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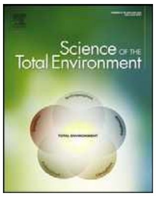

A spatially explicit analysis of wheat and maize yield sensitivity to changing groundwater levels in Hungary, 1961–2010

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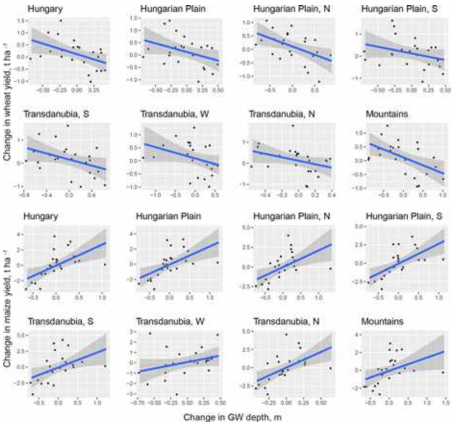
HIGHLIGHTS

- We studied groundwater crop yield relationships in Hungary for 1961–2010.
- There was a significant groundwater decline during the second 25-y warming period.
- Maize demonstrated higher sensitivity to groundwater levels than wheat.
- In drought sensitive areas, groundwater is essential for sustained food production.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater (GW) in many regions is essential for agricultural productivity, especially during drought periods. The shrinking of GW is an important but rarely documented component of the recent global environmental crisis and may threaten food security. The problem cannot be put in proper perspective, because we rarely have datasets long and detailed enough to scrutinise the unfolding effects at regional scales. To address this knowledge gap, we used a 50-y long (1961–2010) and spatially extensive (283 GW wells) dataset from Hungary to examine the GW trends and the sensitivity of the yields of two important crops to GW fluctuations. During 1986–2010, GW levels were significantly (0.21–0.60 m) lower than during 1961–1985 in every region of Hungary and every month of the year. The decrease was 2.24 cm y^{-1} at the country level. Linear and bootstrap resampling tests indicated weak relationship between GW levels and wheat yields but decreasing GW levels accounted for 18–38% of maize yield variability during the 'climate change affected' period of 1986–2010. Calculating the impact of GW on potential food production, a 100 mm higher GW levels would have increased annual maize yields by 0.23 t ha^{-1} on the Hungarian Plain. However, the registered GW decrease caused an estimated maize yield loss

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Ecosystem services
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of 0.65 t ha^{-1}, i.e. 11.6% of the average annual yield during 1986–2010. GW level fluctuations on the plain showed a significant correlation with August–October soil moisture gridded data over much of the agricultural landscapes of Central and Western Europe, indicating a similar situation in a wider European context. To mitigate the cumulative negative impact of GW decrease and the rising temperature, GW recharge via infiltration of retained water would be an adequate solution. Areas of former floodplains with low agroecological suitability, amounting to almost a quarter of the Hungarian Plain could serve as such water retention areas.

1. Introduction

The majority of human calorific intake comes from a very restricted set of crops (FAO, 2018), including wheat (*Triticum spp.*), and maize (*Zea mays*), which are the two main types of cereals in Europe (Eurostat, 2018). Wheat is among the first crops domesticated in the Fertile Crescent (Lev-Yadun et al., 2000), while maize is a tropical-sub-tropical crop, domesticated in Central America (Sluyter and Dominguez, 2005). Today, both are grown over an area much larger than their original distribution, (FAO, 2018) and mostly as rainfed crops. However, several of the current production areas have strongly fluctuating precipitation patterns, including drought periods (Zwart and Bastiaanssen, 2004; Li et al., 2016; Mukherjee et al., 2019). Bioclimatic studies underline the high climatic sensitivity of key continental regions of wheat and maize production including eastern and central Europe (Kern et al., 2018; Pongratz et al., 2008; Ray et al., 2012). In Hungary, that occupies most of the Carpathian Basin, the negative effects of warming temperature and drought increased from the mid-to late 20th century (Pinke and Lövei, 2017). With the increasing intensity and duration of drought periods, shallow groundwater (GW) plays a decisive role in agricultural productivity (Nosetto et al., 2009; Rizzo et al., 2018; Vörösmarty et al., 2000). During dry periods, rainfed cereals may obtain 50–100% of their water demand from GW (Jalota et al., 2018; Kahlown et al., 2005; Yang et al., 2007). Recent climate change and the projected climate impact during the 21st century may significantly reduce GW recharge rates through increasing evaporation and altered spatio-temporal precipitation patterns (Taylor et al., 2013), creating a situation that poses a risk to global food security.

GW is related to a multitude of ecosystem functions and supports many services (TEEB 2010). It is an ecosystem good itself in the provisioning goods and services class (Haines-Young and Potschin, 2018; Maes et al., 2016). While the importance of GW – providing water for drinking and regulating floods and droughts through surface water interactions – is straightforward, the supporting role of GW is rarely investigated (Czúcz et al., 2018, Maes et al., 2016). GW systems hold an estimated 97% of the global freshwater stocks (Trenberth and Asrar, 2014). They have a relatively slow dynamics, making them highly vulnerable to overexploitation and pollution (EC, 2000, 2006). GW supply is vital for lakes and wetlands (Kløve et al., 2011; Perkin et al., 2017; Zhou et al., 2009), and an estimated 42% of irrigation water also comes from GW (Döll et al., 2012). Human dependence on GW increased over the past modernization phases of agriculture, while this natural resource, especially of shallow GW can be vulnerable to anthropogenic landscape transformation (Hornbeck and Keskin, 2014) and climate change (Kumar, 2012). Excessive GW extraction can negatively affect agricultural production, especially when interacting with climatic effects. There are several spectacular examples of grave consequences due to overexploitation of GW resources, leading to the collapse of agriculture in extensive areas such as the Midwestern United States (Basso et al., 2013; Glazer and Likens, 2012), in the intensively irrigated North China Plain (Foster et al., 2004; Kendy et al., 2004; Piao et al., 2010) and Syria (Châtel, 2014; Aw-Hassan et al., 2014).

GW assessments focus mainly on aquifers (Zheng et al., 2010) and river basins (Arnold et al., 2000) frequently in narrow time windows (Bell et al., 2008; Bonsor et al., 2018; Rodell et al., 2009), or focusing on crisis areas (Horner et al., 2009; Fehér, 2015). Published long-term analyses of GW levels that use data at a national-scale are infrequent (but see Konikow, 2013). Although the European Community requires a standardised monitoring of GW ecosystems (EC, 2000), we have no long-term landscape-scale quantitative assessments from Europe; the majority of studies come from the US (Konikow, 2013; Chaudhuri and Ale, 2014), China and the Indian subcontinent (Shamsudduha et al., 2009). In these areas, substantial GW decrease and subsequent problems were registered. The decadal medians of deep GW levels declined by about 22 m in Texas from the 1930s to 2000s (Chaudhuri and Ale, 2014). Decreasing GW levels in the majority of agricultural and urbanized areas and increasing GW levels in the estuarine and coastal landscapes due to rising sea levels were registered in the Ganges-Brahmaputra-Meghna Delta during 1985–2005 (Shamsudduha et al., 2009). In the intensively irrigated North China Plain, a globally important food producing landscape (Kendy et al., 2004; Piao et al., 2010), the water table level declined by an estimated 10–30 m between 1964 and 1998 (Foster et al., 2004). In the absence of empirical data, sophisticated global GW models (Fan et al., 2013; de Graaf et al., 2014,) attempted to fill our knowledge gap on GW dynamics.

The importance of shallow GW dynamics and its interaction with rainfed crop yields is recognised (Acharyya, 2014; Cisneros et al., 2014; Mercau et al., 2016), yet many analyses deal with GW based irrigation impact on cereal yields (Musick et al., 1994; Sun et al., 2015; Zwart and Bastiaanssen, 2004), but not with GW-rainfed crop yield relationships. Analysing the ratio of GW stress and potential caloric demand, Gleeson et al. (2012) concluded that due to overexploitation, GW stress potentially affects about 1.7 billion people and could limit the potential to increase agricultural production via limited irrigation opportunities over vast areas, including the Danube Basin. Water deficit sensitivity coefficients, calculating the effect of evapotranspiration on different crop species indicate a high vulnerability during the mid-stage vegetation period both in winter wheat and maize (Allen et al., 1998; Doorenbos and Pruitt, 1977; Gao et al., 2017). During dry periods, rainfed cereals may obtain 50–100% of their water demand from GW (Kahlown et al., 2005; Yang et al., 2007). Outside this range, yields are limited either by water logging or insufficient water availability (Wang et al., 2015). GWL mapping and high-resolution crop yield data from Cordoba Province, Argentina specific GW depths, at which crop development is optimal (wheat: 0.7–1.6 m; maize: ~1.5–2.5 m) (Nosetto et al., 2009). Under continental climate, higher GW levels may evolve mainly in winter and early spring affecting winter crops (Mercau et al., 2016; Bozán et al., 2018a). But due to the high evapotranspiration deficit of this climate zone, shallow GW has more positive than negative impacts on cereals (Zipper et al., 2015). Kahlown et al. (2005) suggest that the maximum wheat yield is obtained at an optimum 1.5 m GW depth in a semi-arid area of Pakistan. In case of maize, GWLs below 2.5 m depth have little contribution to plant development in semi-arid monsoon and arid regions (Gao et al., 2017; Luo and Sophocleous, 2010). These data showing the sensitivity of rainfed cultivations to GW levels, and along with the high ratio of rainfed crops worldwide (42–59%, FAO, 2014; Meier et al., 2018) highlight the global importance of quantifying the influence of GW levels on rainfed crop yields at a higher spatial resolution, and over a longer time period than currently available.

Here, we aim to examine the changes of GW level means, and yield means of two major grains, wheat and maize, and the GW level-yield association for two 25-y long periods between 1961 and 2010 at regional-scale in Hungary, a major cereal producer of Europe where up to 98% of arable land is rainfed. We also aim to estimate the value of food production (provisioning) service of GW ecosystems on the Great Hungarian Plain at a landscape level. Additionally, given that soil moisture is usually related to GW levels, we also examine the spatial correlation of the soil moisture on the Great Hungarian Plain with the CLM 1979–2016 ERA-interim soil moisture dataset (0.25°×0.25°) for Europe in the 1986–2010 period. We hypothesised that (i) due to a warming climate, GW level means of the examined 283 wells decreased between 1961 and 1985 and 1986–2010. This, in turn (ii) increased the GW impact on cereal yields from the first 25-y period to the second one. On the basis of crop sensitivity to water deficit and the seasonal bioclimatic conditions in Hungary we supposed that (iii) maize yields would show a strong statistical relationship with GW level of July and August. Finally, on the basis of the spatial relationship of the annual precipitation means in Hungary, we assumed that (iv) a relatively strong (>40%) spatial correlation will be visible between GW levels on the Great Hungarian Plain and the gridded soil moisture (0–100 cm) values in the Carpathian Basin for 1986–2010.

2. Material and methods

2.1. Study area

Our study area extended to the whole of present-day Hungary, a land-locked, small (96,000 km2) country in southeastern Europe, dominated by lowlands and hills. Hungary lies in one of the most closed basins on Earth, where the domestic runoff is only 5% of the total surface flux indicating significant dependency from upstream foreign watersheds; this value is also the lowest in Europe (Somlyódy, 2011). The hydrological exposure exists also in subsurface conditions as intermediate and regional GW flow regimes provide 10–100 mm y^{-1} upward recharge, influencing GW levels in the plains (Tóth, 1970). The importance of this subsurface water flux is high because approximately two-third of the rainfed croplands in the country falls into the “moderately cool, dry” and “moderately cool, moderately dry” Feddema climate categories (Acs et al., 2014), and experience 50–250 mm y^{-1} climatic water deficit (Table 1). Using landscape geographical classifications based on climatic and relief conditions (Mezősi, 2017) the 19 Hungarian counties were grouped into six agroecological regions (Table 1). Five of them were homogenous, dominated by lowlands, hills or mountains. The sixth, northern Transdanubia, was composed of a mix of plains, hills and mountains.

2.2. Data sources

We used data from 283 wells of the Hungarian GW monitoring network and county-scale data of annual wheat and maize yields during 1961–2010 (HCSO, 2012). The period was determined by the availability of GW data for Hungary. The GW monitoring wells in Hungary are situated mainly on plains and low hills, low-lying valleys and foothills, showing a strong overlap with cropland (Fig. 1). The depth of the GW at these wells is measured daily. Agricultural production in Hungary mostly relies on precipitation: currently, only 1.8–2.4% of croplands are irrigated and even during the 1970s, the period of most extensive irrigation, did not reach >8% (Bozán et al., 2018b; Eurostat, 2019). We used county-scale data of annual wheat and maize yields during 1961–2010, obtained from agricultural statistics (HCSO, 2018). There are no separate data on yields by winter or spring-sown common wheat (*Triticum aestivum*), durum wheat (*T. durum*) or spelt (*T. spelta*) in the Hungarian agricultural statistics. However, the share of winter wheat was so high (94–97% during 2010–2018) (HCSO, 2018) that the wheat production data were considered to refer to winter wheat exclusively.

2.3. Data analysis

We matched cereal yields (at county-scale resolution, i.e. NUTS 3 statistical regions of the European Community) with the GW data, calculating county-scale monthly GW averages from the daily GW depth data. Next, we divided the time periods into two 25-y intervals: 1961–1985 and 1986–2010. The bioclimatic protocol (Suggitt et al., 2017) requires the analysis of data over 30-year long periods which our 50-year-long data series could not fulfil. Comparing our 25-y period with a 30-y one (Tables S1, S2), however, did not indicate a significant difference. Therefore, we decided to analyse changes in GW and cereal yield over the above two 25-year-long periods. Bioclimatologically, the first covers most of the 1961–1990 period which is generally used as reference period (IPCC, 2013), while the second one similarly covers the period of recent climate change when the frequency and intensity of droughts sharply increased in the country (Arvai et al., 2018; Pinke and Lövei, 2017). Hence, within the present work, we use the terms ‘reference period’ for the first and ‘warming climate period’ for the latter one.

All data were normally distributed, suitable for parametric tests. To minimise the influence of agro-technological development on cereal yields, data were de-trended using the first-difference method (Nicholls, 1997). The statistical association between GW and crop yield was tested using linear models and loess (Cleveland, 1993) for 1961–1985 and 1986–2010, respectively. Regression coefficients were tested by bootstrap resampling (5000 replicates) using the *boot* package in R (Davison and Hinkley, 1997). Following Ceglar et al.'s (2017)

Table 1
Geographic characterisation of the studied regions in Hungary.

Region	Area, km^2	Agricultural area - LULC class ratio, %	Arable land - LULC class ratio, %	Forest and seminatural area - LULC class ratio, %	Average of:				
					Position, m.a.s.l.	Slope, %	Top soil clay content, %	Annual precipitation, mm	Actual evapotranspiration, mm
Lowland									
Hungarian Plain, N	12,143	67.5	57.3	23.5	109.4	0.9	20.5	577	604
Hungarian Plain, S	23,919	73.9	64.3	17.8	95.0	0.6	26.5	551	582
Hilly									
Transdanubia, S	14,200	61.1	52.0	30.2	149.1	4.8	20.9	680	661
Transdanubia, W	7,121	54.9	43.8	37.4	191.8	4.6	20.5	677	589
Mixed									
Transdanubia, N	22,211	57.9	48.4	29.2	168.8	3.9	18.9	682	592
Mountains	13,430	53.5	40.8	38.8	212.0	8.1	29.3	581	611

LULC = Land use, land cover; (Szilagyi and Kovacs, 2011).

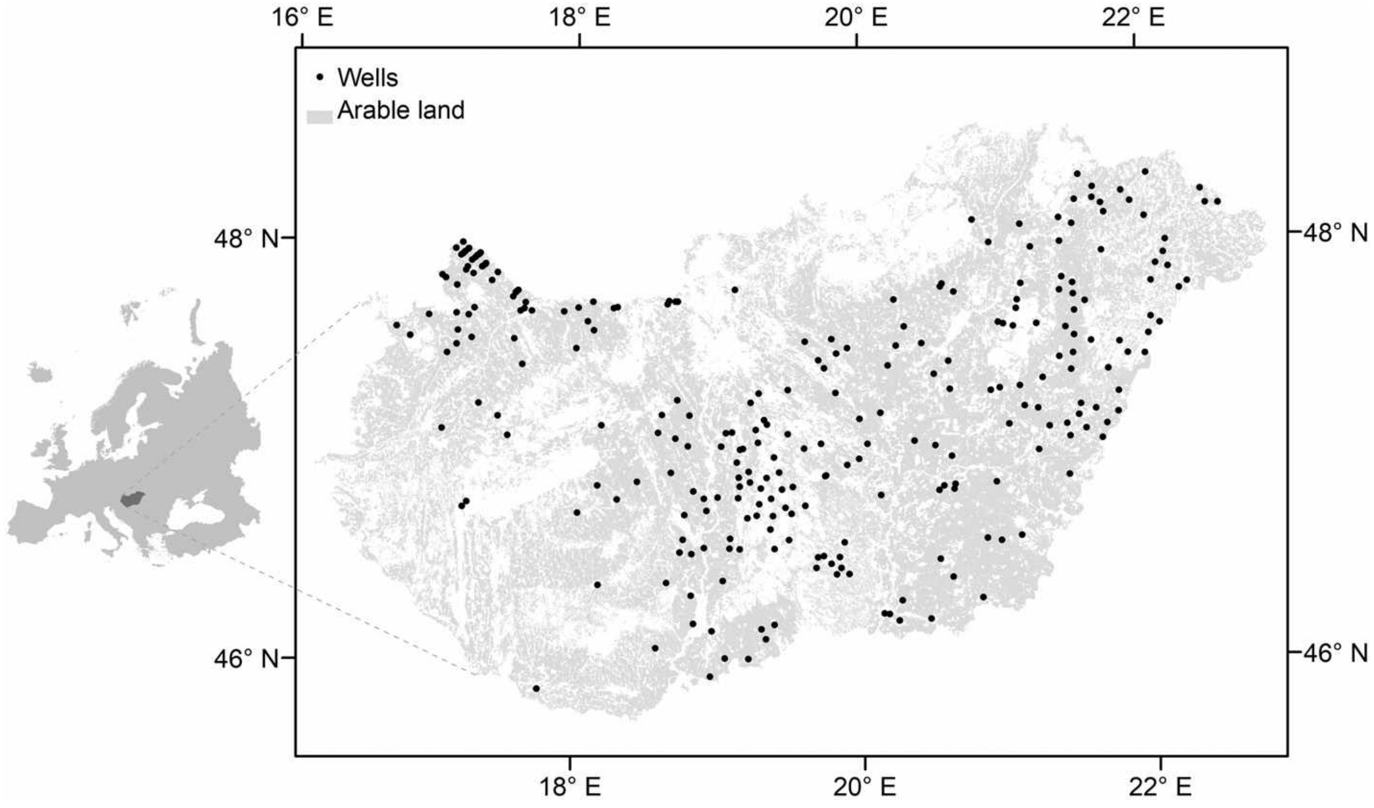

Fig. 1. The distribution of groundwater measuring wells and their overlap with arable land in Hungary (Sources: National Directorate of Water Management; CORINE Land Cover, 2006).

approach, we calculated the linear regression between the monthly averages of GW depth and the annual cereal yields, separately for each region. In the light of these test results, groups of months were selected with the closest GW-cereal yield relationships, and we tested the effect of GW level variation in these periods on cereal yields. Here, we used the term of sensitivity as it is specifically defined by IPCC (2007): “degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise)”. Regression coefficients of statistical associations between living communities and environmental drivers are frequently defined as indices of sensitivity to environmental conditions e.g. in anomalous cases (Seddon et al., 2016). Our expectation was that GW levels would show the strongest relationship in the most drought prone summer months, when water lack was the biggest within the year, thus, the role of GW to fill this gap was decisive. Consequently, regression coefficients of the analyses would be indicators of sensitivity of the studied plants to GW. Subsequently, using the equations thus obtained, we estimated the impact of the long-term change in GW on grain yields. In order to test the potentially wider spatial validity of these relationships, we correlated the GW data on the Hungarian Plain with the European CLM 1979–2016 ERA-interim soil moisture dataset (0.25°×0.25°) (Copernicus, 2015) using the KNMI Climate Explorer tool (Trouet and Van Oldenborgh, 2013).

3. Results

3.1. Characterisation of the GW timelines

The 25-y average of shallow GW levels was significantly lower in 1986–2010 than in 1961–1985 at country, as well as regional levels (in every region); the same was found for the seasonal averages (Table 2, Tables S2 and S3, Figs. 2 and 3). GW decreased by 2.24 cmy^{-1} at the country-scale and by 1.2 cmy^{-1} on the Hungarian Plain (Table 2).

The multiannual fluctuation in the regional GW averages showed a ca. 5-y-long cyclicity (Fig. 2). This pattern, however, disappeared in the majority of regions during the early 1980s, when an almost 15-y-long permanent decrease was observed (Fig. 2). Subsequently, GW resources refilled. The second 25-y period, however, was characterised by larger amplitudes of GW level fluctuation (Fig. 2). Two regions, northern and western Transdanubia showed a different picture. Both had a persistent GW level decrease (Fig. 2 and Fig. S1) from the late 1970s until the late 2000s.

GW monthly averages reached their inner-annual minimum in early autumn. The recharging of the GW stocks commenced at the end of the year and peaked in spring, reaching the average root depth of wheat (Fig. 3). Similarly to the annual and seasonal averages (Fig. 2, Table 2

Table 2
August–October and annual averages (± S.D.) of GW depth in two 25-y periods (1961–1985 and 1986–2010) in Hungary and its six agroecological regions.

Region	Average depth of groundwater, m			
	Whole year		August–October	
	1961–1985	1986–2010	1961–1985	1986–2010
Hungary	−2.59 ± 0.16	−3.15 ± 0.17	−2.76 ± 0.13	−3.30 ± 0.16
Hungarian Plain	−2.55 ± 0.18	−2.85 ± 0.19	−2.74 ± 0.15	−3.02 ± 0.18
Lowland				
Hungarian Plain, N	−2.72 ± 0.22	−3.10 ± 0.22	−2.90 ± 0.20	−3.27 ± 0.21
Hungarian Plain, S	−2.44 ± 0.17	−2.69 ± 0.19	−2.66 ± 0.14	−2.87 ± 0.18
Hilly				
Transdanubia, S	−2.93 ± 0.23	−3.23 ± 0.23	−3.20 ± 0,20	−3.47 ± 0.23
Transdanubia, W	−2.46 ± 0.21	−2.79 ± 0.20	−2.69 ± 0.19	−2.98 ± 0.20
Mixed				
Transdanubia, N	−2.47 ± 0.14	−3.11 ± 0.15	−2.59 ± 0.13	−3.19 ± 0.14
Mountains	−3.07 ± 0.26	−3.49 ± 0.26	−3.25 ± 0.23	−3.65 ± 0.24

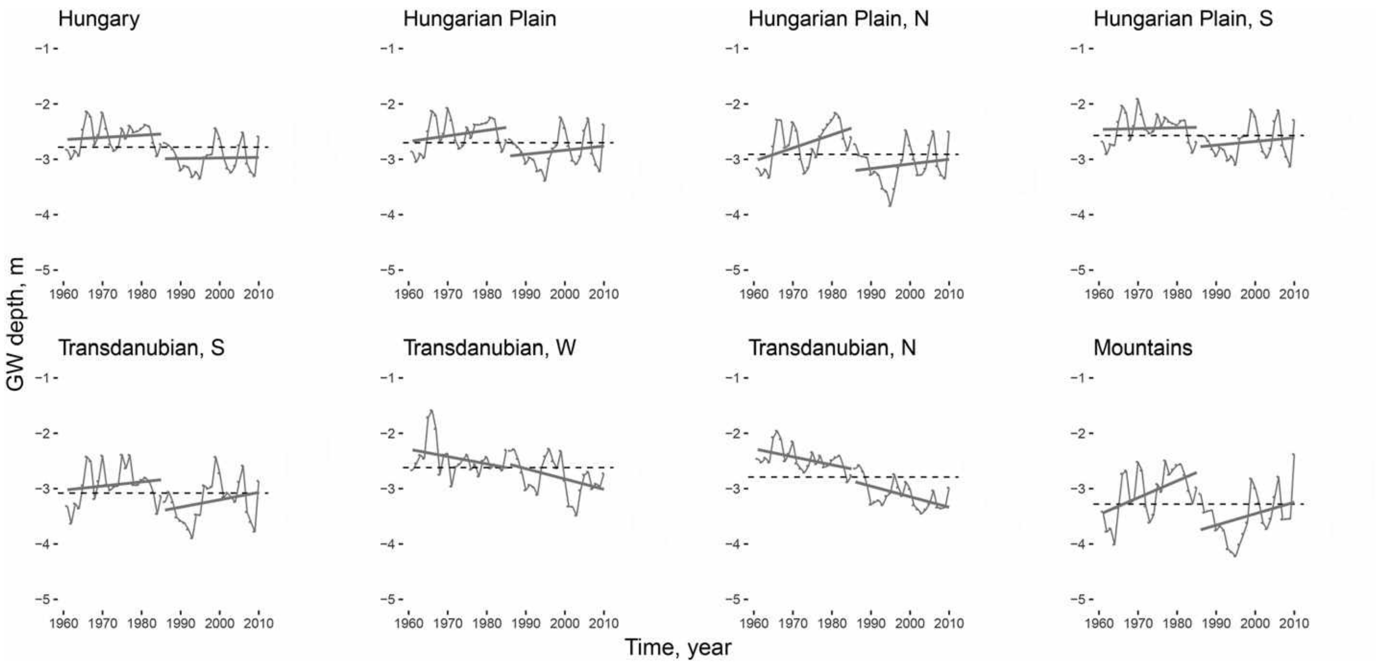

Fig. 2. Trends in annual average GW depths in Hungary and its six bioclimatic regions, between 1961 and 2010. Dashed line indicates the 50-y average, continuous lines depict the averages over the two 25-y periods.

and Table S2), GW decreased in every month from 1961 to 1985 to 1986–2010 (Table S3). The biggest decreases happened in winter and early spring, except in western Transdanubia, where the summer months saw the most severe decline. The changes in variability (standard deviation) showed bigger differences: during the first months of the year, they became smaller in the majority of the regions, while they increased during the rest of the year (Table S3).

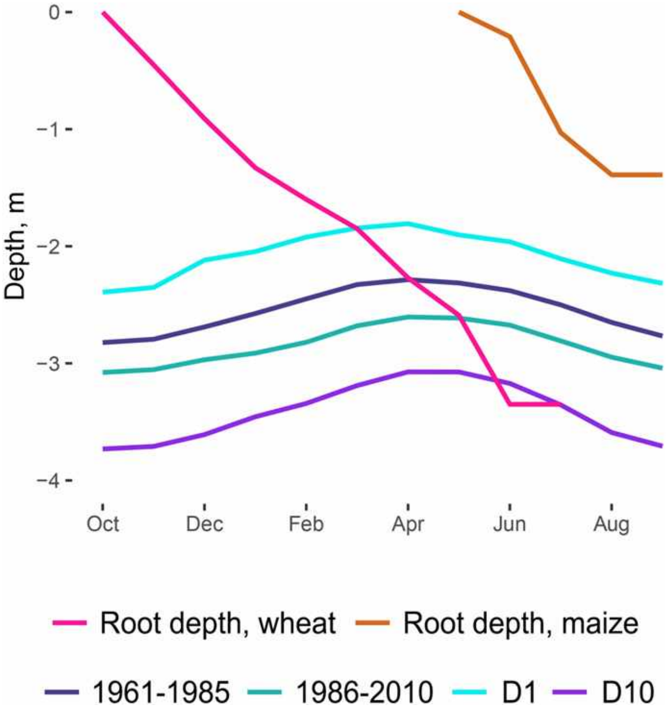

Fig. 3. The depth of GW table in the Hungarian Plain over two 25-y periods (1961–1985 and 1986–2010) and the average root depth of wheat (data from Kmoch et al., 1957) and maize (data from Ordóñez et al., 2018) during a hydrological year (October–September). D1 and D10 = the highest and the lowest deciles of the monthly average of GW levels during 1961–2010.

3.2. Cereal yield trends (1961–2010)

Cereal yields steeply increased from the 1960s to the mid-1980s, when a long stagnation commenced to dominate the second 25-y period. A non-significant trend-like decline was observed in wheat yields ($y = -0.0348\times + 73.684$; $p = 0.09$, $R^2 = 0.12$) during 1986–2010, with a strikingly bigger variation during the second period (Fig. 4), and a significant but very slow increase in maize yields ($y = 0.0432\times - 80.794$; $p = 0.02$, $R^2 = 0.06$) also with a strong interannual variation (Fig. S1).

This country-scale dynamics in cereal yield masked a reassortment of regional ranks during the two periods (Fig. 5). Relative changes in wheat yields were not very large, though: only the ranking of the southern part of the Hungarian Plain decreased. Bigger changes were registered for maize: the hilly regions of southern and western Transdanubia became top producing areas, while the relative productivity of the Southern Hungarian Plain substantially decreased (Fig. 5). Yield averages of the studied cereals were significantly lower in the Mountains region than elsewhere during both 25-y periods.

3.3. The effect of GW on cereal yields

We found negative relationships between monthly GW levels during the October–May period and cereal yields in every region (Fig. 7, Table S5). This mainly non-significant impact characterised the majority of the wheat life cycle spanning the October–July period but only the germination phase of maize (between late April and May). During 1961–1985, GW levels had mainly non-significant negative associations with wheat yield, with the highest impact on wheat yield of GW levels in April and May and in the Mountains region and in the northern Hungarian Plain (Fig. 7). GW levels in these months showed significant negative relationships with wheat yield on the whole Hungarian Plain too (Table S4). The earlier, significant relationships with early spring GW levels disappeared during the 1986–2010 period, when wheat yield showed a significant relationship with GW levels during the period of October–December in the Mountains region while only with the November GW levels on the Hungarian Plain. In the case of maize, higher GW levels in the summer and the early autumn months (June–October)

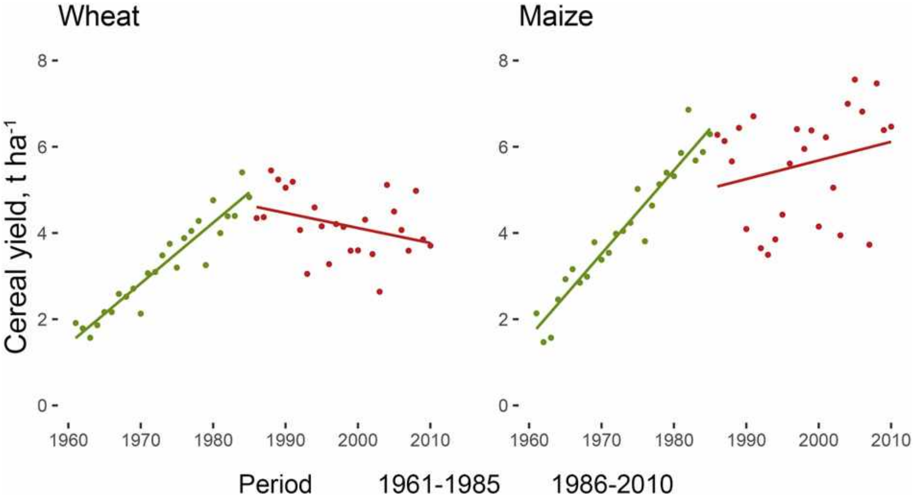

Fig. 4. Annual yields of wheat and maize in Hungary during 1961–1985 and 1986–2010. Data are annual averages at the country level.

had a positive impact on the studied grain yields in both 25-y periods (Table S5). In the warming period (1986–2010), GW-maize yield relationships became much tighter than during the reference period, and in the most drought prone month of August, GW levels showed an explicitly strong impact on maize yields at the country-scale, in northern Transdanubia and the southern Hungarian Plain.

Regression tests indicated that the largest GW impact on wheat yields was registered during April–May almost in every region for 1961–1985. Contrary, August–October GW levels showed the closest relationship with maize yields during 1986–2010. In case of maize, this result basically matched our hypothesis. The determination coefficients of GW-maize yield associations between 1986 and 2010 proved significant in every region except western Transdanubia. The closest relationship appeared in the southern Hungarian Plain region (Figs. 6 and 7, Table S5).

3.4. Estimating the contribution of groundwater to yield

On the basis of the positive relationship between August–October GW averages and maize yields during 1986–2010, we estimated the effect of GW on yield in the most productive region of the country, the Hungarian Plain. The calculated equation was:

$y = 2.3784\times - 0.0488$, ($R^2 = 0.33$, $p < 0.01$).where y is maize yield, and x is GW level depth in m. This equation suggested that a 1 m GW level increase would result in a 2.33 t ha^{-1} yield increase in this region, under the conditions registered during 1986–2010. Given that during the 1986–2010 period, the average depth of August–October GW levels was 0.28 m lower than during 1961–1985, this caused an estimated reduction in maize yields by an estimated 0.65 t ha^{-1} y^{-1} during this period.

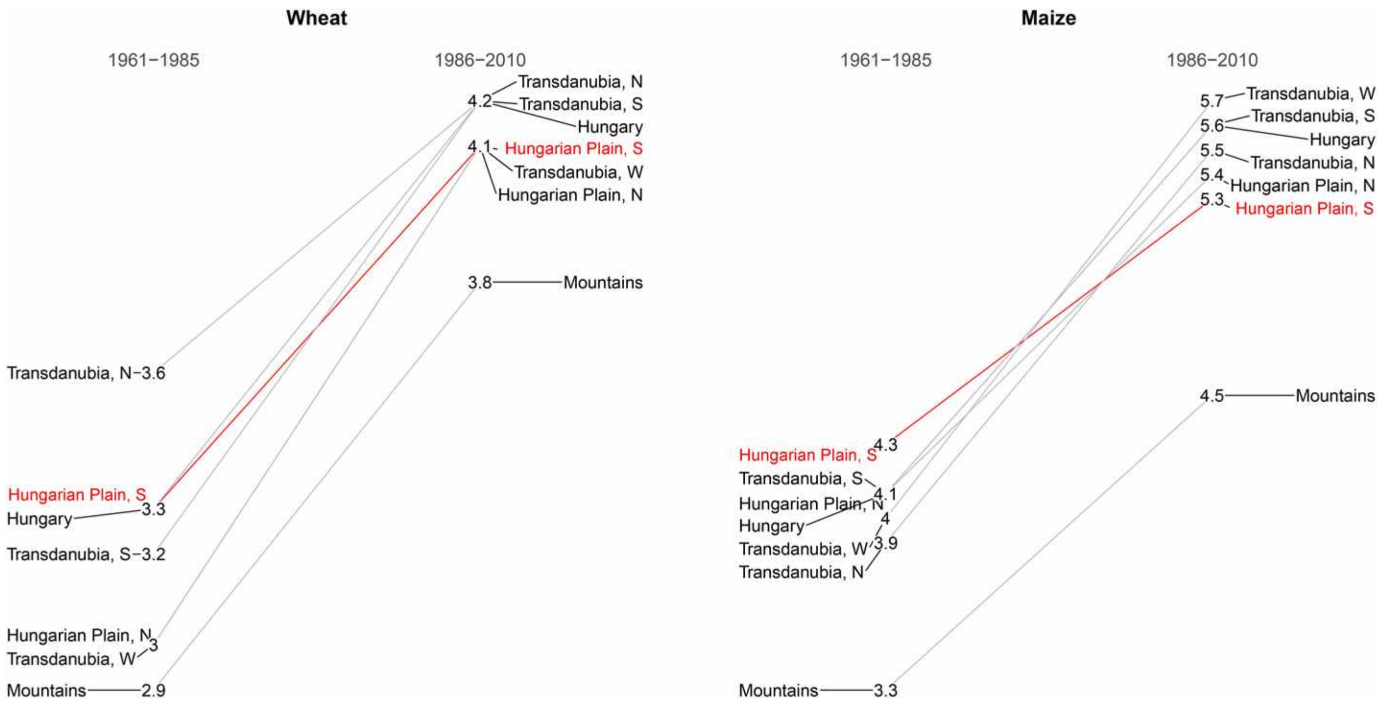

Fig. 5. Rank changes in regional wheat and maize yields (t ha^{-1}) between 1961 and 1985 and 1986–2010. Data from the region with the largest decrease in groundwater levels is marked in red.

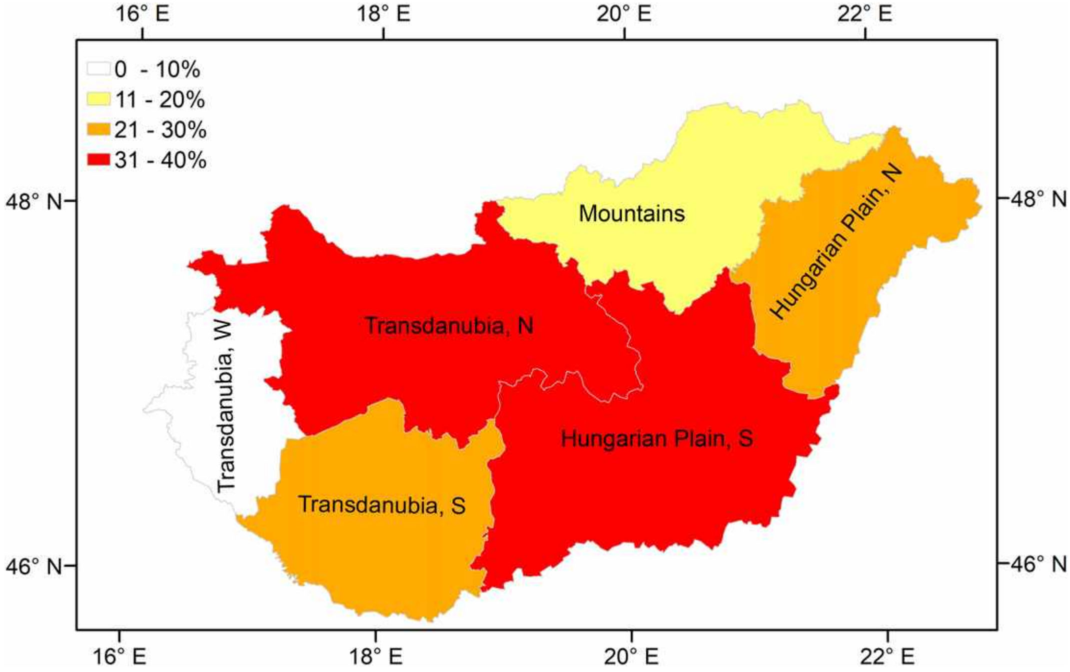

Fig. 6. Regional sensitivity map of maize yield to groundwater for Hungary (1986–2010). Legend: coefficients of determination between August–October GW depth and annual maize yields.

3.5. Territorial validity

GW fluctuations of the Hungarian Plain in August showed a statistically significant correlation with gridded CLM data ($r > 0.40$; $p < 0.10$) over almost the whole central European region, and also in southern Scandinavia, the Seine and Rhine Basins (in France and Germany, respectively), collectively covering a major part of the European agricultural landscape (Fig. 8). This spatial correlation narrowed to the eastern Carpathian Basin during September and October (Fig. 8).

4. Discussion

The analysed long-term data indicated a significant GW level decrease between the reference period (1961–1985) and the 'warming period' (1986–2010) at country and regional levels in every month. This decline in Hungary is not an isolated phenomenon but one of the general symptoms of the recent global environmental crisis (Famiglietti, 2014; Fan et al., 2013; Konikow, 2011) and is probably relevant for a major part of the European continent (Fig. 8). GW levels accounted for 10–38% of maize yield variability in Hungary during 1986–2010 with relatively high spatial heterogeneity. The increasing sensitivity to droughts and warming temperature extremes (Pinke and Lövei, 2017) causes an increased dependence of crops on GW (Jalota et al., 2018; Vörösmarty et al., 2000). Calculating the effect of GW on potential food production, a supposed increase of 100 mm in GW would have increased annual maize yields by 0.23 t ha^{-1} on the Hungarian Plain. The registered GW decrease caused an estimated maize yield loss of 0.65 t ha^{-1} y^{-1} instead. Such a scenario may confronts European agriculture, especially on the lowlands, with a serious challenge (Toreti et al., 2019), also indicated by the observed stagnation of wheat and maize yields in Hungary during the same (1986–2010) period.

Comparing the regional GW-maize yield associations, the region (western Transdanubia) with positive precipitation-evapotranspiration balance and an absence of serious negative artificial impact on GW levels – thus less sensitivity to drought – (Table 1) showed the weakest GW-maize yield association. At the same time, the southern Hungarian Plain where the precipitation-evapotranspiration deficit is the highest (Table 1), maize yields proved the most sensitive to GW fluctuations (Table 3). Furthermore, maize yield increased the most in the western Transdanubian region, while the relative productivity of the southern Hungarian Plain decreased remarkably. Rising temperature triggers increasing evapotranspiration but human activities can also influence GW fluctuations. An example of this is from northern Transdanubia where GW levels continued to decline until the mid-2000s. The cause of this is the diversion of River Danube as part of a hydrological megaproject. The Gabcikovo Dam, completed in 1992, which depleted GW stock in its wide surroundings (Kerekes et al., 1994). Although studies formerly called attention to the negative effects of the dam project (Memorial of the Republic of Hungary, 1994), our study is the first case when this negative effect was documented at a regional-scale and over a long time period. Our findings that maize yield became highly sensitive to August–October GW levels within northern Transdanubia (Table 3) where climatic conditions suitable for farming since precipitation-evapotranspiration balance was positive (Table 1), but negative dam-effect was reconstructed, also confirm this point.

Similarly to other parts of the continent, e.g. the Netherlands (Van Lanen and Peters, 2000), the persistent decrease of GW levels in Hungary between the early 1980s and late 1990s coincided with frequent droughts (Pálfai, 2004; Spinoni et al., 2015). Similar deterioration was observed in other GW-dependent ecosystems, threatening food security (Gleeson et al., 2012; Griebler and Avramov, 2015) and living conditions (Kløve et al., 2011) for hundreds of millions of people. Apart from crop fields, natural ecosystems, including the last remains of steppic communities on the Hungarian Plain can also be negatively affected by sinking GW levels (Ács and Simonffy, 2013; Hydrological and Environmental Protection Central Directorate, 2010, 2015).

Our seasonal analysis uncovered a turning point in May after which the negative effect of GW fluctuation on cereal yields changed to a positive one. We suggest that the negative winter and spring GW-cereal yield associations were related to the inner-annual GW fluctuation (Fig. 3). The winter-spring period is the accumulation phase of GW due to low evapotranspiration rates, with the added effect of snowmelt as well as spring rains (Bozán et al., 2018a). In fact, excessive snowmelt

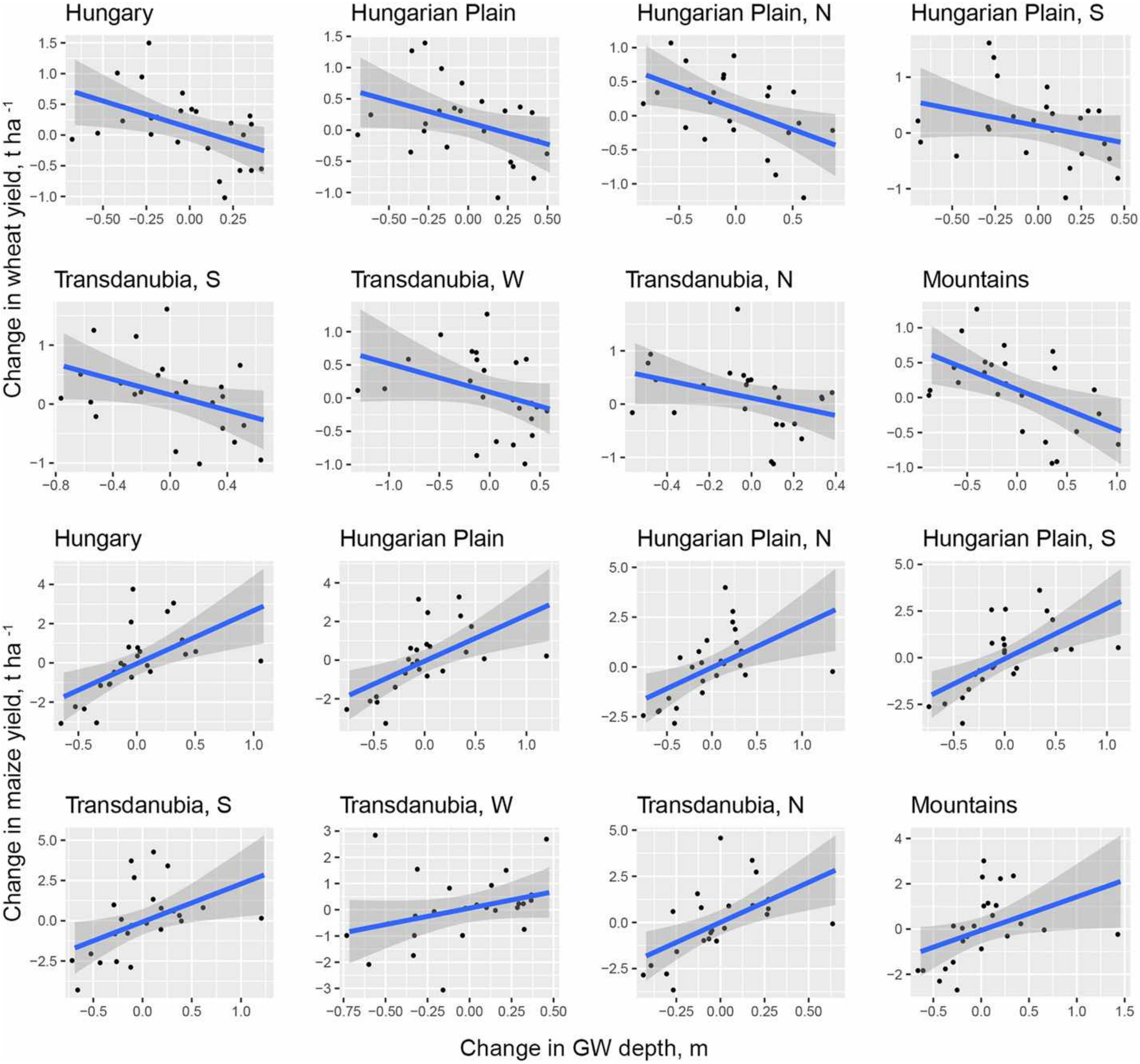

Fig. 7. Statistical relationships between the first differences of April–May GW averages and annual wheat yields in 1961–1985 and August–October GW averages and annual maize yields in 1986–2010 by regions and a country scale in Hungary. Dark grey shading indicates the 95% confidence intervals.

and rain can may saturate the upper soil layers and harm the developing cereals (Florio et al., 2014). This is also the period of GW floods, a characteristic hydrological event on the areas of former wetlands, which occurs on almost a quarter of Hungarian croplands (Pálfai, 2004). However, the weakness of the negative association suggests that high GW levels or GW floods had no significant effect on cereal yields at the regional-scale even on the Hungarian Plain where GW floods are frequent (Bozán et al., 2018a). The positive and negative effects of local GW levels cancel each other out at the regional-scale.

The weakness of the statistical relationship between GW and wheat yield can be attributed to the deep rooting of this plant (Fig. 3), which during the second and third development phases of its root system (Kmoch et al., 1957), i.e. during most of the vegetative period, reaches depths close to the GW table. This direct contact was presumably not affected by regional GW fluctuations. The positive GW impact on maize was strongest when considering GW levels during August–October, in the period with the highest drought vulnerability, and when the evapotranspiration deficit of maize is acute (Láng et al., 2006; Slette et al., 2019). Considering the number of factors and the complexity of processes, the applied statistical methods provide only estimates and a general insight into the GW-cereal yield relationship (Stoll et al., 2011). For a deeper understanding a more detailed, deterministic methodology would be needed, including data on root development, soil types, meteorological conditions and local terrain morphology, which are currently almost lacking.

On alluvial plains, such as most of Hungary, shallow GW levels are highly determined by surface water dynamics and vice versa (Sophocleous, 2002). Hungary has a network of 42,600 km of drainage channels created to protect low-lying reclaimed agricultural lands against GW floods. This network channels an average of 1.77×10^9 m^3 water every year from drought prone plains into rivers (Pinke et al., 2018; Somlyódy, 2011). This drainage system operates continuously

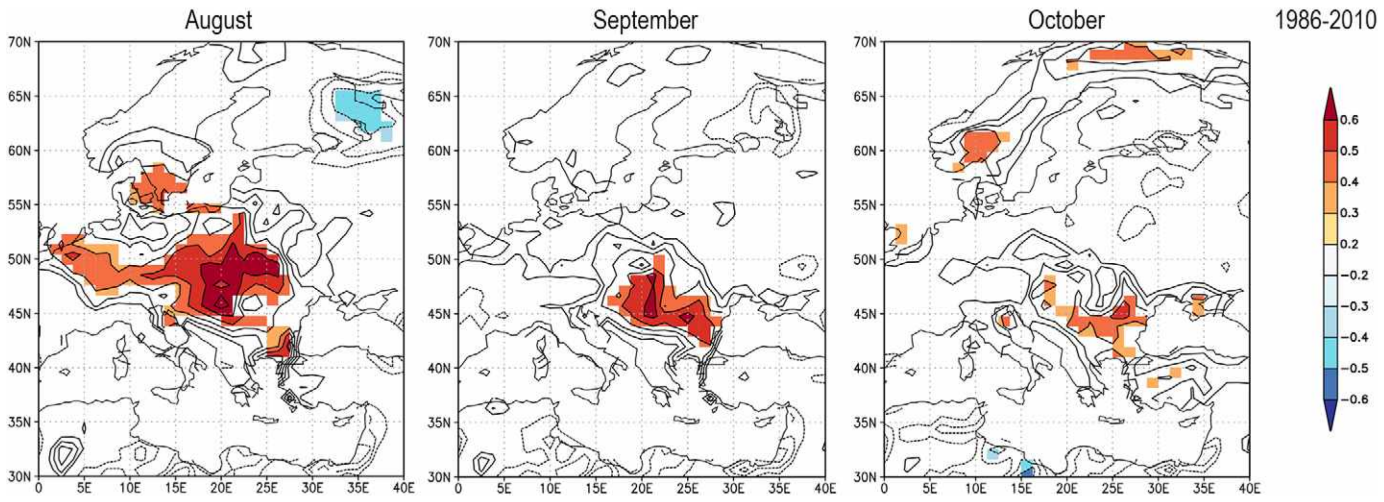

Fig. 8. Spatial correlation between groundwater table fluctuations on the Hungarian Plain (August–October) and the gridded soil moisture (0–100 cm) values of the CLM 1979–2016 ERA-interim (30–70°N and 0–40°E) database in 1986–2010.

and decreases water table not only during GW floods (winter and spring), but also during drought periods (Hydrological and Environmental Protection Central Directorate, 2010, 2015). This water management practice and the escalating drought vulnerability since the 1980s (Arvai et al., 2018) triggered a hydrological crisis in the sandy areas between the Danube and the Tisza rivers (Kohán and Szalai, 2014), as well as in the north-eastern Nyírség Sand Ridge region (Mezősi, 2017). The documented significant relationship between August–October GW levels and maize yields indicated that draining GW stocks by the canal system was detrimental to maize yields and the GW channelization was not in the interest of agriculture. In our analysis, GW fluctuation explained the highest percentage (38%) of maize yield variances in the most drought vulnerable area of the country (southern Hungarian Plain) (Pálfai, 2004; Spinoni et al., 2015), and this is where the GW channel system is also the most extensive (Hydrological and Environmental Protection Central Directorate, 2010, 2015).

Table 3
Determination coefficients (R^2) and 95% confidence intervals (CI) of the groundwater level cereal yield associations during 1961–1985 and 1986–2010.

Period, Region	$GW_{Apr–May}$~Wheat		$GW_{Aug–Oct}$~Maize	
	R^2	CI	R^2	CI
Reference period, 1961–1985				
Hungary	0.22*	0.02–0.50	0.17*	0.00-0.46
Hungarian Plain	0.15	0.01–0.40	0.07	0.00–0.40
Lowland				
Hungarian Plain, N	0.25*	0.04–0.50	0.00	0.00–0.03
Hungarian Plain, S	0.09	0.00–0.67	0.17*`	0.00-0.58
Hilly				
Transdanubia, S	0.16	0.01–0.43	0.04	0.00–0.26
Transdanubia, W	0.07	0.00–0.23	0.00	0.00–0.01
Mixed				
Transdanubia, N	0.13	0.00–0.35	0.13	0.00-0.40
Mountains	0.28*	0.06–0.51	0.01	0.00–0.06
Climate warming period, 1986–2010				
Hungary	0.03	0.00–0.19	0.32*	0.02–0.64
Hungarian Plain	0.03	0.00–0.19	0.33*	0.03–0.64
Lowland				
Hungarian Plain, N	0.00	0.00–0.06	0.29*	0.01-0.63
Hungarian Plain, S	0.03	0.00–0.19	0.38*	0.07-0.66
Hilly				
Transdanubia, S	0.03	0.00–0.24	0.22*	0.01–0.49
Transdanubia, W	0.01	0.00–0.06	0.07	0.00-0.42
Mixed				
Transdanubia, N	0.00	0.00–0.14	0.32*	0.03-0.60
Mountains	0.00	0.00–0.02	0.18*	0.00-0.51

* Significant relationship ($p < 0.05$); Abbreviations: $GW_{Aug–Oct}$ = average depth of groundwater table during August–October (m); $GW_{Apr–May}$ = average depth of groundwater table during April–May (m).

Stopping drainage, retaining excess water (Kozma, 2013; Sprenger et al., 2017; Vituki, 2017) especially in areas of former wetlands that have low agroecological suitability (Mitsch and Mander, 2017; Pinke et al., 2018) would be an adequate solution for reserving GW, and this would mitigate the negative effects of climate change (Griscom et al., 2019). This, although appears in documents of environmental policy (EC, 2000; Hydrological and Environmental Protection Central Directorate, 2010, 2015; Hungarian Ministry of Internal Affairs Hydrological Directorate, 2015), is not yet practiced. Other sustainable ways of recharge could include the reuse of treated wastewater for irrigation (Reznik et al., 2017), to decrease evaporation through reduced tillage, by covering the soil surface by mulch, optimizing water use via precision irrigation (Tilman et al., 2002) and slowing precipitation runoff in rural and urban environments via green infrastructure developments (EC Biodiversity Strategy to 2020 (COM(2011) 244)).

5. Conclusions

The exceptional heatwaves and drought events of recent years that are expected to increase further with ongoing climate change (Toreti et al., 2019) show how critical water supply is for supporting food production. Several examples on the destructive consequences of the climate induced impacts on GW levels support Savenije et al.'s (2014) conclusion: "avoiding the impact of an eventual crash [of groundwater resources] is now the greatest challenge that humanity has faced since it started to manipulate its environment". We showed that two of the world's main crops, wheat and maize were not just sensitive to climate warming, but also vulnerable to sub-surface changes in GW levels, which are often disregarded. In the present study we showed how groundwater, an invisible, but fundamental supporting ecosystem service can have a strong influence on another, well quantified ecosystem service, food production. While for climate warming there is hitherto no solution that we can easily implement, GW levels can and are being influenced by human actions. Our quantitative results can be seen as an alarm signal to urgently implement a climate smart land use system that explicitly considers GW levels. Shedding light on such causal relationships is essential for the sustainable functioning of ecosystems supporting and maintaining an intricate set of ecosystem services. Putting these connections into an ecosystem services framework enhances the understanding of how intertwined relationships are and draws attention to how strongly we depend on a healthy balance between supporting and provisioning services.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.136555.

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