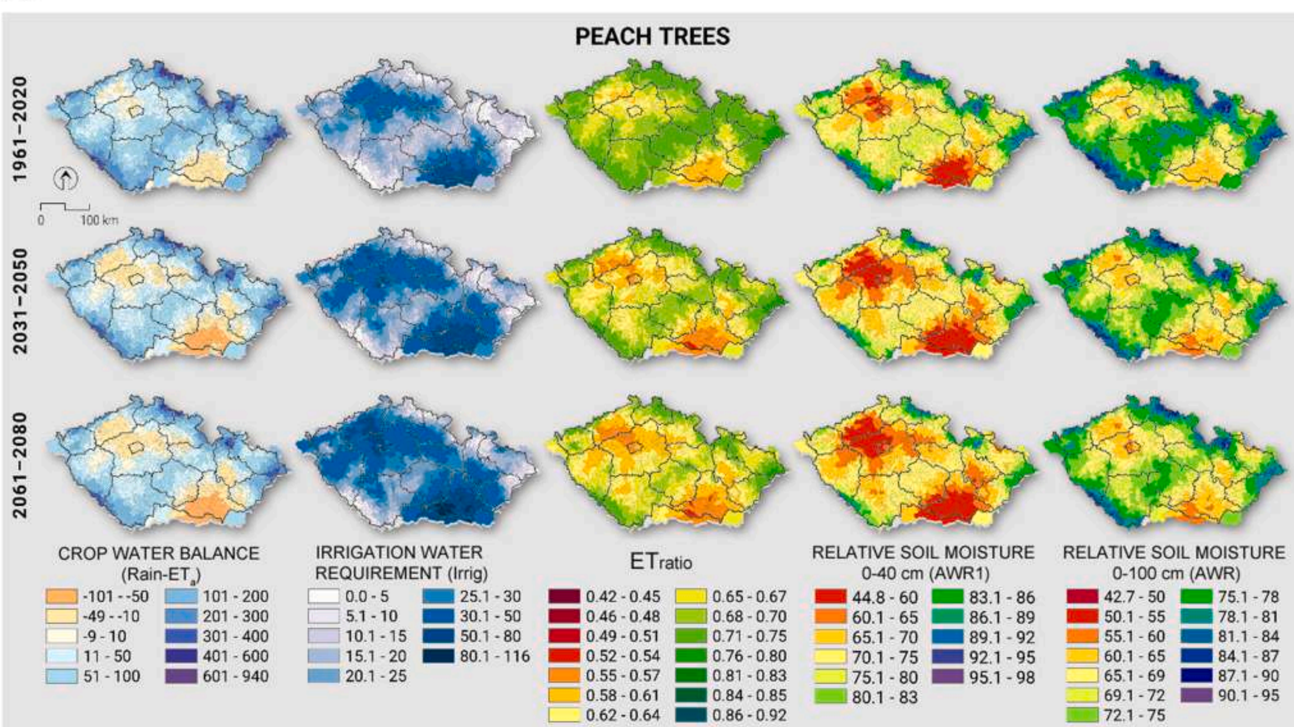


Fig. 7. (*continued*).

warming thus far experienced, yields have stagnated, and quality has declined. This fact means further expenses and higher water requirements in over-irrigation hotspots for premium beer production (Potopová et al., 2021a).

The spatial distribution of the extreme water requirement indicators of alfalfa for hay under current and future climates is documented in Fig. 8e. Maps of the number of days with $ET_{ratio} < 0.4$ (35–42 days) and $AWR1 < 50\%$ (65–135 days) define areas where an extreme lack of soil moisture occurs with fodder production to keep the optimum demand for the livestock sector. Areas with significant water requirements are evident, as there is a significantly higher need for production and maintenance irrigation in South Moravian than in other regions. These indicators also suggest the economic risk of attaining sustainable fodder production in the regions with the most developed animal production

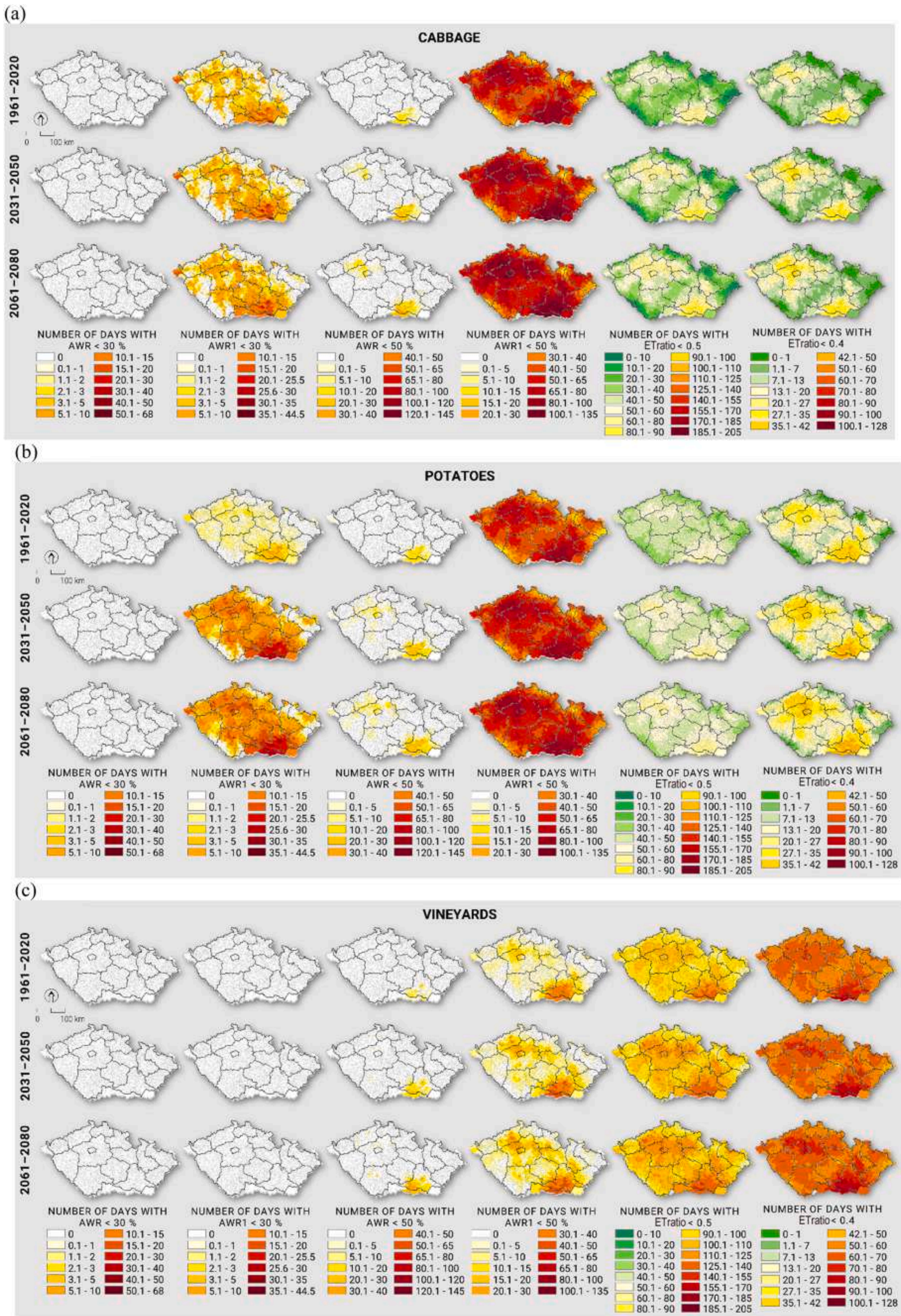


Fig. 8. (a–f) Maps of the number of days with the water use indicators during GS of cabbage (a), early potatoes (b), vineyards (c), hopyards (d), alfalfa for hay (e), and apples (f) for the observed period (1961–2020) and two future periods under RCP4.5 (2031–2050 and 2061–2080).

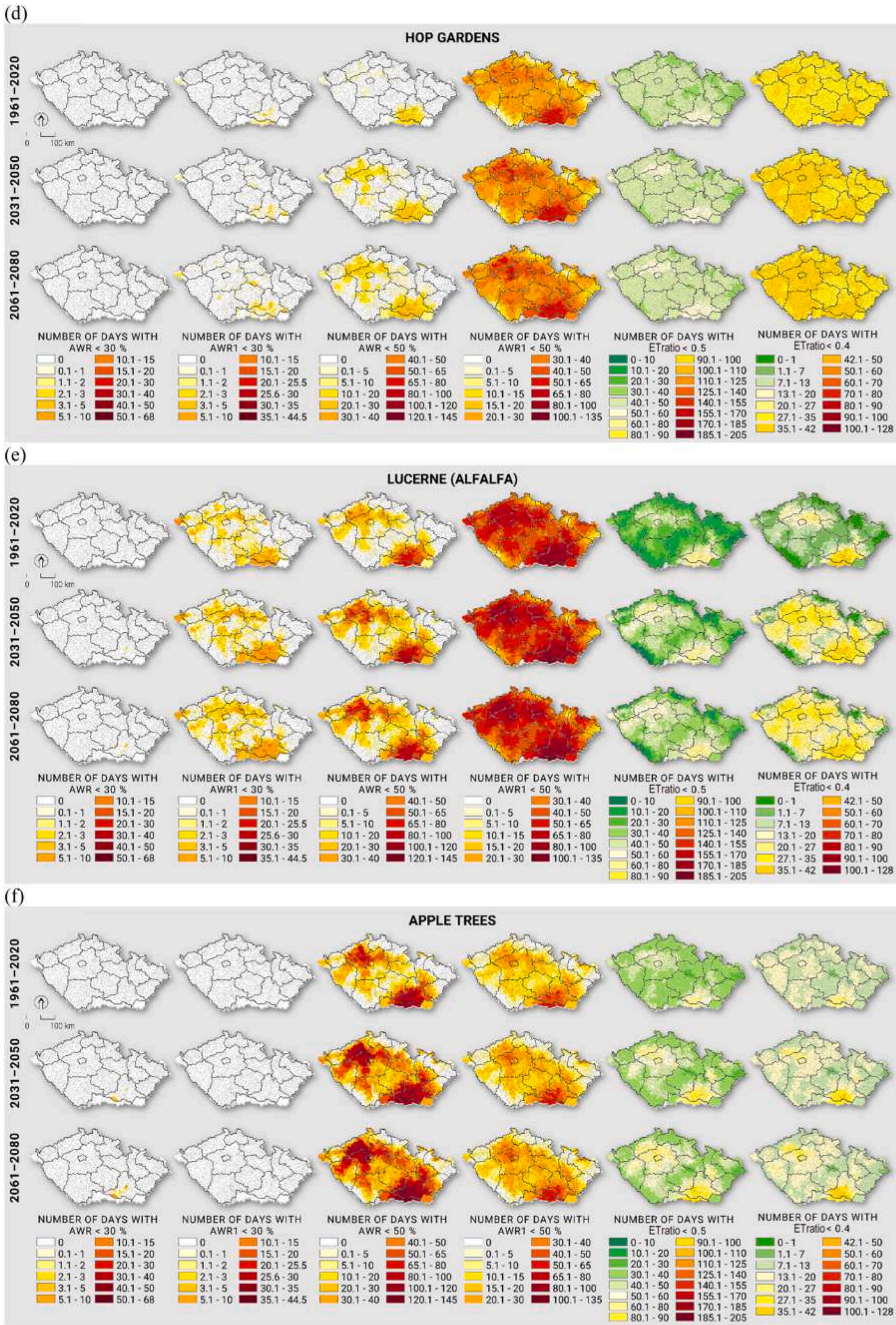


Fig. 8. (*continued*).

(South Bohemian Region and Vysočina Region). Thus, there will be insufficient fodder supply to the livestock sector due to any water stress during the production season under climate change conditions. At the same time, a substantial increase in the amount of water consumed by livestock is expected in areas vulnerable because of water scarcity.

Regional differences in orchards with water use indicators are shown in Fig. 8f (Fig. S16). Even though two regions are expecting strong increases in the number of days with high depletion of soil moisture ($AWR1 < 30\%$) and water demands ($ET_{ratio} < 0.4$), i.e., Central Bohemia (+25%) and South Moravia (+47%), the total amount of irrigation water requirements decreases by 5%, as these two regions only have a small share of the total water requirements for orchards. Thus, irrigation is helpful to maintain the regular functioning of photosynthesis and carbohydrate translocation even under drought stress conditions. The increase in the number of days with $ET_{ratio} < 0.4$ and < 0.5 for the years 2061–2080 relative to 1961–2020 is likely to be in the range of 10–25 days unless countermeasures are taken. In orchard regions, a high number of days with depletion of soil moisture can lead to dramatically decreasing yields.

4.5. Comparison of available water resources and estimated irrigation needs

For the assessment of water resources, three categories of conditions (normal, 5-yr and 10-yr drought) were used based on current water demands and irrigation projections for apple trees (water-intensive) and cabbage under current climatic conditions (1961–2020) and projected climatic conditions according to 5 different climate models (Fig. 9a,b; Fig. 10a,b). Within the scenario of the current demands, real withdrawals are considered instead of the permitted withdrawals, which are approximately 40% higher in the CZ. Within the hydrological and water balance modeling process, we tried to answer the question of whether there are at least theoretical water resources in the CZ in individual UPOVs that could cover possible higher demands for irrigation. Fig. 9a,b shows available water resources for each UPOV, under normal conditions and drought periods (only the minimum residual flows) (Balvín et al., 2021), from the reservoirs (until full retention capacity) or the interbasin, and the demand for all water uses (i.e., surface and groundwater extractions). The wet GCMs simulate comparable results of available water resources with current conditions (irrigation needs for cabbage), while the remaining GCMs simulate a decline (from 18% to 26%) in water resources for both horizons, especially for dry periods when no water resources are available in most of the area. Water resources are available only in the mountainous areas of the CZ, which are not suitable for agriculture, and the lower Elbe River. The available water resources are mainly in the first half of the hydrological year (November-September) and therefore do not occur at the same time as the GS in the CZ, during which time there are water deficits, especially where there is insufficient water management infrastructure.

The modeling results were aggregated into eight subbasins and for the whole CZ. Fig. 10a,b depict available water resources (irrigation needs for cabbage) for subbasins that are decreasing or are not available under current conditions. Available water resources decrease the most in normal and wet years, provided that this water is available. For example, the decrease in the Dyje (Thaya) basin, according to all GCMs, ranges from 44 million m^3 (20% of available water resources) to 145 m^3 (64%) in a normal year. It should be noted that water resources are still very limited or almost unavailable in the subbasins of the Berounka, Dyje, and Morava Rivers since larger reservoirs are not present.

The change in available resources is also related to their deficits. Figs. S10,11 shows the deficits for current and future climatic conditions based on current needs and the needs for irrigation of apple trees and cabbage. For current needs, the water deficits vary in units of percent for all GCMs. When irrigation is considered, the deficits increase even for wet GCMs. For the BNU, HadGEM2, and IPSL models, the change in deficit is almost double for the period 2061–2080.

Figs. S10,11 show aggregated available water for the CZ, which remains almost the same under the CNRM and MRI GCMs and decreases significantly for the BNU, IPSL, and HadGEM2 GCMs. These declines are observed throughout and, as mentioned, occur primarily in the first half of the hydrologic year. Without water management infrastructure, these resources cannot then be used, particularly in the second half of the growing season.

Simulations of the hydrological and water balance according to the 5 GCMs indicate that the main catalyst for changes in the natural water regime in the CZ is the change in air temperature as the main proxy for evapotranspiration, where the water regime changes significantly in the summer months (30–50% decrease) and the streams are mainly supported by baseflow and direct runoff. An increase in runoff of 10–30% can be expected in the winter months due to changes in the total amount of snowpack. The hydrological model estimates a significant decrease (up to 40%, based on the chosen GCM) in the median annual flow compared to 1961–2020 (up to 55% in drought periods). This phenomenon is predicted across all river basins, with a more pronounced decline in catchments prone to produce water deficit (Thaya and Berounka). Crop-specific irrigation needs produce shifts in units of a percent to this value. To meet the increased irrigation needs, it will be necessary to retain this water so that it can be used later in the year, especially in catchments where this infrastructure is lacking.

5. Discussion

In our study, we implemented hydrological models with crop models that consider future crop production developments and climate data of the entire GS and compute the most suitable crop for each raster cell within UPOV. In this kind of research, there are two main constraints: (i) cropland area and length of GS would remain unmodified by climate change; however, considering the future higher temperatures (Potopová et al., 2018; Zahradníček et al., 2020), both patterns might change; and (ii) these results represent just one realization of the possible future irrigation water requirements. Therefore, our focus was to discuss the uncertainties related to the choice of the model and scenario. The SoilClim model has been shown to explain between 74% and 80% of the daily ET_a variability measured by eddy covariance and Bowen ratio systems over 3 sites and 6 crops, with root mean square errors (RMSEs) ranging from 0.49 and 0.99 mm/day (Trnka et al., 2015a, 2015b). SoilClim also performed well at the lysimetric station Hirschstetten in Austria over several years for three soils, explaining up to 63% (topsoil) and 74% (subsoil) of the observed soil moisture, with RMSEs ranging from 2.82% to 4.23% for both layers. Under field conditions, we found SoilClim to explain 63% of topsoil and 74% of subsoil soil moisture variability (Trnka et al., 2015a). SoilClim reproduces well changes in the long-term soil moisture dynamics in the topsoil, especially during April to September periods, i.e., the window critical for irrigation. SoilClim also reproduced well trends in the reference evapotranspiration proxy, i.e., pan evaporation between 1968 and 2010 (Trnka et al., 2015b). SoilClim was shown to explain over 62% of the daily topsoil soil moisture variability for April-September during 1961–2018 at Doksany station. This is an improvement of over 55% reported for the 1961–2012 period by Trnka et al. (2015a) arising from using the improved soil parametrization of SoilClim used in this study. The SoilClim model has also been used several times in combination with the GCM models and coupled with the BILAN model before this irrigation study, in a number of other regions (Vizina et al., 2015; Trnka et al., 2016; Melišová et al., 2020). The comparison of projected irrigation characteristics with other studies is difficult due to the different climate models used in our study, which reach different levels of regional warming toward the end of the 21st century (MRI – wet and cold; CNMR – wettest and hot; IPSL – hot; BNU – cold and HadGEM – dry and hot). Another problem is that the projection of 21st-century irrigation water requirements and available water for sensitive agricultural crop commodities across the CZ has not yet been thoroughly assessed. There is also the issue that decreases in

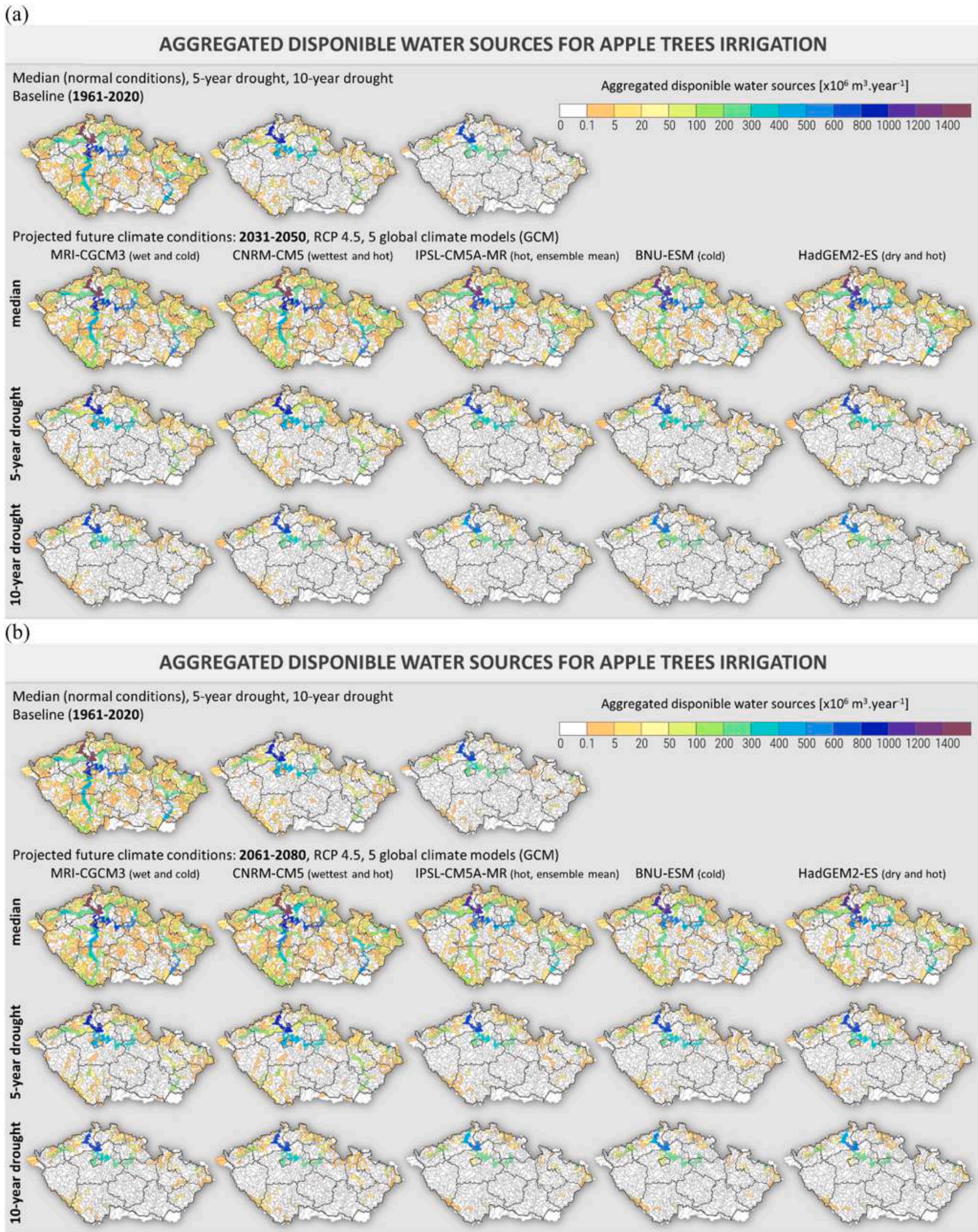


Fig. 9. (a,b) UPOVs disponible water for current and future conditions according to the five GCMs for a normal year, 5-yr and 10-yr drought (irrigation demands for apples) for Sc1 and Sc2.

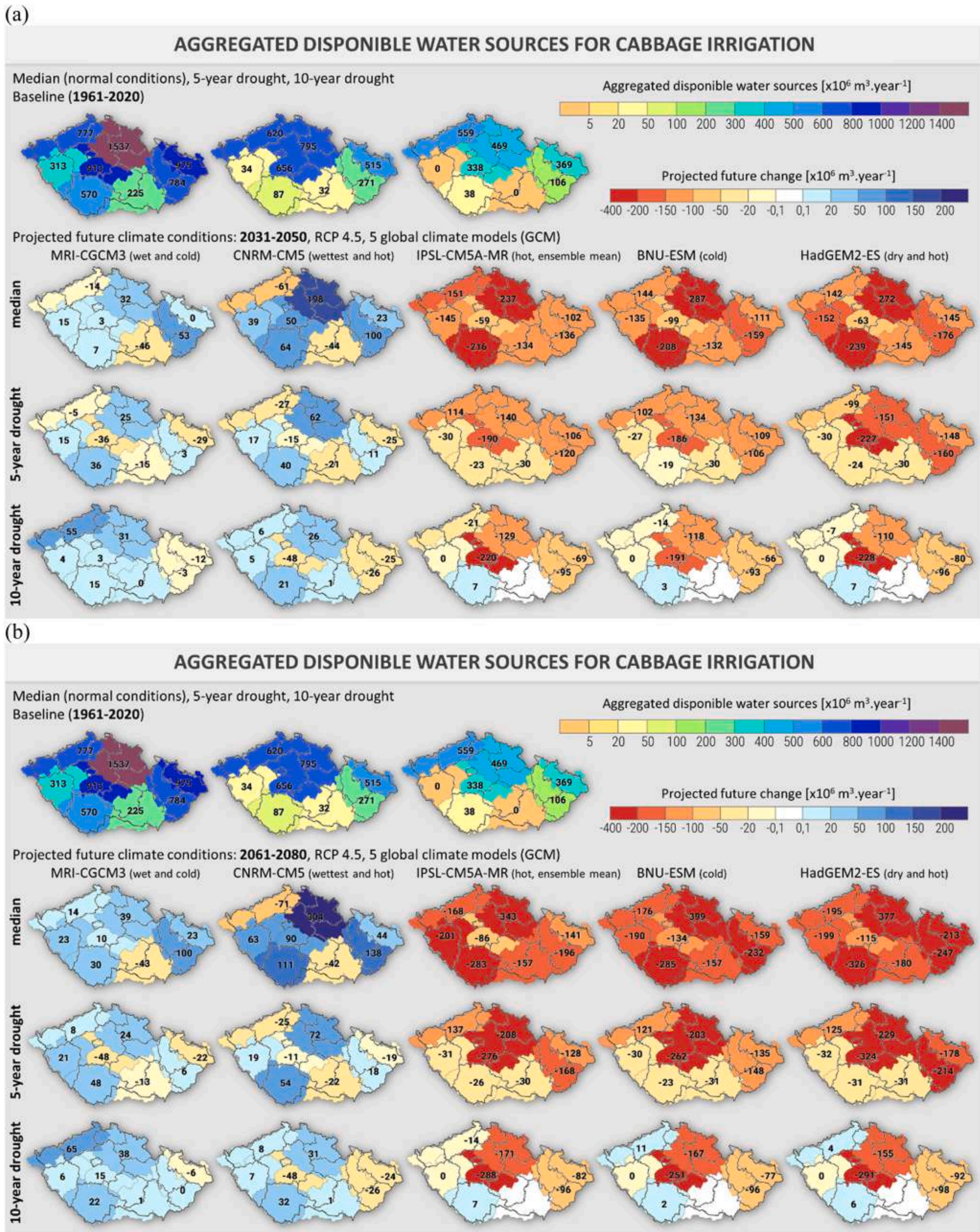


Fig. 10. (a,b) Aggregated disponible water resources in subbasins for the current and future conditions (2031–2050 and 2061–2080) according to the five GCMs for a normal year, 5-yr drought and 10-yr drought (irrigation demands for cabbage).

water consumption in current irrigation water requirements in many UPOVs were not based on a reduction in the water demands of crops but only on the decline in irrigation equipment. More detailed information on the categorization of crop water balance is provided by Duffková et al. (2020), who showed that over 80% of spring crop regions in the CZ were threatened with medium to severe water scarcity. Another study conducted in the southern part of the CZ (Lamačová et al., 2018) projected future water balance scenarios under RCP4.5 for the periods of 2021–2050 and 2071–2100. Both studies underline that the growing trend for the occurrence of dry periods will lead to the expansion of irrigated fields. In addition, the water supply within both underground and surface resources has been declining. There is concern about whether there will be enough water for irrigation in dry years (Duffková et al., 2020).

The estimation of potential evapotranspiration and actual evapotranspiration in CMIP5 multimodel future projections for Europe was also discussed by Dezsi et al. (2018). The study concluded that ET_o increases by approximately 50–100 mm by the 2020s and approximately 75–125 mm by the 2050s for Europe. Another challenge lies in the representation of how crop cover affects actual evapotranspiration and soil moisture conditions concerning changes under rising temperature and CO_2 levels (Dusenge et al., 2019; Lenka et al., 2020, 2021).

Our mapping results (Figs. 5–7) demonstrated that the changes in AWR and AWR1 under nonirrigated arable land, permanently irrigated land, and complex cultivation patterns may not be monotonic; rather, it is possible that in some croplands, soil moisture might first increase in response to increasing precipitation but then decrease because ET_0 may increase faster than precipitation as temperature rises (Cook et al., 2015; Chen et al., 2018). The topsoil may have a lower water loss, probably due to the decreased evaporation from the soil surface under irrigated vegetables, in contrast to alfalfa for hay, orchards, and vineyards where the soil has permanent plant cover. The low water content of the root zone limits the ET_a to rates below the potential, and the reduction in ET_o due to increasing CO_2 has a relatively high impact on the optimization of irrigation water productivity. Therefore, the ET_{ratio} is a good indicator for designing irrigation scheduling in agricultural water management, especially for vegetables where the water supply is mainly through irrigation. In this case, the variations in ET_{ratio} are highly influenced by irrigation water supply, especially under different irrigation levels.

Since the depth of 60 cm represents a limit for most types of vegetables, where the roots almost no longer penetrate, it is evident that the greatest economic effect of irrigation occurs in years with 5-yr and 10-yr drought. This would consequently lead to water deficits, and the possibility of irrigation provides benefits in drought years when the full water capacity to guarantee a high yield will be 70% on lighter to medium soils and 55–40% on heavy soils. However, it is precisely in these crops that efficient irrigation systems (especially drip irrigation) can be used, which offsets the relatively higher need for *AWR* by higher irrigation efficiency. This finding was consistent with Siebert et al. (2017) and Thiery et al. (2020), who emphasized that irrigated crops, which account for more than 40% of global yields, benefited from capped temperature extremes. However, these favorable influences only occurred because the irrigation extent more than quadrupled during the 20th century.

In the areas with low soil retention capacity, the stabilizing effect of irrigation on hops and orchards is evident, with a relatively small increase in water consumption. Tsuchida and Yakushiji (2017) related that the dry weight of apricot trees declined over an approximately 3-month period of drought stress; therefore, a period of drought stress longer than two months is likely to cause visible tree growth inhibition. Cherry trees under dry soil conditions resulted in decreased accumulation of carbohydrates. Irrigated apricot trees maintained a high leaf water potential, photosynthetic rate, and ET_{ratio} rate, regardless of lower *AWR1 and AWR*.

The largest effect in the expected climate is irrigation for fodder crops, which is partly due to the highest water demands. However, it is evident that the greatest economic effect of irrigation occurs in years with 5-yr and 10-yr drought; however, in these years, the risk of lack of moisture will be significantly higher. The same results were achieved by Žalud et al. (2017) and Trnka et al. (2015, 2020, 2021). At the pan-European level, Schaldach et al. (2012) highlighted that changes in the irrigated area between 2000 and 2050 increase by 18% from 181.202 km^2 to 214.028 km^2.

6. Conclusion

This research combined the existing national irrigation standard with the well-calibrated SoilClim model and BILAN-WATERES hydrological models to develop projections of irrigation water requirements under future climate conditions. The study identified regions with likely increases in irrigation water requirements due to climate change. Additionally, catchments that would not be able to support such an increase in the water demand with the existing water reservoir infrastructure were demarcated.

Most water consumption catchments were detected in lowland catchments with high farm stocking rates, characterized by the highest frequency of days with a lack of soil moisture and days with high irrigation needs. In the current climatic conditions and the normal year, at least 90% of the water sources for existing irrigation systems can be ensured from existing water sources, except for some catchments in the Dyje River basin. With an increase in drought events with a probability of 5 yr, it is impossible to satisfy the demands on water resources in the Dyje River basin (South Moravia) and in the Rakovnicka and Louny regions (Central Bohemia). During drought events with a probability of 10 yr, significant problems will manifest in several catchments in the Upper Elbe and Upper Vltava regions.

Vegetable crops have relatively lower requirements, while orchards are very demanding. The average irrigation water requirement will increase by 10.2%, and the water requirement will be higher in orchards, hopyards, vineyards, and fodder crops and lower in early potatoes and vegetables. An increase in future potential irrigation amount will be required to satisfy crop evapotranspiration. It will not be possible to keep significant areas under irrigation in each growing season with respect to water resources. Construction or use of existing small reservoirs for irrigation will be a necessity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by National Research Projects: (a) SS02030027 “Water systems and water management in the Czech Republic in conditions of the climate change”. (b) SustES - Adaptation strategies for sustainable ecosystem services and food security under adverse environmental conditions” (CZ.02.1.01/0.0/0.0/16_019/0000797). (c) Vulnerability of selected fodder production to support the demand of livestock and renewable energy sectors under climate change conditions (CZ.02.2.69/0.0/0.0/19_073/0016944).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2021.107337.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements – FAO Irrigation and Drainage

Paper 56. FAO – Food and Agriculture Organization of the United Nations, Rome, Italy, p. 290. ISBN 92-5-104219-5.
Ambika, A.K., Mishra, V., 2019. Observational evidence of irrigation influence on vegetation health and land surface temperature in India. Geophys. Res. Lett. 46, 13441–13451. https://doi.org/10.1029/2019GL084367.
Balvín, P., Vizina, A., Nesládková, M., Blöcher, J., Makovcová, M., Moravec, V., Hanel, M., 2021. Minimum residual flows for catchments in the Czech Republic. Water 13, 689. https://doi.org/10.3390/w13050689.
Bastiaanssen, W.G.M., Allen, R.G., Droogers, P., D'Urso, G., Steduto, P., 2007. Twenty-five years modeling irrigated and drained soils: state of the art. Agric. Water Manag. 92, 111–125. https://doi.org/10.1016/j.agwat.2007.05.013.
Bisselink, B., Bernhard, J., Gelati, E., Adamovic, M., Guenther, S., Mentaschi, L., De Roo, A., 2020. Climate change and Europe's water resources, EUR 29951 EN, Publications Office of the European Union, Luxembourg. ⟨https://doi:10.2760/15553⟩.
Boeck, H.J.D., Bassin, S., Verlinden, M., Zeiter, M., Hiltbrunner, E., 2016. Simulated heat waves affected alpine grassland only in combination with drought. New Phytol. 209, 531–541. https://doi.org/10.1111/nph.13601.
Chen, F., Xu, X., Barlage, M., Rasmussen, R., Shen, S., Miao, S., Zhou, G., 2018. Memory of irrigation effects on hydroclimate and its modeling challenge. Environmental Research Letters 13, 064009. https://doi.org/10.1088/1748-9326/aab9df.
Cody, K.C., 2018. Upstream with a shovel or downstream with a water right? Irrigation in a changing climate. Environ. Sci. Policy 80, 62–73. https://doi.org/10.1016/j.envsci.2017.11.010.
Cook, B.I., Shukla, S.P., Puma, M.J., Nazarenko, L.S., 2015. Irrigation as an historical climate forcing. Climate Dynamics 44, 1715–1730. https://doi.org/10.1007/s00382-014-2204-7.
Czech State Standard., 1994. Office for Standards, Metrology and Testing. ČSN 75 0434: Determining water requirements for irrigation (in Czech) 32.
Dang, T.D., Chowdhury, A.F.M.K., Galelli, S., 2020. On the representation of water reservoir storage and operations in large-scale hydrological models: implications on model parameterization and climate change impact assessments. Hydrol. Earth Syst. Sci. 24, 397–416. https://doi.org/10.5194/hess-24-397-2020.
Dezsi, Ş., Mîndrescu, M., Petrea, D., Rai, P.K., Hamann, A., Nistor, M.M., 2018. High-resolution projections of evapotranspiration and water availability for Europe under climate change. Int. J. Climatol. 38 (10), 3832–3841. https://doi.org/10.1002/joc.5537.
Dolák, L., Řezníčková, L., Dobrovolný, P., Štěpánek, P., Zahradníček, P., 2017. Extreme precipitation totals under present and future climatic conditions according to regional climate models. In: Vačkář, D. (Ed.), Climate Change Adaptation Pathways from Molecules to Society, first ed. pp. 27–37.
Döll, P., Siebert, S., 2002. Global modeling of irrigation water requirements. Water Resour. Res. 38, 8–1–8–10. https://doi.org/10.1029/2001WR000355.
Drastig, K., Prochnow, A., Libra, J., Koch, H., Rolinski, S., 2016. Irrigation water demand of selected agricultural crops in Germany between 1902 and 2010. Sci. Total Environ. 569–570, 1299–1314. https://doi.org/10.1016/j.scitotenv.2016.06.206.
Dubrovsky, M., Trnka, M., Holman, I.P., Svobodova, E., Harrison, P.A., 2014. Developing a reduced-form ensemble of climate change scenarios for Europe and its application to selected impact indicators. Clim. Chang. 128, 169–186 https://doi.10.1007/s10584-014-1297-7.
Duffková, R., Holub, J., Fučík, P., Rožnovský, J., Novotný, I., 2019. Long-term water balance of selected field crops in different agricultural regions of the Czech Republic using Fao-56 and soil hydrological approaches. Sustainability 11, 5243. https://doi.org/10.3390/su11195243.
Dusenge, M.E., Duarte, A.G., Way, D.A., 2019. Plant carbon metabolism and climate change: elevated CO_2 and temperature impacts on photosynthesis, photorespiration and respiration. New Phytol. 221, 32–49. https://doi.org/10.1111/nph.15283.
El-Naggar, A.G., Hedley, C.B., Horne, D., Roudier, P., Clothier, B.E., 2020. Soil sensing technology improves application of irrigation water. Agric. Water Manag. 228, 105901 https://doi.org/10.1016/j.agwat.2019.105901. https://ideas.repec.org/a/eee/agiwat/v228y2020ics0378377419308170.html.
Fader, M., Shi, S., 2016. Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements. Hydrol. Earth Syst. Sci. 20 (2), 953–973. https://doi.org/10.5194/hess-20-953-2016.
Fan, J., McConkey, B., Wang, H., Janzen, H., 2016. Root distribution by depth for temperate agricultural crops. Field Crop. Res. 189, 68–74. https://doi.org/10.1016/j.fcr.2016.02.013.
Fowler, W.B., Helvey, J.D., 1974. Effect of large-scale irrigation on climate in the Columbia Basin. Science 184, 121–127. https://doi.org/10.1126/science.184.4133.121.
Giorgi, F., Gutowski, W.J., 2015. Regional dynamical downscaling and the CORDEX initiative. Annu. Rev. Environ. Resour. 40, 467–490. https://doi.org/10.1146/annurev-environ-102014-021217.
Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D., Allen, R.G., 2018. The paradox of irrigation efficiency. Science 361, 748–750. https://doi.org/10.1126/science.aat9314.
Hanel, M., Vizina, A., Martínková, M., Horáček, S., Porubská, D., Fendek, M., Fendeková, M., 2014. Changes of drought characteristics in small Czech and Slovakian catchments projected by the CMIP5 GCM ensemble. Hydrology in a changing world: environmental and human dimensions, IAHS 78–83.
Hlavinka, P., Trnka, M., Balek, J., Semerádová, D., Hayes, M., Svoboda, M., Eitzinger, J., Možný, M., Fischer, M., Hunt, E., Žalud, Z., 2011. Development and evaluation of the SoilClim model for water balance and soil climate estimates. Agric. Water Manag. 98, 1249–1261. https://doi.org/10.1016/j.agwat.2011.03.011.
King, D.A., Meyer, W.S., Connor, J.D., 2019. Interactive land use strategic assessment: an assessment tool for irrigation profitability under climate uncertainty. Agric. Water Manag. 224, 105751 https://doi.org/10.1016/j.agwat.2019.105751.
Kresovic, B., Matovic, G., Gregoric, E., Djuricin, S., Bodroza, D., 2014. Irrigation as a climate change impact mitigation measure: an agronomic and economic assessment of maize production in Serbia. Agric. Water Manag. 139, 7–16. https://doi.org/10.1016/j.agwat.2014.03.006.
Lamačová, A., Hruška, J., Trnka, M., Štěpánek, P., Zahradníček, P., Meitner, J., Farda, A., 2018. Modelling future hydrological pattern in a Bohemian Forest headwater catchment. Silva Gabreta 24, 47–67.
Lenka, N.K., Lenka, S., Thakur, J.K., Yashona, D.S., Shukla, A.K., Elanchezhian, R., Singh, K.K., Biswas, A.K., Patra, A.K., 2020. Carbon dioxide and temperature elevation effects on crop evapotranspiration and water use efficiency in soybean as affected by different nitrogen levels, 1-10 Agric. Water Manag. 230, 105936. https://doi.org/10.1016/j.agwat.2019.105936.
Lenka, N.K., Lenka, S., Yashona, D.S., Jat, D., 2021. Elevated temperature and low nitrogen partially offset the yield, evapotranspiration, and water use efficiency of winter wheat under carbon dioxide enrichment, 1–14 Agric. Water Manag. 250, 106856. https://doi.org/10.1016/j.agwat.2021.106856.
Machlica, A., Horvát, O., Horacek, S., Oosterwijk, J., Van Loon, A.F., Fendeková, M., Van Lanen, H.A., 2012. Influence of model structure on base flow estimation using BILAN FRIER and HBV-light models. J. Hydrol. Hydromech. 60 (4), 242–251.
Mahmoud, S.H., Gan, T.Y., 2019. Irrigation water management in arid regions of Middle East: assessing spatio-temporal variation of actual evapotranspiration through remote sensing techniques and meteorological data. Agric. Water Manag. 212, 35–47. https://doi.org/10.1016/j.agwat.2018.08.040.
Melišová, E., Vizina, A., Staponites, L.R., Hanel, M., 2020. The role of hydrological signatures in calibration of conceptual hydrological model. Water 12, 3401. https://doi.org/10.3390/w12123401.
Mondaca-Duarte, F.D., Mourik, S. van, Balendonck, Voogt, J., Heinen, W., Henten, M., van, E.J., 2020. Irrigation, crop stress and drainage reduction under uncertainty: a scenario study. Agric. Water Manag. 230, 105990 https://doi.org/10.1016/j.agwat.2019.105990.
Nadal, M., Flexas, J., 2019. Variation in photosynthetic characteristics with growth form in a water-limited scenario: implications for assimilation rates and water use efficiency in crops. ⟨https://doi.org/10.1016/J.AGWAT.2018.09.024⟩.
Perea, R.G., Daccache, A., Díaz, J., Poyato, E.C., Knox, J.W., 2018. Modelling impacts of precision irrigation on crop yield and in-field water management. Precis. Agric. 19 (3), 497–512. https://doi.org/10.1007/s11119-017-9535-4.
Pfister, S., Scherer, L., Buxmann, K., 2020. Water scarcity footprint of hydropower based on a seasonal approach - global assessment with sensitivities of model assumptions tested on specific cases. Sci. Total Environ. 724, 138188 https://doi.org/10.1016/j.scitotenv.2020.138188.
Potopová, V., Zahradníček, P., Štěpánek, P., Türkott, L., Farda, A., Soukup, J., 2017. The impacts of key adverse weather events on the field-grown vegetable yield variability in the Czech Republic from 1961 to 2014. Int. J. Clim. 37, 1648–1664. https://doi.org/10.1002/joc.4807.
Potopová, V., Štěpánek, P., Zahradníček, P., Farda, A., Türkott, L., Soukup, J., 2018. Projected changes in the evolution of drought on various timescales over the Czech Republic according to Euro-CORDEX models. Int. J. Climatol. 38, e939–e954. https://doi.org/10.1002/joc.5421.
Potopová, V., Cazac, V., Boincean, B., Soukup, J., Trnka, M., 2019. Application of hydroclimatic drought indicators in the transboundary Prut River basin. Theor. Appl. Clim. 137, 3103–3121. https://doi.org/10.1007/s00704-019-02789-w.
Potopová, V., Trnka, M., Hamouz, P., Soukup, J., Castraveț, T., 2020. Statistical modelling of drought-related yield losses using soil moisture-vegetation remote sensing and multiscalar indices in the south-eastern Europe. Agric. Water Manag. 236, 106168 https://doi.org/10.1016/j.agwat.2020.106168.
Potopová, V., Lhotka, O., Možný, M., Musiolková, M., 2021a. Vulnerability of hop-yields due to compound drought and heat events over European key-hop regions. Int. J. Climatol. 41, E2136–E2158. https://doi.org/10.1002/joc.6836.
Potopová, V., Tűrkott, L., Musiolková, M., Možný, M., 2021b. The compound nature of soil temperature anomalies at various depths in the Czech Republic. Theor. Appl. Climatol. 146, 1257–1275. https://doi.org/10.1007/s00704-021-03787-7.
Riediger, J., Breckling, B., Svoboda, N., Schröder, W., 2016. Modelling regional variability of irrigation requirements due to climate change in Northern Germany. Sci. Total Environ. 541, 329–340. https://doi.org/10.1016/j.scitotenv.2015.09.043.
Schaldach, R., Koch, J., Beek, T.A.D., Kynast, E., Florke, M., 2012. Current and future irrigation water requirements in pan-Europe: an integrated analysis of socio-economic and climate scenarios. Glob. Planet. Chang. 94–95, 33–45. https://doi.org/10.1016/j.gloplacha.2012.06.004.
Shah, H.L., Zhou, T., Huang, M., Mishra, V., 2019. Strong influence of irrigation on water budget and land surface temperature in Indian subcontinental river basins. J. Geophys. Res. Atmos. 124, 1449–1462. https://doi.org/10.1029/2018JD029132.
Siebert, S., Webber, H., Zhao, G., Ewert, F., 2017. Heat stress is overestimated in climate impact studies for irrigated agriculture. Environ. Res. Lett. 12, 054023 https://doi.org/10.1088/1748-9326/aa702f.
Sordo-Ward, A., Granados, A., Iglesias, A., Garrote, L., Bejarano, M.D., 2019. Adaptation effort and performance of water management strategies to face climate change impacts in six representative basins of Southern Europe. Water 11, 1078. https://doi.org/10.3390/w11051078.
Sorooshian, S., AghaKouchak, A., Li, J., 2014. Influence of irrigation on land hydrological processes over California. J. Geophys. Res. Atmos. 119, 13137–13152. https://doi.org/10.1002/2014JD022232.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2011. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. 93, 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1.

Thiery, W., Davin, E.L., Lawrence, D.M., Hirsch, A.L., Hauser, M., Seneviratne, S.I., 2017. Present-day irrigation mitigates heat extremes. J. Geophys. Res. Atmos. 122, 1403–1422. https://doi.org/10.1002/2016JD025740.

Thiery, W., Visser, A.J., Fischer, E.M., Hauser, M., Hirsch, A.L., Lawrence, D.M., Lejeune, Q., Davin, E.L., Seneviratne, S.I., 2020. Warming of hot extremes alleviated by expanding irrigation. Nat. Commun. 11, 290. https://doi.org/10.1038/s41467-019-14075-4.

Trnka, M., Rötter, R.P., Ruiz-Ramos, M., Kersebaum, K.C., Olesen, J.E., Žalud, Z., Semenov, M.A., 2014. Adverse weather conditions for European wheat production will become more frequent with climate change. Nat. Clim. Chang. 4, 637–643. https://doi.org/10.1038/nclimate2242.

Trnka, M., Brázdil, R., Balek, J., Semerádová, D., Hlavinka, P., Možný, M., Štěpánek, P., Dobrovolný, P., Zahradníček, P., Dubrovský, M., Eitzinger, J., Fuchs, B., Svoboda, M., Hayes, M., Žalud, Z., 2015a. Drivers of soil drying in the Czech Republic between 1961 and 2012. Int. J. Climatol. 35, 2664–2675. https://doi.org/10.1002/joc.4167.

Trnka, M., Brázdil, R., Možný, M., Štěpánek, P., Dobrovolný, P., Zahradníček, P., Balek, J., Semerádová, D., Dubrovský, M., Hlavinka, P., Eitzinger, J., Wardlow, B., Svoboda, M., Hayes, M., Žalud, Z., 2015b. Soil moisture trends in the Czech Republic between 1961 and 2012. Int. J. Climatol. 35, 3733–3747. https://doi.org/10.1002/joc.4242.

Trnka, M., Semerádová, D., Novotný, I., Dumbrovský, M., Drbal, K., Pavlík, F., Vopravil, J., Štěpánková, P., Vizina, A., Balek, J., Hlavinka, P., Bartošová, L., Žalud, Z., 2016. Assessing the combined hazards of drought, soil erosion and local flooding on agricultural land: a Czech case study. Clim. Res. 70, 231–249 https://doi: 10.3354/cr01421.

Trnka, M., Hlavinka, P., Možný, M., 2020. Czech Drought Monitor System for monitoring and forecasting agricultural drought and drought impacts. doi.org/10.1002/joc.6557 Int. J. Climatol. 40, 5941–5958. https://doi.org/10.1002/joc.6557.

Trnka, M., Balek, J., Brazdil, R., Dubrovsky, M., Eitzinger, J., Hlavinka, P., Chuchma, F., Možny, M., Prašil, I., Růžek, P., Semeradova, D., Štěpanek, P., Zahradniček, P., Žalud, Z., 2021. Observed changes in the agroclimatic zones in the Czech Republic between 1961 and 2019. Plant Soil Environ. 37 (3), 154–163. https://doi.org/10.17221/327/2020-PSE.

Tsuchida, Y., Yakushiji, H., 2017. Effect of high temperature and drought stress on carbohydrate translocation in Japanese Apricot 'Nanko' trees. Hortic. J. 86 (3), 311–316. https://doi.org/10.2503/hortj.OKD-040.

van Vliet, M.T., Donnelly, C., Strömbäck, L., Capell, R., Ludwig, F., 2015. European scale climate information services for water use sectors. J. Hydrol. 528, 503–513. https://doi.org/10.1016/j.jhydrol.2015.06.060.

Vizina, A., Horáček, S., Hanel, M., 2015. Recent developments of the BILAN model. Vodohospodářské technicko-ekonomické informace 57(4–5) 7–10. ⟨https://10.46555/VTEI.2015.06.001⟩.

de Vrese, P., Hagemann, S., 2018. Uncertainties in modelling the climate impact of irrigation. Clim. Dyn. 51, 2023–2038. https://doi.org/10.1007/s00382-017-3996-z.

Vyskoč, P., Beran, A., Peláková, M., Kožín, R., Vizina, A., 2021. Preservation of drinking water demand from water reservoirs in climate change conditions. Vodohospodářské technicko-ekonomické informace 63 (3), 4–18.

Wang, C., Wang, Z., Yang, J., 2019. Urban water capacity: irrigation for heat mitigation. Comput. Environ. Urban Syst. 78, 101397 https://doi.org/10.1016/j.compenvurbsys.2019.101397.

Wang, X.J., Zhang, J.Y., Ali, M., Shahid, S., He, R., Xia, X., Jiang, Z., 2016. Impact of climate change on regional irrigation water demand in Baojixia irrigation district of China. Mitig. Adapt. Strateg. Glob. Chang. 21, 233–247. https://doi.org/10.1007/s11027-014-9594-z.

Wisser, D., Frolking, S., Douglas, E.M., Fekete, B.M., Vörösmarty, C.J., Schumann, A.H., 2008. Global irrigation water demand: variability and uncertainties arising from agricultural and climate data sets. Geophys. Res. Lett. 35, L24408 https://doi.org/10.1029/2008GL035296.

Wriedt, G., Van der Velde, M., Aloe, A., Bouraoui, F., 2009. Estimating irrigation water requirements in Europe. J. Hydrol. 373 (3–4), 527–544. https://doi.org/10.1016/j.jhydrol.2009.05.018.

Yalew, S.G., Pilz, T., Schweitzer, C., Liersch, S., van der Kwast, J., Van Griensven, A., van der Zaag, P., 2018. Coupling land-use change and hydrologic models for quantification of catchment ecosystem services. Environ. Model. Softw. 109, 315–328. https://doi.org/10.1016/j.envsoft.2018.08.029.

Zahradníček, P., Brázdil, R., Štěpánek, P., Trnka, M., 2020. Reflection of global warming in trends of temperature characteristics in the Czech Republic, 1961–2019. Int. J. Climatol. 41, 1211–1229. https://doi.org/10.1002/joc.6791.

Žalud, Z., Hlavinka, P., Prokeš, K., Semerádová, D., Balek, J., Trnka, M., 2017. Impacts of water availability and drought on maize yield – a comparison of 16 indicators. Agric. Water Manag. 188, 126–135. https://doi.org/10.1016/j.agwat.2017.04.007.

Zhao, T., Wang, Q.J., Schepen, A., Griffiths, M., 2019. Ensemble forecasting of monthly and seasonal reference crop evapotranspiration based on global climate model outputs. Agric. For. Meteorol. 264, 114–124. https://doi.org/10.1016/j.agrformet.2018.10.001.

Zou, X., Li, Y., Cremades, R., Gao, Q., Wan, Y., Qin, X., 2013. Cost-effectiveness analysis of water-saving irrigation technologies based on climate change response: a case study of China. Agric. Water Manag. 129, 9–20. https://doi.org/10.1016/j.agwat.2013.07.004.