European Journal of Agronomy 140 (2022) 126579

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Changing patterns of soil water content and relationship with national wheat and maize production in Europe

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ARTICLE INFO

Keywords:
Available soil water
ERA5 Land
European map
Mapping climate change
Moisture-cereal yield relationship
Soil moisture content
Soil water-cereal nexus

ABSTRACT

The warming of the climate and shrinking freshwater resources pose serious challenges to European agriculture. Meeting these challenges demands a thorough knowledge of the major trends in soil moisture patterns across the continent over time. Charting the available soil water (ASW) content (m^3 m^{-3}) derived from the ERA5 Land dataset in grid cells of 0.1° × 0.1°, the highest values occurred in the Alpine, Baltic and West Balkan countries, as well as in North Western Europe. However, a major part of the Mediterranean and the Carpathian-Balkan regions and Eastern Europe recorded the driest soils over recent decades. The annual average ASW decreased over almost the entire continent from 1981 to 2007, but to the greatest degree in Eastern Europe, while Northern Europe suffered least of all. For the summer half of the year, the available water content of the top 28 cm soil significantly decreased in 45.5 % of European croplands, while only 1.0% showed a significant moisture increase. Summer half-year moisture declined across almost the entirety of Eastern Europe, threatening the reproductive stage of wheat and maize vegetation period. Soil water content had a significant positive impact on wheat yields in an estimated 64.3 % of European wheat fields, and a negative one in 5.7 %. In the case of maize yields the positive impact of ASW was present in an estimated 89.4 % of maize-growing areas, explaining an estimated 46–72 % of maize yield variances in the majority of top European maize-producing countries. In contrast to wheat, negative soil water content impact for maize in the continent was not observed. Significant ASW - wheat and ASW - maize yield relationships were found with decreasing summer half year ASW in 32.0 % and 35.2 % of European croplands, respectively. The coexistence of the crop yield dependence on soil moisture and the decrease in available soil water content pose a considerable threat to grain production stability over extensive regions of Eastern and Western Europe. These warning signs call for an effective intervention on behalf of soil water conservation in European croplands.

1. Introduction

Europe has generated almost half of global food exports in recent decades (Iglesias et al., 2011), and due to the rapid technological convergence of Eastern Europe the continent has strengthened its role as a centre of cereal production (FAO, 2022). The warming climate and shrinking freshwater resources (Famiglietti, 2014), however, pose a serious challenge to European agriculture (Lu et al., 2019). The worsening environmental conditions, such as a long-term drying trend (Dai, 2013; Sheffield and Wood, 2008; van der Schrier et al., 2006) linking to the abandonment of rural landscapes, have drastically reduced the area of cereal fields in the Mediterranean region and in Central Europe over recent decades (FAO, 2022; Hatna and Bakker, 2011). It may well be that Western Europe is expected to be less affected by global warming (Jacobs et al., 2019), but nonetheless, the region has already experienced unprecedented heatwaves in 2003 (Luterbacher et al., 2004) and 2018–2019 (Buras et al., 2020; Mitchell et al., 2019). The magnitude of the 2018 and 2019 heatwaves exceeded that of 2003, a heatwave which itself caused an estimated 30 % decrease in gross primary production in Europe (Ciais et al., 2005). As Toreti et al. (2019) rightly observe, these are warning signals for the future.

Plants, including cereals, obtain the majority of their water supply from the soil via their root systems. Precipitation decline and/or increased potential evapotranspiration driven by heat waves (Trnka

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https://doi.org/10.1016/j.eja.2022.126579
Received 8 February 2021; Received in revised form 17 March 2022; Accepted 6 July 2022

et al., 2009), as well as human activity (e.g., groundwater extraction, drainage and tillage) dry out soils and could create critical situations for vegetation (Herceg et al., 2019; Hornbeck and Keskin, 2014; Liu et al., 2015). In addition, as an element in a positive feedback, soil moisture deficit may trigger further extremes of heat (Fischer et al., 2007; Hirschi et al., 2011). For this reason, soil moisture drought is a widely discussed phenomenon (Samaniego et al., 2018), and the conservation of soil water content is a core issue in climate change adaptation and mitigation policies (FAO, 2013; IPCC, 2019). Unfortunately, observed soil moisture data are relatively scarce and short term (Robock et al., 2000). So, to calculate spatially and temporally explicit estimations of soil moisture fluctuation and extreme moisture stress, meteorological data and, increasingly, remotely sensed parameters are used as various moisture indices (Balsamo et al., 2009; Liu et al., 2011; McNally et al., 2017), such as the SMI (soil moisture index) (Samaniego et al., 2013), SMDI (soil moisture deficit index) (Narasimhan and Srinivasan, 2005), PDSI (Palmer drought severity index) (Palmer, 1965) or CMI (crop moisture index) (Palmer, 1968). The temperature and precipitation based drought indices, however, are not always capable of estimating the available soil moisture content (Mishra and Singh, 2010; Samaniego et al., 2013).

Following a long period covering almost the whole 20th century, and in the absence of any clear trend in the European soil moisture, a significant drying trend could be identified as beginning in the aftermath of the 1982/1983 El Niño event (Briffa et al., 1994; Dai et al., 2004). The main driver of this drying trend was a significant increase in temperature (Briffa et al., 2009; Vicente-Serrano et al., 2014). A further moisture decline is predicted in the near future over almost the entire European domain, but especially in the Mediterranean, Scandinavia and Eastern Europe, including the central part of European Russia and northern Ukraine (Dai, 2013; Grillakis, 2019). Analysing the top 10 cm soil moisture layer between 1979 and 2016, a significant decline was observed in 12 % of Europe, while any significant increases were confined to < 3 % of the territory (Pan et al., 2019). Soil moisture dynamics in deeper soil layers, however, remain relatively unknown. Reconstructions show groundwater depletion in the major aquifers of the temperate zone (Famiglietti, 2014; Pinke et al., 2020), suggesting similar decreasing moisture trends in deeper soil zones as the capillary fringe follows the lowering groundwater.

Under conditions of a warming climate and rising concentrations of atmospheric CO_2, a more pronounced loss of maize (*Zea mays*) yields is predicted in Central Europe and France by the mid-21st century, while wheat (*Triticum aestivum*) is expected to be more tolerant to soil water depletion (Webber et al., 2018). Meanwhile, a significant decrease in soil water content is predicted for the vegetation periods over the main part of the continent for the late 21st century, alongside an increase in the annual availability of surface water in the Alpine and Artic regions (Samaniego et al., 2018). In Germany, at least, soil moisture is the meteorological variable with the greatest explanatory power in relation to variance in silage maize yield (Peichl et al., 2018). A reduction in soil moisture actually increases silage maize yields of the country in May, while in the driest months, August and September, the effect is the opposite (Peichl et al., 2018). Johnen et al. (2014) also found a significant, though weak relationship between available soil water (ASW) content and winter wheat yield in the northern part of the North German Plain. For Poland, Piniewski et al. (2020) projects drastically increasing soil moisture stress and drought vulnerability of maize, potato and spring cereals for the period 2021–2050. Overall, though a number of studies have focused on soil moisture assessment, historical assessments measuring soil moisture content and crop yield nexus extensively in Europe are practically non-existent.

This research aims to take a step towards addressing this underexplored aspect. By using Mann-Kendall trend tests and GIS methods, we will analyse the direction and the significance of trends in the changes in volumetric soil water content in the top 100 cm soil layers and map the patterns of this changes. Then, we will test the statistical relationship between the multi-annual variability of ASW content (a derived index of soil moisture) and wheat and maize yields. The area considered comprises the European countries, including Turkey, for the period 1993–2017 (in the case of territorially contiguous European countries, 1981–2017). We assumed that the coefficients of the ASW-crop yield relationship will increase from north to south as well as from west to east along the latitudinal and longitudinal wetness gradient. It is, however, hypothesized that a different pattern is to be expected in the Mediterranean, where rain-fed cultivation has often been transformed into irrigated cropland in recent decades (FAO, 2016; Lecina et al., 2010; Zwart and Bastiaanssen, 2004).

2. Material and methods

Soil moisture data were retrieved from the European Space Agency's ERA5-Land dataset, which presents monthly averaged volumetric (m^3 m^{-3}) soil water content at 0–7 cm, 7–28 cm, 28–100 cm and 100–289 cm intervals, using a 0.1° × 0.1° grid (Sabater, 2019). The soil moisture content of the ERA5-Land dataset is calculated with the European Centre for Medium-Range Weather Forecasts' (ECMWF's) Integrated Forecasting System (IFS) model, using the H-TESSEL land surface hydrology scheme (Balsamo et al., 2009). In the model, water balance of the top soil is calculated by solving the moisture-based Richards equation. For the calculation of the moisture-dependent hydraulic conductivity and diffusivity of the layers, the Mualem-van Genuchten formulations (van Genuchten, 1980) are used. Model layers of each cell are homogenously parametrized according to the dominant soil texture class of the cell, derived from the Food and Agriculture Organization of the United Nations (FAO) Digital Soil Map of the World (DSMW) (FAO, 2003). The DSMW is available at 5′ × 5′ resolution, and it provides soil information about two layers: 0–30 cm and 30–100 cm. In H-TESSEL, the soil texture of the 30–100 cm layer is used for the entire soil column (from surface to 289 cm). The upper boundary condition of the model is infiltration minus surface evaporation. At the bottom of the model columns free drainage (unit gravity flow) is used as boundary condition. However, this introduces some degree of uncertainty regarding the soil moisture content of the deeper soil layers as with the free drainage boundary. In summary, shallow groundwater and its effect on soil moisture are not taken into account in the model.

Data for cereal yields and harvested area at regional (NUTS2) or county (NUTS3) scale are not available neither for Europe nor the EU (Eurostat, 2022; López-Lozano et al., 2015). Wheat and maize yield data available at country (NUTS1) level for all European countries from the FAO agriculture dataset (FAOSTAT, 2022). Considering the available datasets of wheat and maize yield and harvested area and the targeted spatio-temporal framework, it was concluded that only the FAO country-scale dataset would be suitable for this study. The period covered by the study (1993–2017) was determined by the fact that several European countries, including important grain producers, achieved independence in the years of 1991 and 1992. Turkey was included, but the smallest countries, Lichtenstein, Luxemburg and San Marino, for which there is no data in the FAO datasets, or Malta, which has a very small cropland area (ca. <100 km^2), as well as Russia and the Caucasian countries of Armenia, Azerbaijan and Georgia, were excluded. Between 2013 and 2017, Turkey generated more than 10 % of European wheat yield (FAOSTAT, 2022).

First, the croplands of Europe were mapped by selecting those grid cells from the EarthStat cropland 5′ × 5′ grid dataset (Ramankutty et al., 2008) in which croplands cover at least 20 % of the cell area. The 20 % threshold was determined by trial and error; the goal was to exclude spatially separated croplands in mostly mountainous areas while keeping the transition zones between wide contiguous croplands and adjacent areas with other land-use types. The cells selected were merged and polygonised at the country and regional scales (Tables 1 and 2, Supplementary material Fig. S1).

Next, monthly time series of ASW of the 0–7 cm, 7–28 cm and

Table 1

The spatial ratio (%) of the direction of available soil water content change in the 0–28 cm soil layer by European regions in different seasonal windows between 1981 and 2017.

Period	Direction of change	Europe	Western Europe©	Eastern Europe[‡]	Central Europe[§]	Southern Europe[◊]	Northern Europe[#]
Whole year	Significant Negative	27.3	12.1	83.7	13.0	12.5	4.8
	Non-significant negative	52.6	70.0	15.7	58.4	59.6	61.3
	Significant Positive	0.4	0.1	0.0	0.1	0.4	4.0
	Non-significant positive	19.8	17.7	0.7	28.5	27.5	29.9
Winter	Significant Negative	7.8	2.5	20.5	1.2	10.4	0.2
	Non-significant negative	48.6	61.0	67.2	34.7	38.8	27.7
	Significant Positive	5.0	0.3	0.0	12.0	4.8	14.1
	Non-significant positive	38.6	36.2	12.3	52.1	45.9	58.0
Summer	Significant Negative	45.5	34.9	95.7	42.9	19.6	24.5
	Non-significant negative	43.4	44.2	3.6	54.0	66.3	49.4
	Significant Positive	1.0	3.3	0.0	0.0	0.1	1.9
	Non-significant positive	10.2	17.6	0.7	3.1	14.0	24.2
April –July	Significant Negative	40.4	39.7	80.9	33.7	16.5	21.7
	Non-significant negative	51.7	47.3	18.5	65.2	72.3	54.0
	Significant Positive	0.1	0.2	0.0	0.0	0.0	0.4
	Non-significant positive	7.9	12.9	0.7	1.1	11.2	23.9
July –August	Significant Negative	37.3	10.9	87.2	26.0	41.4	0.0
	Non-significant negative	38.0	36.3	12.1	54.1	46.3	42.1
	Significant Positive	3.6	12.3	0.0	0.0	0.2	7.5
	Non-significant positive	21.1	40.5	0.7	19.9	12.0	50.4

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Table 2

The spatial ratio (%) of the direction of soil water content change in the 28–100 cm soil layer by European regions in different seasonal windows between 1981 and 2017.

Period	Direction of change	Europe	Western Europe©	Eastern Europe[‡]	Central Europe[§]	Southern Europe[◊]	Northern Europe[#]
Whole year	Significant Negative	42.3	27.2	93.2	22.7	40.2	12.7
	Non-significant negative	40.1	58.3	6.2	54.5	33.4	54.4
	Significant Positive	1.5	0.7	0.0	2.2	1.8	5.8
	Non-significant positive	16.0	13.7	0.7	20.5	24.6	27.1
Winter	Significant Negative	24.1	5.1	71.8	5.7	25.8	0.4
	Non-significant negative	41.7	61.8	25.6	40.7	35.4	45.5
	Significant Positive	4.3	1.2	0.0	9.8	4.6	8.8
	Non-significant positive	29.9	31.9	2.6	43.8	34.2	45.4
Summer	Significant Negative	49.7	45.2	94.2	40.2	31.8	22.0
	Non-significant negative	40.7	39.6	5.1	56.1	56.5	47.8
	Significant Positive	0.6	1.3	0.0	0.0	0.3	3.3
	Non-significant positive	9.0	13.8	0.7	3.7	11.3	26.9
April –July	Significant Negative	40.9	49.5	77.3	25.0	21.8	16.8
	Non-significant negative	50.6	44.2	22.0	69.9	59.4	65.4
	Significant Positive	0.1	0.1	0.0	0.0	0.3	0.4
	Non-significant positive	8.4	6.2	0.7	5.1	18.5	17.3
July –August	Significant Negative	44.1	27.6	94.4	34.4	37.1	3.3
	Non-significant negative	43.9	52.2	4.8	62.9	49.7	51.7
	Significant Positive	1.9	5.0	0.0	0.0	0.3	8.4
	Non-significant positive	10.2	15.3	0.8	2.7	12.9	36.6

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28–100 cm layers were calculated for ERA5-Land cells overlapping (by rule of majority) the cropland polygons for the period1981–2017. ASW was interpreted as the actual volumetric soil water content (θact, m^3 m^{-3}) above permanent wilting point of the soil (θwp, m^3 m^{-3}). This amount of water is available for water uptake of plant root that largely determines plant water supply (the amount of water available for root water uptake). Therefore, ASW was used in this study as the soil moisture indicator most relevant to plant growth and ultimately, crop yield. The soil moisture content of the near-surface soil layer can fall below θ_{wp} due to evaporation, and this would lead to negative ASW values. However, water stress-induced limitation on plant growth becomes independent of soil moisture once the permanent wilting point is reached. Thus, ASW was limited to 0 if θact was smaller than θ_{wp}. In contrast to the lower limit (wilting point), an upper limit (i.e., field capacity) for water content was not considered, as – except for extreme conditions – the typical ranges of soil saturation do not inhibit crop water uptake (Taylor and Ashcroft, 1972; Wesseling et al., 1991). Soil moisture contents at the permanent wilting point were assigned to the filtered ERA5-Land cells based on the soil type map (retrieved from ERA5-Land database) (Hersbach et al., 2018) and the corresponding θ_{wp} values of the ECMWF used in the IFS model. Of the seven distinguished in H-TESSEL on a global scale, four were found to be present on European croplands: (i) coarse, $\theta_{wp,coarse} = 0.059$; (ii) medium, $\theta_{wp,medium} = 0.151$; (iii) medium-fine, $\theta_{wp,medium\text{-}fine} = 0.133$, and (iv) very fine, $\theta_{wp,very\ fine} = 0.335$.

Then, spatial averages of monthly ASW were calculated for the cropland polygons in each country and region for the periods 1993–2017 and 1981–2017, as noted above. Beside year-to-year spatial averages of regional ASW, subperiodical averages, linear trends, and slope of linear trends were calculated for 1981–1999 and 2000–2017 (Fig. 1). The slope of the trendline was estimated by the least squares method and it was visualised by a locally weighted least squares regression (loess) model through the application of the `kendall` (Hipel and McLeod, 1994), `ggthemes` (Cleveland, 1993; Few, 2012), and `ggplot2` packages (Wickham, 2016) in an R environment (Fig. 1). The equation of the slope of linear correlation is $a = r \times \left(\frac{sy}{sx}\right)$ where a = slope, r = coefficient of linear correlation, sy = standard deviation of y parameters and sx = standard deviation of x parameters. For the detailed code of the loess method applied, see Supplementary material Table S6. Subperiodical averages were tested for significance by Welch-t tests. In case of regions, USDA and World Bank regional classification were used as follows:

Central Europe: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Montenegro, North Macedonia, Poland, Romania, Serbia, Slovakia and Slovenia; Eastern Europe: Belarus, Moldova and Ukraine;.

Northern Europe: Estonia, Finland, Latvia, Lithuania, Norway and Sweden;.

Southern Europe: Greece, Italy, Portugal, Spain and Turkey;.

Western Europe: Austria, Belgium, Denmark, France, Germany, Ireland, Netherlands, Switzerland and the United Kingdom.

For the studied periods (1993–2017 and 1981–2017), crop yield data are available at country scale. In contrast to volumetric soil moisture content (the raw data in the ERA5-Land database), the use of ASW assures the comparability among soil types, and it preserves its physical meaning when spatially averaged. The spatially averaged ASW time series of the 0–7 cm and 7–28 cm layers were aggregated in one layer (0–28 cm) using weighted averages, with the thicknesses of the layers as weights. Ultimately, the ASW of the 0–28 cm and 28–100 cm layers were used in further analysis, because these are the main depth ranges at which cereal root water uptake takes place. The top layer is especially important, since an estimated 50 % of the roots of the major crops can be found in the upper 15 cm soil layer (Fan et al., 2016). Two main seasons can be designated in the annual hydrological cycle of the soils in the temperate climate zone: (i) the recharging phase lasting from autumn to early spring, which is characterized by a positive soil hydrological balance, and (ii) the discharging phase between mid-spring and early autumn, which is characterized by a negative soil hydrological balance. Hence, the recharging and the discharging phases roughly correspond to the winter and the summer halves of the year in the Northern Hemisphere. Nonetheless, the actual timing of the switch from recharge to discharge, and vice versa, can vary from year to year and shows some differences across the climatic zones of the European area. The most important species of cultivated grain is winter wheat in most of Europe (FAOSTAT, 2021); it is typically sown between September and October and harvested in June and July (U.S. Department of Agriculture, 2021) (Supplementary material Table S5). Vernalisation, a vegetative growth stage of winter wheat, when the plant is dormant, falls in late autumn and winter (Acevedo et al., 2002), when the intensity of transpiration is low and soils are often saturated. During this period, high soil water content, and most of all oversaturation, may negatively affect the plant (Bozán et al., 2018; Mercau et al., 2016). In a continental climate, a late

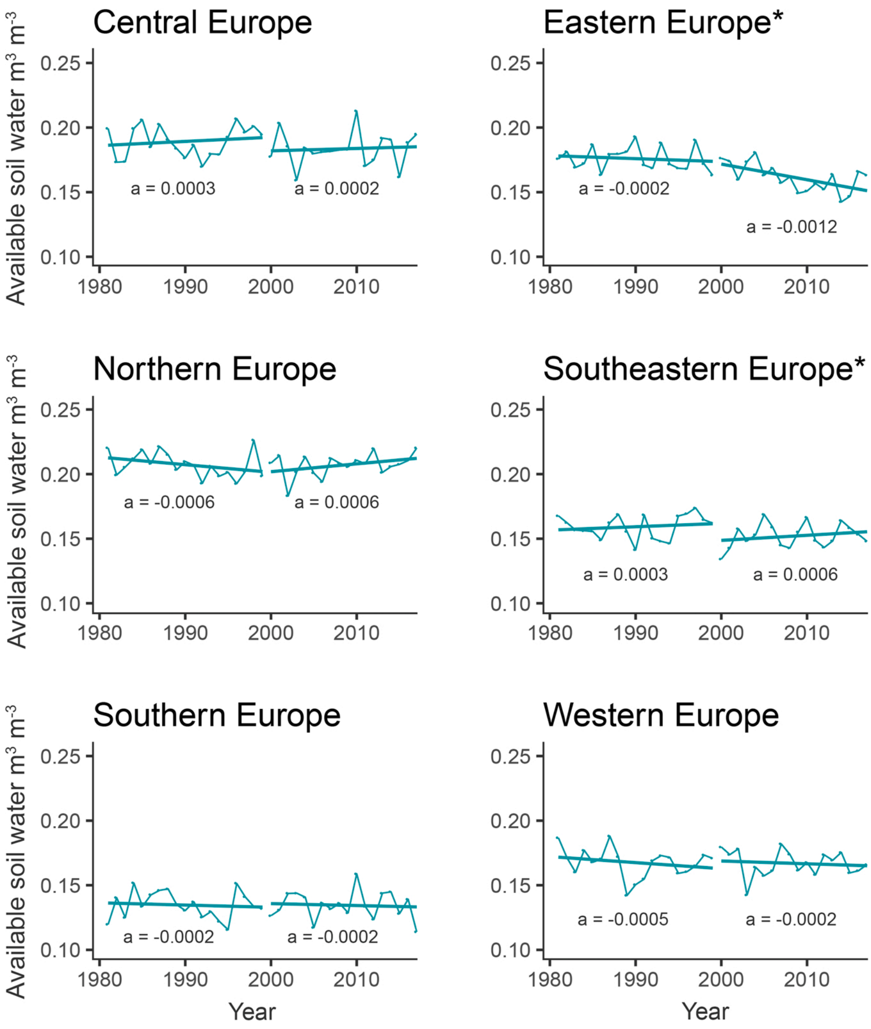

Fig. 1. Regional averages of the 0–28 cm layer available soil water (AWS) content in European croplands for 1981–1999 and 2000–2017. Dashed lines indicate the average soil water content for 1981–2017, straight lines show linear trends for the periods 1981–1999 and 2000–2017, a = slope, * = significant differences between annual average AWS of 1981–1999 and 2000–2017. Western Europe: Austria, Belgium, France, Germany, Ireland, Netherlands, Switzerland and the United Kingdom; Eastern Europe: Belarus, Moldova and Ukraine; Central Europe: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Montenegro, North Macedonia, Poland, Romania, Serbia, Slovakia and Slovenia; Southern Europe: Greece, Italy, Portugal, Spain and Turkey; Northern Europe: Estonia, Finland, Latvia, Lithuania, Norway, and Sweden. Regions sequenced by the quantity of harvested wheat and maize.

spring turning point was discovered in soil water – yield relationships when the negative effect of saturation disappears and the impact of soil water on yields becomes positive (Peichl et al., 2018; Pinke et al., 2020). By way of contrast, the maize sowing period varied between March and May (Dobor et al., 2016; Maresma et al., 2019; U.S. Department of Agriculture, 2021), while it is harvested from August to November. Beyond these aspects, the aim was to examine the trends in those phenological periods when the potential evapotranspiration the highest and thus moisture has the most intensive impact on of the studied cereals (Irmak et al., 2015; Kimball et al., 2019). The active leaf development of winter wheat starts in spring (March–April), intensifying evapotranspiration thereafter (Acevedo et al., 2002; U.S. Department of Agriculture, 2021). Therefore, April–July (Irmak et al., 2015) and July–August (Kimball et al., 2019) were selected as the phenological phases to be studied in the case of winter wheat and maize, respectively. On the basis of the above considerations, the direction and the significance of trends in the changes in ASW content were analysed in each grid cell falling inside a cropland polygon using Mann-Kendall trend tests, applying the `kendall` package in an R (Hipel and McLeod, 1994). For the detailed code of the combined R and GIS method that was used in the calculations performed on 0.1° × 0.1° grid cells (Fig. 2) see Supplementary material Table S7. The periods studied for trend analysis were the hydrological winter (October to March) and summer (April to September) halves of the year, and the periods of April–July and July–August. This was done for both the 28–100 and the 0–28 cm soil layers, the latter calculated as a weighted average from the 0–7 and 7–28 cm soil layers with the thicknesses of the layers as weights, as described above. Then, using regression and nonparametric bootstrap resampling methods (Canty and Ripley, 2017; Davison and Hinkley, 1997), the relations were tested between the first differences of the country-scale averages of 0–28 cm ASW and crop yields as explanatory and response variables for the periods of April–July and July–August. The normality and multicollinearity of the studied variables were tested using the `car` package (Fox and Weisberg, 2019), Shapiro–Wilk tests (Shapiro and Wilk, 1965), QQ plots and variance inflation factor (VIF) tests (O'Brien, 2007).

3. Results

3.1. Changes in soil water content across the European croplands from 1981 to 2017

The country-scale average AWS in the 0–28 soil layer varied in the

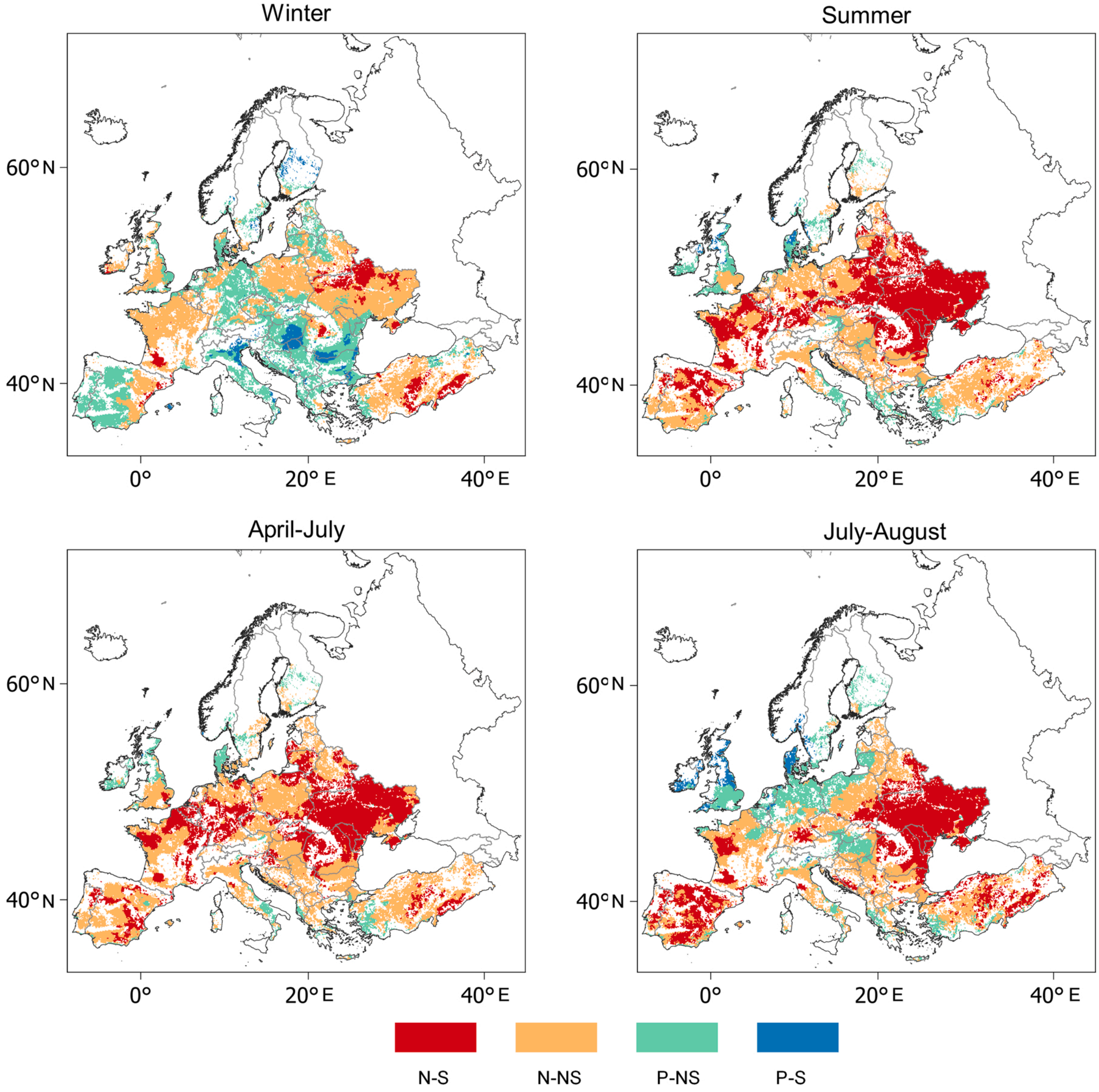

Fig. 2. Seasonal trends of available water content change in the 0–28 cm soil layer in European croplands between 1981 and 2017. Calculations performed for 0.1° × 0.1° grid cells. N: negative slope; P: positive slope; S: significant; NS: non-significant.

following ways: annually 0.15–0.24 m^3 m^{-3} ; in winter 0.17–0.25 m^3 m^{-3} ; in summer 0.13–0.23 m^3 m^{-3} (Fig. 1; Supplementary material Fig S2, Table S2). The highest ASW was found in the Alpine and Baltic (including Finland) regions, and the West Balkan countries, as well North Western Europe, while a major part of the Mediterranean and the Carpathian-Balkan regions, and Eastern Europe had the driest soils. Over almost the entire continent, the inter-annual minimum occurred in the months of July to September. In some years, October was the driest month in Central Europe, the Iberian Peninsula, and Scandinavia. ASW peaked almost everywhere between December and April, but in Western Europe, this also happened in November and May, as well. The inter-annual fluctuation of soil water content in croplands was highest in the Mediterranean Region; the amplitude of fluctuation decreased northwards and westwards (Supplementary material Fig. S2, Table S2). The smallest seasonal differences were found in Finland and Switzerland, representing the top countries on the "European soil moisture rank list" (Supplementary material Table S2).

Between 1981 and 2017, the annual average of soil water content decreased on most European croplands, both in the top 28 cm and in the 28–100 cm soil layers (Fig. 2, Supplementary material Fig. S4, Tables 1, 2). A significant decrease in the annual soil water content was detected in 27.3% of European croplands and only a small area, 0.4 % of the cells, showed any significant increase in the 0–28 cm soil layer from 1981 to 2017 (Fig. 2, Table 1). The changes were more intense in the deeper (28–100 cm) soil moisture layer, where a significant decrease was observed in 42.3 % of the grid cells studied and a significant increase took place in merely 1.5 % of the cells during the last four decades (Table 2, Supplementary material Table Fig. S4 and Table S4). The decrease in the mean annual water content of the top 28 cm soil layer was continuous in France, Romania and Eastern Europe, but the downward trend broke in Italy in the late 1990s and the previously lost ASW was recharged between 2000 and 2017. In the 28–100 cm soil layer, however, a permanent decrease affected almost all important grain producing countries, with the exceptions of Bulgaria and Italy (Supplementary material Fig. S4). A soil water decline was observed in Eastern and Western Europe between 1981 and 1999 (Fig. 1). In the other four regions, soil water did not change significantly in this period. Since 2000, the soil water of croplands decreased in each region, but the dynamics of decrease accelerated precipitously in the eastern part of the European continent with Moldovan, Ukrainian and Romanian croplands experiencing the most extensive ASW decline (Fig. 2). Regionally, annual average ASW decreased in Eastern Europe the most ($t = 5.19$, $df = 17$, $p < 0.01$) from 1981 to 1999–2000–2017, while Northern Europe suffered least of all (Table 1, Supplementary material Table S3).

The dynamics of ASW was different during the two hydrological half-years. In the summer half, soil water content decreased significantly in 45.5 % of the grid cells featured in the study, while only 1.0 % of the cells showed a significant increase (Fig. 2). The most serious seasonal ASW decline happened in Eastern Europe, where practically all croplands (95.7 %) experienced a significant water content decline in the top 28 cm soil layer during the summer period (Table 1). Besides Eastern Europe, ASW loss in the driest months affected Southern Europe the most (Table 1). Moreover, summer soil water content declined significantly in almost third of Western European croplands. Country-scale averages of April–September cropland soil water decreased significantly in most of the important Central, Eastern and Western European grain producing countries, with the exception of the United Kingdom, Hungary, Italy and Spain (Supplementary material Table S3). Significant increases in the top 28 cm soil water summer content occurred in the majority of the British Isles, Denmark, Austria, Southern Italy, Greece and Albania, and the Mediterranean coast of Turkey (Fig. 2).

Within the summer itself, differences in soil water dynamics were apparent in the hottest months, July and August. Although the top 28 cm ASW decreased significantly in an estimated 37.3 % of European croplands, a significantly increasing trend emerged across an extensive Western and Northern European zone including the majority of the British Isles, the North European Plain, the Low Countries, and extending into Hungary and the eastern half of the European Mediterranean (Fig. 2, Table 1). The spatial distribution of significant April–July ASW decreases in the top 28 cm soil layer from 1981 to 2017 is much more homogenous compared to summer soil water means (Table 1). Alongside Eastern Europe, Western European croplands also suffered a noticeable soil water loss, and the ratio of cells with significantly increasing soil water was negligible in the years 1981–2017. Winter halve-year ASW content increased significantly in Italy, Hungary, and countries situated in Northern Balkan, while July-August ASW content increased in the British Islands, Denmark and Norway (Supplementary material Table S3).

During the hydrological winter, soil water significantly decreased in 27.3 % of European croplands and increased merely in 5 % (Fig. 2). In Central and Northern Europe the balance was basically positive; but in Southern and Western Europe and above all in Eastern Europe the ratio of areas with winter soil water loss to those with an increase rose significantly (Table 1). Moreover, only Eastern European countrywide averages displayed significantly decreasing trends in the deeper soil layer (28–100 cm) during the winter half year (Table 2). The winter soil water content significantly increased in 12.1 % of Scandinavia, whereas only 0.2 % was affected by significant decrease. Interestingly, croplands in countries surrounding the Adriatic Sea, along with Austria and Hungary, experienced a significant increase in soil water content in the winter half year.

3.2. Soil water and cereal yield associations

The association between soil water content and cereal yield was found to be strongest in the uppermost soil layers, while it was weaker when it was the water content in deeper layers that were considered (Fig. 3, Supplementary material Table Fig. S5, S6). During the period of 1993–2017, significant relationships appeared between available soil water and wheat yield with a positive regression slope in an estimated 64.3% of the area under wheat cultivation in Europe and with a negative regression slope in 5.7 % of that area (Fig. 3). Wheat did not display any significant dependence on ASW in almost one third of Europe. A positive regression slope characterised ASW - wheat yield relationship in Central and Eastern Europe, Germany, Italy, Spain and Turkey (Fig. 3). The highest degree of dependence of wheat on ASW content was observed in Spain, Moldova and Turkey, where the variances of the 0–28 cm ASW level accounted for 77 %, 62 %, and 41 % of wheat yield variances, respectively (Fig. 3). A negative association between ASW and wheat yield occurred in three countries: Belgium ($R^2 = 0.28$; $df = 22$; $p < 0.01$) and Ireland ($R^2 = 0.33$; $df = 22$; $p < 0.01$). A negative and non-significant association was found between ASW and wheat yield variances in most of Western Europe and the Western Balkan countries.

Maize generally displayed a stronger dependence on soil water than wheat. Of the countries in which the association between the 0–28 cm layer available soil water content and the maize yield was significant, it was positive in every country over the entire vegetation period, as well as in the high summer season (July–August) (Fig. 3). This country-scale analysis indicates that ASW had a significant positive impact on maize yields in an estimated 89.4 % of the areas where maize was harvested in the period 1993–2017. Almost 11 % of European maize-growing area did not show any significant dependence on soil water (Fig. 3), and an estimated 92.1 % of this area is situated in the Mediterranean region. There was no country in which available soil water content had a negative impact on maize yields. The strongest relationships ($R^2 = 0.46–0.75$) occurred in Central Europe. A very high degree of sensitivity of the maize yield to ASW was discovered in the biggest Western European producers, France and Germany, where 66 % and 68 % of yield variance was explained by soil water fluctuations in the 0–28 cm soil layer during July–August. In Romania and Hungary, the third and the fourth biggest European maize producers on the continent in 2013–2017, fluctuations in soil water accounted for 46 % and 62 % of

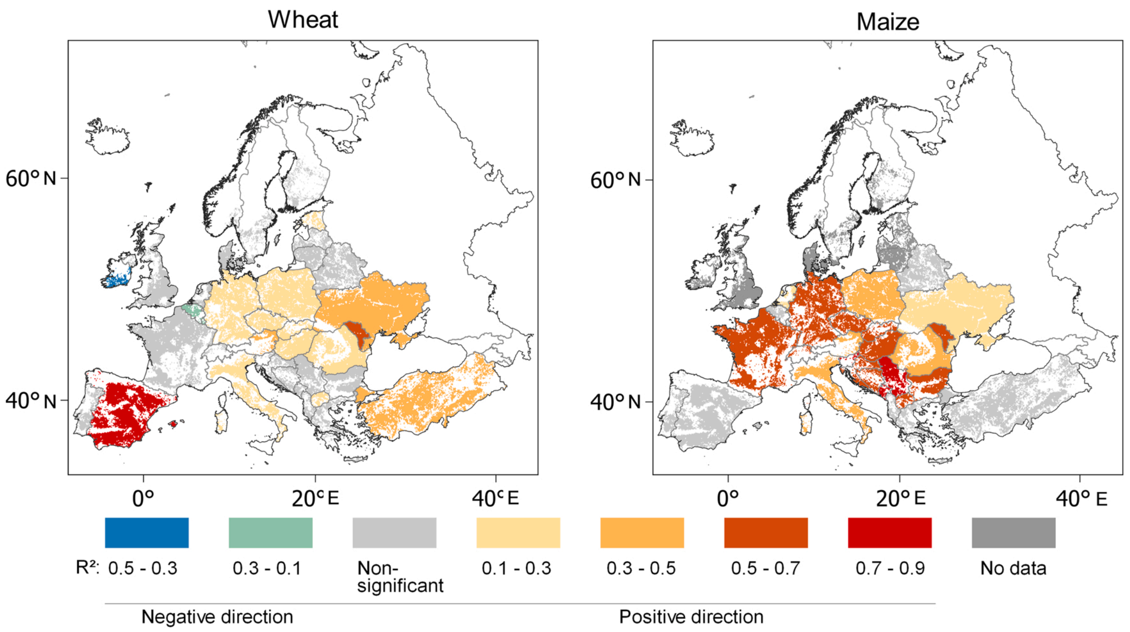

Fig. 3. Coefficients of determination (R^2) between 0 and 28 cm ASW and crop yields in the European croplands in the period 1993–2017.

maize yield variances, respectively. These four big producers generated an estimated 35 % of European maize production in 2013–2017. In Ukraine, the biggest European maize producer, a weak statistical relationship ($R^2 = 0.19$; df = 22; $p = 0.02$) was calculated for the 0–28 cm ASW and maize yield for July–August. Soil water did not show a significant relationship with maize yield in Belarus, but the 0–28 cm ASW explained 60 % of Moldovan maize yield variation. Among the South European countries, a significant association between soil water and maize yield was found only in Italy ($R^2_{\text{Jul–Aug}} = 0.47$; df = 22; $p < 0.01$).

A decreasing trend in summer half year available soil water content was found to match up with significant associations with positive regression slopes between ASW and wheat and maize yield in 32.0 % and 35.2 % of European croplands, respectively (Fig. 4). These vulnerable areas were characteristically to be found in a broad zone between 44° and 54° latitudinal belt stretching from France to Ukraine, but in the case of wheat this sensitivity was discovered to be present in Spain and Turkey, too. The combination of simultaneously increasing ASW and a positive soil water – yield relationship was not found anywhere in European croplands. At the same time, the extension of spatial co-occurrence of a decreasing soil water trend and a negative regression slope of the association between soil water and yields or the co-occurrence of an increasing soil water trend and a positive regression slope of the relationship between moisture and yields was negligible.

4. Discussion

A significant decrease has characterized summer half year (April–September) soil water content in 45.5% of croplands across Europe over the last four decades. On the contrary, only about 8% of the area experienced decreasing soil water content in the winter hydrological half year (October–March). So, it covered the total growing period of maize and a considerable part of the active growing period of winter wheat that was characterized by a significant moisture loss, and the consequence of this was the reduction of the gross primary productivity of European ecosystems (Ciais et al., 2005). Almost all croplands of Eastern Europe were affected by ASW decline in the growing season,

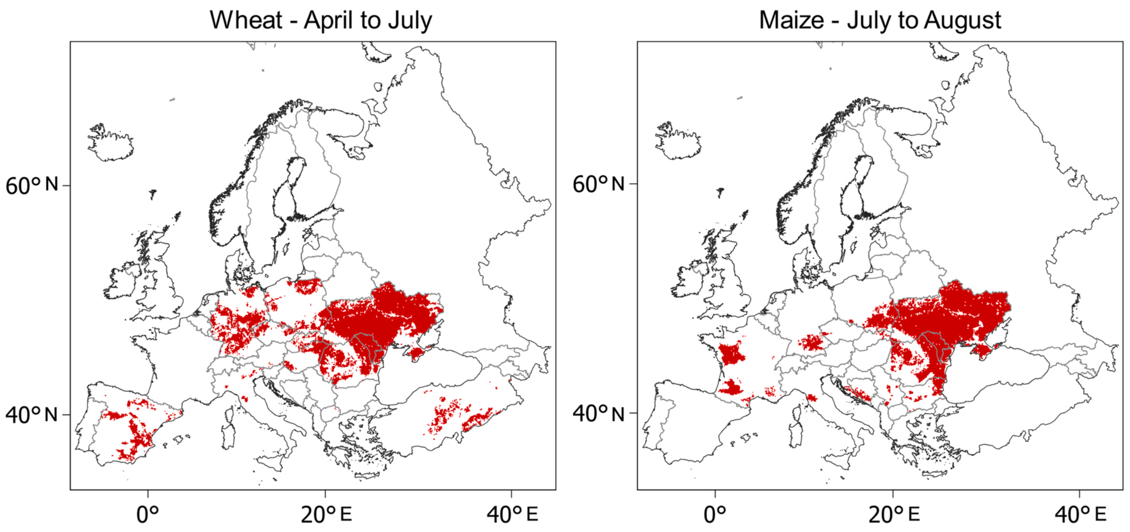

Fig. 4. Overlap of (i) significant 0–28 cm layer available soil water content decrease in the April–July and July–August time windows (1981–2017) and (ii) significant relationship with a positive regression slope between 0 and 28 cm layer available soil water content and wheat and maize yields in Europe 1993–2017.

however, almost ∼ 40 % of croplands also faced significant losses in Central and Western Europe. This means that three important grain producing regions of Europe were all affected by this unfavourable tendency in soil hydrology. Moreover, a main part of these three regions suffered the co-occurrence of a decreasing soil water trend and a significant dependence of yields on soil water (Fig. 4). As for the future, with the intensifying evapotranspiration and increasing frequency of droughts and heatwaves that come with a warming climate, it is practically certain that rainfed cultivation will depend increasingly on groundwater driven soil water content (Greve et al., 2018). During the driest and hottest months, when cereals experience an evapotranspiration deficit, shallow groundwater becomes a key source of soil moisture (IPCC, 2019; Zipper et al., 2015).

The European map of ASW – wheat relationships displays a rather variegated pattern for the period 1993–2017. The highest coefficients of determination appeared in Spain, then in Eastern Europe and Turkey (Fig. 3). The dependence of maize production on ASW showed a different spatial pattern in Europe. The strongest relation between ASW content and maize yield was observed in Western and Central Europe and the Northern Balkan Peninsula (Fig. 3), indicating an increased sensitivity of maize production in relation to ASW content under continental climate. In the Ukraine and Central Europe, where almost all croplands are located in the continental climatic zone, beside soil moisture – yield relationships the decrease of available soil water content was also significant (Fig. 4). By contrast, the majority of Southern Europe did not show signs of a significant relationship between ASW and maize, probably because the majority of Mediterranean maize cultivation has shifted to irrigation over recent decades (FAO, 2016; Lecina et al., 2010; Zwart and Bastiaanssen, 2004). This agro-hydrological strategy moved Mediterranean maize yields into the top positions of the continental yield rank lists, while the cultivation of cereals with lower yield potential (e.g. wheat) was almost abandoned (FAO, 2022; Santana et al., 2010; Scheffers and Pecl, 2019). It should further be noted that available soil water content has had a considerably higher impact on maize than on wheat yields (Fig. 3).

Increasing grain production, and basically the yields of a few key crops, is a pillar of global food supply. From the 1990s, Eastern European regime changes resulted in a rapid technological transfer, triggering a substantial increase in agricultural productivity, resulting in the area becoming a major global supplier of grain (Swinnen et al., 2017; Pinke et al., 2022). Since climate warming pushes croplands from their traditional locations towards cooler climate zones (from south to north in the Northern Hemisphere), Poland, Germany and Eastern Europe, including Russia, are home to the areas with the biggest potential for the cereal field growth (Liu et al., 2016). In other words, the northern part of Eastern and Central Europe is an important region for productivity increase and cropland area extension due to climate change. Because of its relative technological underdevelopment, this is the region where the major part of European yield gap, i.e. yield growing potential, was identified (Schils et al., 2018). The industrialisation of agricultural activity, however, through e.g. soil compaction and the reduction of soil biota consist hampers root development, thereby decreasing the stress resistance of plants and increasing the drought vulnerability of soils (Lipiec et al., 2003). Other examples of negative large-scale effects of agriculture are badly-timed ploughing (Pittelkow et al., 2015b), exaggerated groundwater drainage (Pinke et al., 2018) and groundwater exploitation (Hornbeck and Keskin, 2014; Pepliński, 2021). These processes intensify soil moisture decline, threatening grain production stability under continental climate (Liu et al., 2015). The results presented here, in line with previous research (Bakucs et al., 2020; Kern et al., 2018), constitute a warning sign in the southern part of Eastern and Central Europe where the most severe decline in soil water content and drought vulnerability was discovered (Olesen et al., 2011).

ASW content in the deeper soil layers (28–100 cm) declined over a more extensive area than in the upper one (0–28 cm). The spatial co-occurrence of small or negligible long-term water content changes in the top layers and a significant decrease in moisture content in the deeper layers have two main implications: (i) Rising ambient temperature and increasing frequency and duration of droughts intensify the water utilisation of plants from the deeper soil layers while further depletion of top layers is limited by the permanent wilting point of the top soils. (ii) While there is no significant trend in the annual and seasonal precipitation sums within the spatiotemporal framework considered here (Trenberth, 2011; van Wijngaarden and Syed, 2015), the frequency of high intensity rainfalls – and thus the fraction of precipitation that is "lost" to surface runoff – is increasing, and the ratio of annual surface infiltration is decreasing (IPCC, 2019). The reduced amount of infiltrated water is still capable of partly compensating for the soil moisture deficit of the top layers, but cannot maintain recharge rates for the deeper ones. In other words, periods in which ASW in the top layers is above field capacity and thus percolation to deeper layers can happen have become less frequent. In lowlands, shallow groundwater provides an additional source of soil moisture (and transpiration) that may compensate for changes in the water balance of the deeper soil layers. However, as upward fluxes from groundwater to shallow soil layers are not taken into account in the soil water budget module of the ECMWF model that produced the ERA5-Land data (Sabater, 2019), the contribution of groundwater and its effects on available soil water content trends remain unknown. Another limitation of the available data should be mentioned. Perhaps surprisingly, data for cereal yields and harvested area are not available at either the regional (NUTS2) or county (NUTS3) scale and again, neither for Europe nor the EU (Eurostat, 2022). On the contrary, diverse agricultural county level data are available on open access for North America including the U.S. and Canada for the past 50–150 years (Canada, 2022; USDA, 2022). These considerations and the results contained herein underline the need for the development of a deeper understanding of large-scale deep-layer moisture trends and groundwater – moisture interactions as well as the interconnected impacts of environmental and socio-economic factors on agricultural areas that cover almost third of Europe without Russia (Ramankutty et al., 2008).

One of the foremost challenges for environmental policy is the successful mitigation of the decline in observed soil water – as well as, more generally, the global groundwater crisis (Famiglietti, 2014) that is a key aspect in the global environmental crisis. The significantly decreasing available soil water content linked to more intense, more frequent, and longer-lasting droughts threatens not only agricultural cultivation, but a broad tranche of ecosystems in Europe (Meehl and Tebaldi, 2004). Therefore, soil water conservation practices deserve more attention, and particularly in drier regions of Europe (Olesen et al., 2011; Pittelkow et al., 2015a). The adaptation methods traditionally suggested include the relocation of certain land uses towards less drought prone regions, e.g., from south to north (Trnka et al., 2015). But land management techniques in e.g. conservation agriculture (Kertész and Madarász, 2014) provide further farm-level opportunities to address the issue, for example, with sowing densities (Lobell et al., 2020), no-till (Pittelkow et al., 2015b) and mulching (Chen et al., 2007). Considering the typically strong hydraulic relationship between surface waters and soil moisture or shallow groundwater, different solutions for water retention, including the restoration of wetlands through systematic and controlled flooding as a managed aquifer recharge (MAR), are appropriate forms of climate change mitigation strategies at landscape scale (Stefan and Ansems, 2018). As a part of climate smart land use systems (Lipper et al., 2014) MAR can be efficiently used to enhance the drought resilience of plains, which are central to agricultural production (Tran et al., 2019). The utilisation of floodwater for MAR in arid and semi-arid regions is a concept subject to intensive research (Sprenger et al., 2017). In recent decades, wetland restoration has increasingly been considered a key step towards the achievement of climate mitigation goals (IPCC, 2019). Currently, the European Union is setting its sights on rehabilitating 25,000 km of its rivers with their floodplains (EU, 2020). Putting this plan into action may effectively raise groundwater table and ameliorate soil moisture conditions in European regions that are important for the human food supply Schils et al., 2018).

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

Acknowledgements

This paper was supported by the National Research, Development and Innovation Office – NKFIH PD 18 Grant Project no. 128970, the NRDI Fund (TKP2020 IES, Grant No. TKP2020 BME-IKA-VIZ) and is a contribution to the Global Land Programme as well as the PAGES Landcover6k and 2 K working groups.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126579.

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