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Assessing the combined hazards of drought, soil erosion and local flooding on agricultural land: a Czech case study

Miroslav Trnka[1,2,*], Daniela Semerádová[1,2], Ivan Novotný[3], Miroslav Dumbrovský[4], Karel Drbal[5], František Pavlík[6], Jan Vopravil[3], Pavla Štěpánková[5], Adam Vizina[5], Jan Balek[1,2], Petr Hlavinka[1,2], Lenka Bartošová[1], Zdeněk Žalud[1,2]

[1]Global Change Research Centre, Czech Academy of Sciences, Belidla 986/4a, Brno 60300, Czech Republic
[2]Department of Agrosystems and Bioclimatology, Mendel University in Brno, Zemedelska 1, Brno 61300, Czech Republic
[3]Research Institute for Soil and Water Conservation, Žabovřeská 250, 156 27 Praha 5 – Zbraslav, Czech Republic
[4]Faculty of Civil Engineering, Department of Landscape Water Management, Brno University of Technology, 60200 Brno, Czech Republic
[5]T. G. Masaryk Water Research Institute, Mojmirovo nam. 16, Brno 61200, Czech Republic
[6]State Land Office, Husinecká 1024/11a, 130 00 Praha 3, Czech Republic

ABSTRACT: Present-day agriculture faces multiple challenges, including ongoing climate change that is at many locations combined with soil degradation. The deterioration of soil properties through unsustainable agricultural practices and changing climate could lead to a fall in productivity beyond the point of no return with devastating effects on ecosystem services in large areas. Identifying areas with the highest hazard levels should therefore be a top priority. The key hazards for agricultural land in the Czech Republic considered in this study include the occurrence of water stress in the topsoil layer during both the first and second half of the growing season, the proportion of fast-drying soils, the risk of sheet and ephemeral gully erosion and the risk of local floods originating primarily from agricultural land. The results clearly marked regions where primary attention should be given to reduce the level of the hazards and/or to increase cropping capacity. These regions were found to be concentrated in the southeastern and northwestern lowland areas. Typical areas with the highest hazard levels were identified: regions with low precipitation and a high proportion of soils with a degraded or naturally occurring low water-holding capacity, and those with steeper than average slopes and terrain configurations in relatively large catchment areas that have urbanized countryside landscapes located at their lower elevations. Despite some limitations, the methods presented in this paper can be applied generally as the first step in developing strategies for efficient reduction of hazard levels.

KEY WORDS: Soil moisture · Sheet erosion · Ephemeral gully erosion · Critical point · Fast-drying soil · Vulnerability · Climate change

1. INTRODUCTION

Food security and its relationship with ongoing climate change featured prominently in the 5th Assessment Report of IPCC Working Group II. The chapter on food security (Porter et al. 2014) has been discussed in great detail, and its conclusions provide a set of key messages for world political leaders (IPCC 2014). The urgency of prioritizing agronomy research that allows humankind to produce sufficient amounts of high-quality food in a sustainable way is driven by multiple pressures. First, there is the sheer

*Corresponding author: mirek_trnka@yahoo.com

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challenge of increasing food production by 60–70% by 2050 to feed a global population estimated to increase to over 9 billion. Second, that challenge must be achieved using less water and energy than is used today, as agriculture is under pressure to decrease its water, carbon and energy footprints to become sustainable in the long term. Third, the challenge of ongoing climate change showing warming trends across the globe is already leading to changes in the distribution of climate variability and extremes (Rahmstorf & Coumo 2011, Gourdji et al. 2013, Liu & Allan 2013), while a high uncertainty remains in the relationship between global warming and climate variability (Huntingford et al. 2013). There is also concern about deteriorating food quality, which was highlighted by Myers et al. (2014), that projects a lower protein content in key C3 crops than exists at present, or risks posed by the future occurrences of pests and diseases in some key agricultural production regions (e.g. Svobodová et al. 2014). At the same time, there is ever-growing concern with regard to soil fertility. According to the EEA (1998), damage to Europe's soils from modern human activities is increasing and leading to irreversible soil loss due to erosion, local and diffuse contamination and the sealing of soil surfaces. In western and northern Europe, the sealing of soil surfaces due to increased urbanization and new infrastructure is the main cause of soil degradation. Land area in the Czech Republic is about 10.6% urban, with a yearly increase of about 0.4%. In the Mediterranean, soil erosion is the main cause of soil loss. The areas with the most severe soil loss from both wind and water erosion include the Balkan Peninsula, the Black Sea region, and also some central European countries such as the Czech Republic and Slovakia (EEA 1999). The European Union (EU) Mediterranean countries also have severe soil erosion problems, which in some cases are at a critical stage and could lead to desertification. Alarming is the possibility of areas currently not at risk (e.g. parts of the Mediterranean or the Alps) reaching advanced degradation status that cannot be reversed within 2 or 3 generations, with some areas having reached this status over 2 decades ago (e.g. Van Lynden 1994). Central Europe is also showing signs of serious problems in this regard.

Previous studies assessing the agricultural impacts of climate change have demonstrated that the effects depend on the crops being grown, cropping season and region (e.g. Olesen et al. 2007), and very few have considered cropping system responses to changes in the frequency and severity of climatic extremes (e.g. Ruiz-Ramos et al. 2011). However, it is well known that the impacts of such extreme events can be substantial (e.g. Reyer et al. 2013). Studies by Trnka et al. (2014, 2015a) showed that, despite the large uncertainty in climate projections within the CMIP5 ensemble, the overall frequency of adverse events is much more likely to increase than to decrease across the European domain, including Central Europe. It is also obvious that soil degradation is intertwined with the increased drought risk as degraded soils tend to have smaller infiltration rates and much smaller water-holding capacity.

Existing research confirms that climate conditions in April–June have the most profound impact on the yield of field crops (e.g. Hlavinka et al. 2009, Kolář et al. 2014). The interannual yield variance explained by the interannual changes in a single climatic variable could reach 50% on a regional scale (Brázdil et al. 2009, Trnka et al. 2016, this issue). A recent analysis indicated that climatic variability influences yield variability in Central Europe more now than it did in the late 19th and early 20th centuries (e.g. Trnka et al. 2012). Most of the explanatory power of the model was derived from a negative sensitivity to temperature and drought. Interestingly, the biggest changes in drought sensitivity from the late 19th to the late 20th century were found in the regions where processes (wind and water-driven) of soil erosion and of overall soil degradation are considered severe. An awareness of this problem has led to increased attention being paid to the issues of drought vulnerability and soil degradation in recent years (e.g. Trnka et al. 2015b, Zahradníček et al. 2015, etc.). Many farmers partially mitigate drought impacts through crop selection, irrigation, and modified tillage practices, but in many cases, they struggle economically, as the economic returns, especially in dry years, are extremely poor (Vopravil et al. 2012). Until recently, at the state level, the emphasis of disaster management has been largely on the response to and recovery from droughts, with little or no attention paid to drought mitigation, preparedness, prediction and monitoring. The situation is better in relation to soil erosion and local flood risks due to existing EU rules (Panagos et al. 2015), but these measures are usually not intertwined with measures aimed at decreasing the impact of droughts. Increased losses from droughts (as observed in 2000, 2003, 2012 and 2015) suggest a growing societal vulnerability to this hazard. At the same time, erosion risks and the rate of soil degradation are still unsustainable in some areas despite a number of existing measures being taken (Vopravil et al. 2012). It has also been felt by both the Agrarian Chamber (representing the great majority of farmers

in the Czech Republic) and some governmental organization (e.g. the State Land Office) that major revisions are needed of existing policies related to the management of soil degradation frequently associated with intensive rains and increased drought risks due to climate change. Therefore, a multidisciplinary task force was formed and supported, called the Master Plan of Landscape Water Management of the Czech Republic (F. Pavlik pers. obs.). It has been recognized that there must be an inevitable shift in policies to change drought management from a reactive, crisis-management approach to a proactive, risk-management approach. At the same time, these measures must complement and support existing policies aimed at suppressing processes of soil degradation. While the former requires detailed monitoring, early warning and planning between events (e.g. Wilhite 2000), the latter can be achieved only through a comprehensive and regionally tailored and coordinated set of long-term policies. The final goal is to lower the risks in real terms arising from the impacts of drought and soil degradation for the whole of the Czech Republic through the implementation of an efficient strategy. Among other factors, this strategy includes selecting areas and 'actors' (i.e. farmers) facing the highest risk and providing them with the proper support as early as possible to prevent a situation from deteriorating beyond the 'point of no return'.

The development and implementation of the methodological framework into an operational procedure considers the overall risk for the Czech Republic's rural landscape as being a function of hazard, exposure and vulnerability (Giupponi et al. 2015). The ultimate goal of the whole procedure is the quantification of these risks, putting into place policies and measures leading to risk reduction, and ensuring their adoption in practice through the use of demonstration areas, as well as through technical and financial assistance. This may be achieved only when hazards, vulnerability and exposure are known, allowing for the calculation of the expected damages related to the risks associated with different hazardous scenarios. Clearly, the first step required is a proper analysis of the hazards themselves.

While according to Kappes (2012), multi-hazard assessment may be understood as an assessment of 'the totality of relevant hazards in a defined area', the present study uses the concept of 'more than one hazard'. The research presented here focuses on drought and soil degradation hazard assessments for the agricultural landscape of the Czech Republic. While the potential indicators for describing the hazards to agricultural land are numerous, their applicability depends both on their policy relevance and the availability of data. We attempt to provide concept hazard and vulnerability to key decision-makers (agricultural producers, natural resource managers, and others), as well as provide them with spatially explicit information. The goal of this study was to develop a method for assessing hazards posed by drought, erosion and floods using geographic processing techniques. The objectives were: (1) identify key indicators that define agricultural drought, soil erosion and local flood hazards for agricultural land across the Czech Republic; (2) evaluate the weight of the indicators that contribute to the combined hazard; and (3) classify and map the combined hazard.

2. MATERIALS AND METHODS

2.1. Setting

The first step towards the implementation of the proposed framework is the identification of the context in which it will be applied. This involves identifying regions with the highest hazards so that the next steps of risk assessment (vulnerability and exposure assessments) and policy application can be targeted to these regions (Fig. 1). Fig. 1a–c shows the Czech Republic's main orographic features and soil characteristics that, together with climate conditions, help to illustrate why land degradation and drought need to be assessed together. The country's mean altitude is 430 m (CSO 2005), and it lacks large mountain chains. However, the combination of the country's morphology, which is dominated by uplands and highlands, the occurrence of areas with considerable slopes even at low altitudes, and the comparatively large field blocks explain why over half of agricultural and especially arable land is exposed to strong water and wind erosion (Janeček et al. 2012). The fact that the most intensively farmed regions are also dotted with high numbers of settlements increases the number of areas in which floodwater from relatively small catchments over the agricultural land poses a frequent hazard for these settlements. The hazard is also higher than in comparable regions of Austria, due to much larger field blocks that contain a single crop. Most Czech agriculture is rain-fed, with irrigation being available for <4% of the area (Batysta et al. 2015) and only ~1.5% being actively used (Batysta et al. 2015). While the Czech Republic's mean annual precipitation of

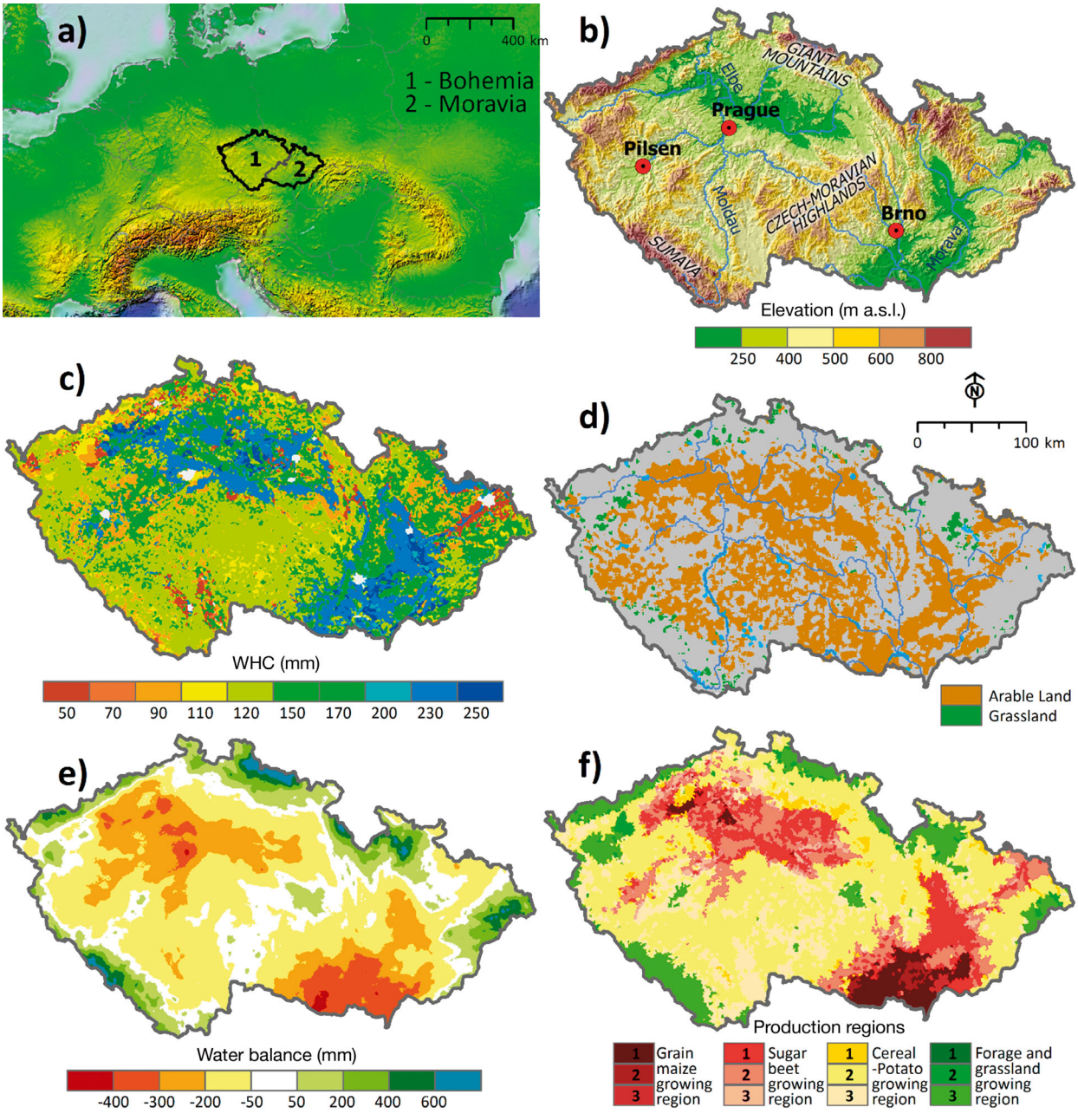

Fig. 1. (a) Overall location of the Czech Republic case study region in Central Europe. (b) Main orographic features of the country. (c) Water-holding capacity (WHC) of the soil in the first 100 cm of the soil profile. (d) Main areas of arable land and grassland for which the assessment was primarily carried out, with other land-uses colored grey. (e) Difference between sum of annual precipitation and annual potential evapotranspiration. (f) Agrometeorological zoning of the country into 4 main production zones. In each production zone 3 sub-classes are distinguished: (1) prime agricultural soil; (2) could be used for agricultural production with limitations; (3): not suitable as agricultural land

700 mm would generally be sufficient, some key producing regions in the northwest and southeast show much lower precipitation totals (450 and 500 mm, respectively). Given the high interannual variability and shifts in the distribution of precipitation, in many seasons production is severely limited by the availability of water. In fact, rain-fed agriculture is only sustainable thanks to a generally favorable distribution of precipitation and to soil that holds enough water to allow crop survival through episodes of drought that are sometimes prolonged (Hlavinka et al. 2009). According to Trnka et al. (2009), the June–August sum of precipitation for the Czech Republic is on average higher than 1/3 of the annual

rainfall total (ranging from 27 to 43%). The driest season that accounts for less than 1/5 of the annual precipitation is winter (December–February). Winter precipitation (if in the form of snow) allows for a recharging of the soil profile just before the growing season, reducing the effects of severe droughts in the early part of growing season, which is critical for crop yield formation (e.g. Hlavinka et al. 2009). As Fig. 1e shows, the majority of the lowlands show higher potential evapotranspiration than precipitation, in particular in the areas where precipitation is the lowest. This deficit is the highest in the southeast, which in addition to low levels of precipitation, also has the highest temperatures and the most hours of sunshine compared to the rest of the country. Climate and soil conditions together with the terrain predetermines the agricultural use of each area. The Czech Republic is traditionally divided into 4 production regions, with those growing sugar beets being the most productive (Fig. 1f), followed by maize-producing regions.

2.2. Indicators of hazards

The potential indicators that could be used for the assessment of hazards are numerous. Because the focus of this study was on assessing combined hazards for agricultural land, we focused on the indicators that in our view can best be used to quantify these hazards. An analysis of the literature, suggestions from specialists, and data availability formed the fundamental assumptions underlying the methodology we used.

In the first step towards the assessment of the combined hazard (Fig. 2) for the agricultural lands analyzed, we identified the following hazards as being the most critical ones:

(a) Drought occurring during the growing season;

(b) Pre-existing poor soil conditions decreasing the ability of the soil to hold water (fast-drying soils);

(c) Increased susceptibility to water erosion, including the occurrence of concentrated runoff pathways;

(d) Pre-existing infrastructure and/or settlements in the path of the concentrated runoff pathways.

It was also clear that the occurrence of one hazard at a greater intensity might contribute to the effects of other hazards becoming more severe. For example, prolonged droughts lead to the disintegration of the soil structure and to a decrease in the vitality of the crop cover, which makes the area more vulnerable to soil erosion (Fig. 2).

2.2.1. Agricultural drought during the growing season

We selected the number of days during which soil moisture was <30% of the relative soil water content (i.e. the percentage to which water fills the soil pores between the so-called wilting point and field capacity) in the topsoil, which was defined as the layer between 0.0 and 0.4 m. The calculation procedure has been explained in detail by Hlavinka et al. (2011) and was further tested by Trnka et al. (2015a,b) and carried out for agricultural land (Fig. 1d). It relies on the SoilClim model (Hlavinka et al. 2011) based on the model of Allen et al. (1998), and accounts for the following factors and processes:

- Water accumulation in snow cover and subsequent melting
- Water-holding capacity of the soil
- Influence of the slope and aspect on the energy balance
- Influence of the type of the vegetation on daily evapotranspiration, interception and runoff
- Dynamically changing properties of the plant cover based on the phenology phase estimated through thermal time (including sowing, harvest, leaf area index, rooting depth, and crop height)
- Influence of underground water and shallow water tables

As the indicator of drought hazard, we selected the median number of days per season (based on 1991–2014 data) with a saturation of the surface soil layer below 30%, which is a good proxy for drought damage to agricultural crops according to our observations (e.g. Zahradníček et al. 2015). In general, this value could be considered as the level below which the physiological processes of the plant begin to be significantly limited by a lack of water (e.g. Larcher 2003). While decreases in the relative saturation of the soil below 50% slows a plant's intake of water, at values below 30% it is no longer able to produce sufficient turgor, and growth stagnates. The calculations were performed in 500 m grids covering the whole of the Czech Republic (Trnka et al. 2015b). Based on the drought-yield relationship, we divided the growing season into 2 parts, April–June and July–September. In the former, mostly spring- and winter-sown cereals (usually harvested in July) are known to be affected the most (e.g. Hlavinka et al. 2009), while the latter season represents the time period in which latter-maturing crops (e.g. maize, potatoes or sugar beets) can be negatively affected.

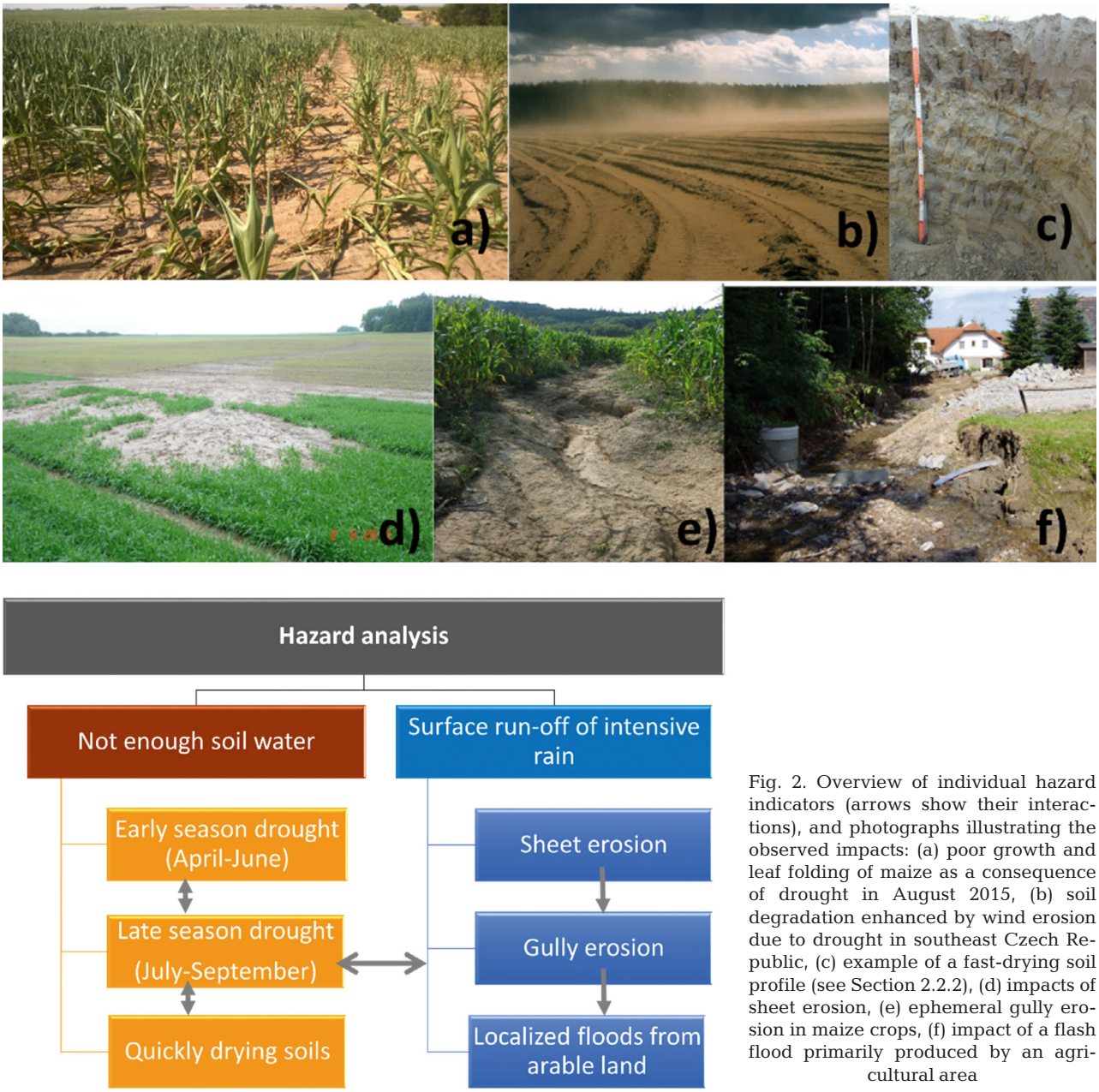

Fig. 2. Overview of individual hazard indicators (arrows show their interactions), and photographs illustrating the observed impacts: (a) poor growth and leaf folding of maize as a consequence of drought in August 2015, (b) soil degradation enhanced by wind erosion due to drought in southeast Czech Republic, (c) example of a fast-drying soil profile (see Section 2.2.2), (d) impacts of sheet erosion, (e) ephemeral gully erosion in maize crops, (f) impact of a flash flood primarily produced by an agricultural area

2.2.2. Fast-drying soils

While the occurrence of drought is primarily driven by climate, and the definitions used account for the influence of terrain, vegetation cover and soil water-holding capacity, it was felt that specific local soil conditions needed to be taken into account. Therefore, the proportion of fast-drying soils that tend to be particularly negatively affected by drought was considered. Fast-drying soils are the result of soil processes that are driven by a long-term lack of water in the soil and the intensive mineralization of organic matter, which leads to a decrease in soil fertility and its water-holding capacity. In the Czech Republic, this issue is of concern in the northwestern and southeastern parts of the country. Including fast-drying soils as a hazard indicator is justified by the fact that the extent of this area has been expanding over the past decades, and the occurrence of fast-drying soils in a region indicates a heightened hazard. The expansion of fast-drying soils is driven by erosion, and many areas with very fertile soils <100 yr ago (e.g. chernozems) are presently fast-drying soils consisting of an underlying loess (giving

at least a hope of restoring soil fertility) or sand from the original bottom of the sea that was once present in these areas. The process is accelerated by ongoing climate change connected with the increasingly frequent occurrence of long periods of drought and also by unsuitable tillage practices with a low resupply rate of organic matter to the soil. Determining the occurrence of fast-drying soils was performed through an evaluation of a high-resolution (5 × 5 m) map of the soil conditions, based on information obtained from the soil database that is maintained and permanently updated by the Research Institute for Soil and Water Conservation (RISWC), which includes extensive data on soil and associated components of the environment. Only agricultural land (Fig. 1d) was considered.

2.2.3. Sheet, interrill and rill soil erosion

The first indicator of an erosion hazard for agricultural land (Fig. 1d) focuses predominantly on so-called sheet erosion (i.e. the transport of loosened soil particles by overland flow). We used an approach based on the universal soil loss equation (USLE) (Wischmeier & Smith 1978), which accounts for rainfall erosivity factor (R), soil erodibility factor (K), topographic factors (slope and length) and cropping management factors (C and P). The topography factors were estimated according to the modified equation of Desmet & Govers (1996) using a 5 × 5 digital elevation model. The efficiency factor of erosive rainfall was set at R = 40 MJ ha^{-1} cm h^{-1} (Janeček et al. 2012), and the C factor was based on the actual crop proportions at the same resolution as the slope and length estimates. After estimating annual soil loss, those 5 × 5 m grids showing an annual potential loss higher than 4 t ha^{-1} (i.e. the nationally enforced limit) were marked as those with a significantly higher than permissible erosion rate.

2.2.4. Rill and ephemeral gully erosion

In addition to the classic erosion furrows on the surface slopes of arable land, there are also so-called rills and ephemeral gullies present, which differ from the classic erosion furrows because of their cross-sectional area (>1 square foot or >0.09 m^2) (Morgan 2005). These features tend to appear in places where the basin shape leads to a concentration of the outflowing surface water. They can either follow the flow path of excess water, or they can follow linear landscape elements such as land boundaries, furrows created by agricultural practices or unpaved country roads. The term ephemeral expresses the temporariness of these elements, which are rehabilitated by tillage of the growing season, but they tend to reappear in the same place in the next growing season under the 'right' farming and weather conditions.

For the analysis of ephemeral gully erosion hazards, the method of plotting potential paths of runoff concentration at a resolution of 5 m was used. This method is based on the modeling of flow accumulation from drainage areas, the interpretation of the nature of the terrain and the visual interpretation of aerial photos of the affected land blocks. Contributing areas were used to automatically generate the direction and accumulation of runoff over a digital terrain model with manual correction using raster topographic maps and aerial orthophotos (Dumbrovský 2011).

2.2.5. Localized floods originating from agricultural land

Catastrophic floods with tragic consequences in the Odra river basin in 2009 and similar well-documented events in the following years vividly demonstrate that settlements can be significantly affected in places where there is no (and has not been) any known permanent stream (Drbal 2009). Drbal & Dumbrovský (2009) reported that even a contributing area of 5 ha is sufficient to generate a flow that can cause severe damage to property. The causal factors critical for the formation of a concentrated runoff were determined based on the number of recent flood events from torrential rainfall, and parameters were set to estimate so-called 'critical points'. A critical point (CP) was defined as the point where the trajectory of the concentrated runoff penetrates into the municipality. CPs were thus determined based on the intersection of a municipality (urban) boundary with concentric lines of a track drainage area contributing to a region ≥0.3 km^2. As the area affected by torrential rainfall tends to be limited, the contributing area was also limited to 10 km^2. Torrential rainfalls, while very localized, occur fairly frequently between April and September and in particular over the summer months. However, the spatiotemporal localization of torrential rainfalls or even the mapping of return probabilities is not possible with the present dataset. Therefore, in this analysis we assumed that torrential rain could occur at any location in the Czech Republic.

Table 1. Indicators for the individual hazards

Hazard	Indicator as used at the cadaster unit level	Grid resolution (m)	Unit	Reference period
Early season drought	Median number of days with soil moisture below 30% of maximum available soil water-holding capacity at the surface layer (0–0.4 m) in April–June	500	Days per season	1991–2014
Late season drought	Median number of days with soil moisture below 30% of maximum available soil water-holding capacity at the surface layer (0–0.4 m) in July–September	500	Days per season	1991–2014
Fast-drying soils	Proportion of fast-drying soils per unit of arable land in the cadaster	5	%	Continuously updated
Sheet erosion	Proportion of the arable land in the cadaster unit with significantly higher than permissible erosion rate (>4 t ha^{-1} yr^{-1})	5	%	Continuously updated
Ephemeral gully erosion	Contributing area to ephemeral gully erosion pathways from arable land in the cadaster unit	5	Hectare	Continuously updated
Localized flood from arable land	Proportion of the cadaster unit area belonging to the contributing area for critical points	5	%	Continuously updated

2.3. Multiple hazard analysis

After selecting the key hazards, the indicators that best represented them were formulated. Table 1 lists the indicators for the individual hazards, while Fig. 2 illustrates the impacts that the indicators represent. The original quantification of the indicators was based on different resolutions, with data on drought occurrence being available as a 500 × 500 m grid and the remaining indicators being calculated at a resolution of 5 m due to the importance of the local terrain conditions. As the study aimed at identifying the areas with the highest hazard level for policy-making purposes, the indicators were aggregated at the level of the cadaster unit, which is the smallest administrative unit in the Czech system. Territory in the Czech Republic is composed of 13 091 cadaster units with a mean area of 6 km^2. For each cadaster unit, the value of each indicator was calculated. All indicators were normalized using a *z*-score approach. It is one of the most commonly used normalization procedures in which all indicators are converted into a common scale with an average of zero and a standard deviation of one. The scale described in Table 2 was applied to communicate the results to the stakeholders. As 6 indicators were used, weighting was considered to express the relative importance of individual indicators to calculate a composite hazard index. Weights are essentially value judgments, and thus, they are essentially subjective and can make the objectives underlying the construction of a composite index explicit (e.g. Giupponi et al. 2015). In this case, we applied equal weights to all indicators. In the final determination of the regions with the highest hazards, we combined an averaging of the *z*-scores due to their transparency with an identification of regions affected by at least 2 of the 6 indicators with a *z*-score below −2. The latter was performed to limit the shortcomings of the averaging approach, as a bad score in one criterion can be offset by a good score in another one, even if there is no interaction among the criteria. Apart from the cadaster units, the so-called 4th-order catchments were considered as an alternative spatial unit for aggregating the hazard analysis results. There are almost 9000 of these 4th-order catchments in the Czech Republic, which have a fairly variable area, and a mean area of 9.6 km^2.

2.4. Mapping

The final result of the combination of factors was a numeric value, which was calculated through the 'union' mathematical function in ERDAS Imagine GIS by a simple averaging of the *z*-scores of all 6 indicators. As a second approach, the frequency with

Table 2. *z*-score table used to interpret the standardized values of the indicators, as used in Figs. 4, 5 & 7

Indicator interpretation	*z*-score range
Above average	0–0.5
Markedly above average	>0.5 and <1.0
Highly above average	1.0–1.5
Very highly above average	>1.5 and <2.0
Extremely above average	2.0 and higher

which a given cadaster unit had a *z*-score <–2.0 for a particular indicator was also mapped. For the analysis, heavily urbanized cadasters were excluded, as were the cadaster units with a large proportion of surface mines (especially in the northwestern part of the country) and water bodies. In general, a low value for a *z*-score is an indicator that in the given cadaster unit, the hazard value is proportionally higher than in the rest of the country. Therefore, a very low combined *z*-score signals the occurrence of multiple hazards. The occurrence of a *z*-score below –2.0 means that for a given indicator, the cadaster unit belongs to several dozen cadaster units with extremely high levels for that particular hazard. These two approaches were then combined in the final map. Finally, we compared the newly developed classification of the cadaster units according the level of multiple hazards with the extent of the less-favored areas (LFA) as defined in accordance with European Commission (EC) regulation 1305/2013, which is used to support areas with existing natural constraints.

2.5. Climate change scenarios

To evaluate the impact of climate change on the values of the selected indicators, we tested the change in the number of days with drought stress in the topsoil layer during the period April–June. For each 500 m grid, the weather data were modified based on the expected climate change conditions for the region. To be able to assess the development of conditions during 2021–2040, we modified 1981–2010 daily weather data using a delta approach and 5 climate models. These models were selected as representations of mean values (IPSL: model of the Institute Pierre Simon Laplace, France) and to best capture the variability of expected changes in precipitation and temperature (BNU: Beijing Normal University, China; MRI: Meteorological Research Institute, Japan; CNRM: National Centre for Meteorological Research, France; and HadGEM: Hadley Centre Global Environment Model, UK). These models were picked from 40 climate models available in the CMIP5 database (Taylor et al. 2012). These projections used the Representative Concentration Pathway (RCP) 4.5 greenhouse gas concentration trajectory and a climatic sensitivity of 3.0 K. Before using all meteorological data as input for subsequent steps, the SnowMAUS model (Trnka et al. 2010) was applied to estimate the appearance of snow cover. In this way, daily precipitation totals were modified to better match the real timing and amount of water infiltration into the soil considering probable snow accumulation, melting and sublimation.

3. RESULTS AND DISCUSSION

3.1. Agricultural drought and the proportion of fast-drying soils

As shown in Fig. 3a,b, the median number of days under drought conditions in the most affected areas is >30 if we consider the whole growing season. For most of the arable land, the value is >10 d yr^{-1}, with the maxima being achieved not only in the southeast of the Czech Republic but also in parts of the northeast, in the northwest area of so-called central Bohemian region and in the southwest. The areas with a high incidence of dry days also include the southern edge of the Czech and Moravian Highlands in the center of the country (Fig. 1a). If we consider the *z*-score results (Fig. 4a,b), it is clear that the highest drought hazard is indicated over a fairly large and continuous area in the lowlands of the southeast of the Czech Republic and through a number of smaller regions in the northwest, north-central and, to a lesser degree, in the southwest and northeast. The drought hazard depends on which part of the growing season it is. In the first half of the growing season, the west of the Czech Republic tends to be affected more (Fig. 4a), while the southeast follows an opposite pattern, with drought hazards in the east of the Czech Republic increasing significantly from July to September (Fig. 4b).

Hazards posed by a high proportion of fast-drying soils are limited to 2 principal areas at the west and southeast of the country. While partly overlapping with areas that have an increased agricultural drought risk, these areas are not identical. Fast-drying soils are not present at a number of areas potentially influenced by agricultural drought, notably those in the agricultural lowlands of the southwest, north-central and northeast of the country. Obviously, combining a high proportion of fast-drying soils with a high probability of a greater number of drought days increases the hazard level in the respective cadaster units. This criterion also reflects a gradual decline in the fertility area due to a prolonged lack of water, unsustainable rates of erosion and organic matter depletion caused by human activity, and it reflects decreases in soil fertility that are not fully captured by the indicators of agricultural drought, as these calculations did not consider the processes of land degradation leading to the estab-

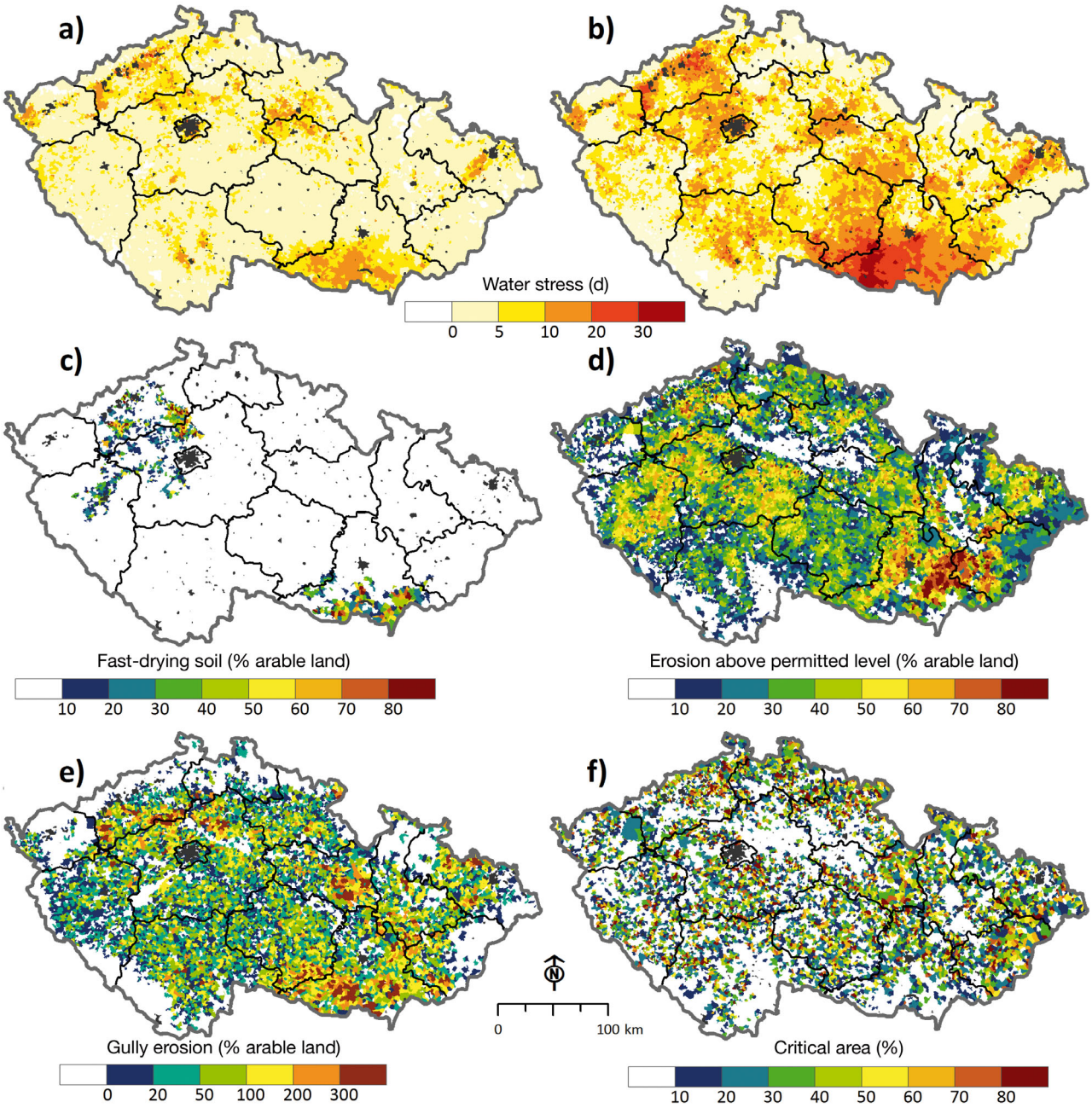

Fig. 3. Map of indicators used for hazard assessment (see Table 1) at the cadaster unit level: (a,b) number of days with water stress in the topsoil (0–40 cm) in (a) April–June and (b) July–September, (c) proportion of arable land in the fast-drying soils category, (d) percentage of arable land within the cadaster unit with erosion rate above permissible levels, (e) proportion of area contributing to ephemeral gully erosion pathways from arable land, (f) proportion of cadaster unit area belonging to contributing area for critical flood points

lishment of fast-drying soils over the last 3 decades. Figs. 3c & 4c clearly show that in terms of fast-drying soils, the most affected areas are concentrated in the southeastern Czech Republic and in an even larger area to the west of Prague and around Pilsen. These areas are likely still expanding, and their growth is proportional to the intensity of the erosion processes.

3.2. Sheet and ephemeral gully erosion

The hazard posed by sheet erosion affects the majority of the key agricultural areas, with the exception of flat areas around large rivers (Elbe and Morava). It is clear that a high percentage of the arable land is at risk of a higher than permissible rate of soil loss (>4 t ha^{-1} yr^{-1}), which is a major cause for

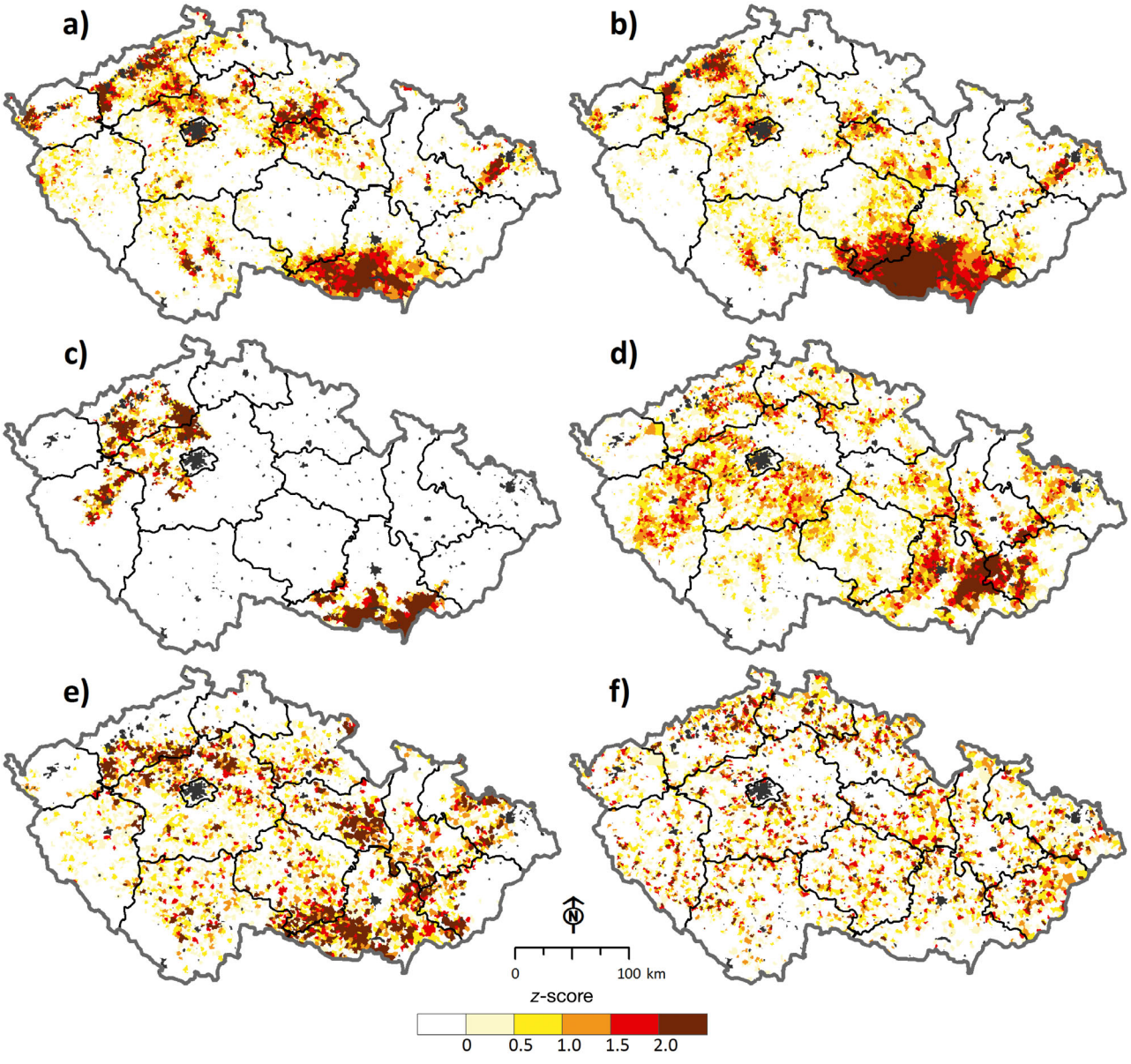

Fig. 4. Hazard indicators expressed as *z*-score at the cadaster unit level: (a) days with water stress in the topsoil (0–40 cm) in (a) April–June and (b) July–September, (c) arable land in the fast-drying soils category, (d) proportion of arable land within each cadaster unit with erosion rate above permissible levels, (e) proportion of drainage area within each cadaster unit contributing to ephemeral gully erosion pathways from arable land, (f) proportion of cadaster unit area belonging to the contributing area for critical points

concern (Fig. 3d). The problem is particularly pronounced in the southeast of the country (albeit in different regions than those affected by drought and fast-drying soils), as Fig. 4d indicates. In each region, one can find 'hot-spots' that are at a markedly greater risk of sheet erosion than the surrounding areas but without a notable 'center', as in the case of the southeast region. On the other hand, the lowest hazard level (apart from areas already listed) is found in the southwest (Fig. 4d).

Compared to the hazard of sheet erosion, the hazard posed by ephemeral gully erosion is more evenly spread across the country. The identification and plotting of potential paths of concentration runoff were based on the modeling of flow accumulation from their collection (contributing) areas, interpretation of the nature of the terrain and a visual interpretation of aerial photos for the affected fields of arable land. We identified >29 000 paths of potential ephemeral gully erosion (pathways for concentrated flow)

with a total length of nearly 11 963 km, and for each ephemeral gully erosion path, the contributing area of the arable land was calculated. It is obvious that in some cadasters, the contributing areas are very high (over 200 or 300 ha), indicating potentially large water flows in cases of extreme precipitation (Fig. 3e). Compared to the areas affected by sheet erosion, the areas where ephemeral gully erosion hazards are the greatest tend to be more concentrated, creating an 'arc' in the east of the country and then a 'belt' in the northwest. Using the USLE, land users often underestimate erosion on agricultural fields because it does not account for the loss of soil from ephemeral gullies. It is estimated that ephemeral gully erosion is responsible for up to 20–40% of the total volume of the sediment from erosion. This is approximately the same magnitude as that of sheet erosion, and has thus far not been accounted for in any hazard analysis. Bennett et al. (2000) presented estimates for the percentage of total soil loss from agricultural watersheds due to ephemeral gullies ranging from 20 to 100%.

While there is currently no method in the Czech Republic for identifying and predicting the occurrence of sediment delivery from this type of erosion, it needs to be seriously considered, due to its share of the total erosion rate. It is obvious that high erosion rates caused both by sheet and ephemeral gully erosion are, in combination with frequent droughts and unsuitable agronomy practices, the leading causes behind the gradual spreading of the presence of fast-drying soils.

3.3. Localized floods originating from agricultural land

Analysis of the hazard posed by local floods originating from arable land included 6248 municipalities across the Czech Republic, with >35 437 intersections of potential water flow paths with built-up area boundaries, and 9261 were identified as critical points and thus potentially dangerous (Drbal 2009). In total, the contributing areas of these critical points constitute >23% of the total area of the Czech Republic. For the analysis, the proportion of agricultural land in each cadaster unit that belongs to the contributing area of a so-called 'critical point' (hazard profiles of flash flood risks on boundaries of built-up areas) was considered as the indicator. Unlike for sheet or ephemeral gully erosion, other agricultural land use apart from just arable land was considered in this analysis. Out of all the indicators, the results from this analysis show that the hazards due to flooding are the most evenly spread across the country (Fig. 3f), and it is not possible to pinpoint any particularly vulnerable regions (Fig. 4f). It is critically important that this hazard be included, as it leads to direct threats to property (Fig. 2) and human lives, and could be at least partly addressed by proper agronomic practices.

3.4. Combining the individual hazard indicators

The percentage of territory where the hazard level is highly above average or worse is 8% (Fig. 5a). Within the multi-criteria analysis, we simultaneously examined how a large part of the territory of the Czech Republic meets at least one of the criteria for an extreme degree of risk (Fig. 5b). This combined approach provides, in our view, a good overview of the areas where the hazard level is significantly higher than the rest of the territory. The last step of this analysis was to define the territory that may be considered to be at a particularly high risk. As such, we considered a territory where the average value of the z-scores was >1.5 and/or where at least 2 criteria had z-scores >2.0 to be at a high risk. These criteria are met by 4.5% of the territory in the Czech Republic. The percentage is slightly higher when 4th-order river basins are used instead of cadaster units due to a higher mean basin area within the regions with the highest risks. As Fig. 5c shows, 2 areas can be pinpointed as the most at risk. These most vulnerable regions constitute areas where attention and resources should be given the highest priority. This analysis should be taken as an attempt to provide an objective approximation of the most vulnerable regions, and it should be stressed that similar results were found when only 4 indicators were applied (omitting ephemeral gully erosion and combing the 2 drought-day indicators into a single indicator) or when basins were used instead of cadaster units. While there was a great deal of general agreement between the individual approaches, the local differences between the versions suggest that local knowledge should also be applied and that the delimitation of the endangered areas should be inclusive rather than rigid.

The multi-criteria analysis presented here tries to define particularly endangered areas in the Czech Republic in terms of drought hazard and exposure to the risks of erosion (Fig. 6). This analysis indicates relatively 'typical' hazard areas, which include the regions of northwest Bohemia and south Moravia. Northwest Bohemia in particular is at risk from hydrological drought, and these areas have the smallest

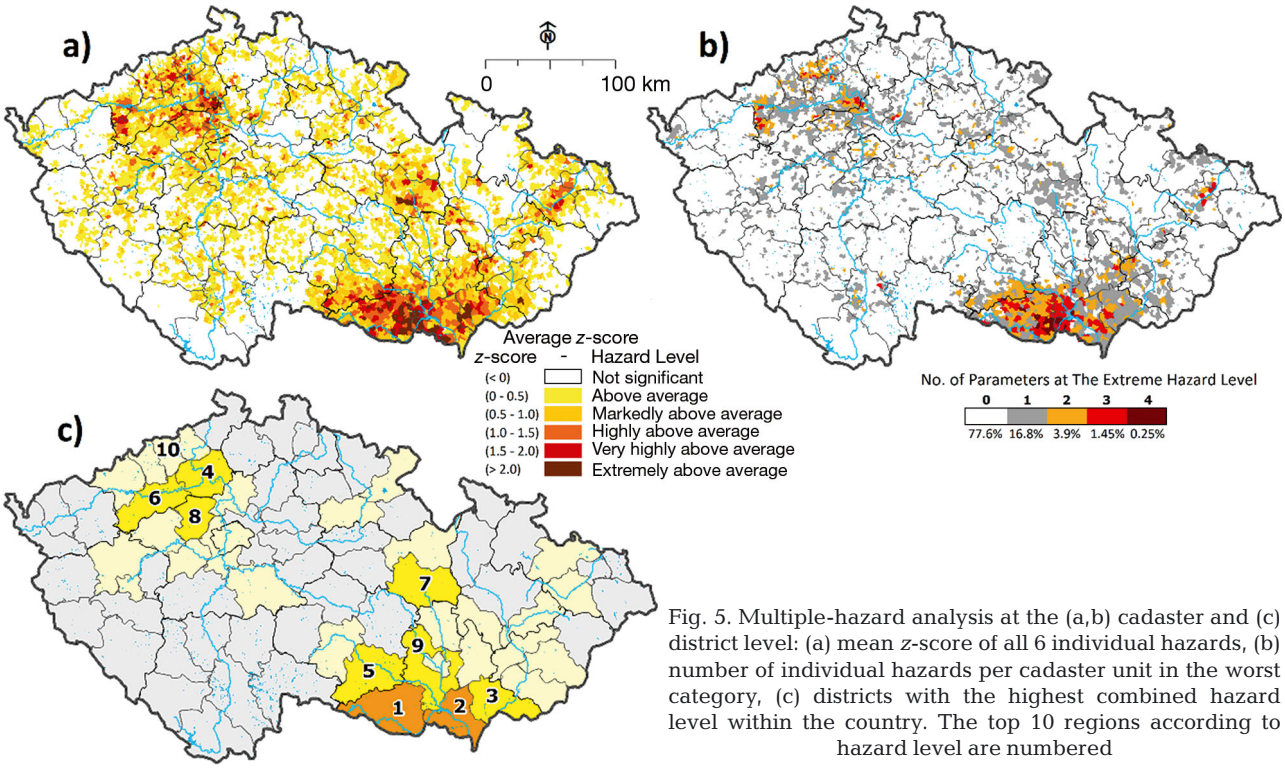

Fig. 5. Multiple-hazard analysis at the (a,b) cadaster and (c) district level: (a) mean *z*-score of all 6 individual hazards, (b) number of individual hazards per cadaster unit in the worst category, (c) districts with the highest combined hazard level within the country. The top 10 regions according to hazard level are numbered

availability of water resources. These territories also have agroclimatic conditions typical of the corn and sugar beet-growing regions (Fig. 6b) that include the most fertile regions of the country. At the same time, the cadaster units identified as the most vulnerable using the multiple hazard approach show only a 10% overlap with the presently defined LFAs, as Fig. 6a indicates. LFA is a term used within the EU (and defined according a set of EU-based criteria) to describe an area with natural handicaps (lack of water, climate, short crop season and tendencies of depopulation), or that is mountainous or hilly, as defined by its altitude and slope. As the LFAs are defined through the use of more or less common European criteria, it leads to a paradox whereby the regions with the highest combined hazards from drought and soil degradation receive significantly less support than the LFA areas. As LFA regions have seen significant improvement in their agroclimatic conditions and overall productivity thanks to climate change over past 2 decades, it has led to an imbalance that the LFA introduction has attempted to rectify.

3.5. Change in climate conditions

The estimated risks posed by the hazards discussed here are not likely to remain stable in the near future. We demonstrate this in the case of the number of drought days in April–June for the period 2021–2040, assuming an RCP 4.5 emission scenario that predicts a fairly modest increase in CO_2 concentrations. All 5 global circulation models show a marked increase in *z*-score levels compared to baseline (Fig. 7). The rate of occurrence of the most extreme level (*z*-score >2.0) is, under the baseline climate, 5.7%, and the average for 2021–2040 is estimated at 14.2% (with the range of the 5 GCMs considered being 10.9–20.1%), which is an almost 3-fold increase in the frequency of this most extreme category. Such changes would mean profound increases in the overall drought hazard. In the southeast, the expansion of the highest hazard area occurs in a northward direction, while in the west, the expansion covers the Elbe River lowland. Both areas are presently considered to be the most fertile regions in the country. An additional factor of concern is the occurrence of drought 'spots' across the entire country, with the only exception being the northeast region. The increased incidence of drought in these sites is driven primarily by a lower soil water-holding capacity. These results indicate that hazard levels are not static and are likely to change in the future. In addition, this dynamic (i.e. hazard levels in relation to climate change) must be considered when areas most at risk are defined. What was surprising, how-

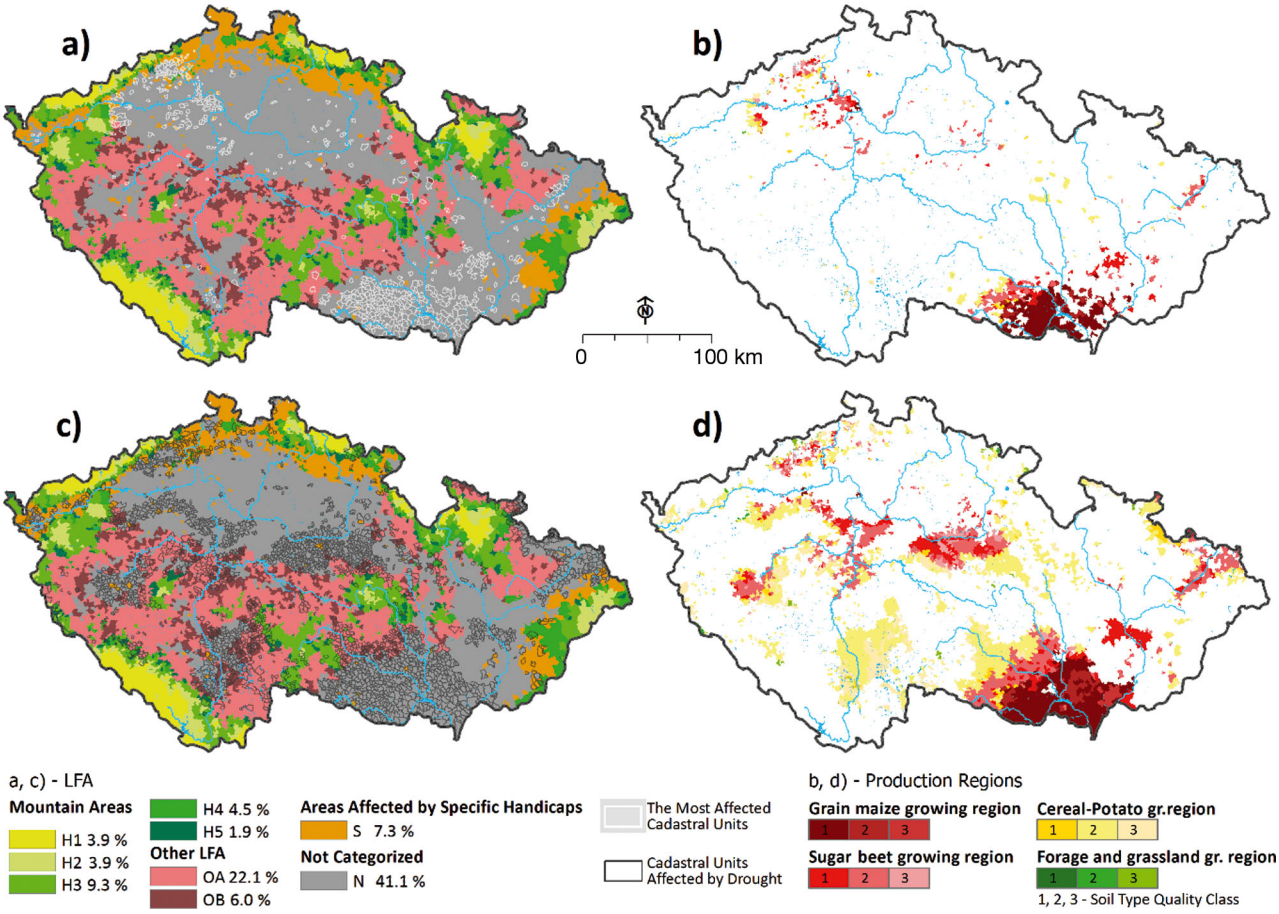

Fig. 6. (a,b) Drought risk and (c,d) multiple hazards. Comparison of cadaster units most at risk from (a) drought and (c) multiple hazards with less-favored areas (LFAs). Agroclimatological production regions belonging to cadaster units with (b) high drought and (d) multiple hazards. Areas marked H1-5 are limited by the altitude and slopes; areas OA and OB by slopes and soil conditions; areas marked S are primarily limited by need to protect water resources

ever, was the magnitude of the predicted changes that could occur over such a short time-frame in the near future. The probability of extreme drought increases considerably under predicted future climate conditions, and these changes may occur much more quickly than is generally anticipated. This leaves relatively little time for a response.

3.6. Uncertainty in hazard classifications

Apart from the presented approach using the 6 hazard indicators and cadaster units, 2 other approaches were tested. One relied on only 4 indicators (drought stress was considered for the entire April–September period, and gully erosion was omitted), and we also considered using 4th-order catchments instead of cadaster units. The use of 4 indicators would increase the weight of each one, while making the approach simpler. The overall area affected by the highest risk levels was slightly smaller but was consistent with the finding presented above (this paragraph). However, it was felt that drought effects in particular were underestimated when using only 4 indicators. As Fig. 4a,b shows, there are considerable differences between the drought hazards in the periods April–June and July–September. When these 2 indicators were considered as a single April–September indicator, some of the areas with known and persistent drought hazards in the northwest of the Czech Republic were left out of the evaluation. Similarly, not including ephemeral gully erosion as a factor led to the omission of some areas where major damage has occurred, as documented in Fig. 2.

The analysis presented here shows the urgent need for explicitly accounting for climate change. This is fairly easy in the case of drought-day-based indicators, as the methodology is flexible and de-

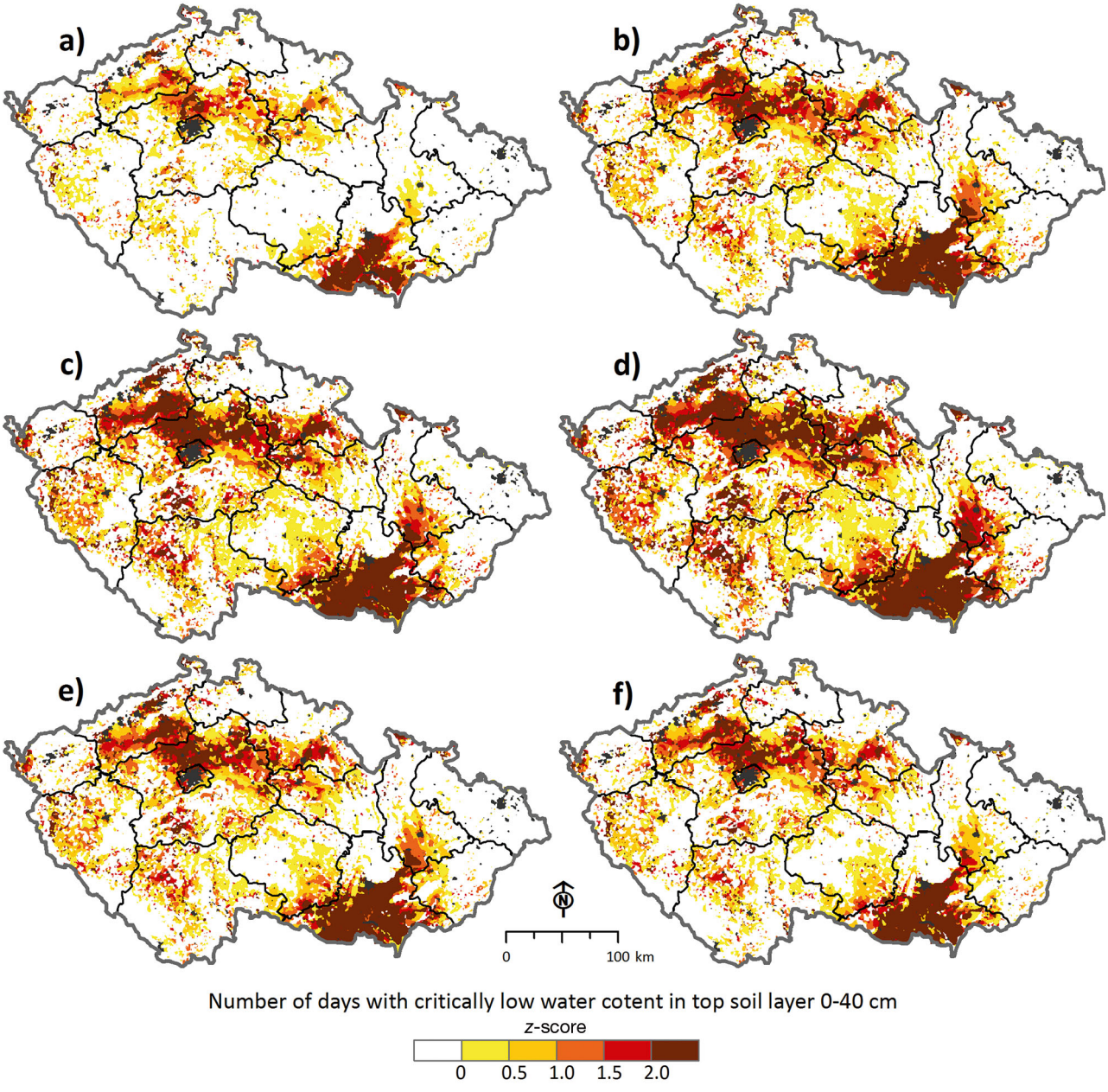

Fig. 7. Hazard of water stress in April–June in the topsoil (0–40 cm) expressed as *z*-scores at the cadaster unit level. (a) The period 1991–2014 was used as the baseline, and *z*-scores for (b–f) the period 2021–2040 were estimated from this baseline. The following models are represented: (b) IPSL, (c) HadGEM, (d) MRI, (e) CNRM, (f) BNU (see Section 2.5 for abbreviations)

signed to handle the effects of climate change (e.g. Trnka et al. 2015a). However, it will be more of a challenge for the remaining 4 indicators. In the case of fast-drying soils, the dynamics of persistently drying soil profiles speeding up soil degradation should be accounted for. Similarly, in the case of sheet and ephemeral gully erosion, changes in the probability of major precipitation events need to be considered, as do changes in the phenological calendar. While there is a general view that the occurrence of higher-intensity events is more likely under future climate conditions (increasing the potential erosion from each event), there is also clear data from previous studies showing the protective effect of vegetation cover. All of these factors need to be analyzed and researched prior to conducting multi-hazard assessments for determining the effects of future climate conditions.

3.7. Analyzing water resources in areas with the highest hazard

The Czech Republic is situated in a region with annual precipitation that ranges from 450 mm in dry regions to 1300 mm in mountainous regions; however, as the country is located on the continental divide, its water resources are driven primarily by rainfall. Previous research (e.g. Hlavinka et al. 2009, Trnka et al. 2012) has shown that areas with considerable lack of water in the top layer of the soil might hamper agriculture, as yields are closely related to the water balance (e.g. Hlavinka et al. 2009, Trnka et al. 2012). Occasional water shortages do not usually result from the overall unavailability of water resources, but rather from the spatiotemporal variability of water supply/demand and the high degree of water resource exploitation.

However, as Hanel et al. (2012) and Trnka et al. (2015b) have indicated, water availability is likely to change due to the projected changes in temperature and precipitation (i.e. an increase in temperature over the whole year and no change in annual precipitation, but with a decrease in precipitation in the summer and an increase in winter). Fig. 8 shows interactions between shifts in rainfall amounts and evapotranspiration. Higher precipitation totals are more than matched by the increase in actual evapotranspiration, as estimated with the BILAN model (Vizina et al. 2015). In summer, although precipitation decreases, the increase in actual evapotranspiration is not as large as would be expected from the increase in temperature (and hence potential evapotranspiration), because it is limited by available water. The observed changes in the difference between precipitation and potential evapotranspiration are shown in Fig. 8 and are becoming more negative in spring and summer.

Trnka et al. (2015b) and Hanel et al. (2012) used different approaches, but agreed on changes in the amount of water fixed in snow. This influences both runoff and the speed of the snow melt, and underground water recharge. An important factor for the changes in runoff is a shift in the snow melt from early spring to winter.

The combination of reduced precipitation and increased temperature leads to measures that attempt to protect water resources. Practical experience indicates that the most robust and effective measures are those that increase the water supply (in our case specifically, the reconstruction of old — or the design of new — reservoirs or water transfer systems) in high-hazard areas.

3.7. Using multi-hazard analysis results in land consolidation process

The approach developed in this paper can be used in the process of land consolidation. It is a multifunctional tool for sustainable development of the land. Land consolidation spatially and functionally arranges the land in the public's interest and consolidates or splits parcels while ensuring its accessibility. Land consolidation provides the conditions for improving the environment, land resource protection, and water management and for improving the ecological stability of the landscape. Land consolida-

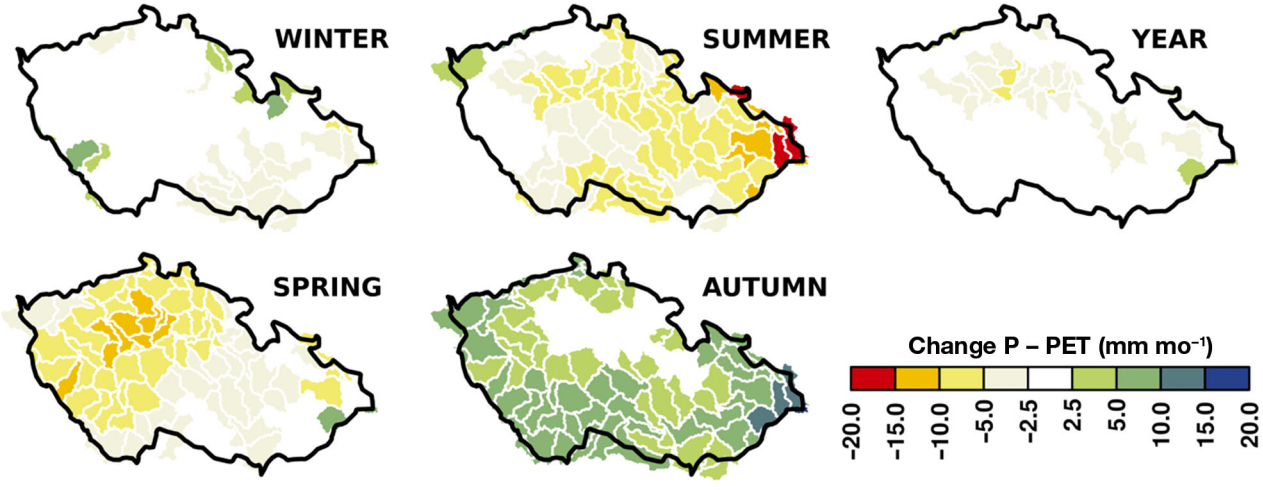

Fig. 8. Changes in observed difference in precipitation (P) and potential evapotranspiration (PET) between the periods 1961–1980 and 1981–2005 for 3rd-order river basins

tion is performed pursuant to Act No. 139/2002 Coll.

This consolidation is the only process in the Czech Republic to solve complex issues in rural areas, including the realization of measures that are in the public's interest. It also addresses considerable issues relating to the property of citizens and legal entities. Therefore, it is obvious that this complex set of issues cannot be managed without objective sources of information. The identification of the most vulnerable areas in the Czech Republic through a multi-hazard analysis is an important source of information in guiding the prioritization of the land consolidation process and its spatial targeting for the State Land Office. In this way, the State Land Office will receive unique material that can be used to improve their ability to mitigate the impacts of climate change. In addition, it will be able to effectively participate in the establishment of a legislative and economic framework that could possibly realize adaptation measures acceptable to agricultural entities.

4. CONCLUSIONS

The mapping of multiple hazards for agricultural land is intended as a first but crucial step in the assessment of the vulnerability of the agricultural sector to the occurrence of drought and extreme precipitation events under the present conditions and under the predicted future climate conditions in the Czech Republic. The map presented here synthesizes a variety of data and serves as an indicator of areas deserving more detailed attention. The key hazards for agricultural land in the Czech Republic include the occurrence of water stress in the topsoil layer during both the first and second half of the growing season, the proportion of fast-drying soils, the risk of sheet and ephemeral gully erosion and the risk of local floods originating primarily from agricultural land. The generation of *z*-scores was used as a standardization method, and a combination of an equal-weighting scheme and *z*-scores below −2.0 signaling the most extreme values were used in drafting the final output map. The final output map also shows results aggregated at the district level to clearly mark regions where primary attention should be given to reduce the level of the hazards and/or to increase cropping capacity. These regions are concentrated in the southeastern and northwestern lowland areas. As for typical areas with the highest hazard levels, we can identify regions with below-average precipitation and a high proportion of soils with a degraded or naturally occurring low water-holding capacity, and those with steeper than average slopes and terrain configurations in relatively large catchment areas that have urbanized landscapes located at their lower elevations. This study also allows for the definition of cases in which data quality limits the usefulness of such hazard mapping. While state of the art digital elevation models were used, the information on the actual soil status had to rely on data from complex soil surveys carried out in the 1970s. While these data have been constantly updated, the last comprehensive campaign completely assessing soil status was carried out approximately 40 yr ago. As the next step in this research, farms in the areas with the highest hazard levels were selected as sites to conduct detailed and thorough assessments of the hazards present and to perform a complete vulnerability analysis. Based on this pilot study of farms and ground-level validation of the concept, a national vulnerability map will be prepared that will also include social aspects of vulnerability.

Despite some limitations, the methods presented in this paper serve as a step forward in developing techniques for reducing hazard levels at the individual cadaster unit, especially in the process of land adjustment, which aims at improving the organization, productivity and sustainability of agricultural production and the optimization of ecosystem services. Our results also point to the fact that the present definition of the LFA does not match the areas threatened by increased drought and erosion hazards, and that other mechanisms should be introduced to support sustainable and viable farming in these regions. This is especially important given that many of the areas at considerable risk are in the regions that are nominally the most productive land in the country and that have the highest taxes levied per hectare of land and the lowest level of support. As we have also shown, ongoing climate change will considerably change the hazard levels compared to those present today. Drought and soil loss are likely to become even more dominant factors affecting production in the future, and therefore, the adaptation of the agrarian sector to these coming conditions is critical. In addition, understanding the present hazard levels can and should lead to adjustments in agricultural practices and to the selection of more appropriate cropping patterns to obtain maximum financial yields during years with normal precipitation, and to reduce declines in crop yields and income loss during drought years, while at the same time conserving the soil. The multiple-hazards map presented here can help decision-makers visualize hazards and communicate them to farmers, natural resource managers

and others. The education of the Czech Republic's decision-makers about these multiple hazards has already begun, and includes both grassroots as well as responsible decision-makers, both in the executive and legislative branches of the government.

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Editorial responsibility: Donald Wilhite (Guest Editor), Lincoln, Nebraska, USA

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